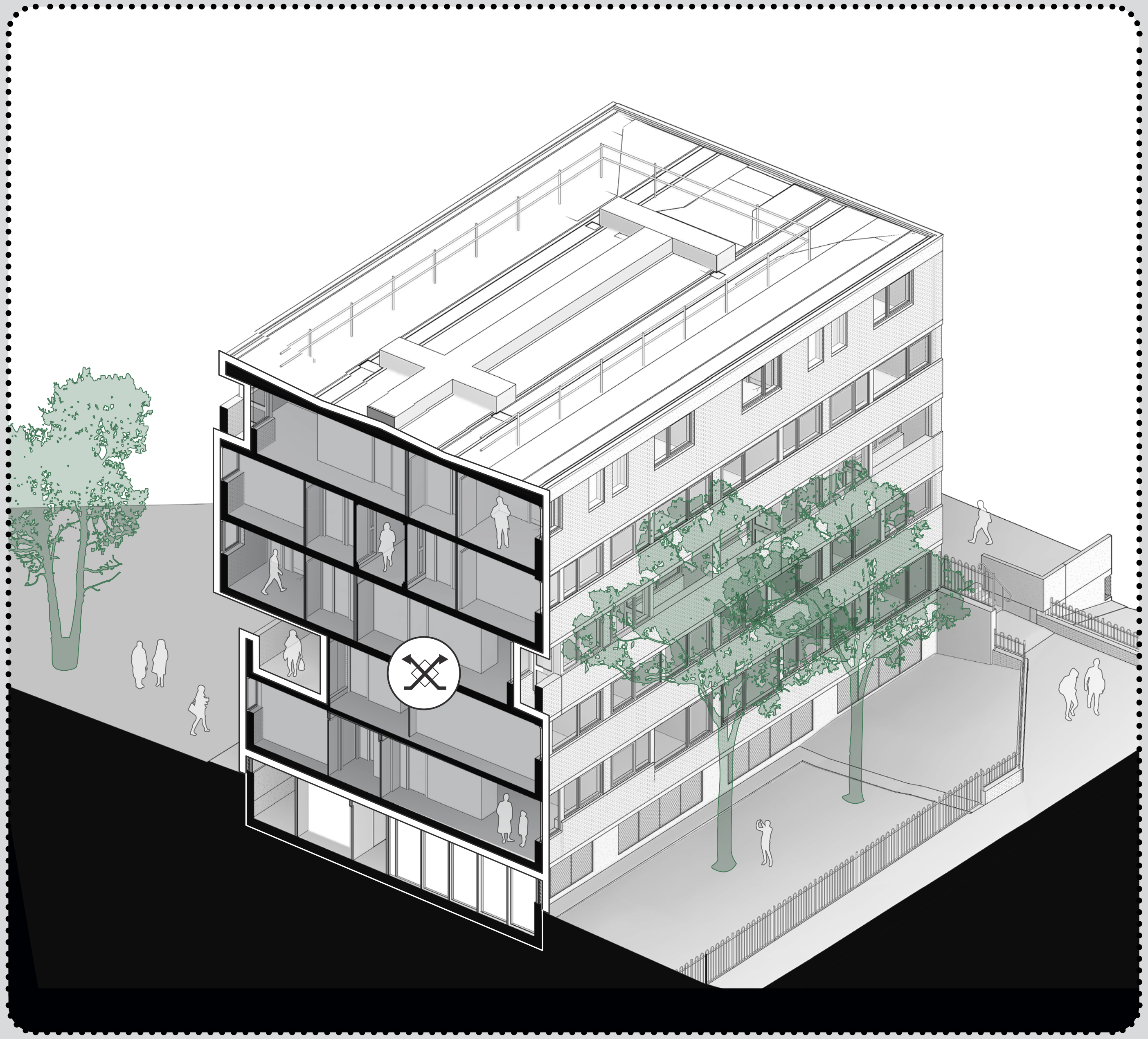
Perkins&Will Research

LIFE CYCLE IMPACT OF RETROFITS

a method to identify optimal retrofit measures based on their life cycle impact and cost, presented through a case study



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Innovation Incubator, London 2022

INTRODUCTION

The potential retrofit market in the UK is vast due to the amount of retrofits required to meet the 2050 Net Zero challenge. There are 1794 registered social landlords according to the Greater London Authority, all of which have a spend budget to upgrade their housing stock. Proposing appropriate measures to improve the performance of the existing housing stock and reduce the carbon footprint may seem like a straightforward task, usually driven by local legislation and existing standards. However, elements that reduce operational energy may be extensive and/or contain a high amount of Life Cycle Carbon which may actually result in increasing the total Carbon that the building will emit over its Life Cycle. This evaluation can usually only be conducted at detailed design stage or later, after decisions on implemented measures have already been made.

The proposed methodology presented in this document can be used in briefing/ concept design stages of retrofit projects, where the evaluation and balancing of different measures need to be quickly identified to set out the scope. There is currently no known tool on the market that can assemble data in the correct format required to evaluate a retrofit in this manner.

By having an established methodology, a better level of service can be provided to clients with a quick evaluation of different schemes. Housing schemes which are usually low in architectural fees, can be particularly benefited from a schematic evaluation method which will reduce the amount of abortive work and prevent delays in the detailed design phase or later. Applying this method can achieve a better income stream for the office and make more efficient use of consultant fees for hard pressed social registered landlords with tight construction spend budgets. It is hoped fewer schemes would mean those that are delivered would be of a higher specification, quality, and satisfaction to residents who may currently go through numerous consultations before projects are delivered.

The proposed method allows the evaluation of single or multiple features within a project to be evaluated quickly and demonstrate where the optimum values lie. This would provide proof of concept and a further iteration could use primary carbon data models or future climate tapes to show how the material optimization would change over time to allow the client to evaluate risk over a larger timescale.

THE CASE STUDY

The London studio is currently working on a housing estate retrofit project. The retrofit is focused on improving energy performance, comfort, and carbon footprint with various measures including external wall insulation, roof insulation, windows, PVs, switch from Gas to District heating system, etc.

Due to perceptions of fire safety, the client brief also requires that no combustible materials are used, including timber, and many measures will likely require heavy-duty steel frames in order to be implemented, due to existing structure limitations. No holistic analysis has been conducted so far, on the environmental impact, cost, need or required extent of these measures in a Life Cycle perspective.

The client is making decisions without adequate understanding or knowledge of the balance between cost, carbon, and energy. Decisions are rather based on fragmented sources of information produced by different consultants and different methods, that focus on meeting specific requirements of local legislation without investigating optimal solutions for the project's energy performance and carbon emissions.

A decision-making process like the one presented in this document could have enabled different approaches and interventions to be assessed and discussed with the client early-on in order to make informed decisions and prevent abortive work.

ABSTRACT

The methodology presented in this report is developed to assist refurbishment projects in the early stages to establish a sustainable retrofit strategy. Through an analysis of the energy efficiency, life cycle carbon and cost of various retrofit measures, the method can give guidance on what measures should be pursued in a project and which ones should be avoided. The method is presented though a case study, based on an actual residential refurbishment project, but it is appropriate for any building typology.

The presented method should be used in early design stages, such as RIBA Stage 0-2 in the UK, where the refurbishment strategy has not yet been established, and therefore materials, suppliers, construction methods etc. are largely undefined. This gives the analysis great flexibility to investigate various alternatives, but also presents limitations on the accuracy of the inputs used, which are discussed further in the report. Various assumptions described in this report have to be made in order to conduct the analysis but also to reduce the time required and make it a feasible method.

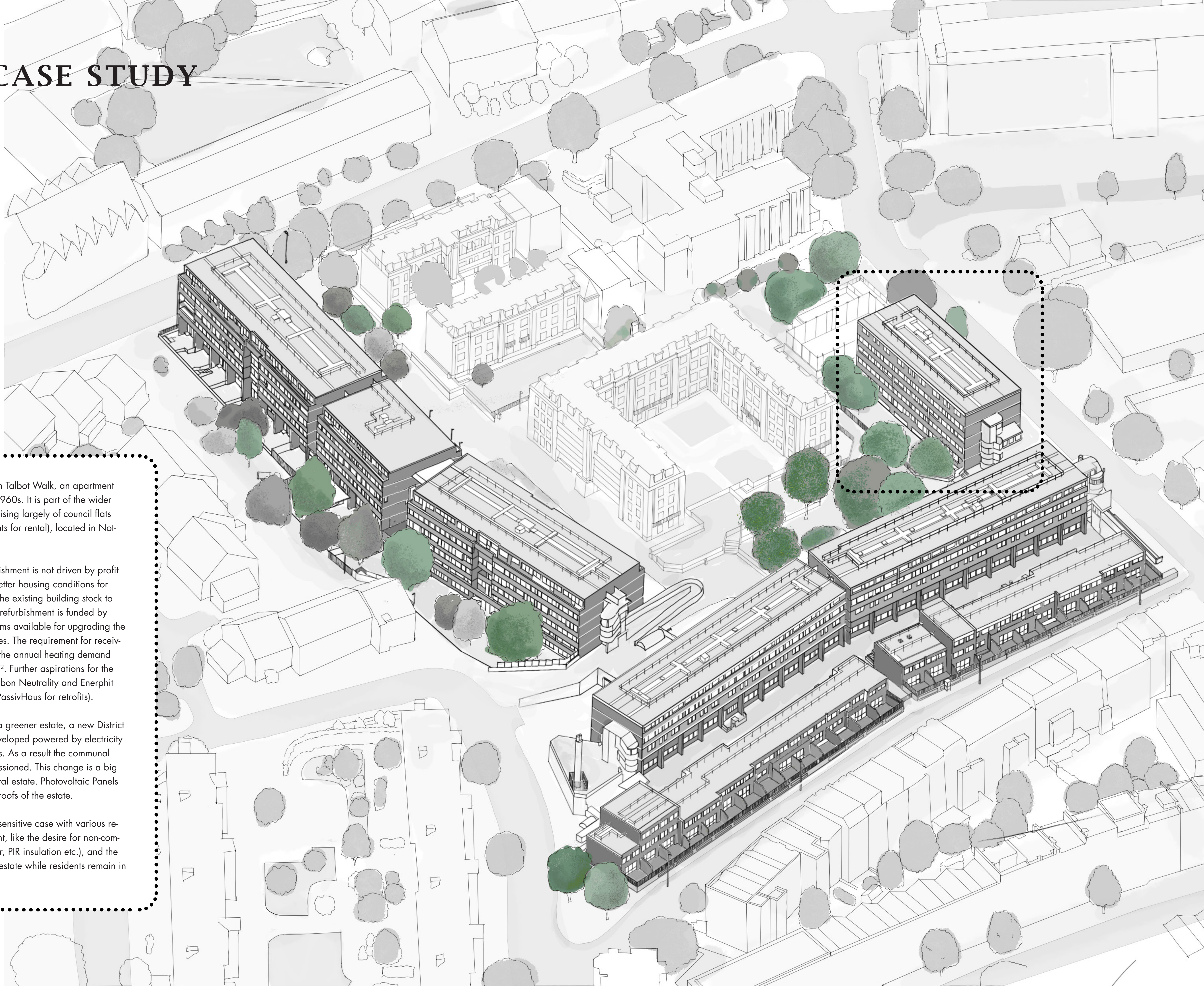
This study is the first step in a sequence of actions that should be taken during the entire design process to ensure that any refurbishment proposal is efficient and feasible. Studies like this one can give confidence to support our proposed strategies, reduce abortive work and direct our clients to the right decisions.

Establishing a sustainable, evidence-based strategy early on is a key part of a successful retrofit which enables client aspirations to be aligned with realistic targets and the budget. The final conclusions of the analysis will need to be verified by consultants and engineers to confirm the results, and refine the measures if required, as more information about the project, construction method and materials becomes available.

The study presented within this report has a limited scope since it is aimed for early design stages. However, the scope could be broadened if needed, and the general methodology could be used for later stages when more information is available.

CONTENTS

1 THE CASE STUDY



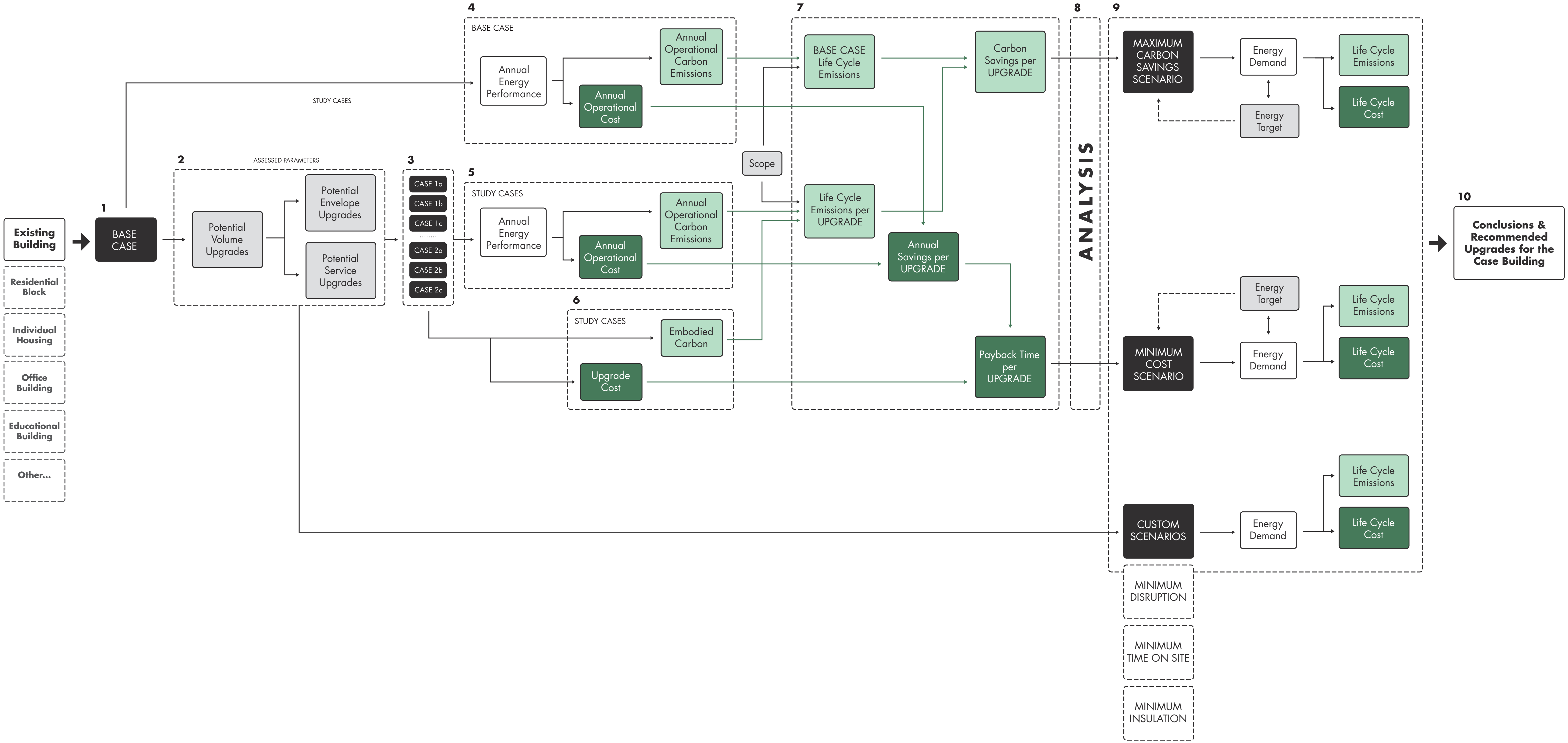
The case study is focusing on Talbot Walk, an apartment building constructed in the 1960s. It is part of the wider Lancaster West Estate comprising largely of council flats (public, affordable apartments for rental), located in Notting Hill, West London.

As a public estate the refurbishment is not driven by profit but by a desire to provide better housing conditions for the occupants and improve the existing building stock to reduce CO_2 emissions. The refurbishment is funded by Government Funding Programs available for upgrading the existing stock of public estates. The requirement for receiving the funding is to reduce the annual heating demand of the building to 50kWh/m². Further aspirations for the estate include achieving Carbon Neutrality and Enerphit performance (equivalent to PassivHaus for retrofits).

As part of the measures for a greener estate, a new District Heating Network will be developed powered by electricity and other renewable sources. As a result the communal gas boilers will be decommissioned. This change is a big step towards a Carbon neutral estate. Photovoltaic Panels will also be installed on the roofs of the estate.

The project is a particularly sensitive case with various restrictions, placed by the client, like the desire for non-combustible materials (like timber, PIR insulation etc.), and the requirement to refurbish the estate while residents remain in their homes.

2 THE METHOD



1 Establish Base Case. Base Case is usually the Existing Building Status, but it could include relevant updates to the existing building which are scheduled to happen and will influence the results (e.g. change of heating system, ventilation, shading etc.)

2 Calculate the Energy performance of the Base Case, Annual Operational Cost and Operational Carbon Emissions. The Energy can refer to any relevant demand like Heating, Hot Water, Cooling, Electricity etc.

3 Establish proposed upgrade measures that will be explored. These can include any possible measures and upgrades and can relate to many aspects of the building (e.g. services, Envelope, Shape, PVs, Shading etc.)

4 Establish the variations of the explored measures (parameters) and organise the study cases. Create models and establish a workflow to run the parametric calculations efficiently.

5 Calculate the Embodied Carbon and Cost of the proposed measures. Carbon and cost per unit or sqm is advised.

6 Calculate the Energy performance, Annual Operational Cost and Operational Carbon Emissions for every study case.

7 Life Cycle Assessment of the Cost and Environmental Impact of the proposed upgrades in terms of Payback Years and Carbon Savings.

8 Analyse the results. Identify the measures that result in the most Carbon savings and the ones that have an acceptable Payback Time.

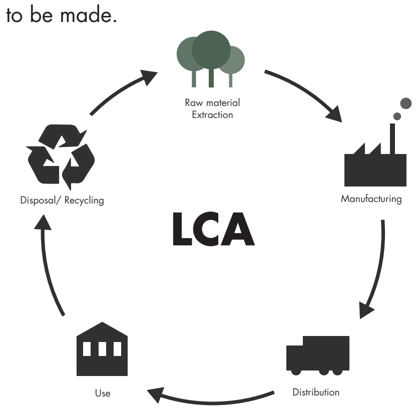
9 Establish the two scenarios of maximum carbon savings and minimum payback time and any other scenarios relevant to the building case. Calculate the Energy Performance of the scenarios to ensure any energy targets are met. Calculate Payback Time and Carbon Savings.

10 Compare the different scenarios and establish the recommended measures for the building.

3 SCOPE & TARGETS

CARBON EMISSIONS

The savings on CO_2 Equivalent emissions will be used as a metric to compare the environmental impact of different retrofit measures. The Life Cycle analysis will include emissions from embodied carbon and operational energy which is part of the Use stage of the building (refer to LCA diagram on the right). The scope for embodied carbon will be Cradle to Gate, A1-A3. The reason is that in early design stages the exact products and construction methods are largely undetermined. In addition, in the analysed case, any building components installed during the retrofit can be assumed to stay on the building till the end of its life, and scenarios for the end of life and disposal of the building are hard to be made.



The Life Cycle can be set to be the building's life expectancy, refurbishment scope (50 years in this case) or vary for different up-grades depending on their lifetime. In this study the Life Cycle is set to be 30 years, which means the project will explore measures to minimise its total Carbon Emissions by 2052.

The reason for the short Life Cycle reflects the idea that we should start reducing the environmental impacts of construction immediately. Any measure taken today to reduce energy will have a positive impact at some point in the future in terms of CO_2 emissions, but to implement this measure we will have to emit CO_2 emissions now which is something we should limit as well.

More importantly, the production of materials used in construction like insulations, aluminium, steel, etc. has multiple environmental impacts besides Global Warming Potential, like, Eutrophication, Acidification, Water use, Ozone Depletion etc. These impacts will not necessarily be offset by the reduction on operational energy and are largely attributed to material manufacturing.

The reason behind this date is also symbolic and aligns with the UK's pledge to be Carbon Neutral by 2050. It is expected that by then the UK's energy production will largely shift to renewable or other alternative energy sources to reduce Carbon emissions fur-ther.

ENERGY USE

The estate will need to achieve at least 50kWh/m² annual heating demand in order to receive the funding for the refurbishment. The study will primarily aim for a 20% lower target of 40kWh/m² to account for discrepancies observed between simulations and actual energy performance of buildings. The potential of the project to achieve the Enerphit target of 20kWh/m² will also be explored.

PAYBACK TIME

The British Building Code suggests that retrofit measures that result in less than 15 years payback time should be pursued.

LIMITATIONS

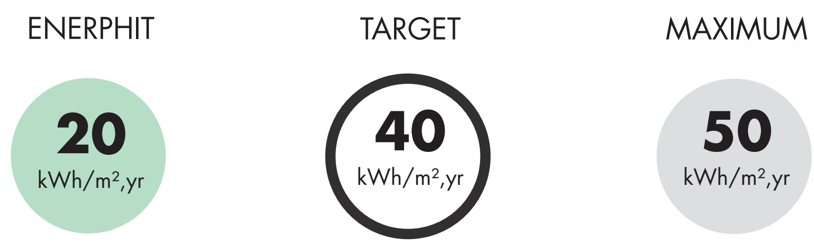
The scope for the Life Cycle materials is limited to a Cradle to Gate (A1-A3) analysis. This a considerable limitation as a lot of the Carbon emission in building construction are emitted from the transportation of the materials and the energy and material use on site to assist construction. Mechanical systems may also consume energy during their life cycle. These impacts are not taken into consideration.

Depending on the stage of a project the LCA scope could be broadened to include A4 and A5 stages to account for Transportation and Construction Impacts. Impacts from the stage use (B) for mechanical systems could also be included if information is available.

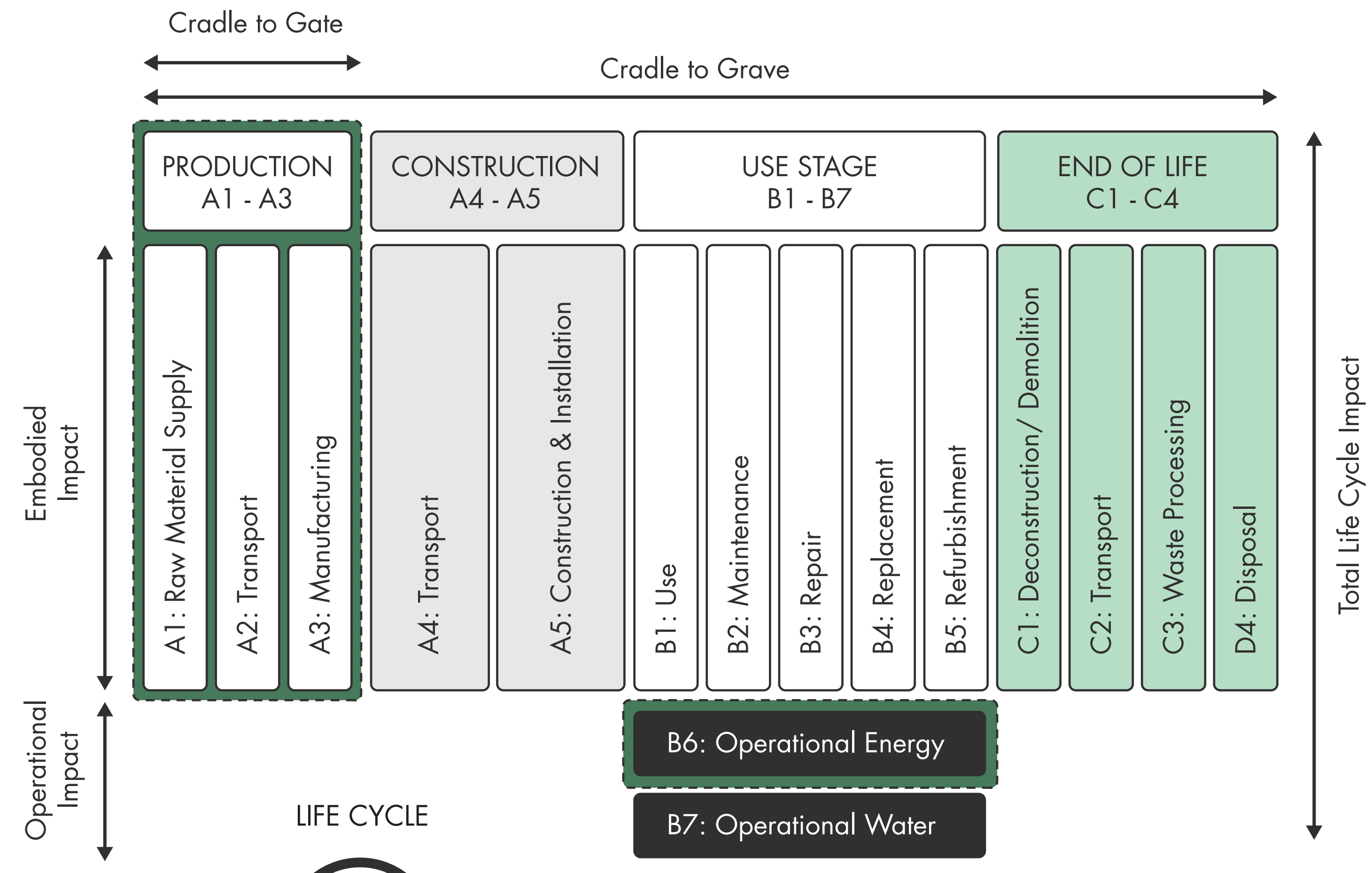
The environmental impacts from operational energy are also assumed to be consistent through the Life Cycle of the building. In many countries and the UK, the CO_2e emissions from electricity will be decreasing due to the implementation of renewable sources. This effect could be included if information is available, but it will increase the number of calculations and time of the analysis considerably.

The scope of this study does not take into account changes in energy prices through the course of the determined Life Cycle. Depending on the number of parameters investigated and available scenarios on energy prices, this can be an interesting aspect to investigate. The Payback Time as a metric it also does not consider the value of money in the future. Net present Value (NPV) could be used if this aspect needs to be investigated. Payback years however is an easier metric to understand.

ENERGY TARGETS



LCA SCOPE



LIFE CYCLE

4 PARAMETERS & VARIABLES

4.1 BASE CASE

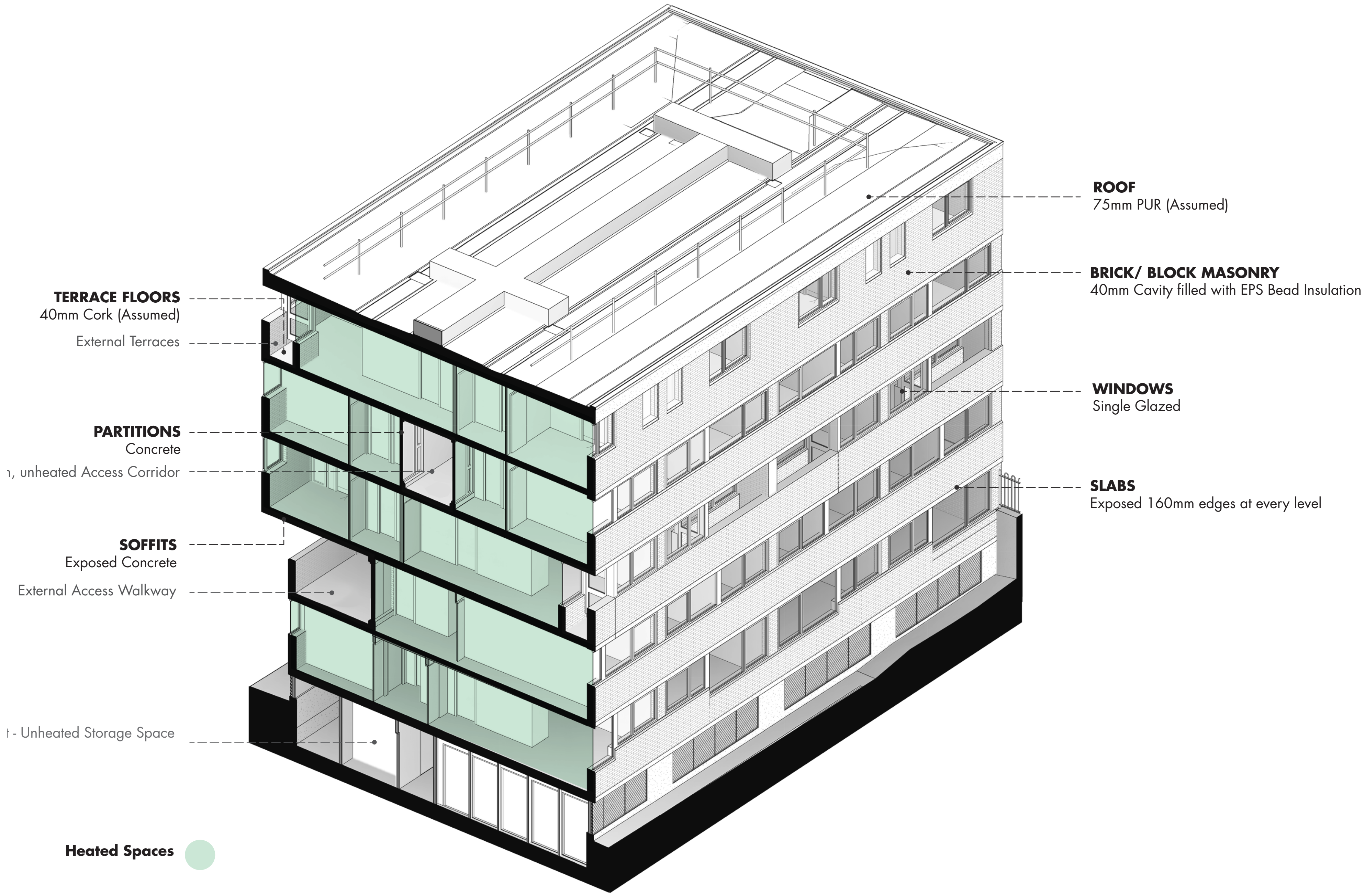
The base case of the study needs to reflect the existing building and be as close to reality as possible. However, measures or upgrades that are going to be implemented to the building and are out of the scope of the project but which are going to affect the overall performance of the building should be included. These could include a change of the heating system, upgrades to the lighting system, change of external doors, change of use, etc.

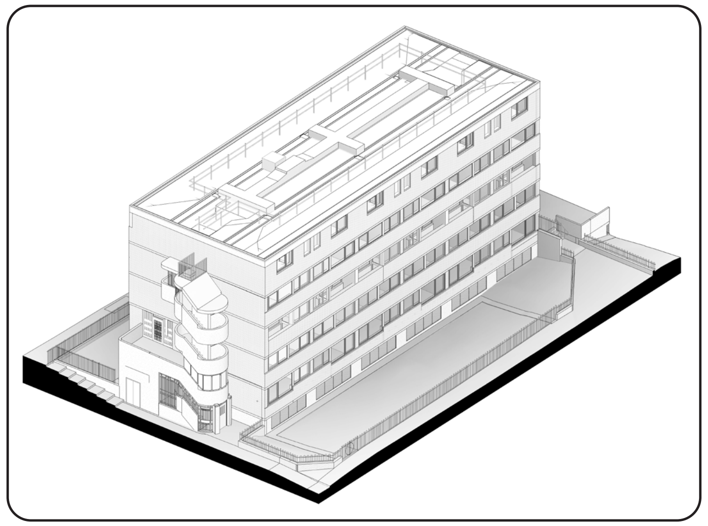
The base case of this study is based on the existing building envelope which is concrete structure with masonry walls and open "aired" access corridors. There is also an un-heated basement which is used as a commercial space for storage.

The existing building has timber single glazed windows and minimal insulation in the roof and terraces from the 1960s. The masonry consists of an inner leaf of concrete blockwork and an outer leaf of brickwork with 60mm of cavity which was filled with EPS bead insulation a few years ago.

The building has no mechanical ventilation system and relies on infiltration and active natural ventilation (residents opening their windows). The airtightness of the building was measured to be approximately 1.3 Air Changes per hour (standard pressure), higher than anticipated.

The estate has a communal gas plant providing domestic hot water and heating through radiators which is scheduled to be decommissioned and replaced with a District Heating System powered by electrical Air-source heat pumps. The new District Heating Network is going to be used as the heat source for the Base Case.





4.2 INPUT PARAMETERS
volume & geometry upgrades

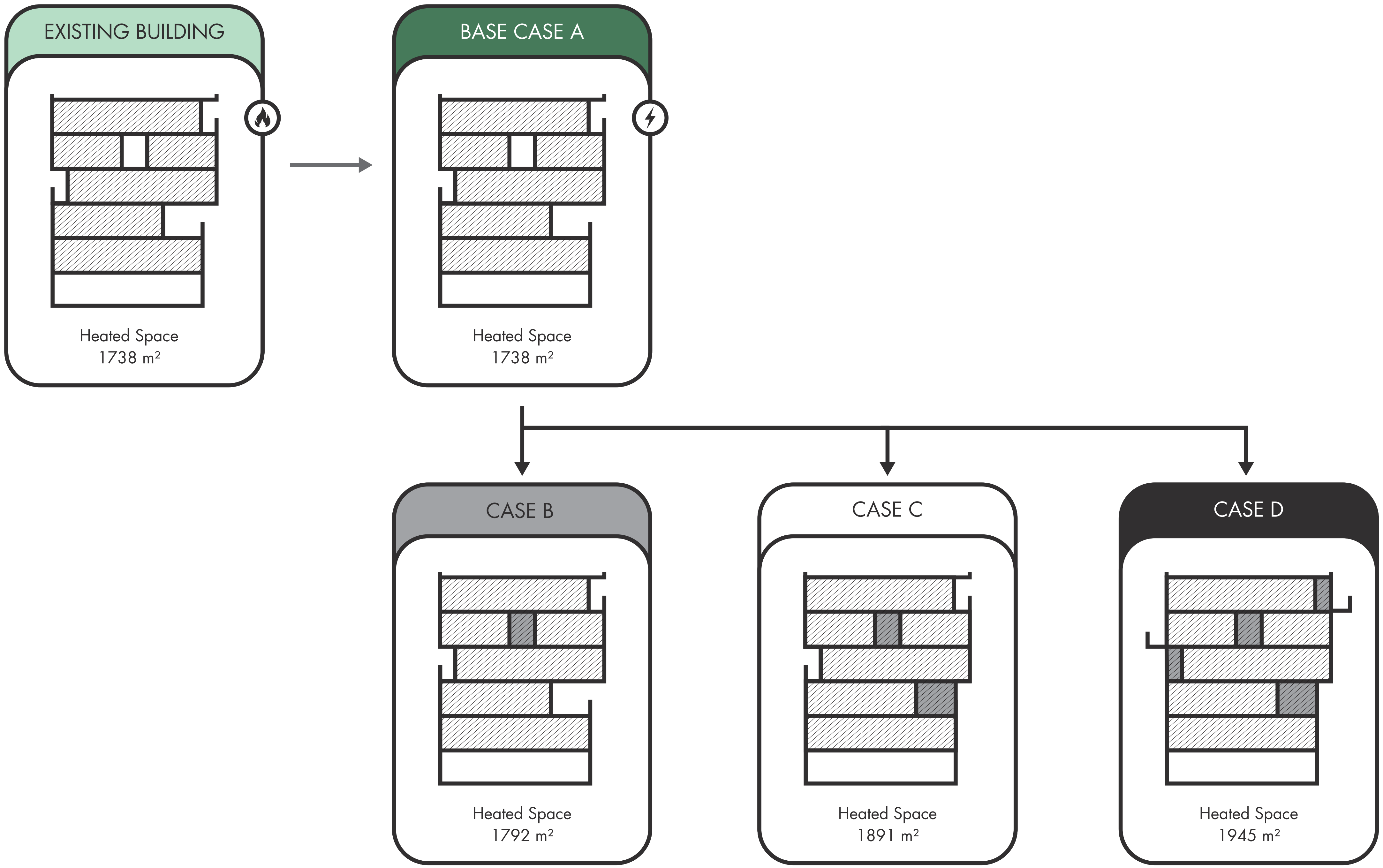
CASES

Case A
The Base Case is based on the existing building conditions. However, the heating source will be assumed to be District Heating with Air Source heat Pumps (Electrical) as this is an upgrade which will happen in the next few years.

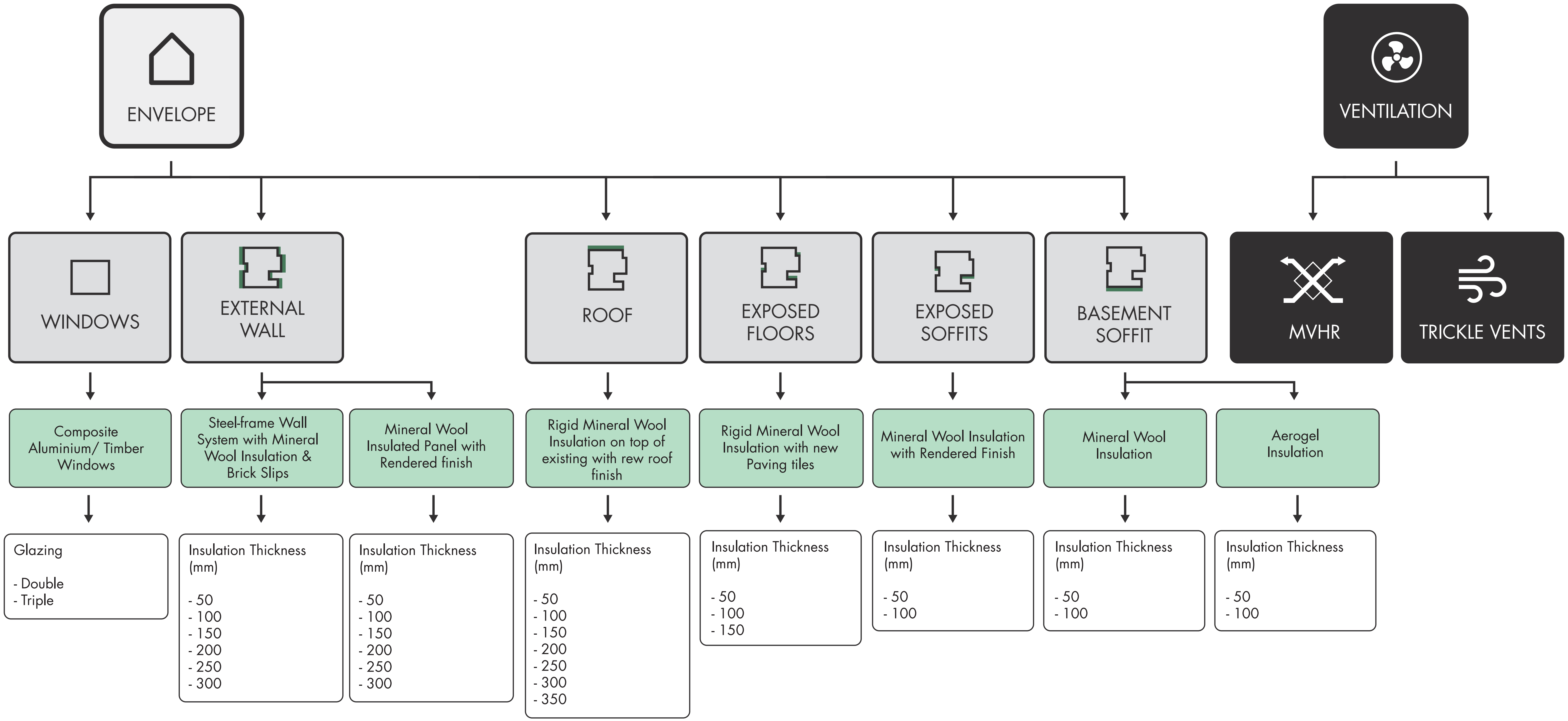
Case B
Internalising the Upper corridor by providing doors to each end is a straightforward solution.

Case C
Internalising the Upper Corridor in addition to the Lower Walkway further simplifies the building shape, providing less surface to volume ratio but at the same time considerable increasing the total heated area of the building by 5%. The walkway also functions as a public outdoor amenity space which will be lost if internalising.

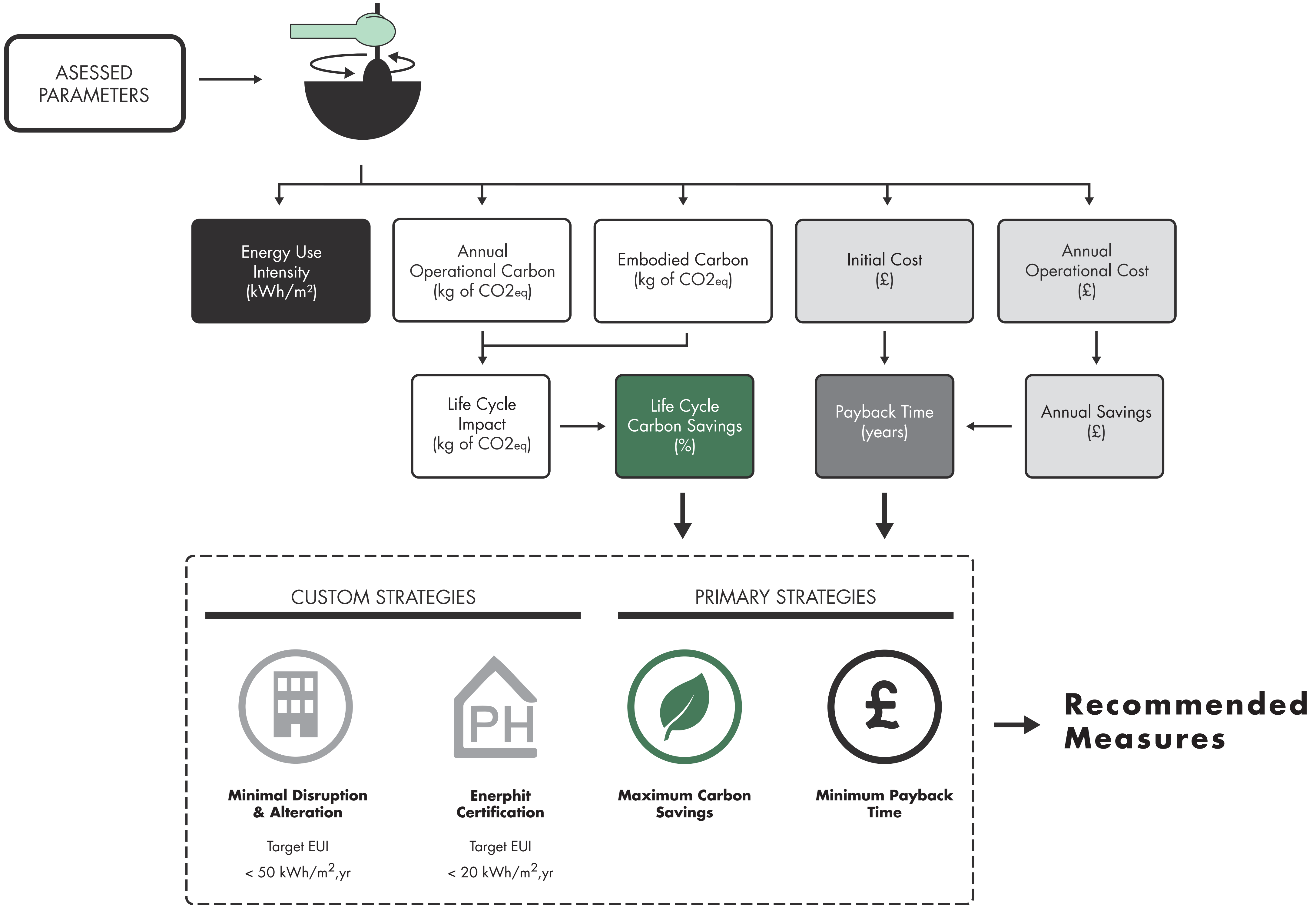
Case D
Internalising the corridor, walkway and terraces provides the most efficient form for the building but further increases the total heated area. The loss of private amenity space is deemed unacceptable by the residents; therefore the provision of external bolt-on balconies is a crucial component of this case.



4.3 INPUT PARAMETERS
services & envelope upgrades



4.4 OUTPUT VARIABLES



Energy Use Intensity (EUI)
The total energy required to heat a building expressed as kWh per square meter of heated space. The energy depends on the COP of the heating system. In this study the energy calculated includes only the ideal loads required to keep the operational temperature of the building to 21°C. Heating energy used to provide hot water and electricity used for any mechanical systems are excluded.

Annual Operational Carbon
The annual Carbon emissions resulting from the energy consumed to heat the building. The emissions are expressed as kg or tons of Carbon Dioxide (CO2) equivalent, which is a measure of how much emitted gases contributes to global warming, relative to CO2. The emissions of every kWh per fuel source was taken from Government sources and it varies by country.

Embodied Carbon
The embodied carbon resulted from the production, construction, use and end of life of a product is also expressed as kg or tons of Carbon Dioxide (CO2) equivalent. In this study, only embodied carbon for the stage of production was considered.

Life Cycle Impact (LCI)
The total of embodied carbon and operation carbon emissions through a Life Cycle or period.

Life Cycle Carbon Savings (LCCS)
The % of total Carbon reduction from the base Case.

Initial Cost
The cost of an upgrade in pounds (£) or other currency. Typical or specific rates per construction or material can be used. Infor-mation can be obtained by a Quantity Surveyor, suppliers, or other sources.

Annual Operational Cost
The cost of the heating energy in pounds or other currency. The energy rates can be obtained from energy providers or websites.

Annual Savings
The annual savings in Operational Cost resulting from implementing an improvement to the building which reduces its energy con-sumption.

Payback Time (PT)
The amount of years it will take to recover the initial cost of the proposed upgrade. It is calculated by diving the Initial Cost with the Annual Savings.

Scenarios
Study cases which combine measures that are found to result to the maximum Carbon Savings, short Payback Time or other factors depending on the existing building case.

Recommended Measures
A range of improvements deemed as the most appropriate for the existing building, combining most Carbon Savings with acceptable Payback Time, and other conditions like energy targets, required by the project.

5 CALCULATIONS & RESULTS

5.1 BASE CASE - ENERGY ASSESSMENT

ENERGY SIMULATION

For the Energy Calculations Climate Studio from Solemna was used. Climate Studio is a Rhino plug-in that can conduct Energy and Daylight Calculations. The Grasshopper version of Climate Studio was preferred to provide easy parametric studies. Other Software like SPEED, can be used depending on the proficiency of the user.

SIMULATION SETTING

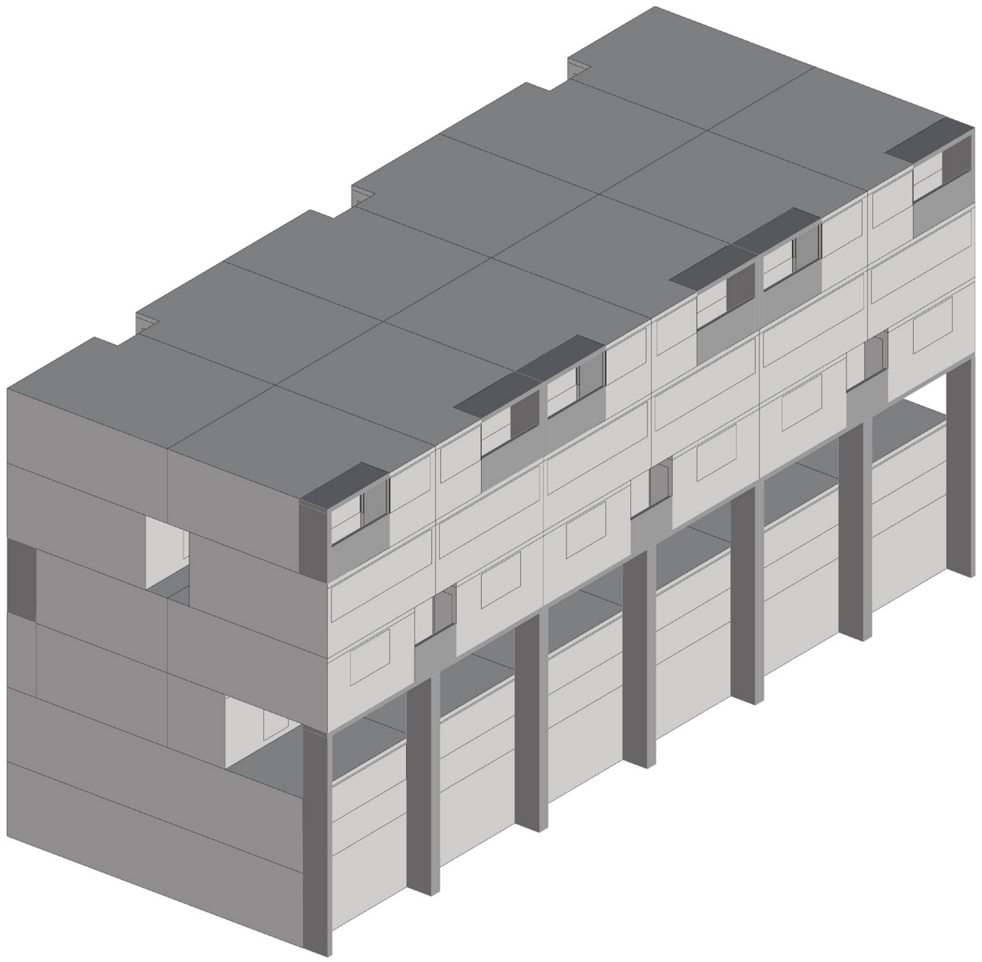
Heated Area	1738 m²
Heating System	District Heating/ Electricity
COP (Typical Air-Source Heat Pump)	2
Temperature Setpoint	21°C
VENTILATION	
Airtighness (as measured)	1.3 ACH
Natural Ventilation	Enebled when > 25 °C
LOADS	
People	0,035 p/m²
Equipment	5 W/m²
Lights	5 W/m²
Schedule	Midrise Apartment
SIMULATION	
Engine	Energy +
Time Steps	4
Climate file (epw)	London Gatwick
Solar Distribution	Full Exterior
U-VALUES W/m2,K	
External Masonry Wall	0.57
External Concrete Wall	3.45
Roof	0.46
Terrace Floor	0.92
Soffits	3.36
Slab above Basement	2.34
Internal Floors	2.34
Internal Wall	2.85
WINDOWS - Single Glazed	
U-value W/m2,K	6
g-value	0.9
Light Transmission	0.9
Operable Area	60%
Frame Area	20%

CARBON & COST CALCULATION

The average Gas & Electricity prices for London were used. The CO2e emissions per kWh for Gas & Electricity were obtained from the Government website (https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020). The cost and CO2e are assumed unchanged for the whole Life Cycle Analysis of this study. Predictions on energy prices or changes in the emissions can be used instead if known.

ENERGY PRICES & IMPACT

Gas price	£ 0.042/kWh
Electricity Price	£ 0.189/kWh
Gas CO2e Emissions	0.12387 kg/kWh
Electricity CO2e Emissions	0.23314 kg/kWh



Annual Heating Demand

117.4
kWh/ m²

Annual Operational Carbon

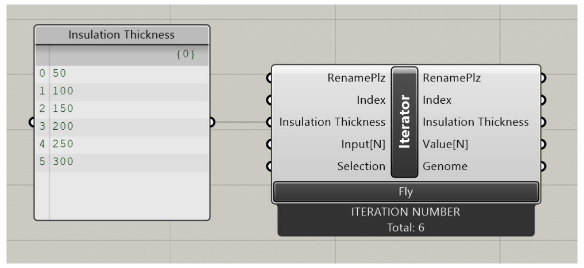
47.6
tn CO2e

Annual Operational Cost

38.6
x10³ £

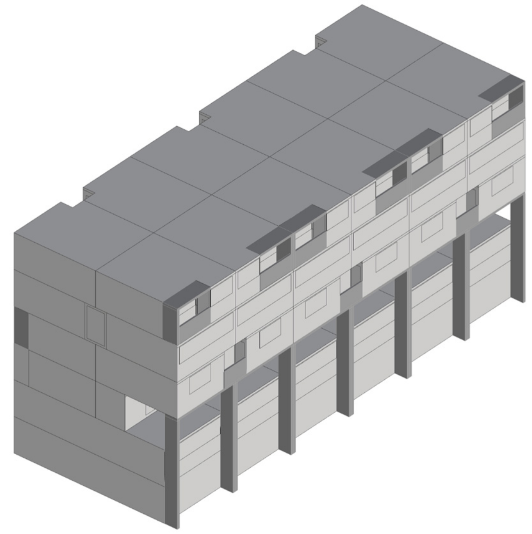
5.2 STUDY CASES - ENERGY ASSESSMENT

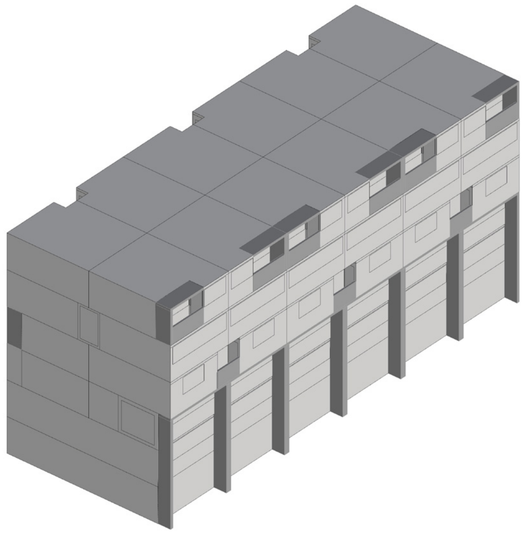
The impact of every upgrade in the energy, cost and carbon emissions is assessed individually. Grasshopper plug-ins like Human provide components that can speed-up the calculation of multiple iterations. All results were compiled in Excel where the final calculations were conducted.

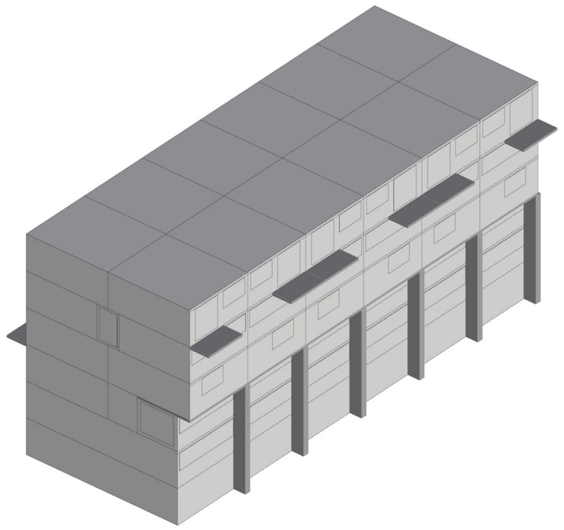


SPECIFIC SIMULATION SETTING

Heated Area	Variable as per Case
Heating System	District Network/ Electricity
COP	2
VENTILATION	
Airtighness	1.3 ACH
Natural Ventilation	Enabled when > 25 °C
Window Operable Area	60%
Trickle Events	0.3 L/s/m²
Mechanical Ventilation	0.3 L/s/m²
Heat Recovery	85%
Improved Airtighness with new windows installation	1 ACH
MATERIALS λ-value W/m,K	
Min. Wool Wall Insulation	0.039
Min. Wool Roof Insulation	0.035
Aerogel Insulation	0.015
Double Glazed Window	3
Triple Glazed Window	1
G-VALUE	
Double Glazed Window	0.65
Triple Glazed Window	0.50
LIGHT TRANSMISSION	
Double Glazed Window	0.81
Triple Glazed Window	0.75
Window Frame Area	20%







CASES	UPGRADES					ENERGY			COST		CARBON
	Building Upgrades	Envelope Upgrades		Area (m_2)	Thickness (mm), Ammount or Window Type	EUI - COP 1 ($kWh/m_{2,}yr$)	Annual EU COP adjusted (kWh/yr)	EUI ($kWh/m^2 yr$)	Annual Energy Cost	Annual Savings	Annual Operational CO_2e Emissions (kg)
EXISTING BUILDING	No upgrades	-		-	-	234.7	453247	260.8	£ 18,946	-	83338
CASE A (BASE CASE)	**Switch to District Heating**	**-**		**-**	**-**	**234.7**	**203961**	**117.4**	**£ 38,549**	**-**	**47551**
CASE B	Internalise corridor at Level 03	-		-	-	179.8	161094	**89.9**	£ 30,447	£ 8,102	37557
	Internalise corridor at Level 03 Constant Natural Ventilation	-		-	-	212.3	190181	**106.1**	£ 35,944	£ 2,604	44339
	Internalise corridor at Level 03 Install MVHR	-		-	18	185.0	165800	**92.5**	£ 31,336	£ 7,213	38655
	Internalise corridor at Level 03 Upgrade Envelope	Roof Insulation on top of 100mm existing		400.7	50	177.1	158690	**88.6**	£ 29,992	£ 8,556	36997
					100	175.9	157576	**87.9**	£ 29,782	£ 8,767	36737
					150	175.2	156932	**87.6**	£ 29,660	£ 8,888	36587
					200	174.7	156513	**87.3**	£ 29,581	£ 8,968	36490
					250	174.4	156219	**87.2**	£ 29,525	£ 9,023	36421
					300	174.1	156001	**87.1**	£ 29,484	£ 9,065	36370
					350	173.9	155832	**87.0**	£ 29,452	£ 9,096	36331
		External Wall Insulation	SFS wall, Insulation & Brick Slips	1042.6	50	163.9	146842	**81.9**	£ 27,753	£ 10,796	34235
					100	159.9	143294	**80.0**	£ 27,082	£ 11,466	33407
					150	157.9	141484	**79.0**	£ 26,740	£ 11,808	32985
					200	156.7	140373	**78.3**	£ 26,531	£ 12,018	32727
					250	155.8	139607	**77.9**	£ 26,386	£ 12,163	32548
					300	155.2	139055	**77.6**	£ 26,281	£ 12,267	32419
			Insulation & Render		50	163.9	146842	**81.9**	£ 27,753	£ 10,796	34235
					100	159.9	143294	**80.0**	£ 27,082	£ 11,466	33407
					150	157.9	141484	**79.0**	£ 26,740	£ 11,808	32985
					200	156.7	140373	**78.3**	£ 26,531	£ 12,018	32727
					250	155.8	139607	**77.9**	£ 26,386	£ 12,163	32548
					300	155.2	139055	**77.6**	£ 26,281	£ 12,267	32419
		Basement Insulation	Mineral Wool	370.0	50	171.1	153281	**85.5**	£ 28,970	£ 9,579	35736
					100	169.5	151845	**84.7**	£ 28,699	£ 9,850	35401
			Aerogel		50	169.0	151434	**84.5**	£ 28,621	£ 9,928	35305
					100	168.2	150660	**84.1**	£ 28,475	£ 10,074	35125
		Terrace Insulation		144.7	50	178.3	159745	**89.1**	£ 30,192	£ 8,357	37243
					100	176.7	158354	**88.4**	£ 29,929	£ 8,620	36919
					150	176.1	157818	**88.1**	£ 29,828	£ 8,721	36794
		Soffit insulation		148.9	50	161.7	144904	**80.9**	£ 27,387	£ 11,162	33783
					100	159.9	143254	**79.9**	£ 27,075	£ 11,474	33398
		New Windows & 1 ACH		323.7	Double Glazed	138.7	124263	**69.3**	£ 23,486	£ 15,063	28971
					Triple Glazed	114.7	102770	**57.4**	£ 19,424	£ 19,125	23960
CASE C	Internalise corridor and walkway	-		-	-	161.5	152745	**80.7**	£ 28,869	£ 9,680	35611
	Internalise corridor and walkway Constant Natural Ventilation	-		-	-	192.0	181612	**96.0**	£ 34,325	£ 4,224	42341
	Internalise corridor and walkway Install MVHR	-		-	18	166.5	157497	**83.2**	£ 29,767	£ 8,782	36719
	Internalise both corridors Upgrade Envelope	Roof Insulation on top of 100mm existing		400.7	50	158.9	150347	**79.5**	£ 28,416	£ 10,133	35052
					100	157.8	149236	**78.9**	£ 28,206	£ 10,343	34793
					150	157.1	148594	**78.5**	£ 28,084	£ 10,464	34643
					200	156.6	148177	**78.3**	£ 28,005	£ 10,543	34546
					250	156.3	147883	**78.2**	£ 27,950	£ 10,599	34477
					300	156.1	147665	**78.1**	£ 27,909	£ 10,640	34427
					350	155.9	147497	**78.0**	£ 27,877	£ 10,672	34387
		External Wall Insulation	SFS wall, Insulation & Brick Slips	923.7	50	146.7	138801	**73.4**	£ 26,233	£ 12,315	32360
					100	143.0	135263	**71.5**	£ 25,565	£ 12,984	31535
					150	141.1	133452	**70.5**	£ 25,222	£ 13,326	31113
					200	139.9	132339	**70.0**	£ 25,012	£ 13,537	30853
					250	139.1	131571	**69.5**	£ 24,867	£ 13,682	30674
					300	138.5	131017	**69.3**	£ 24,762	£ 13,786	30545
			Insulation & Render		50	146.7	138801	**73.4**	£ 26,233	£ 12,315	32360
					100	143.0	135263	**71.5**	£ 25,565	£ 12,984	31535
					150	141.1	133452	**70.5**	£ 25,222	£ 13,326	31113
					200	139.9	132339	**70.0**	£ 25,012	£ 13,537	30853
					250	139.1	131571	**69.5**	£ 24,867	£ 13,682	30674
					300	138.5	131017	**69.3**	£ 24,762	£ 13,786	30545
		Basement Insulation	Mineral Wool	370.0	50	152.9	144615	**76.4**	£ 27,332	£ 11,216	33715
					100	151.3	143122	**75.7**	£ 27,050	£ 11,499	33367
			Aerogel		50	150.8	142694	**75.4**	£ 26,969	£ 11,579	33268
					100	150.0	141887	**75.0**	£ 26,817	£ 11,732	33080
		Terrace Insulation		47.4	50	160.9	152249	**80.5**	£ 28,775	£ 9,774	35495
					100	160.4	151738	**80.2**	£ 28,678	£ 9,870	35376
					150	160.2	151541	**80.1**	£ 28,641	£ 9,907	35330
		Soffit insulation		50.2	50	155.4	147026	**77.7**	£ 27,788	£ 10,761	34278
					100	154.8	146467	**77.4**	£ 27,682	£ 10,866	34147
		New Windows & 1 ACH		354.2	Double Glazed	119.7	113192	**59.8**	£ 21,393	£ 17,155	26390
					Triple Glazed	95.7	90522	**47.8**	£ 17,109	£ 21,440	21104
CASE D	Simplify Geometry/ Balconies	-		-	-	148.6	140604	**72.3**	£ 26,574	£ 11,974	32780.4
	Simplify Geometry/ Balconies Constant Natural Ventilation	-		-	-	163.1	154265	**79.3**	£ 29,156	£ 9,393	35965.3
	Simpify Geometry/ Balconies Install MVHR	-		-	18	153.7	145353	**74.7**	£ 27,472	£ 11,077	33887.6
	Simplify Geometry/ Balconies Upgrade Envelope	Roof Insulation on top of 100mm existing		400.7	50	146.0	141938	**73.0**	£ 26,826	£ 11,722	33091
					100	144.7	140727	**72.4**	£ 26,597	£ 11,951	32809
					150	144.0	140029	**72.0**	£ 26,465	£ 12,083	32646
					200	143.5	139574	**71.8**	£ 26,379	£ 12,169	32540
					250	143.2	139254	**71.6**	£ 26,319	£ 12,230	32466
					300	143.0	139017	**71.5**	£ 26,274	£ 12,274	32410
					350	142.8	138834	**71.4**	£ 26,240	£ 12,309	32368
		External Wall Insulation	SFS wall, Insulation & Brick Slips	910.0	50	134.7	131017	**67.4**	£ 24,762	£ 13,787	30545
					100	131.1	127535	**65.6**	£ 24,104	£ 14,445	29733
					150	129.3	125747	**64.7**	£ 23,766	£ 14,782	29317
					200	128.2	124648	**64.1**	£ 23,558	£ 14,990	29060
					250	127.4	123889	**63.7**	£ 23,415	£ 15,134	28884
					300	126.8	123342	**63.4**	£ 23,312	£ 15,237	28756
			Insulation & Render		50	134.7	131017	**67.4**	£ 24,762	£ 13,787	30545
					100	131.1	127535	**65.6**	£ 24,104	£ 14,445	29733
					150	129.3	125747	**64.7**	£ 23,766	£ 14,782	29317
					200	128.2	124648	**64.1**	£ 23,558	£ 14,990	29060
					250	127.4	123889	**63.7**	£ 23,415	£ 15,134	28884
					300	126.8	123342	**63.4**	£ 23,312	£ 15,237	28756
		Basement Insulation	Mineral Wool	370.0	50	140.3	136425	**70.1**	£ 25,784	£ 12,764	31806
					100	138.7	134932	**69.4**	£ 25,502	£ 13,046	31458
			Aerogel		50	138.3	134505	**69.2**	£ 25,421	£ 13,127	31358
					100	137.5	133698	**68.7**	£ 25,269	£ 13,280	31170
		Soffit insulation		29.4	50	145.1	141150	**72.6**	£ 26,677	£ 11,871	32908
					100	144.8	140816	**72.4**	£ 26,614	£ 11,934	32830
		New Windows & 1 ACH		348.0	Double Glazed	106.5	103573	**53.3**	£ 19,575	£ 18,973	24147
					Triple Glazed	87.3	84864	**43.6**	£ 16,039	£ 22,509	19785

5.3 EMBODIED CARBON & RETROFIT COSTS

For the Embodied Carbon estimations, a combination of OneClick LCA, Environmental Product Declarations and Articles was used. One ClickLCA is an online tool used to calculate the Life Cycle Impact of a building in terms of CO2e emissions.

Quantity Surveyor reports were used to estimate the cost of upgrades. The split of cost between upgrade and variable parameters like insulation thickness was based on typical product prices.

One Click LCA

EPD®

[1] Stephen Finnegan, C. J. (2018). The embodied CO 2 e of sustainable energy technologies used in buildings: A review article. Elsevier.

UPGRADE	DESCRIPTION	Embodied Carbon kg CO2e/m^2	Source	Cost £/ m^2	Source
External Wall - Insulated Steel Frame System with Brick Slips	50mm Mineral Wool - 100kg/m^2	6.6	OneClickLCA	15	QS
	SFS Wall with Brick Slips	21	OneClickLCA	385	QS
External Wall - Insulated rendered Panel	50mm Mineral Wool - 140kg/m^2	9.2	OneClickLCA	20	QS
	Render Finish	0.2	OneClickLCA	130	QS
Roof Insulation	50mm Mineral Wool - 160kg/m^2	10.6	OneClickLCA	30	QS
	Single Ply Bitumen	2.5	OneClickLCA	120	QS
Terrace Insulation	50mm Mineral Wool - 160kg/m^2	10.6	OneClickLCA	30	QS
	Single Ply Bitumen with Paving Slabs	7.9	OneClickLCA	150	QS
Soffit Insulation	50mm Mineral Wool - 140kg/m^2	9.2	OneClickLCA	20	QS
	Soffit Board	0.1	OneClickLCA	80	QS
Slab above Basement Insulation - Mineral Wool	50mm Mineral Wool - 140kg/m^2	9.2	OneClickLCA	20	QS
Slab above Basement Insulation - Aerogel	50mm Aerogel Insulation	65	EPD	400	QS
Double Glazed Composite Window	Aluminium	9.4	OneClickLCA	600	QS
	Timber	2.9	OneClickLCA		
	Glass	26.3	OneClickLCA		
Triple Glazed Composite Window	Aluminium	9.4	OneClickLCA	750	QS
	Wood	2.9	OneClickLCA		
	Glass	39.4	OneClickLCA		
		Embodied Carbon kg CO2e/Unit		Cost £/Unit	
MVHR	MVHR Unit (no ducts etc)	600	[1]	6700	QS
Internalise Upper Corridor	Double Glazed Doors	340	Calculated	5280	QS
Internalise Walkway	Double Glazed Doors & Windows	2340	Calculated	36480	QS
Bolt-on Balcony	Aluminium Balcony System	1400	OneClickLCA	18000	QS

5.4 LIFE CYCLE ASSESSMENT

LIFE CYCLE IMPACT (tons of CO2e)

LCI = Embodied Carbon + Life Cycle Years x Annual Operational Carbon

LIFE CYCLE CARBON SAVINGS (%)

$$LCCS = 1- (LCI_{PROPOSED} - LCI_{EXISTING}) \times 100$$

PAYBACK TIME (years)

PT = Initial Cost / Annual Operational Savings

Net Present Value can be used instead of Payback years to determine the most cost effective measures.

NET PRESENT VALUE (£)

$$NPV = \sum_{t=0} \text{Annual Savings} / (1+r)^t$$

r = discount rate if applicable

CASES	UPGRADES					INITIAL IMPACT		COST		CARBON		
	Building Upgrades	Envelope Upgrades		Area (m_2)	Thickness (mm), Ammount or Window Type	Embodied CO_2e Emissions (kg)	Upgrade Cost	Annual Savings	Payback years	Annual Operational CO_2e Emissions (kg)	Life Cycle CO_2e Emissions (tons)	Carbon Savings
EXISTING BUILDING	No upgrades	-		-	-	0	£ -	-	-	83338	2333	-
CASE A (BASE CASE)	Switch to District Heating	-		-	-	0	£ -	-	-	47551	1331	42.9%
CASE B	Internalise corridor at Level 03	-		-	-	339	£ 5,280	£ 8,102	2	37557	1052	21.0%
	Internalise corridor at Level 03 Constant Natural Ventilation	-		-	-	339	£ -	£ 2,604	1	44339	1242	6.7%
	Internalise corridor at Level 03 Install MVHR	-		-	18	11139	£ 125,880	£ 7,213	18	38655	1093	17.9%
	Internalise corridor at Level 03 Upgrade Envelope	Roof Insulation on top of 100mm existing		400.7	50	5572	£ 65,391	£ 8,556	9	36997	1041	21.8%
					100	9804	£ 77,413	£ 8,767	10	36737	1038	22.0%
					150	14036	£ 89,435	£ 8,888	11	36587	1038	22.0%
					200	18268	£ 101,458	£ 8,968	12	36490	1040	21.9%
					250	22500	£ 113,480	£ 9,023	14	36421	1042	21.7%
					300	26732	£ 125,502	£ 9,065	15	36370	1045	21.5%
					350	30963	£ 137,524	£ 9,096	16	36331	1048	21.3%
		External Wall Insulation	SFS wall, Insulation & Brick Slips	1042.6	50	29260	£ 422,320	£ 10,796	40	34235	988	25.8%
					100	36142	£ 437,959	£ 11,466	39	33407	972	27.0%
					150	43023	£ 453,598	£ 11,808	39	32985	967	27.4%
					200	49904	£ 469,237	£ 12,018	40	32727	966	27.4%
					250	56785	£ 484,876	£ 12,163	41	32548	968	27.3%
					300	63666	£ 500,515	£ 12,267	42	32419	971	27.0%
			Insulation & Render		50	10139	£ 161,670	£ 10,796	16	34235	969	27.2%
					100	19773	£ 182,522	£ 11,466	17	33407	955	28.3%
					150	29406	£ 203,374	£ 11,808	18	32985	953	28.4%
					200	39040	£ 224,226	£ 12,018	20	32727	955	28.2%
					250	48674	£ 245,078	£ 12,163	21	32548	960	27.9%
					300	58307	£ 265,930	£ 12,267	23	32419	966	27.4%
		Basement Insulation	Mineral Wool	370.0	50	3743	£ 49,680	£ 9,579	6	35736	1004	24.6%
					100	7147	£ 57,080	£ 9,850	7	35401	998	25.0%
			Aerogel		50	24389	£ 190,280	£ 9,928	20	35305	1013	23.9%
					100	48439	£ 338,280	£ 10,074	35	35125	1032	22.5%
		Terrace Insulation		144.7	50	3004	£ 31,326	£ 8,357	5	37243	1046	21.5%
					100	4532	£ 35,667	£ 8,620	5	36919	1038	22.0%
					150	6060	£ 40,008	£ 8,721	6	36794	1036	22.2%
		Soffit insulation		148.9	50	1726	£ 20,165	£ 11,162	3	33783	948	28.8%
					100	3101	£ 23,142	£ 11,474	3	33398	938	29.5%
		New Windows & 1 ACH		323.7	Double Glazed	12799	£ 199,476	£ 15,063	14	28971	824	38.1%
					Triple Glazed	17049	£ 248,025	£ 19,125	14	23960	688	48.3%
CASE C	Internalise corridor and walkway	-		-	-	2,679	£ 41,760	£ 9,680	5	35611	1000	24.9%
	Internalise corridor and walkway Constant Natural Ventilation	-		-	-	2,679	£ 41,760	£ 4,224	11	42341	1188	10.8%
	Internalise corridor and walkway Install MVHR	-		-	18	13479	£ 162,360	£ 8,782	19	36719	1042	21.8%
	Internalise both corridors Upgrade Envelope	Roof Insulation on top of 100mm existing		400.7	50	7913	£ 101,871	£ 10,133	11	35052	989	25.7%
					100	12145	£ 113,893	£ 10,343	12	34793	986	25.9%
					150	16377	£ 125,915	£ 10,464	13	34643	986	25.9%
					200	20608	£ 137,938	£ 10,543	14	34546	988	25.8%
					250	24840	£ 149,960	£ 10,599	15	34477	990	25.6%
					300	29072	£ 161,982	£ 10,640	16	34427	993	25.4%
					350	33304	£ 174,004	£ 10,672	17	34387	996	25.2%
		External Wall Insulation	SFS wall, Insulation & Brick Slips	923.7	50	28303	£ 411,244	£ 12,315	34	32360	934	29.8%
					100	34400	£ 425,100	£ 12,984	34	31535	917	31.1%
					150	40496	£ 438,955	£ 13,326	34	31113	912	31.5%
					200	46593	£ 452,811	£ 13,537	34	30853	910	31.6%
					250	52689	£ 466,667	£ 13,682	35	30674	912	31.5%
					300	58786	£ 480,522	£ 13,786	36	30545	914	31.3%
			Insulation & Render		50	11362	£ 180,317	£ 12,315	16	32360	917	31.1%
					100	19897	£ 198,791	£ 12,984	16	31535	903	32.2%
					150	28432	£ 217,265	£ 13,326	17	31113	900	32.4%
					200	36967	£ 235,739	£ 13,537	18	30853	901	32.3%
					250	45503	£ 254,213	£ 13,682	20	30674	904	32.1%
					300	54038	£ 272,688	£ 13,786	21	30545	909	31.7%
		Basement Insulation	Mineral Wool	370.0	50	6083	£ 86,160	£ 11,216	9	33715	950	28.6%
					100	9487	£ 93,560	£ 11,499	9	33367	944	29.1%
			Aerogel		50	26729	£ 226,760	£ 11,579	21	33268	958	28.0%
					100	50779	£ 374,760	£ 11,732	33	33080	977	26.6%
		Terrace Insulation		47.4	50	3552	£ 50,292	£ 9,774	6	35495	997	25.1%
					100	4053	£ 51,714	£ 9,870	6	35376	995	25.3%
					150	4554	£ 53,136	£ 9,907	6	35330	994	25.4%
		Soffit insulation		50.2	50	3148	£ 46,784	£ 10,761	5	34278	963	27.7%
					100	3612	£ 47,789	£ 10,866	5	34147	960	27.9%
		New Windows & 1 ACH		354.2	Double Glazed	14968	£ 233,280	£ 17,155	15	26390	754	43.4%
					Triple Glazed	19619	£ 286,410	£ 21,440	14	21104	611	54.1%
CASE D	Simplify Geometry/ Balconies	-		-	-	28,173	£ 257,760	£ 11,974	23	32780.4	946	28.9%
	Simplify Geometry/ Balconies Constant Natural Ventilation	-		-	-	28,173	£ 257,760	£ 9,393	28	35965.3	1035	22.2%
	Simpify Geometry/ Balconies Install MVHR	-		-	18	38973	£ 378,360	£ 11,077	35	33887.6	988	25.8%
	Simplify Geometry/ Balconies Upgrade Envelope	Roof Insulation on top of 100mm existing		400.7	50	33407	£ 317,871	£ 11,722	28	33091	960	27.9%
					100	37639	£ 329,893	£ 11,951	29	32809	956	28.2%
					150	41871	£ 341,915	£ 12,083	29	32646	956	28.2%
					200	46102	£ 353,938	£ 12,169	30	32540	957	28.1%
					250	50334	£ 365,960	£ 12,230	31	32466	959	27.9%
					300	54566	£ 377,982	£ 12,274	32	32410	962	27.7%
					350	58798	£ 390,004	£ 12,309	33	32368	965	27.5%
		External Wall Insulation	SFS wall, Insulation & Brick Slips	910.0	50	53417	£ 621,760	£ 13,787	46	30545	909	31.8%
					100	59423	£ 635,410	£ 14,445	45	29733	892	33.0%
					150	65429	£ 649,060	£ 14,782	45	29317	886	33.4%
					200	71435	£ 662,710	£ 14,990	45	29060	885	33.5%
					250	77441	£ 676,360	£ 15,134	46	28884	886	33.4%
					300	83447	£ 690,010	£ 15,237	46	28756	889	33.3%
			Insulation & Render		50	36727	£ 394,260	£ 13,787	30	30545	892	33.0%
					100	45136	£ 412,460	£ 14,445	30	29733	878	34.1%
					150	53544	£ 430,660	£ 14,782	30	29317	874	34.3%
					200	61953	£ 448,860	£ 14,990	31	29060	876	34.2%
					250	70361	£ 467,060	£ 15,134	32	28884	879	34.0%
					300	78769	£ 485,260	£ 15,237	33	28756	884	33.6%
		Basement Insulation	Mineral Wool	370.0	50	31577	£ 302,160	£ 12,764	25	31806	922	30.7%
					100	34981	£ 309,560	£ 13,046	25	31458	916	31.2%
			Aerogel		50	52223	£ 442,760	£ 13,127	35	31358	930	30.1%
					100	76273	£ 590,760	£ 13,280	45	31170	949	28.7%
		Soffit insulation		29.4	50	28447	£ 260,695	£ 11,871	23	32908	950	28.7%
					100	28718	£ 261,282	£ 11,934	23	32830	948	28.8%
		New Windows & 1 ACH		348.0	Double Glazed	41570	£ 466,560	£ 18,973	26	24147	718	46.1%
					Triple Glazed	46141	£ 518,760	£ 22,509	24	19785	600	54.9%

6 RESULT ANALYSIS

6.1 RESULT TABLE OVERVIEW

An Excel Table is an easy way to identify the measures with a Payback Time less than 15 years and the measures with the most Life Cycle Carbon Savings. The table on the right is an example where the most Carbon Saving measures are highlighted with a green background while most cost efficient measures are highlighted with a grey background.

This table is the only thing required to draw conlusions of the most efficient measures. However, specific diagrams could be used to portray to the client the effect of different measures.

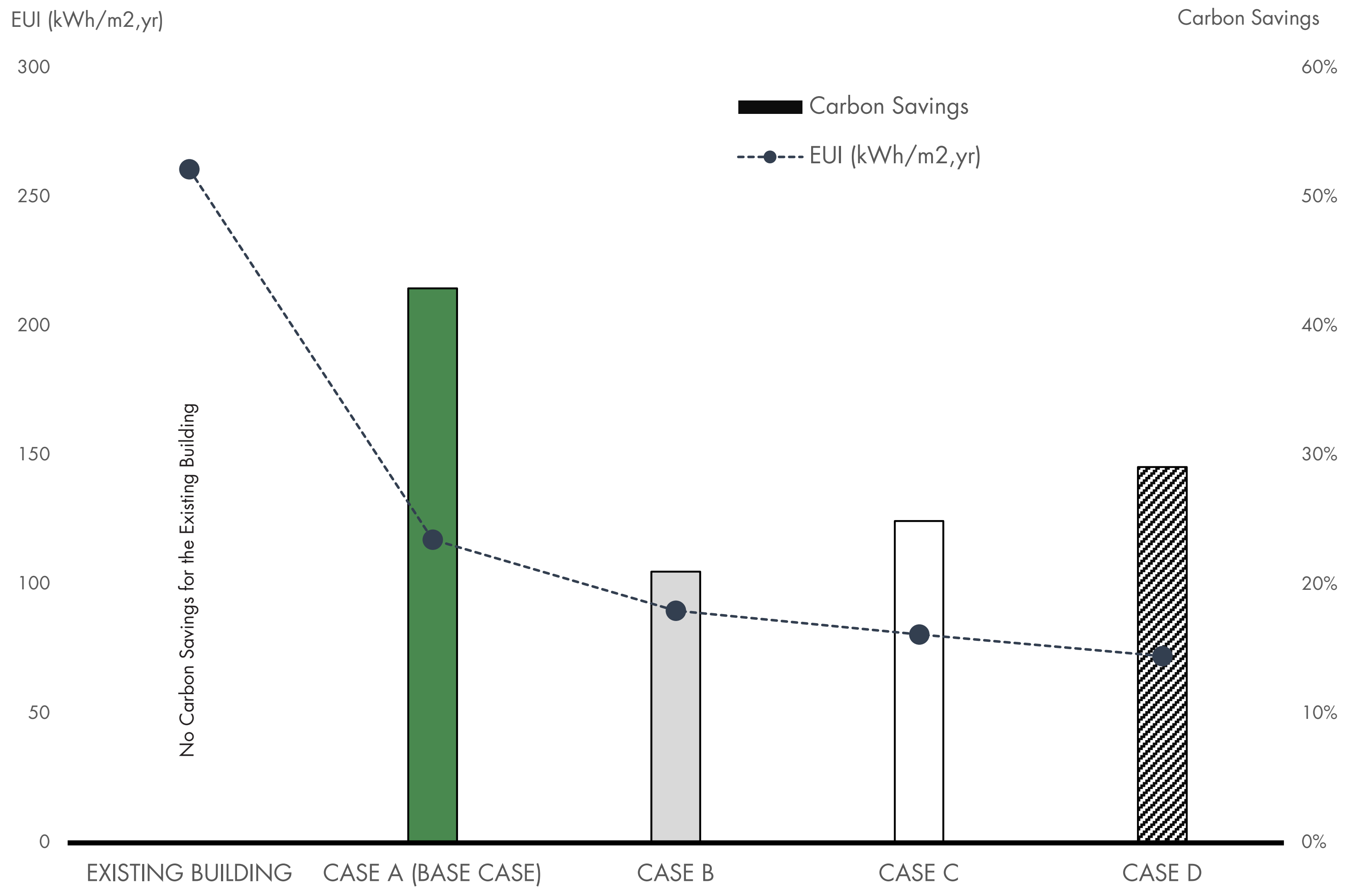
CASES	UPGRADES					INITIAL IMPACT		ENERGY			COST			CARBON				
	Building Upgrades	Envelope Upgrades		Area (m_2)	Thickness (mm), Ammount or Window Type	Embodied CO_2e Emissions (kg)	Upgrade Cost	EUI - COP 1 (kWh/m_2yr)	Annual EU COP adjusted (kWh/yr)	EUI (kWh/m^2yr)	Annual Energy Cost	Annual Savings	Payback years	Annual Operational CO_2e Emissions (kg)	Life Cycle CO_2e Emissions (tons)	Carbon Savings	Total CO_2e Emissions in 60 years (tons)	Carbon Savings in 60 years
EXISTING BUILDING	No upgrades	-		-	-	0	£ -	234.7	453247	260.8	£ 18,946	-	-	83338	2333	-	5000	-
CASE A (BASE CASE)	Switch to District Heating	-		-	-	0	£ -	234.7	203961	117.4	£ 38,549	-	-	47551	1331	42.9%	2853	42.9%
CASE B	Internalise corridor at Level 03	-		-	-	339	£ 5,280	179.8	161094	89.9	£ 30,447	£ 8,102	2	37557	1052	21.0%	2084	27.0%
	Internalise corridor at Level 03 Constant Natural Ventilation	-		-	-	339	£ -	212.3	190181	106.1	£ 35,944	£ 2,604	1	44339	1242	6.7%	2084	27.0%
	Internalise corridor at Level 03 Install MVHR	-		-	18	11139	£ 125,880	185.0	165800	92.5	£ 31,336	£ 7,213	18	38655	1093	17.9%	2330	18.3%
	Internalise corridor at Level 03 Upgrade Envelope	Roof Insulation on top of 100mm existing		400.7	50	5572	£ 65,391	177.1	158690	88.6	£ 29,992	£ 8,556	9	36997	1041	21.8%	2225	22.0%
					100	9804	£ 77,413	175.9	157576	87.9	£ 29,782	£ 8,767	10	36737	1038	22.0%	2214	22.4%
					150	14036	£ 89,435	175.2	156932	87.6	£ 29,660	£ 8,888	11	36587	1038	22.0%	2209	22.6%
					200	18268	£ 101,458	174.7	156513	87.3	£ 29,581	£ 8,968	12	36490	1040	21.9%	2208	22.6%
					250	22500	£ 113,480	174.4	156219	87.2	£ 29,525	£ 9,023	14	36421	1042	21.7%	2208	22.6%
					300	26732	£ 125,502	174.1	156001	87.1	£ 29,484	£ 9,065	15	36370	1045	21.5%	2209	22.6%
					350	30963	£ 137,524	173.9	155832	87.0	£ 29,452	£ 9,096	16	36331	1048	21.3%	2211	22.5%
		External Wall Insulation	SFS wall, Insulation & Brick Slips	1042.6	50	29260	£ 422,320	163.9	146842	81.9	£ 27,753	£ 10,796	40	34235	988	25.8%	2081	27.0%
					100	36142	£ 437,959	159.9	143294	80.0	£ 27,082	£ 11,466	39	33407	972	27.0%	2038	28.6%
					150	43023	£ 453,598	157.9	141484	79.0	£ 26,740	£ 11,808	39	32985	967	27.4%	2019	29.2%
					200	49904	£ 469,237	156.7	140373	78.3	£ 26,531	£ 12,018	40	32727	966	27.4%	2010	29.5%
					250	56785	£ 484,876	155.8	139607	77.9	£ 26,386	£ 12,163	41	32548	968	27.3%	2006	29.7%
					300	63666	£ 500,515	155.2	139055	77.6	£ 26,281	£ 12,267	42	32419	971	27.0%	2005	29.7%
			Insulation & Render		50	10139	£ 161,670	163.9	146842	81.9	£ 27,753	£ 10,796	16	34235	969	27.2%	2064	27.7%
					100	19773	£ 182,522	159.9	143294	80.0	£ 27,082	£ 11,466	17	33407	955	28.3%	2023	29.1%
					150	29406	£ 203,374	157.9	141484	79.0	£ 26,740	£ 11,808	18	32985	953	28.4%	2007	29.7%
					200	39040	£ 224,226	156.7	140373	78.3	£ 26,531	£ 12,018	20	32727	955	28.2%	2000	29.9%
					250	48674	£ 245,078	155.8	139607	77.9	£ 26,386	£ 12,163	21	32548	960	27.9%	1998	30.0%
					300	58307	£ 265,930	155.2	139055	77.6	£ 26,281	£ 12,267	23	32419	966	27.4%	2000	29.9%
		Basement Insulation	Mineral Wool	370.0	50	3743	£ 49,680	171.1	153281	85.5	£ 28,970	£ 9,579	6	35736	1004	24.6%	2148	24.7%
					100	7147	£ 57,080	169.5	151845	84.7	£ 28,699	£ 9,850	7	35401	998	25.0%	2131	25.3%
			Aerogel		50	24389	£ 190,280	169.0	151434	84.5	£ 28,621	£ 9,928	20	35305	1013	23.9%	2143	24.9%
					100	48439	£ 338,280	168.2	150660	84.1	£ 28,475	£ 10,074	35	35125	1032	22.5%	2156	24.4%
		Terrace Insulation		144.7	50	3004	£ 31,326	178.3	159745	89.1	£ 30,192	£ 8,357	5	37243	1046	21.5%	2238	21.6%
					100	4532	£ 35,667	176.7	158354	88.4	£ 29,929	£ 8,620	5	36919	1038	22.0%	2220	22.2%
					150	6060	£ 40,008	176.1	157818	88.1	£ 29,828	£ 8,721	6	36794	1036	22.2%	2214	22.4%
		Soffit insulation		148.9	50	1726	£ 20,165	161.7	144904	80.9	£ 27,387	£ 11,162	3	33783	948	28.8%	2029	28.9%
					100	3101	£ 23,142	159.9	143254	79.9	£ 27,075	£ 11,474	3	33398	938	29.5%	2007	29.7%
		New Windows & 1 ACH		323.7	Double Glazed	12799	£ 199,476	138.7	124263	69.3	£ 23,486	£ 15,063	14	28971	824	38.1%	1751	38.6%
					Triple Glazed	17049	£ 248,025	114.7	102770	57.4	£ 19,424	£ 19,125	14	23960	688	48.3%	1455	49.0%
CASE C	Internalise corridor and walkway	-		-	-	2,679	£ 41,760	161.5	152745	80.7	£ 28,869	£ 9,680	5	35611	1000	24.9%	2139	25.0%
	Internalise corridor and walkway Constant Natural Ventilation	-		-	-	2,679	£ 41,760	192.0	181612	96.0	£ 34,325	£ 4,224	11	42341	1188	10.8%	2139	25.0%
	Internalise corridor and walkway Install MVHR	-		-	18	13479	£ 162,360	166.5	157497	83.2	£ 29,767	£ 8,782	19	36719	1042	21.8%	2217	22.3%
	Internalise both corridors Upgrade Envelope	Roof Insulation on top of 100mm existing		400.7	50	7913	£ 101,871	158.9	150347	79.5	£ 28,416	£ 10,133	11	35052	989	25.7%	2111	26.0%
					100	12145	£ 113,893	157.8	149236	78.9	£ 28,206	£ 10,343	12	34793	986	25.9%	2100	26.4%
					150	16377	£ 125,915	157.1	148594	78.5	£ 28,084	£ 10,464	13	34643	986	25.9%	2095	26.6%
					200	20608	£ 137,938	156.6	148177	78.3	£ 28,005	£ 10,543	14	34546	988	25.8%	2093	26.6%
					250	24840	£ 149,960	156.3	147883	78.2	£ 27,950	£ 10,599	15	34477	990	25.6%	2093	26.6%
					300	29072	£ 161,982	156.1	147665	78.1	£ 27,909	£ 10,640	16	34427	993	25.4%	2095	26.6%
					350	33304	£ 174,004	155.9	147497	78.0	£ 27,877	£ 10,672	17	34387	996	25.2%	2097	26.5%
		External Wall Insulation	SFS wall, Insulation & Brick Slips	923.7	50	28303	£ 411,244	146.7	138801	73.4	£ 26,233	£ 12,315	34	32360	934	29.8%	1970	31.0%
					100	34400	£ 425,100	143.0	135263	71.5	£ 25,565	£ 12,984	34	31535	917	31.1%	1927	32.5%
					150	40496	£ 438,955	141.1	133452	70.5	£ 25,222	£ 13,326	34	31113	912	31.5%	1907	33.2%
					200	46593	£ 452,811	139.9	132339	70.0	£ 25,012	£ 13,537	34	30853	910	31.6%	1898	33.5%
					250	52689	£ 466,667	139.1	131571	69.5	£ 24,867	£ 13,682	35	30674	912	31.5%	1893	33.6%
					300	58786	£ 480,522	138.5	131017	69.3	£ 24,762	£ 13,786	36	30545	914	31.3%	1892	33.7%
			Insulation & Render		50	11362	£ 180,317	146.7	138801	73.4	£ 26,233	£ 12,315	16	32360	917	31.1%	1953	31.5%
					100	19897	£ 198,791	143.0	135263	71.5	£ 25,565	£ 12,984	16	31535	903	32.2%	1912	33.0%
					150	28432	£ 217,265	141.1	133452	70.5	£ 25,222	£ 13,326	17	31113	900	32.4%	1895	33.6%
					200	36967	£ 235,739	139.9	132339	70.0	£ 25,012	£ 13,537	18	30853	901	32.3%	1888	33.8%
					250	45503	£ 254,213	139.1	131571	69.5	£ 24,867	£ 13,682	20	30674	904	32.1%	1886	33.9%
					300	54038	£ 272,688	138.5	131017	69.3	£ 24,762	£ 13,786	21	30545	909	31.7%	1887	33.9%
		Basement Insulation	Mineral Wool	370.0	50	6083	£ 86,160	152.9	144615	76.4	£ 27,332	£ 11,216	9	33715	950	28.6%	2029	28.9%
					100	9487	£ 93,560	151.3	143122	75.7	£ 27,050	£ 11,499	9	33367	944	29.1%	2012	29.5%
			Aerogel		50	26729	£ 226,760	150.8	142694	75.4	£ 26,969	£ 11,579	21	33268	958	28.0%	2023	29.1%
					100	50779	£ 374,760	150.0	141887	75.0	£ 26,817	£ 11,732	33	33080	977	26.6%	2036	28.7%
		Terrace Insulation		47.4	50	3552	£ 50,292	160.9	152249	80.5	£ 28,775	£ 9,774	6	35495	997	25.1%	2133	25.2%
					100	4053	£ 51,714	160.4	151738	80.2	£ 28,678	£ 9,870	6	35376	995	25.3%	2127	25.5%
					150	4554	£ 53,136	160.2	151541	80.1	£ 28,641	£ 9,907	6	35330	994	25.4%	2124	25.5%
		Soffit insulation		50.2	50	3148	£ 46,784	155.4	147026	77.7	£ 27,788	£ 10,761	5	34278	963	27.7%	2060	27.8%
					100	3612	£ 47,789	154.8	146467	77.4	£ 27,682	£ 10,866	5	34147	960	27.9%	2052	28.1%
		New Windows & 1 ACH		354.2	Double Glazed	14968	£ 233,280	119.7	113192	59.8	£ 21,393	£ 17,155	15	26390	754	43.4%	1598	44.0%
					Triple Glazed	19619	£ 286,410	95.7	90522	47.8	£ 17,109	£ 21,440	14	21104	611	54.1%	1286	54.9%
CASE D	Simplify Geometry/ Balconies	-		-	-	28,173	£ 257,760	148.6	140604	72.3	£ 26,574	£ 11,974	23	32780.4	946	28.9%	1995	30.1%
	Simplify Geometry/ Balconies Constant Natural Ventilation	-		-	-	28,173	£ 257,760	163.1	154265	79.3	£ 29,156	£ 9,393	28	35965.3	1035	22.2%	1995	30.1%
	Simpify Geometry/ Balconies Install MVHR	-		-	18	38973	£ 378,360	153.7	145353	74.7	£ 27,472	£ 11,077	35	33887.6	988	25.8%	2072	27.4%
	Simplify Geometry/ Balconies Upgrade Envelope	Roof Insulation on top of 100mm existing		400.7	50	33407	£ 317,871	146.0	141938	73.0	£ 26,826	£ 11,722	28	33091	960	27.9%	2019	29.2%
					100	37639	£ 329,893	144.7	140727	72.4	£ 26,597	£ 11,951	29	32809	956	28.2%	2006	29.7%
					150	41871	£ 341,915	144.0	140029	72.0	£ 26,465	£ 12,083	29	32646	956	28.2%	2000	29.9%
					200	46102	£ 353,938	143.5	139574	71.8	£ 26,379	£ 12,169	30	32540	957	28.1%	1998	30.0%
					250	50334	£ 365,960	143.2	139254	71.6	£ 26,319	£ 12,230	31	32466	959	27.9%	1998	30.0%
					300	54566	£ 377,982	143.0	139017	71.5	£ 26,274	£ 12,274	32	32410	962	27.7%	1999	29.9%
					350	58798	£ 390,004	142.8	138834	71.4	£ 26,240	£ 12,309	33	32368	965	27.5%	2001	29.9%
		External Wall Insulation	SFS wall, Insulation & Brick Slips	910.0	50	53417	£ 621,760	134.7	131017	67.4	£ 24,762	£ 13,787	46	30545	909	31.8%	1886	33.9%
					100	59423	£ 635,410	131.1	127535	65.6	£ 24,104	£ 14,445	45	29733	892	33.0%	1843	35.4%
					150	65429	£ 649,060	129.3	125747	64.7	£ 23,766	£ 14,782	45	29317	886	33.4%	1824	36.1%
					200	71435	£ 662,710	128.2	124648	64.1	£ 23,558	£ 14,990	45	29060	885	33.5%	1815	36.4%
					250	77441	£ 676,360	127.4	123889	63.7	£ 23,415	£ 15,134	46	28884	886	33.4%	1810	36.6%
					300	83447	£ 690,010	126.8	123342	63.4	£ 23,312	£ 15,237	46	28756	889	33.3%	1809	36.6%
			Insulation & Render		50	36727	£ 394,260	134.7	131017	67.4	£ 24,762	£ 13,787	30	30545	892	33.0%	1869	34.5%
					100	45136	£ 412,460	131.1	127535	65.6	£ 24,104	£ 14,445	30	29733	878	34.1%	1829	35.9%
					150	53544	£ 430,660	129.3	125747	64.7	£ 23,766	£ 14,782	30	29317	874	34.3%	1812	36.5%
					200	61953	£ 448,860	128.2	124648	64.1	£ 23,558	£ 14,990	31	29060	876	34.2%	1805	36.7%
					250	70361	£ 467,060	127.4	123889	63.7	£ 23,415	£ 15,134	32	28884	879	34.0%	1803	36.8%
					300	78769	£ 485,260	126.8	123342	63.4	£ 23,312	£ 15,237	33	28756	884	33.6%	1804	36.8%
		Basement Insulation	Mineral Wool	370.0	50	31577	£ 302,160	140.3	136425	70.1	£ 25,784	£ 12,764	25	31806	922	30.7%	1940	32.0%
					100	34981	£ 309,560	138.7	134932	69.4	£ 25,502	£ 13,046	25	31458	916	31.2%	1922	32.6%
			Aerogel		50	52223	£ 442,760	138.3	134505	69.2	£ 25,421	£ 13,127	35	31358	930	30.1%	1933	32.2%
					100	76273	£ 590,760	137.5	133698	68.7	£ 25,269	£ 13,280	45	31170	949	28.7%	1946	31.8%
		Soffit insulation		29.4	50	28447	£ 260,695	145.1	141150	72.6	£ 26,677	£ 11,871	23	32908	950	28.7%	2003	29.8%
					100	28718	£ 261,282	144.8	140816	72.4	£ 26,614	£ 11,934	23	32830	948	28.8%	1998	30.0%
		New Windows & 1 ACH		348.0	Double Glazed	41570	£ 466,560	106.5	103573	53.3	£ 19,575	£ 18,973	26	24147	718	46.1%	1490	47.8%
					Triple Glazed	46141	£ 518,760	87.3	84864	43.6	£ 16,039	£ 22,509	24	19785	600	54.9%	1233	56.8%

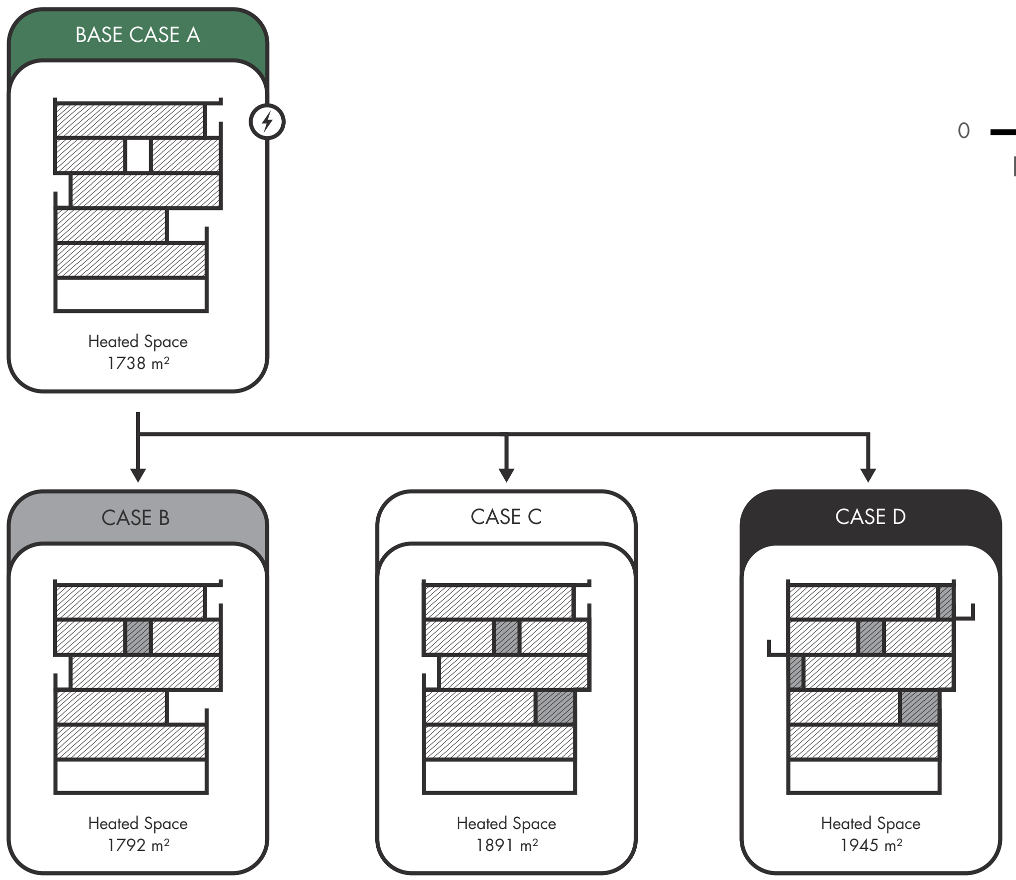
6.2 GEOMETRY UPGRADES

The results show that switching from a Gas Boiler System to a District Heating System is reducing the Energy Use of the building (EUI) by almost 50%. This is largely due to the high Performance Coefficient (COP) that an electric system has compared to Gas Boilers.

Simplifying the shape of the building has a positive impact on both EUI and Life Cycle Carbon Savings (LCCS) even though the total volume of the building and therefore heated space is increased.

The most Carbon Savings appear to be in Case D where the envelope is simplified. The Carbon savings from the reduction of the Energy use seem to offset the Carbon resulting from the installation of bolt-on balconies and windows to internalise the corridors.



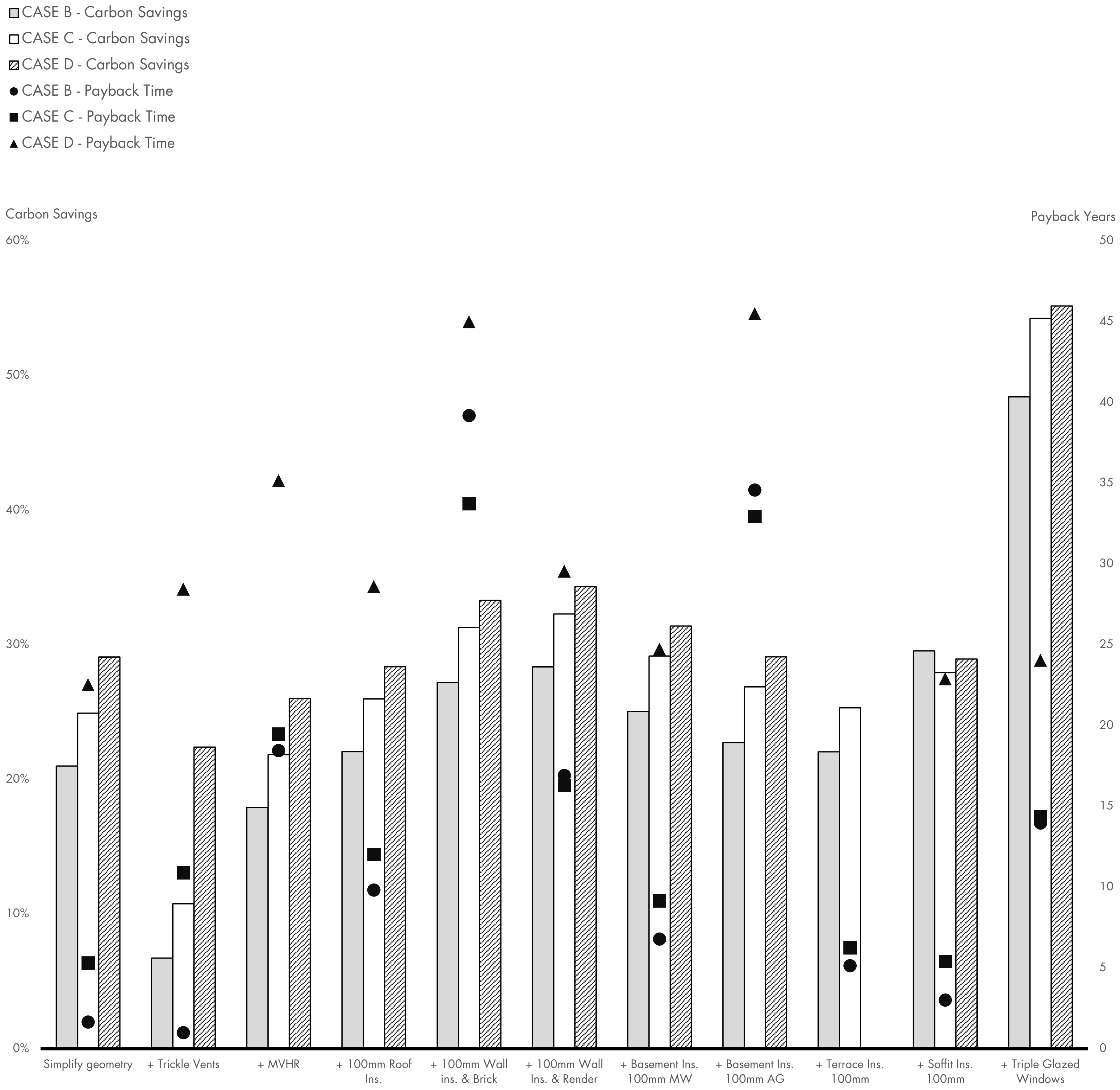


6.3 ENVELOPE UPGRADES OVERVIEW

The replacement and upgrade of windows has the biggest impact on LCCS with a short Payback Time (PT).

Insulating the external walls, soffits and the slab above the unheated basement also have a significant impact on increasing LCCS, while insulating the roof and terraces have little impact.

Payback Time for any upgrades on Case D are well beyond the 15 years target largely to the cost from introducing external balconies.

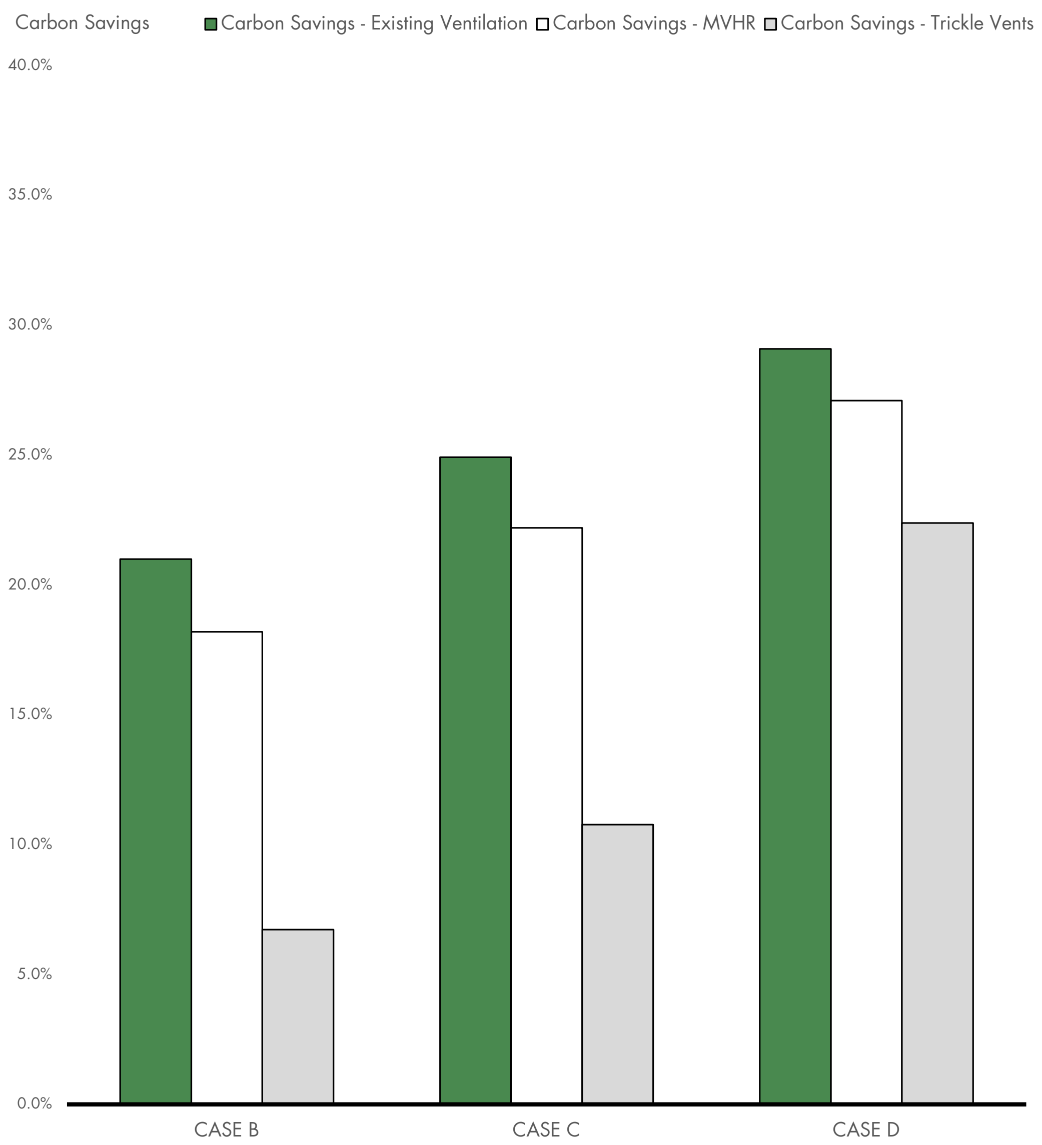


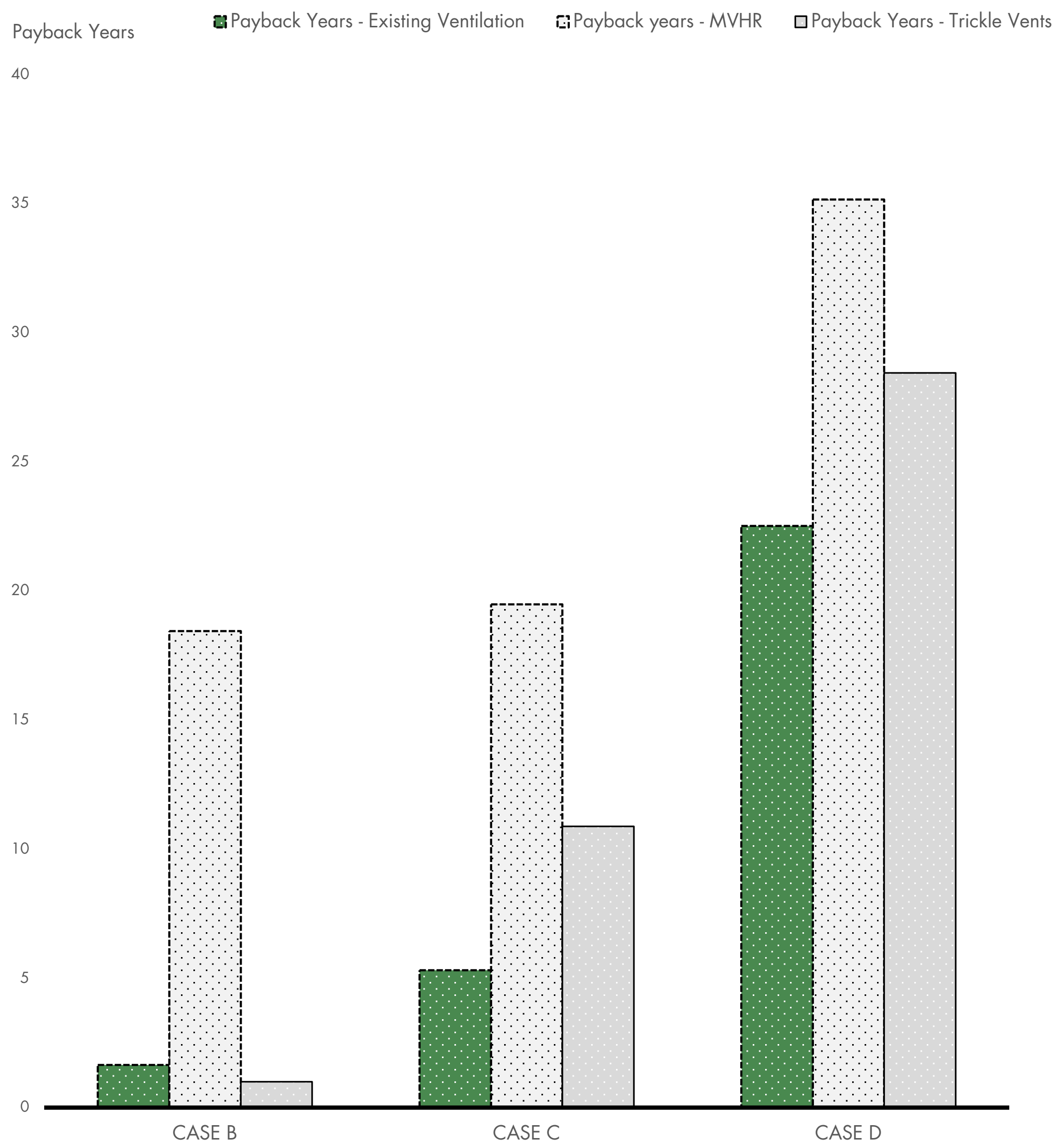
6.4 VENTILATION

The introduction of MVHR systems or Trickle Vents have a negative impact on the LCCS but they are considered neces-sary as the existing building does not currently meet modern regulations regarding ventilation.

From the two options to enhance fresh air supply, an MVHR clearly provides more Carbon Savings than trickle vents. Other benefits of an MVHR include thermal comfort and air filtration.

The PT for introducing an MVHR system is longer than the usual life span of a unit which is 15 years and the initial cost does not include costs associated with installation, ducts and disrution which will make the MVHR installation an even less attractive upgrade.



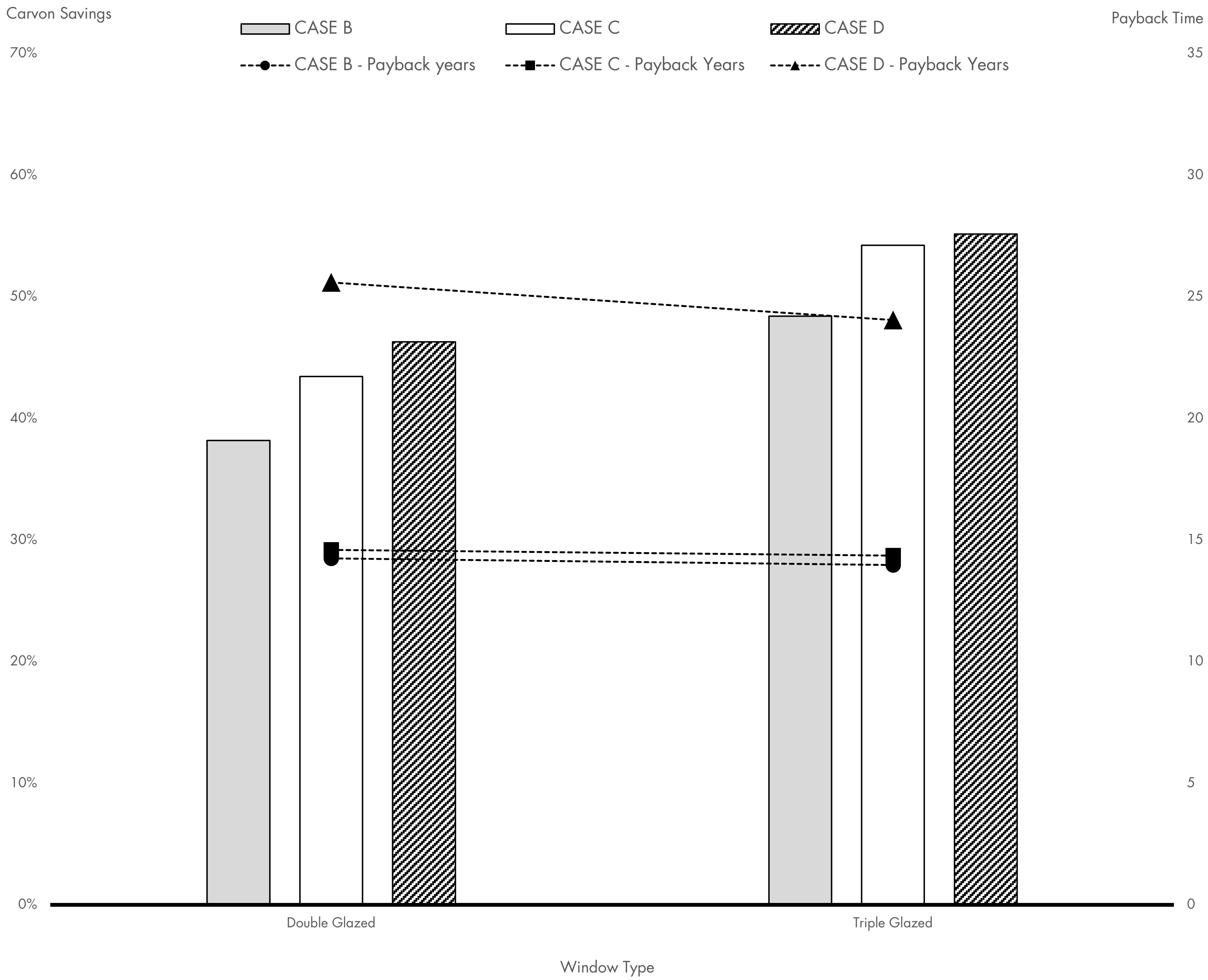


6.5 WINDOWS

Replacing the existing single glazed windows results in the most LCCS between 38 to 55%.

Triple Glazed Units result in most LCCS in all Cases. Payback time (PT) is less than 15 years for both double and triple glazing for Cases C & D.

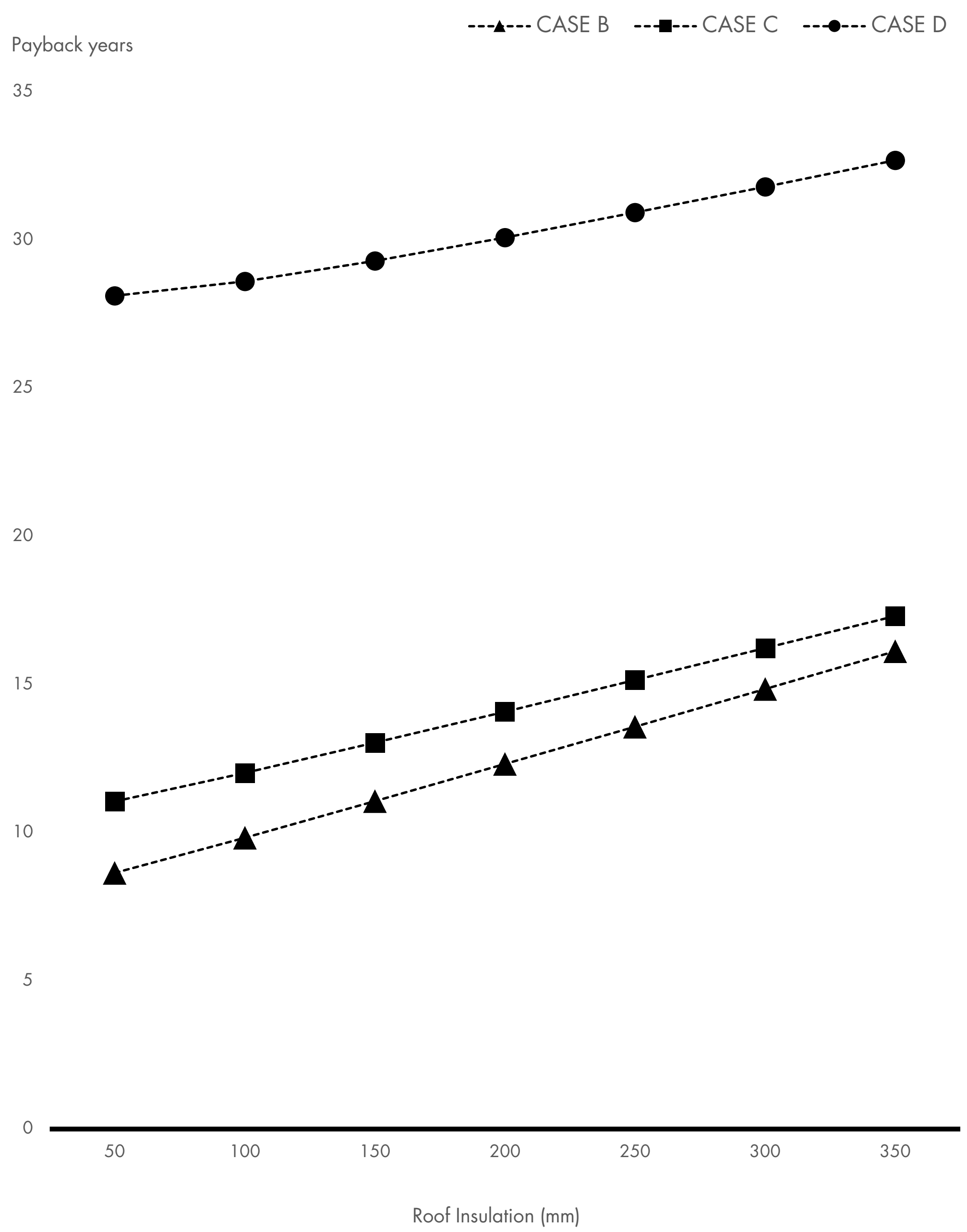
The triple glazing units results in more Carbon Savings because of the higher reduction in operational energy, despite the additional embodied carbon from the third glass pane. The Payback time is similar for both options as the resulted reduction in operational energy costs seems to be analogous to the cost of the units. The triple-glazed units become more efficient as the building envelope improves (CASE D).

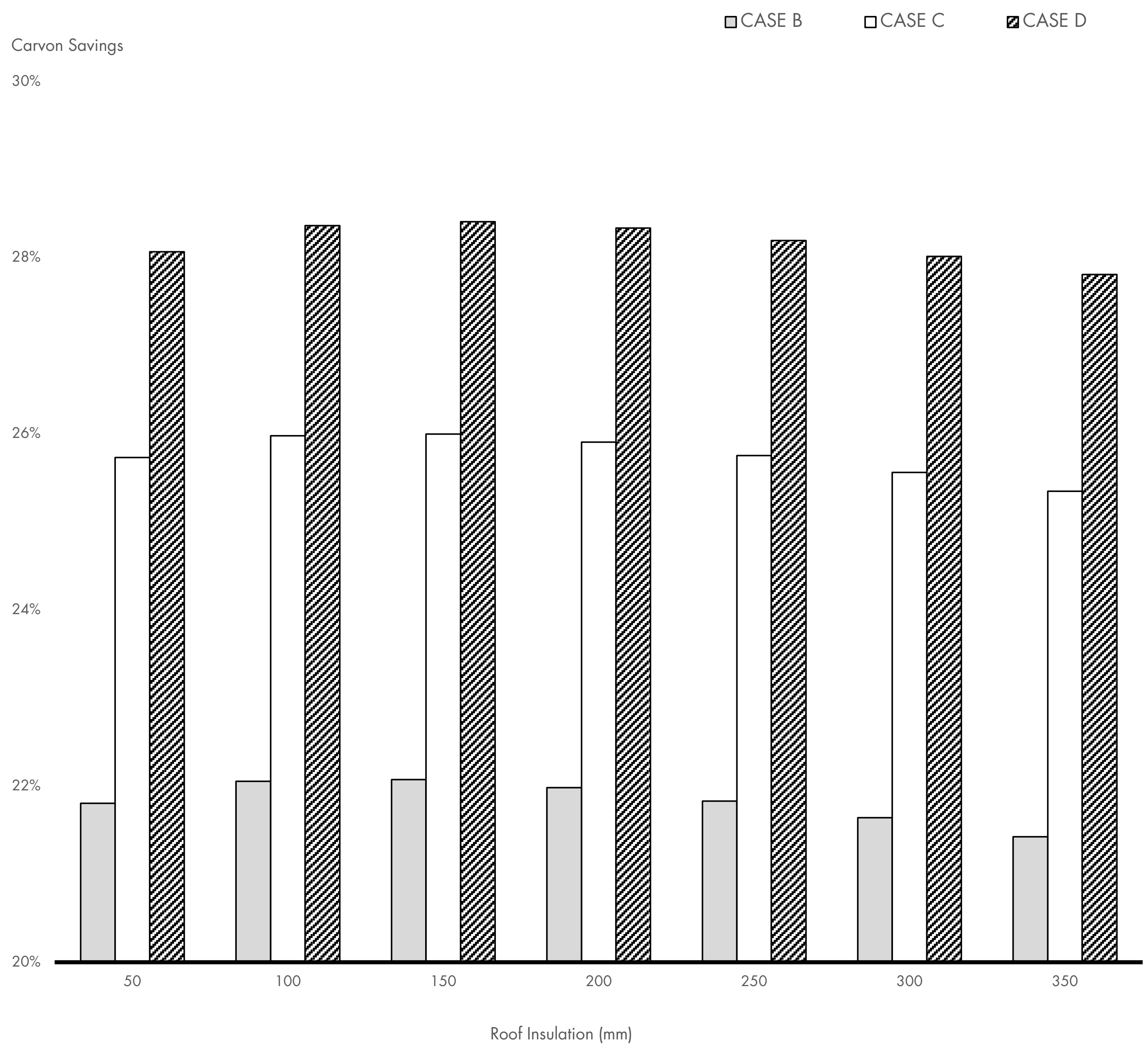


6.6 ROOF INSULATION

Roof Insulation can result in approximately 22 to 28% Carbon Savings with the maximum savings found at 150mm additional insulation. CASE D has the most savings as roof accounts for a larger percentage of the total envelope area.

The Payback Time from insulating the roof is generally within the 15-year target for Cases B and C.

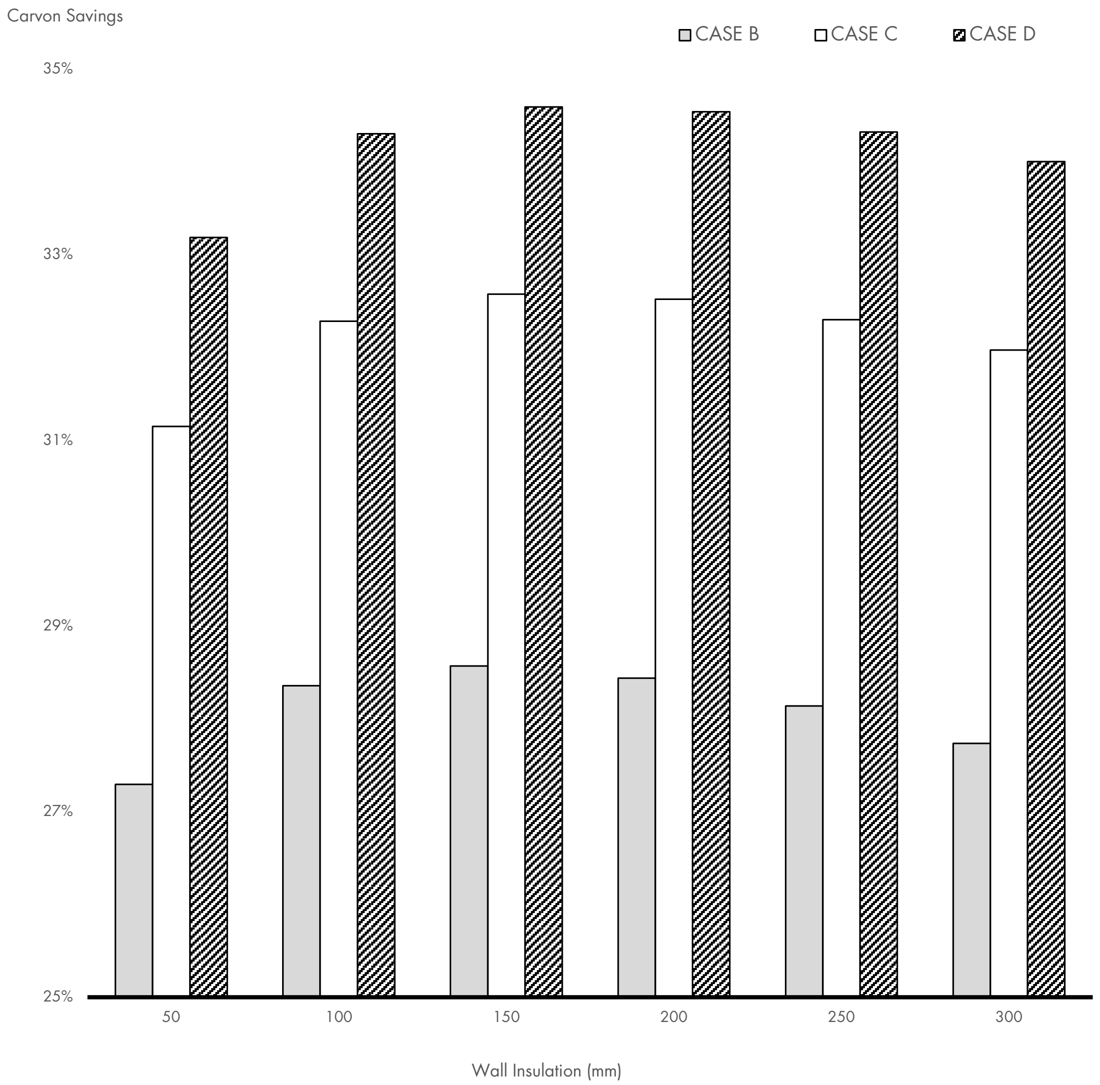


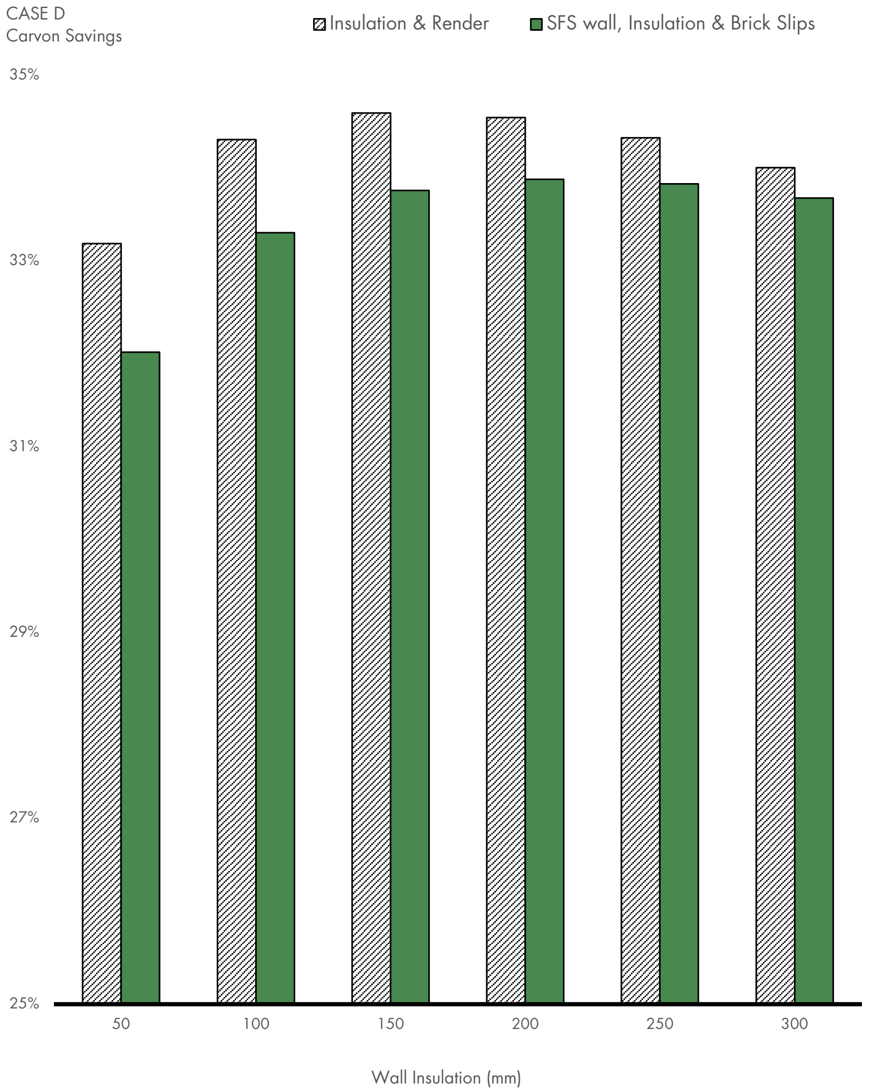


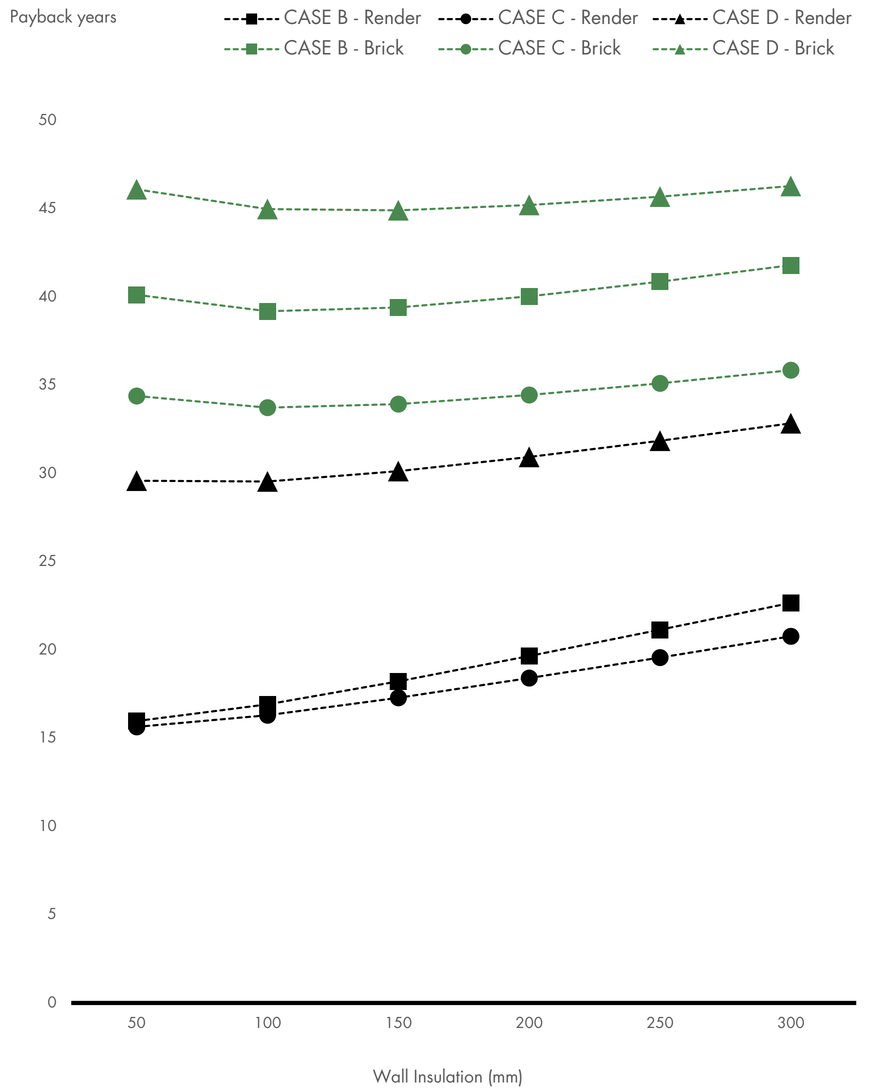
6.7 WALL INSULATION

Insulating the external walls by 150mm results in the most LCCS. Render has less impact than a brick slip system resulting in 1-2% more Carbon Savings.

A Render System of up to 200mm has the lowest PT, between 16 to 20 years.



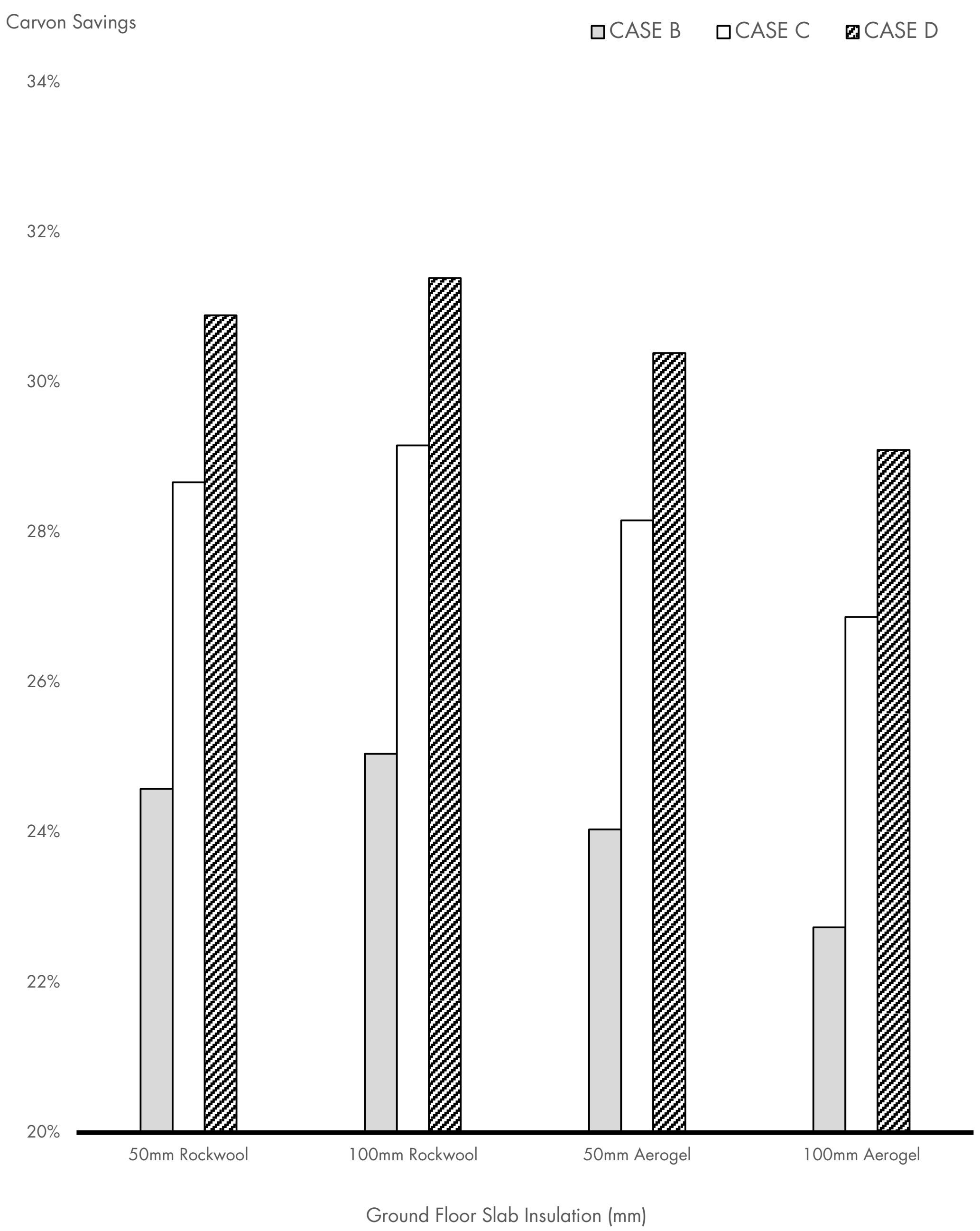


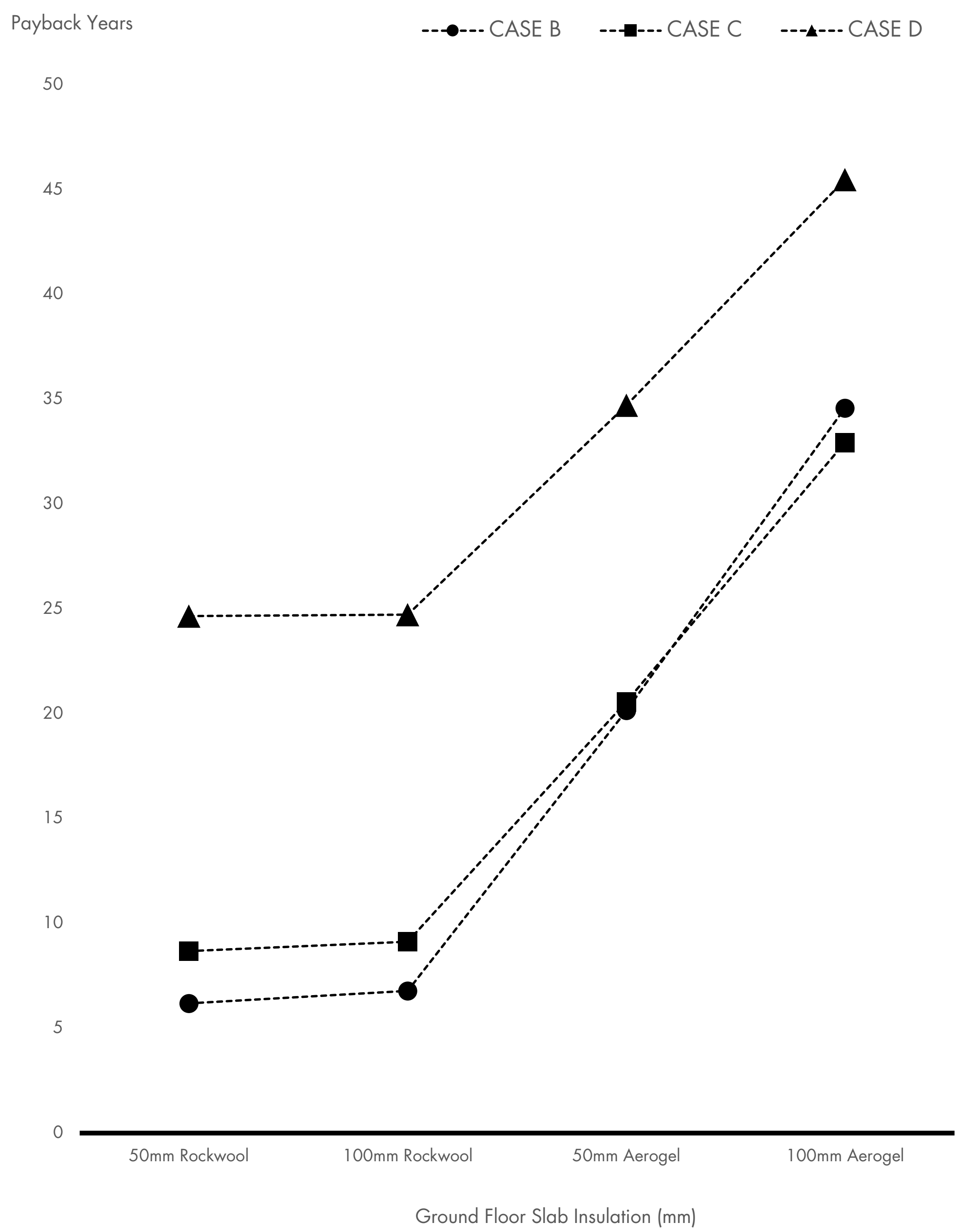


6.8 BASEMENT INSULATION

Insulating the slab above the unheated basement results in Carbon Savings between 23 and 31%. The use of Mineral Wool despite the lower thermal performance results in more Carbon Savings than Aerogel due to Aerogel's high Environmental Impact.

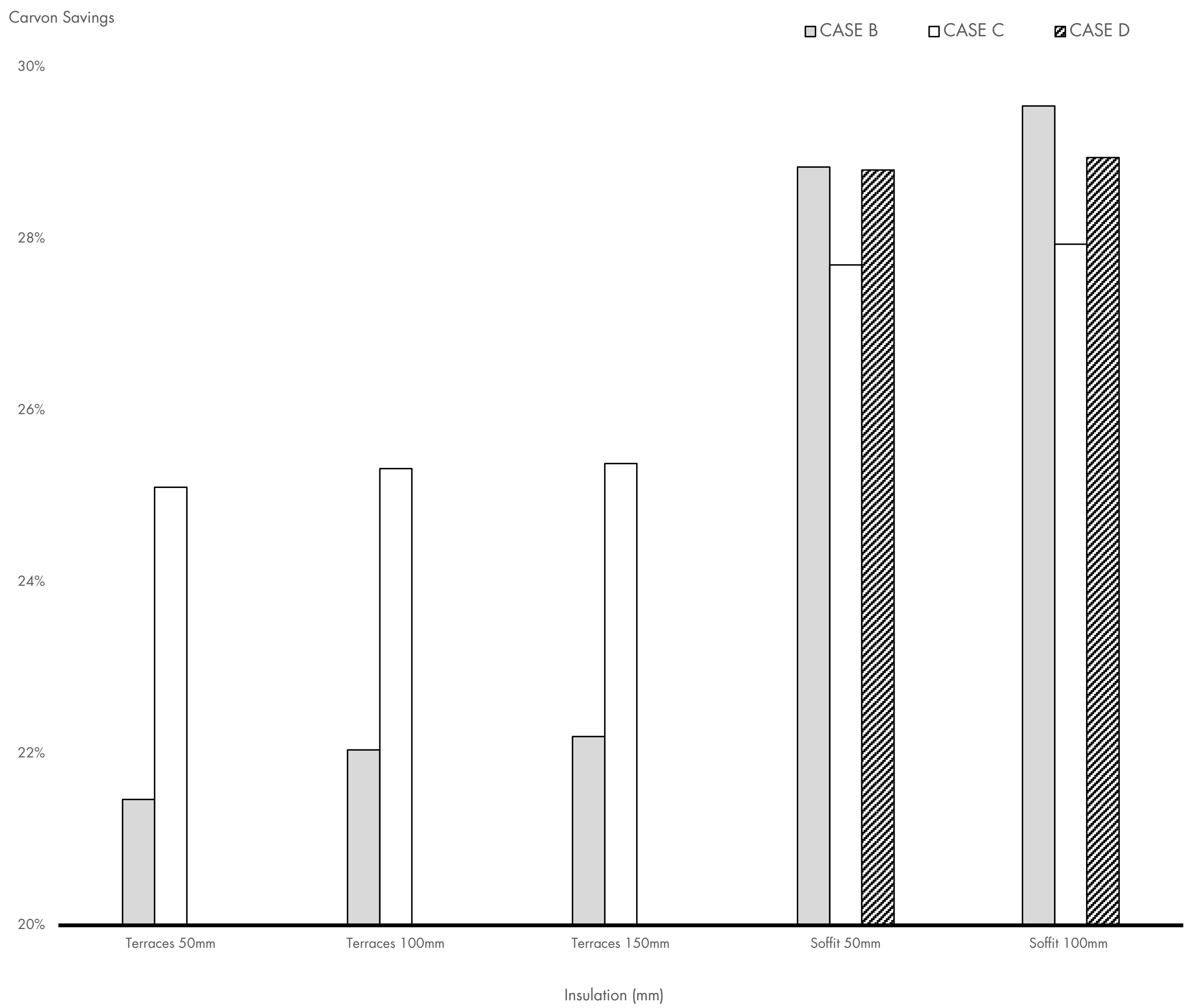
Mineral Wool is also more cost effective with PT under 15 years for Cases B & C.

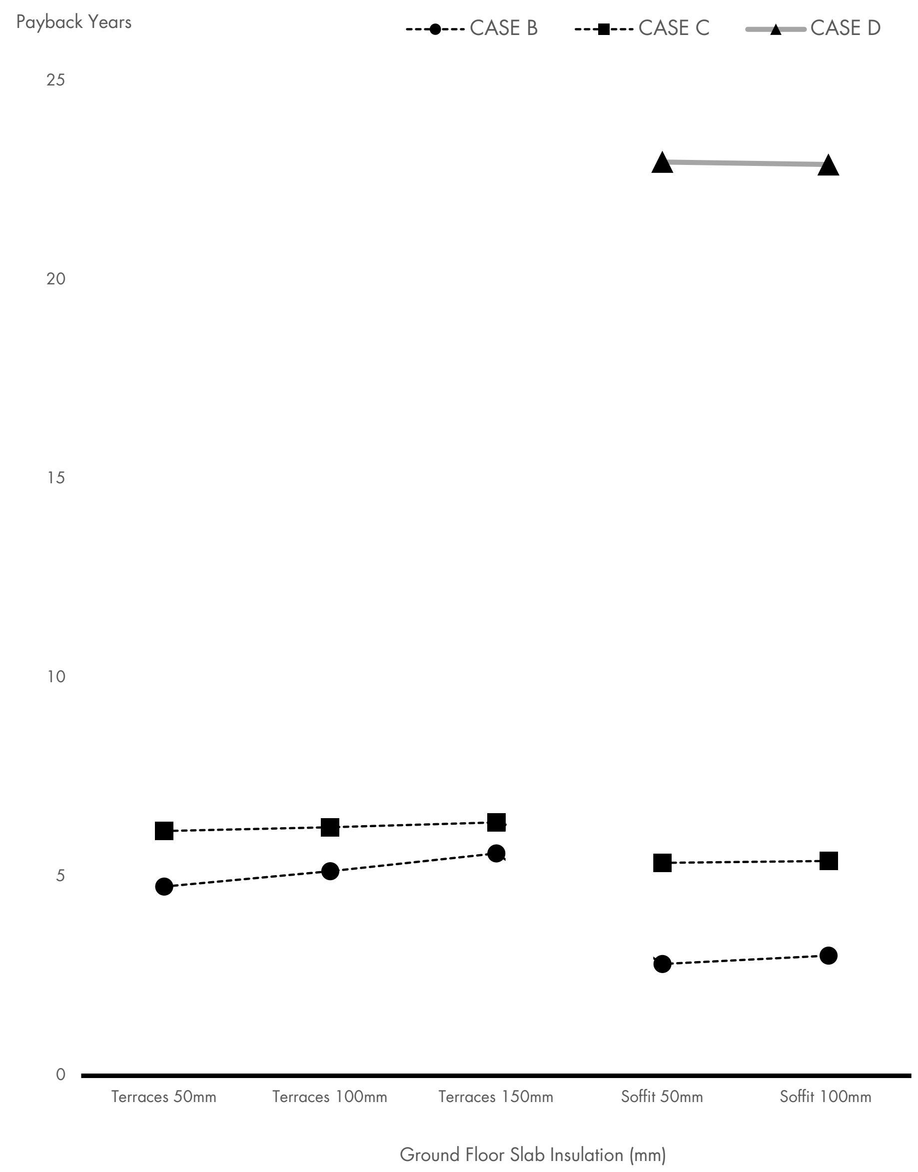




6.9 TERRACES & SOFFIT INSULATION

Insulating the terraces is an upgrade with only a few years Payback Time for Cases B & C and LCCS between 21 and 28%.



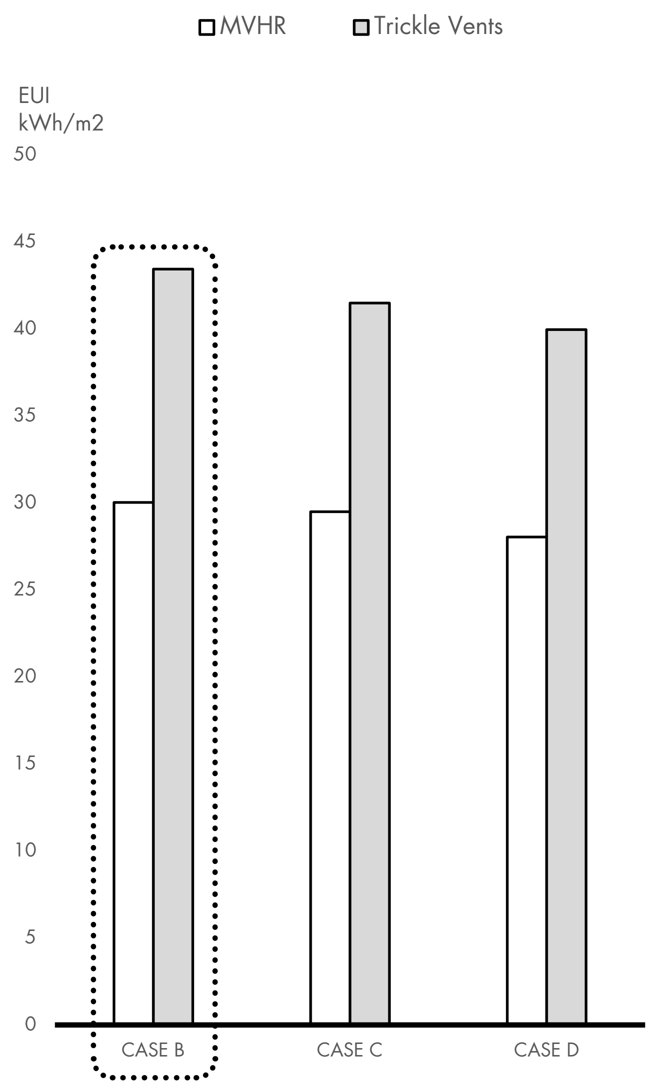


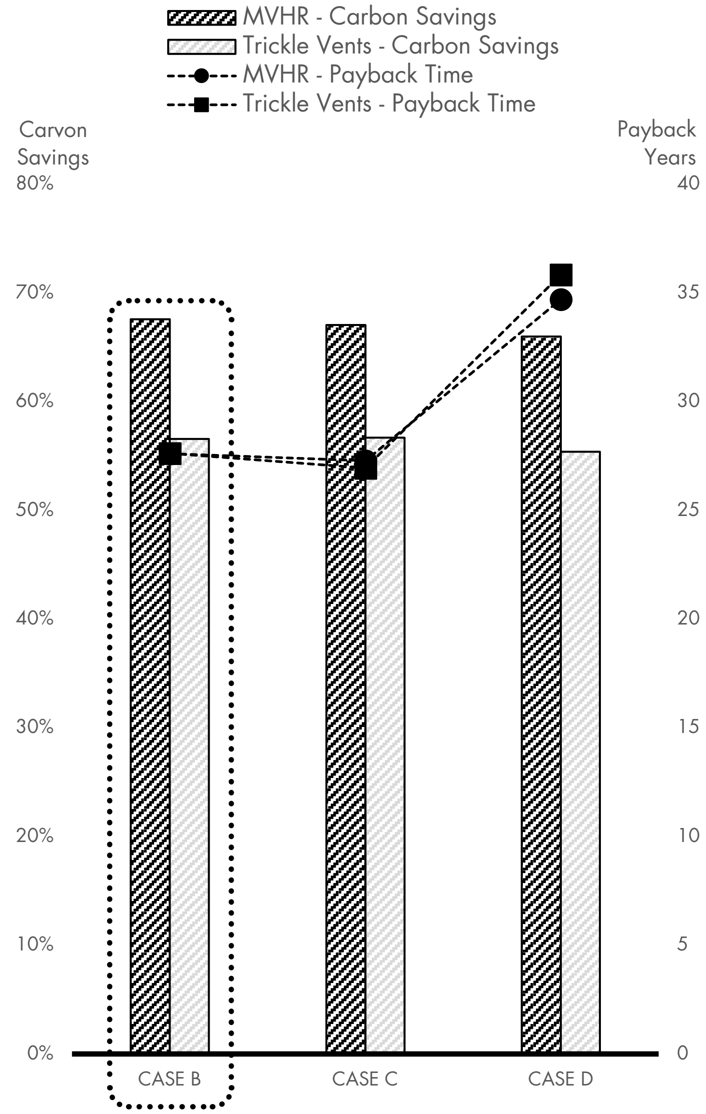
7 STRATEGIES - ASSESSMENT RESULTS

STRATEGY 1
Maximum Carbon Savings

The measures with the most Carbon Savings were combined to form Scenario 1. The use of MVHR or Trickle Vents was tested in combination with the rest of the measures. The results show that as the building envelope becomes more energy efficient, the use of MVHR is overall more advantageous.

Windows	Triple
Roof Insulation	150mm
Wall Insulation	150mm
Wall Finish	Render
Basement Insulation	100mm Mineral Wool
Terrace Insulation	100mm
Soffit Insulation	100mm
Ventilation	MVHR





Heating Demand

31.0
kWh/ m²

Carbon Saving

67
%

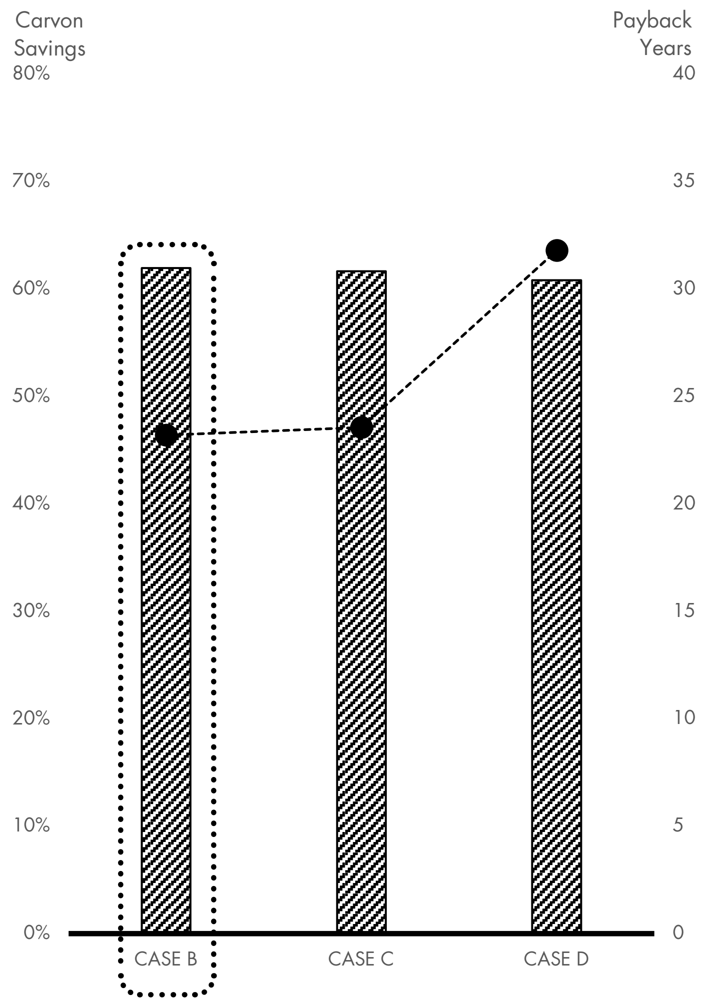
Payback Time

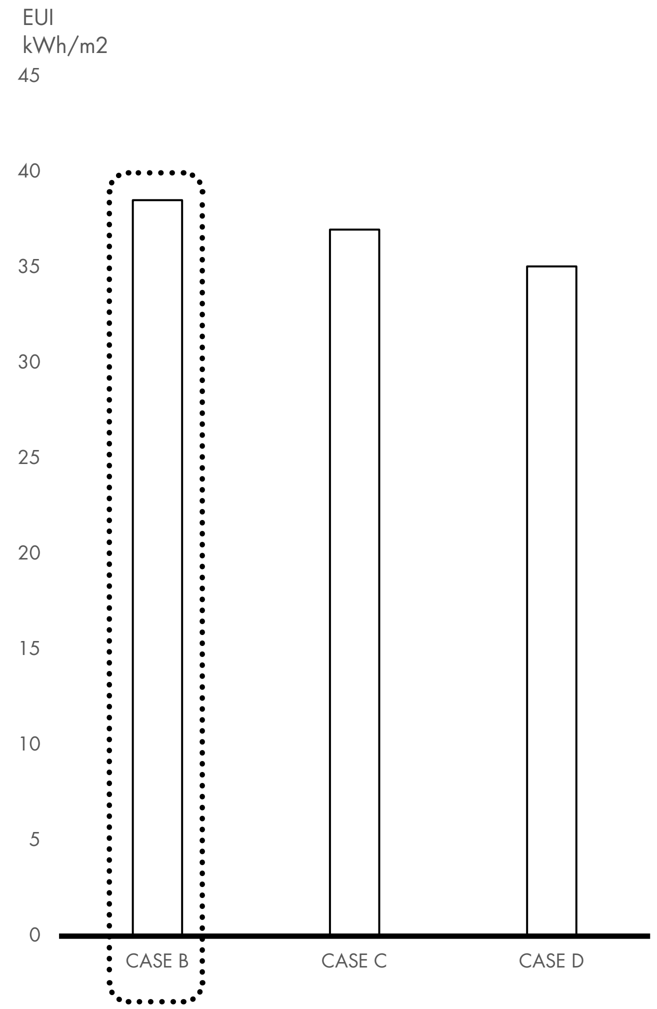
28
years

STRATEGY 2
Minimum Payback Time

Measures with less than 15 years payback time were combined to form Scenario 2. MVHR installation, is included as it is crucial to meet the EUI target of 40kWh/m².

Windows	Triple
Roof Insulation	200mm
Wall Insulation	-
Wall Finish	-
Basement Insulation	100mm Mineral Wool
Terrace Insulation	100mm
Soffit Insulation	100mm
Ventilation	MVHR





Heating Demand

38.5
kWh/ m²

Carbon Saving

62
%

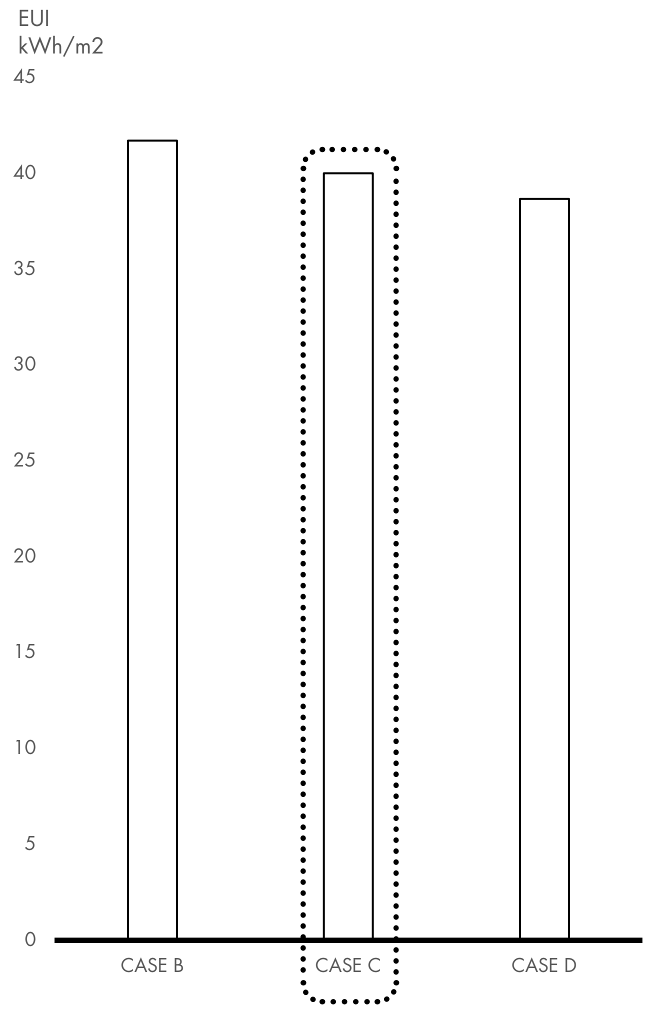
Payback Time

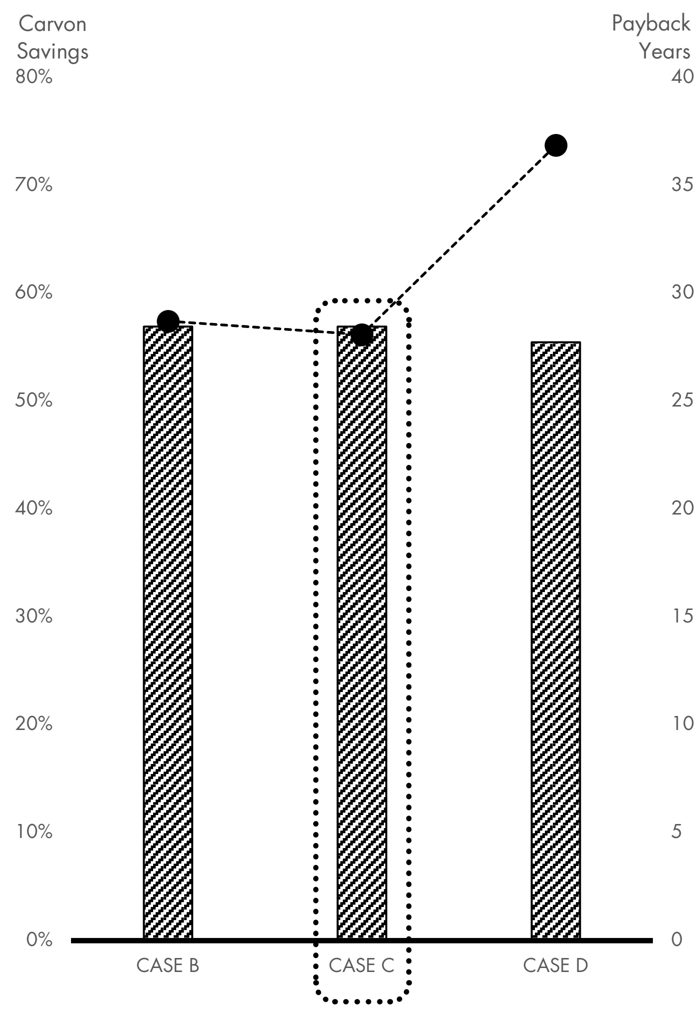
23
years

STRATEGY 3
Minimum Disruption

Measures that will not cause major disruption to residents staying in their apartments during the renovation were combined to form this custom scenario. The installation of MVHRs and addition of Insulation to the Basement are considered the most intrusive measures as they require internal access to the apartments.

Windows	Triple
Roof Insulation	250mm
Wall Insulation	200mm
Wall Finish	Render
Basement Insulation	100mm
Terrace Insulation	150mm
Soffit Insulation	50mm
Ventilation	Trickle Vents





Heating Demand

40.5
kWh/ m²

Carbon Saving

57
%

Payback Time

28
years

STRATEGY 4
Enerphit Certification

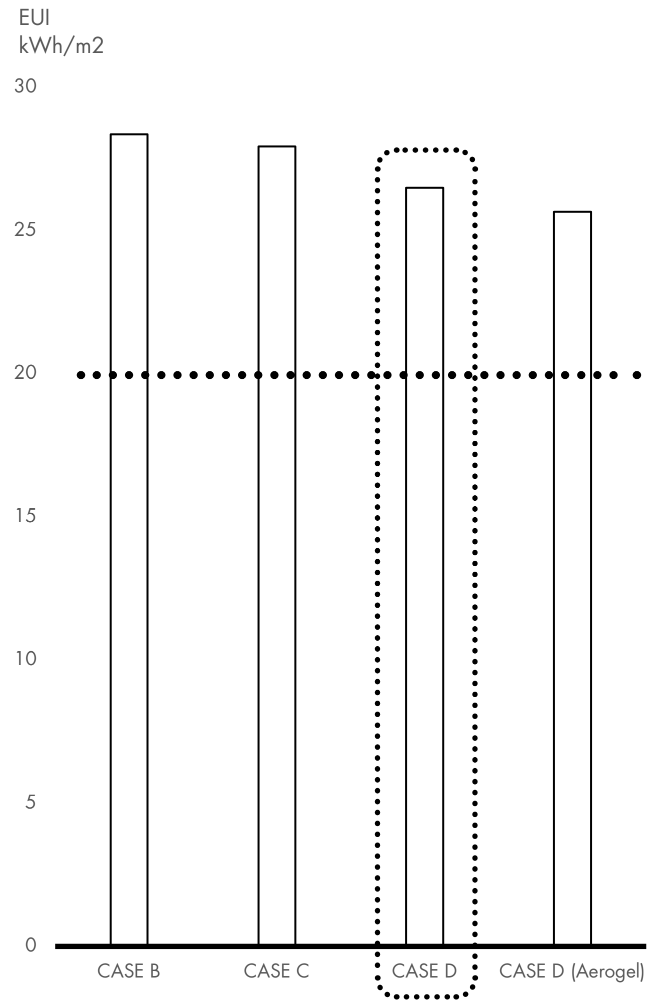
For this scenario, assemblies that reach the recommended Passive House u-values were used were possible. The roof needs additional 350mm of insulation to achieve a u-value of 0.10kWh/m²K and the walls 250mm to achieve 0.15kWh/m²K. In other places additional insulation is not possible due to geometry constrictions.

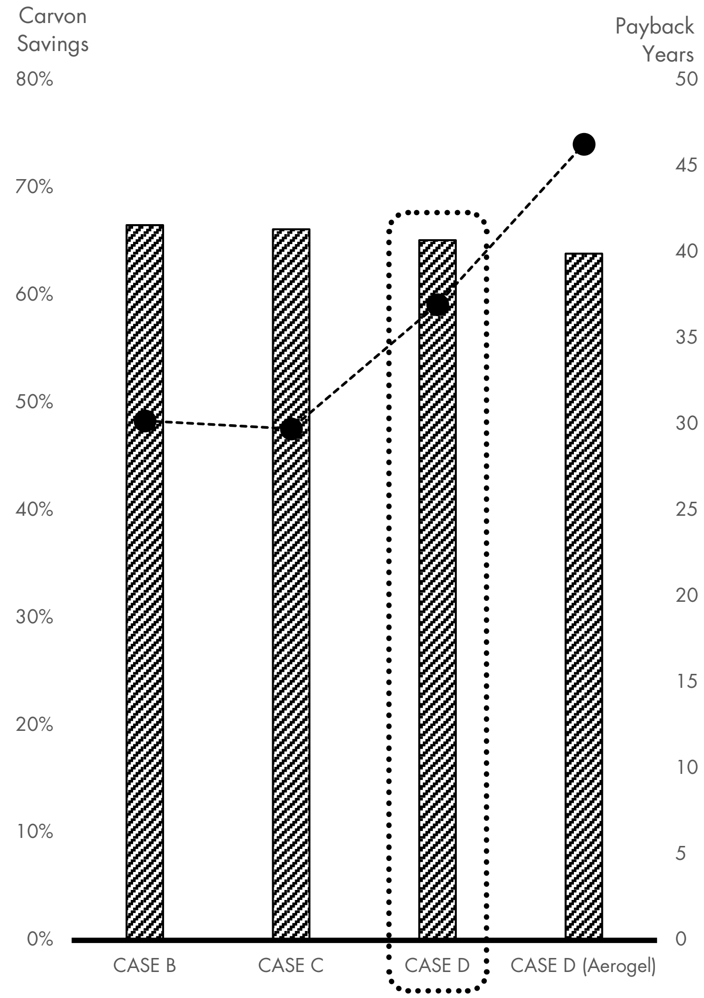
Windows	Triple
Roof Insulation	350mm
Wall Insulation	250mm
Wall Finish	Render
Basement Insulation	100mm
Terrace Insulation	150mm
Soffit Insulation	50mm
Ventilation	MVHR

The measures described above are not sufficient to bring the energy demand bellow 20kWh/m² as required by Enerphit. Replacing the terrace, soffit and basement insulation with high-performance Aerogel insulation was also tested. The use of Aerogel failed to significantly reduce the EUI and at the same time Payback Time increased by almost 10 years.

The above assessments assume an airtightness of 1 ACH which is high from a Passive House Standard perspective which requires an airtightness of approximately 0,5 ACH. The only way to achieve ana Energy use of less than 20kWh/m² is to improve the airtightness of the building which will require further investigation to assess feasibility and cost.

Improving the airtightness below 0.8 ACH will be a crucial step towards a Heating Demand of less than 20kWh/m². The simplification of the envelope is the safest path to an Enerphit Certification, but the omission of the internal terraces provides little benefit in terms of EUI and increases Payback Time significantly.





AIRTIGHTNESS	EUI (kWh/m²)		
	CASE B	CASE C	CASE D
1.00	> 20	> 20	> 20
0.85	> 20	> 20	> 20
0.70	17.3	17.9	16.5
0.55	12.9	12.3	11.4

Heating Demand

26.5
kWh/ m²

Carbon Saving

65
%

Payback Time

37
years

8 CONCLUSIONS

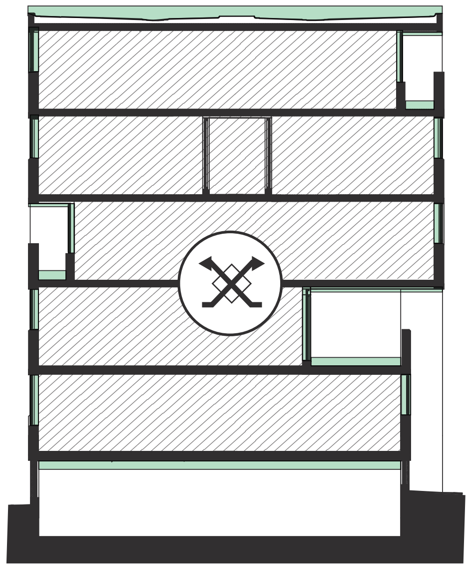
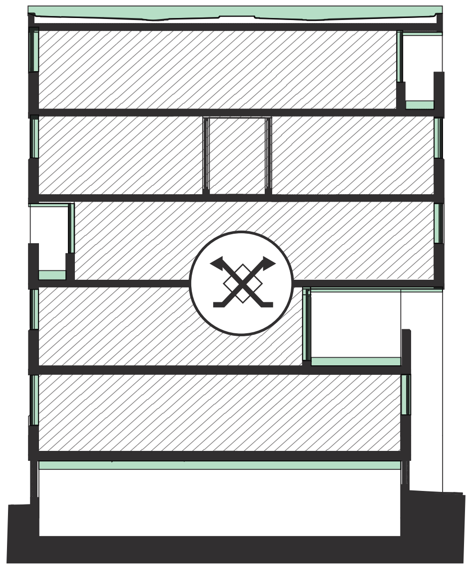
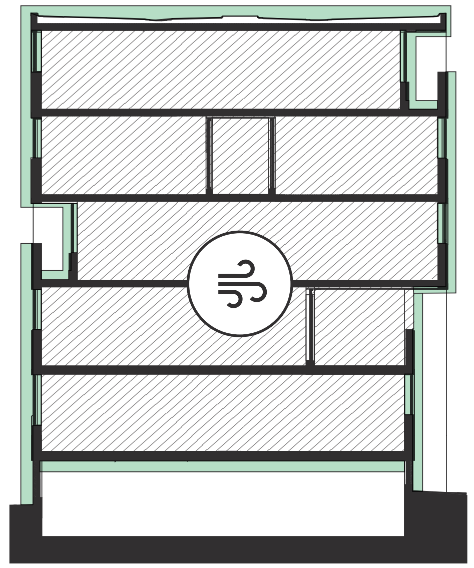
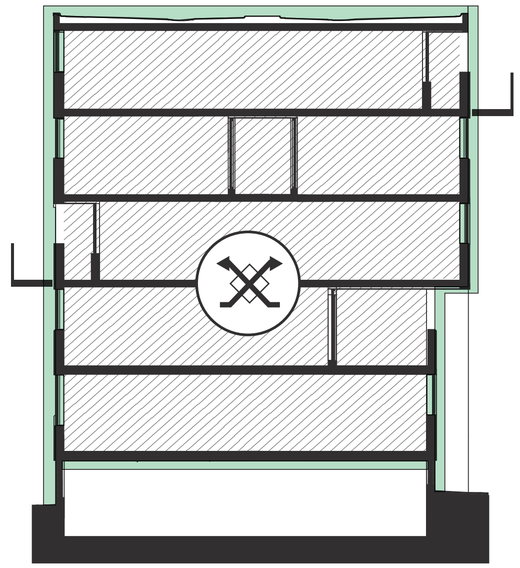
8.1 SCENARIOS OVERVIEW

STRATEGY 1
This strategy aims to minimise the CO_2e emissions of the existing building during its Life Cycle. The achieved EUI of 31kWh/m² is less that what is expected by the current regulations. The Payback Time is 28 years, 5 years more than Scenario 2. The moderate levels of Insulation will provide a new continuous envelope which will reduce thermal bridges and in combination with the MVHR systems will ensure thermal comfort for the residents.

STRATEGY 2
This Strategy aims to minimise the Payback Time of the refurbishment by implementing measures with Payback Time of less than 15 years. The combination of the measures resulted in 23 years PT due to the MVHR system installation. The target of 40kWh/m² could not be achieved otherwise. This scenario shows external wall insulation could be potentially omitted but the effect of the thermal bridges should be carefully assessed.

STRATEGY 3
The Heating Demand target of 40kWh/m² will be hard to achieve without introducing MVHR systems. High levels of insulation to the rest of the building will be required but works requiring access to the flats is reduced.

STRATEGY 4
Achieving Enerphit with less than 20kWh/m² heating Demand will be difficult, and it will depend on the final airtightness of the building. Improving the airtightness could be a costly task, requiring sealing existing penetrations and introducing disruption to the residents. Simplifying the envelope would help achieving airtightness and eliminate thermal bridges, both important steps to achieve Enerphit. However the Payback Time is significantly increased compared to other scenarios making it a potentially costly investment.

	Maximum Carbon Savings	Minimum Payback Time	Minimum Disruption	Enerphit Certification
				
Heating Demand	31.0 kWh/ m²	38.5 kWh/ m²	40.4 kWh/ m²	26.5 kWh/ m²
Carbon Saving	67 %	62 %	57 %	65 %
Payback Time	28 years	23 years	28 years	37 years

8.2 REFURBISHMENT RECOMMENDATIONS

BUILDING
Internalising the Upper access corridor is highly recommended. Internalising the Walkway is optional as it provides little benefit in terms of overall energy consumption, LCA and Payback Time. The simplification of the envelope will minimise the risk of cold bridges, but it will also result in the loss of amenity space. Implications on the energy performance of the lower flats, mostly affected by the open corridor, should also be carefully assessed.

VENTILATION
The installation of MVHR systems increases Carbon Savings and reduces Energy Use significantly when compared to constant natural ventilation through trickle vents. Air quality and thermal comfort is also enhanced. However, the disruption to the residents and impact of duct installation should be considered carefully.

INSULATION TYPE
Mineral Wool Insulation type is recommended through-out the building. High performance Aerogel insulation is not recommended due to high environmental impact and cost.

ROOF
Upgrading the roof with the addition of 150mm of Insulation is recommended as it can improve airtightness and reduce existing thermal bridges.

EXTERNAL WALL
Adding 150mm of external wall Insulation is recommended as it will greatly reduce thermal bridges from the exposed slab edges and improve airtightness. A simple rendered system would be more cost effective. However, the Life Cycle Carbon Savings of this system are not very different to a brick system and may be offset by the non-maintenance nature of brick cladding systems and their recycling potential. Aesthetics and architectural character should also be carefully considered when selecting the cladding system.

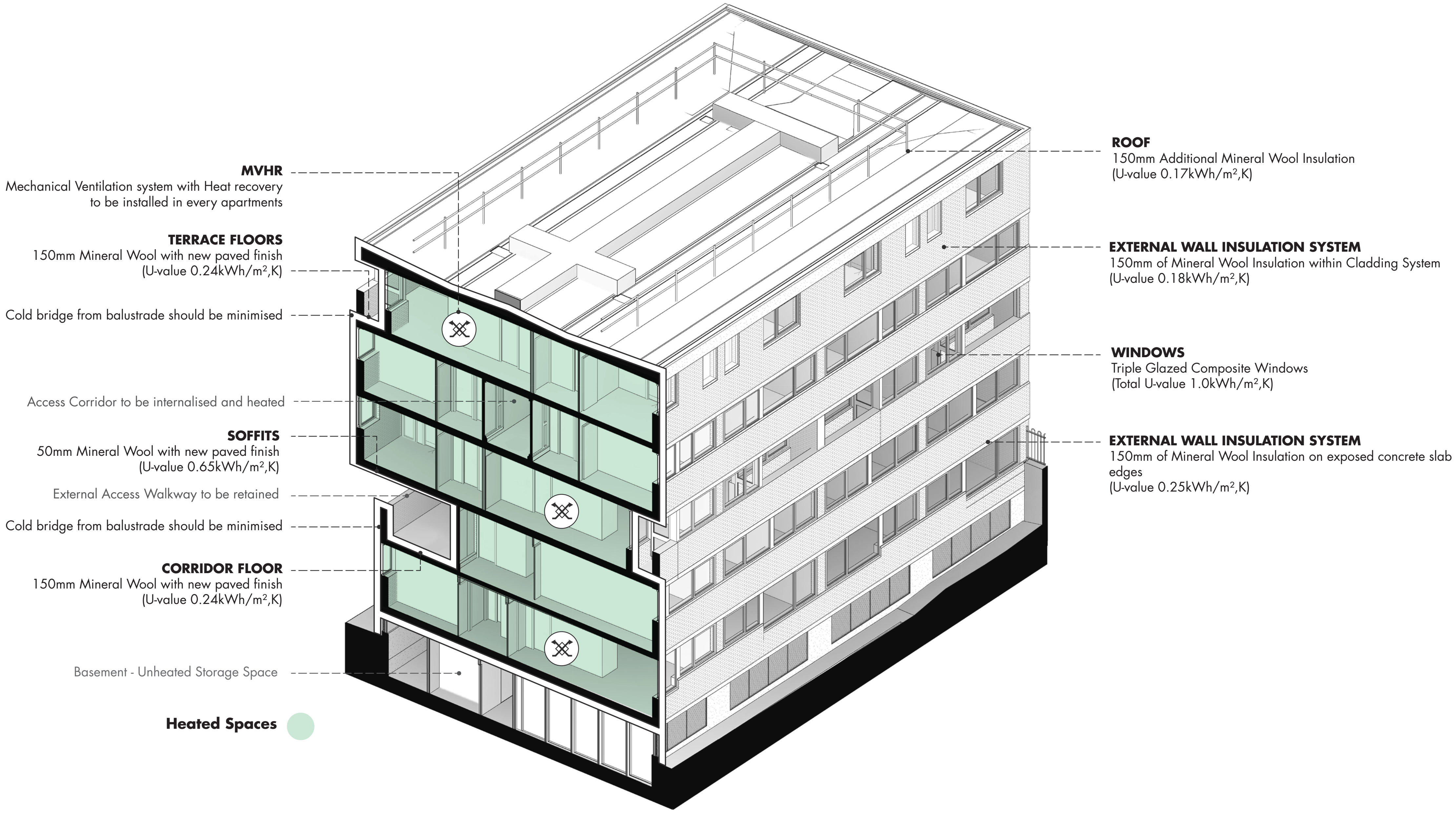
WINDOWS
Upgrading the windows to triple glazing is recommended.

EXPOSED SOFFITS
50mm of Insulation is recommended. More insulation could be considered if the available floor to ceiling height allows.

EXPOSED FLOORS - TERRACES
150mm of Insulation is recommended.

BASEMENT SLAB
Insulating the slab above the unheated basement is not critical to the overall performance of the building and the feasibility and implications of such an action need to be further investigated. It is however recommended that, if possible, the slab should be insulated with 100mm of Mineral Wool on the soffit or floor void to ensure the flats above the unheated basement meet the 40kWh/m² target.

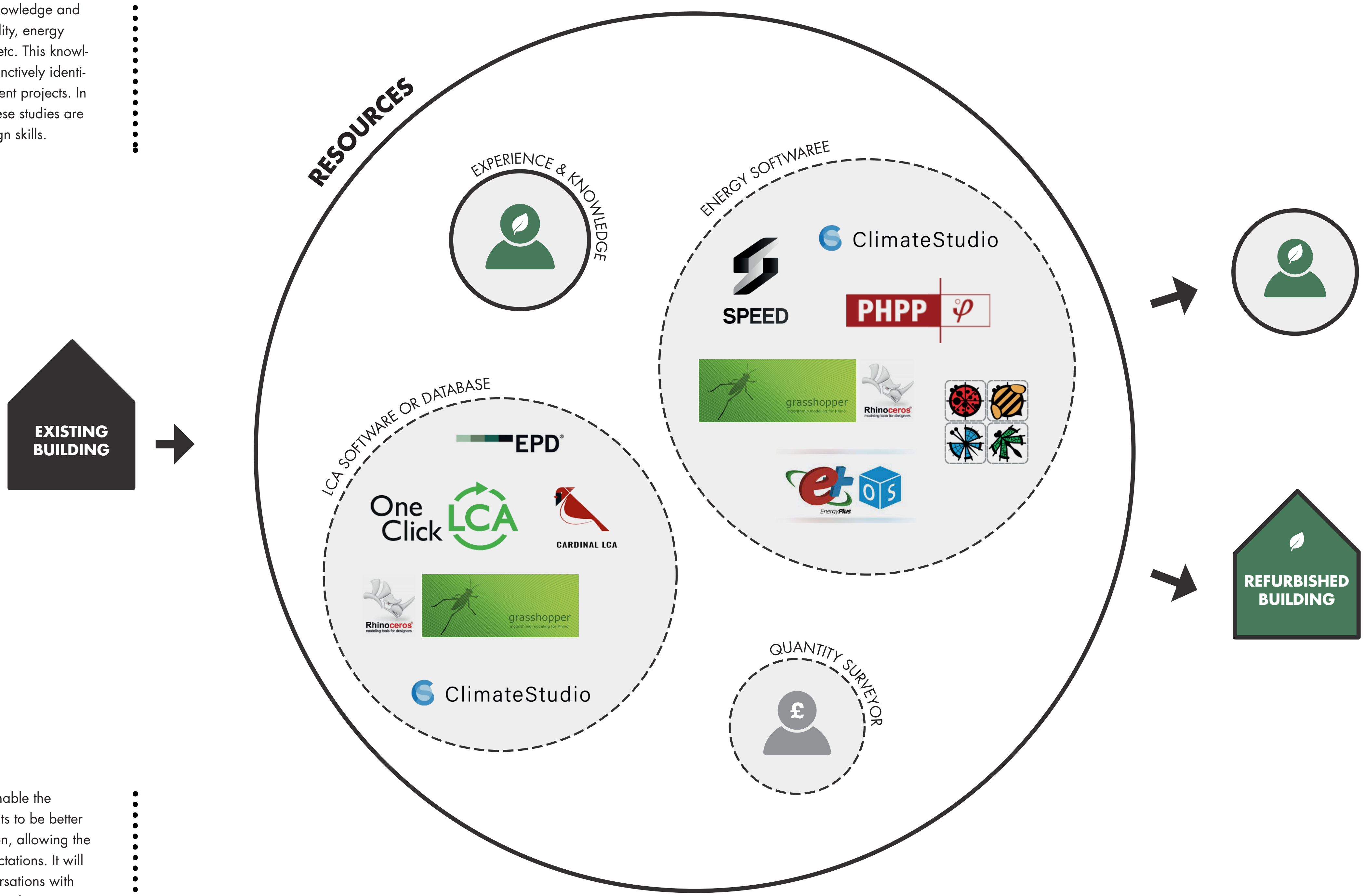
The final recommendations should be a result of comparison between the presented strategies and critical thinking. It should reflect a balanced solution from a Carbon, Cost and Energy Efficiency perspective but with a focus on minimising Carbon Emissions which reflects the office's Net Zero Carbon pledge. In the presented case the "Maximum Carbon Savings" strategy appears to be the most balanced and appealing, so this is the one presented as the final recommendation. The final strategy for the building will have to be coordinated and fine-tuned with the client after the findings are presented.



8.3 METHOD CONCLUSION

The method presented through this case study requires various tools which are largely available within Perkins & Will. The presented analysis can be conducted by people with interest in learning and evolving in the field of LCA and Energy efficiency, but it is important that the process is supervised by people that already have experience and knowledge on these subjects.

These type of studies can help increase the knowledge and understanding within the office, on sustainability, energy efficiency, environmental impact of materials etc. This knowledge will eventually help us to be able to instinctively identify what needs to be done in future refurbishment projects. In addition to provide environmental projects these studies are a way to learn and develop our intuitive design skills.



From a client perspective, these studies will enable the implications of specific client brief requirements to be better understood from a carbon perspective early on, allowing the client to focus on priorities and manage expectations. It will also help clients steer engagement and conversations with residents, so all parties are brought together on the journey towards a holistic net zero carbon future.

Perkins&Will
Research

LIFE CYCLE IMPACT OF RETROFITS
a method to identify optimal retrofit measures based on their life cycle impact and cost, presented through a case study

Vaia Vakouli & Emily Pang
Innovation Incubator, London 2022