Co-funded by the European Union

ERASMUS MUNDUS JOINT MASTER DEGREE

MASTER DEGREE IN SUSTAINABLE DESIGN, CONSTRUCTION AND MANAGEMENT OF THE BUILT ENVIRONMENT

MBUILD

OPTIMIZING DECARBONIZATION & OCCUPANT WELL-BEING IN DEEP RENOVATION WITH THRIVE: A NEB & LEEDv5 INTEGRATED ASSESSMENT FRAMEWORK

TANNER ALEXANDER CLARK

Supervision: Dr. Jorge Rodríguez Hernández (UC) & Dr. David Garcia Sanchez (TECNALIA)

Santander, 2026

U.PORTO

THM TECHNISCHE HOCHSCHULE MITTELHESSEN

UC Universidad de Cantabria

Co-funded by the European Union

ERASMUS MUNDUS JOINT MASTER DEGREE

MASTER DEGREE IN SUSTAINABLE DESIGN, CONSTRUCTION AND MANAGEMENT OF THE BUILT ENVIRONMENT

MBUILD

OPTIMIZING DECARBONIZATION & OCCUPANT WELL-BEING IN DEEP RENOVATION WITH THRIVE: A NEB & LEEDv5 INTEGRATED ASSESSMENT FRAMEWORK

Tanner Alexander Clark

Supervision: Dr. Jorge Rodríguez Hernández (UC) & Dr. David Garcia Sanchez (TECNALIA)

Santander, 2026

U.PORTO THM TECHNISCHE HOCHSCHULE MITTELHESSEN UC Universidad de Cantabria

MBUILD

ERASMUS MUNDUS JOINT MASTER IN SUSTAINABLE DESIGN, CONSTRUCTION AND MANAGEMENT OF THE BUILT ENVIRONMENT

✉ mbuild@fe.up.pt

🌍 www.mbuild.eu

Edited by

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Rua Dr. Roberto Frias
4200-465 Porto
PORTUGAL
☎ +351-22-508-1400
✉ feup@fe.up.pt
🌍 www.fe.up.pt

TECHNISCHE HOCHSCHULE MITTELHESSEN

Wiesenstraβe 14
D – 35390 Gießen
DEUTCSHLAND
☎ +49-641-309-0
✉ info@thm.de
🌍 www.thm.de

UNIVERSIDAD DE CANTABRIA

Avda. De los Castros, s/n
39005 Santander
ESPAÑA
☎ +34-942-20-10-18
✉ informacion.general@unican.es
🌍 https://web.unican.es

Partial reproductions of this document will be authorized provided that the Author is mentioned and reference is made to MBUILD ERASMUS MUNDUS JOINT MASTER IN SUSTAINABLE DESIGN, CONSTRUCTION AND MANAGEMENT OF THE BUILT ENVIRONMENT, Portugal, Germany, Spain, 2026.

The opinions and information included in this document represent only the views of the Author and the Publisher cannot accept any legal or other responsibility in relation to errors or omissions that may exist.

This document was produced from an electronic version provided by the respective Author.

"The wide world is all about you: you can fence yourselves in, but you cannot forever fence it out."

- *JRR Tolkien*

ACKNOWLEDGEMENTS

First and foremost, I want to thank God for guiding me to MBUILD and blessing me with the strength, courage, and aptitude to undertake the grand adventure this master's program has been. I recognize that living in three different countries over the course of two years while being funded to study your passion is not something many get to experience, which has left me humbled and profoundly grateful.

To the Erasmus Mundus initiative and European Union, thank you for developing and funding programs that bring together people from all over our planet. They have created a truly unique experience for us students to grow both academically and personally through such a diverse exchange of cultures and ideas.

To all of the many MBUILD professors that have worked together to share their knowledge and passion which makes this program possible. A special thank you to Jorge Moreira da Costa (UP) for his key role in establishing MBUILD and constant support navigating the logistics of visas and residency that arise from a program of this nature. Also, to Jorge Rodríguez (UC), for all of the guidance provided as my primary supervisor. Thank you for your insights, responsiveness, flexibility, and precise attention to detail which have greatly benefited this final dissertation.

To my colleagues in TECNALIA, who granted the support and working environment that made this dissertation possible, while helping me learn a second language along the way. Especially to my supervisor David Garcia who brought me in and provided the inspiration to lead me to my chosen topic, and Iñigo Uribarri, who has been an invaluable source of information and feedback throughout this process. You have all been a pleasure to work with.

To my fellow MBUILD classmates, getting to know each of you and becoming a family over these past two years has forever changed my life for the better. I never imagined I would be able to call 18 people from all over the world my friends. Thank you for the shared laughs, trips, food, and unique personalities which were the highlight of this whole experience. I sincerely hope that as we go our separate ways we will always stay in touch.

Finally, to my family, especially my parents, and friends back home. Thank you for your love and unwavering support from across the ocean, and the sacrifice of time spent together. You shaped me into the man I am today capable of undertaking this degree. Though I was sad to miss many of our usual shared moments, your presence and encouragement were a constant reminder that home was always there for me. I love you all.

Thank you, obrigado, dankeschön, and gracias!

ABSTRACT

Deep renovation of existing buildings, through industrialized, prefabricated envelopes integrated with energy and ventilation system upgrades, offers a promising pathway towards both achieving global reduction targets for carbon emissions and improving occupant well-being. However, it remains to be thoroughly tested to what extent this type of renovation can simultaneously meet these goals in real projects. Previous research has typically assessed energy, life-cycle carbon, and indoor environmental quality (IEQ) outcomes of deep renovation solutions separately, or at most incorporated two of the three.

The recently released the New European Bauhaus Self-Assessment Method (NEB-SAM) from the EU, and the newest version of the US-based LEED rating system, LEEDv5, are among the most cutting-edge sustainable building frameworks. However, the two come from very different regional backgrounds, are designed for different purposes, and cover scope well beyond major building renovations. To streamline global adoption of optimized deep renovation solutions, a simplified evaluation methodology capturing the best of these frameworks and tailored specifically to deep renovation projects could be beneficial. Therefore, the novel Transatlantic, Holistic Renovation assessment framework for decarbonization, Indoor enVironmental quality, and Equity (THRIVE) is proposed.

THRIVE is built on integrated measures inspired by NEB-SAM indicators and LEEDv5 credits and prerequisites, organized in four analysis blocks covering 1. embodied carbon, 2. operational carbon, 3. IEQ (assessed through daylight, thermal comfort, and indoor air quality), and 4. resilience, aesthetics, and inclusiveness (RAI). User-friendly results are delivered at the measure, block, and project level, enabling the identification of relative strengths and weakness and assisting the user in developing recommendations for improvement.

This paper showcases THRIVE through a case study application to the EU Horizon-funded "AEGIR" project (Grant agreement ID: 101079961). Specifically, to the deep renovation of a demonstration educational building in Spain using innovative strategies which include an industrialized, bio-based envelope, smart ventilation, and an integrated renewable energy hub.

Keywords: Deep renovation, Decarbonization, Occupant well-being, New European Bauhaus, LEEDv5.

GENERAL INDEX

ACKNOWLEDGEMENTS i

ABSTRACT iii

1. INTRODUCTION 1

1.1. GENERAL DISCLAIMERS 1

1.2. STRUCTURE OF DISSERTATION 3

1.3. CONTEXT & MOTIVATION 4

1.3.1. THE PROBLEM 4

1.3.2 THE DEEP RENOVATION SOLUTION 6

1.3.3 SUSTAINABILITY FRAMEWORKS 10

1.4. OBJECTIVES 18

2. STATE OF THE ART 19

2.1. LITERATURE REVIEW 19

2.1.1. APPROACHES TO DEEP RENOVATION IN EUROPE & THE US 19

2.1.2. DECARBONIZATION VIA DEEP RENOVATION WITH PREFABRICATED ENVELOPE SYSTEMS 23

2.1.3. INDOOR ENVIRONMENTAL QUALITY 26

2.1.4. APPLICATION OF SUSTAINBILITY FRAMEWORKS 28

2.2. EXISTING RESEACH GAPS & LIMITATIONS 33

3. METHODOLOGY 35

3.1. OVERVIEW 35

3.2. EMBODIED CARBON 37

3.3. OPERATIONAL CARBON 44

3.4. INDOOR ENVIRONMENTAL QUALITY (IEQ) 53

3.4.1. DAYLIGHT ACCESS 53

3.4.2. THERMAL COMFORT 55

3.4.3. INDOOR AIR QUALITY 58

3.5. RESILIENCE, AESTHETICS, & INCLUSIVENESS 62

3.6. THRIVE INTEGRATED SCORING LOGIC 68

4. CASE STUDY DEMONSTRATION OF THRIVE 75

4.1. AEGIR SPAIN DEMO BUILDING – BACKGROUND 75

4.2. DATA COLLECTION AND SUPPORTING TOOLS 79
4.3. UNCERTAINTY, LIMITATIONS, & ASSUMPTIONS FOR THIS WORK 81
5. RESULTS AND DISCUSSION 89
5.1. STRUCTURE OF RESULTS 89
5.2. EMBODIED CARBON RESULTS 91
5.3. OPERATIONAL CARBON RESULTS 101
5.4. IEQ OUTCOMES 108
5.4.1. DAYLIGHT RESULTS 108
5.4.2. THERMAL COMFORT RESULTS 113
5.4.3. INDOOR AIR QUALITY RESULTS 115
5.5. RESILIENCE, AESTHETICS, & INCLUSIVENESS RESULTS 118
5.6. PROJECT RESULTS 126
5.7. DISCUSSION: CASE STUDY INTERPRETATION & RECOMMENDATIONS 127
5.8. DISCUSSION: REFLECTIONS ON THRIVE & GUIDING FRAMEWORKS 138
6. CONCLUSIONS 145
6.1. GENERAL CONCLUSIONS 145
6.2. SPECIFIC CONCLUSIONS 146
6.3. FUTURE RESEARCH 150

REFERENCES 153
ANNEXES 159
Annex A.1 – Input Quantities for Whole-Life Carbon Assessment 159
Annex A.2.1 – EPD Assignments for Whole-Life Carbon Assessment – Baseline 160
Annex A.2.2 – EPD Assignments for Whole-Life Carbon Assessment – Proposed 162
Annex A.3 – Responsible Sourcing Multi-Attribute Scoring 164
Annex A.4 – IEQ Analysis Room List 166
Annex A.5 – Room-by-Room Daylight Simulation Results 169
Annex A.6 – Inputs for VRP Calculations 176
Annex A.7 – Definitions for Aesthetic / Visual Experience Metrics 178

INDEX OF FIGURES

Figure 1 – Projected Whole-life Carbon Source Breakdown for New Buildings by 2050 (Carrol, 2025) 4
Figure 2 – Greenhouse gas Emission Distribution by Building Stock Activity, Baseline year 2020 (European Commission, 2026) 5
Figure 3 – US Owner-Occupied Housing Stock Share by Year Built (Zhao, 2025) 6
Figure 4 – AEGIR Industrialized Envelope System Typologies (Jay Arnaud & Astudillo Larraz, 2023) 8
Figure 5 – Map of AEGIR Demonstration Buildings; 9
Figure 6 – NEB Dimensions and Working Principles (New European Bauhaus Compass, n.d.) 11
Figure 7 – NEB Levels of Ambition for; Dimensions (Left), Working Principles (Right) (New European Bauhaus Compass, n.d.) 12
Figure 8 – Overview of NEB Self-Assessment Method Workflow (Lourenco et al., 2024) 13
Figure 9 – WELLv2 Concepts (IWBI, 2025) 13
Figure 10 – New NEB-inspired JRC Seville Building Rendering (New European Bauhaus-Inspired Future JRC Site in Seville, n.d.) 14
Figure 11 – Certified LEEDv5 O+M Projects; 15
Figure 12 – Each ALDREN BRP Module (M) with Specific Passport Stamp (Sesana et al., 2021) 20
Figure 13 – INPERSO KPI Selection Methodology (Secondo-Maglia et al., 2024) 21
Figure 14 – US Commercial Building Stock Distribution by Typology (Ghorbany et al., 2025) 22
Figure 15 – Layered configuration of SmartWall Assembly (Katsigiannis et al., 2022) 25
Figure 16 – Inhabitant Wellbeing and Productivity Framework (Saadoon Abdulaali et al., 2020) 26
Figure 17 - Case Study School (Jain et al., 2020); Entrance – West Façade (Left), Central Courtyard (Right) 27
Figure 18 – IEQ Impact on Satisfaction & Productivity, Conceptual Research Model (Hamimi et al., 2017) 28
Figure 19 – CATI: A New Sustainability Culture (Rosado-García et al., 2021) 29
Figure 20 – JRC Geel Site (Bektasiadou, 2024); Current Condition (Left), Post-Reno Rendering (Right) .. 30
Figure 21 – Relationship between Historical Reno Project Aims, LEED-adapted Credits, and Final Score (Baggio et al., 2017) 32
Figure 22 – Proposed **T**ransatlantic, **H**olistic **R**enovation assessment framework for decarbonization, **I**ndoor en**V**ironmental quality, and **E**quity (THRIVE) Methodology Structure (created with Miro) 36
Figure 23 – Life Cycle Stages (Zahrmann, 2024) 37
Figure 24 – Integration Flowchart and Weighting for EC1: Life Cycle Carbon (created with Miro) 40
Figure 25 – Integration Flowchart and Weighting for EC3: Circularity & Sourcing (created with Miro) .. 41
Figure 26 – Integration Flowchart and Weighting for OC1: Emissions & Efficiency (created with Miro) . 44
Figure 27 – Aggregated Results of Analyzed Case Studies (Bienert et al., 2023) 49
Figure 28 – Integration Flowchart and Weighting for OC3: Peak Demand (created with Miro) 50
Figure 29 – Integration Flowchart and Weighting for OC4: Renewable Energy (created with Miro) 50
Figure 30 – Integration Flowchart and Weighting for IEQ1: Daylight Access (created with Miro) 53
Figure 31 – Daylight Simulation Ground Plane Modeling Guidance (LightStanza, n.d.-a) 54
Figure 32 – Integration Flowchart and Weighting for IEQ2: Thermal Comfort (created with Miro) 56
Figure 33 – B.4.3 Indicator Scoring; Adapted from (Lourenco et al., 2024) 56
Figure 34 – Integration Flowchart and Weighting for IEQ3: Indoor Air Quality (created with Miro) 58
Figure 35 – S.5 Building-Scale Performance Class Thresholds (Lourenco et al., 2024) 59
Figure 36 – Integrated Flowchart and Weighting for RAI1: Hazard Resilience (created with Miro) 62
Figure 37 – Wall External Surface Requirements for Fire Spread (HM Government, 2019) 63

Figure 38 – Roof Covering Requirements for Fire Spread (HM Government, 2019) 63
Figure 39 – Integrated Flowchart and Weighting for RAI2: Visual Experience (created with Miro) 64
Figure 40 – Examples of the Four Order Principles for Visual Richness (Lourenco et al., 2024) 65
Figure 41 – Examples of the four Contrast Principles for Visual Richness (Lourenco et al., 2024) 65
Figure 42 – Examples of the four Transparency Principles for Visual Richness (Lourenco et al., 2024) 66
Figure 43 – Integrated Flowchart and Weighting for RAI3: Equitable Accessibility (created with Miro) 67
Figure 44 – Analysis Block Weighting for Project Level Score (created with Miro) 72
Figure 45 – THRIVE Performance Class Thresholds; Adapted from (Lourenco et al., 2024) with AI 72
Figure 46 – Case Study Building Geographic Location; 75
Figure 47 – Case Study Building; Orientation (Left), Satellite View (Right) 76
Figure 48 – Case Study Building (Herrero et al., 2025); 76
Figure 49 – Panel Typology Distribution; North-facing (Left), South-facing (Right) 77
Figure 50 – AEGIR Panel Concept (United Network Studio, 2026) 77
Figure 51 – Case Study Air Handling Unit System Scheme (Herrero et al., 2025) 78
Figure 52 – StoTherm Mineral Assembly Components (Sto, 2020) 82
Figure 53 – ETICS Mass per Functional Unit per EPD (One Click LCA, 2015) 83
Figure 54 – Case Study Simulated Post-Renovation Energy Balance (TECNALIA) 84
Figure 55 – Case Study Custom-modeled Windows, Ground Floor 85
Figure 56 – Metabolic Rate for Common Activities in Children and Adolescents (Gao et al., 2023) 86
Figure 57 – Case Study Main Entrance Clear Widths; Adapted from Arch Drawings with Bluebeam Revu 88
Figure 58 – Structure of Results and Discussion (created with Miro) 90
Figure 59 – Simplified Cross Section for Embodied Carbon Assessments; AEGIR Panel (created with Revit) 91
Figure 60 – Simplified Cross Section for Embodied Carbon Assessments; ETICS (created with Revit) 92
Figure 61 – Simplified Cross Section for Embodied Carbon Assessments; ETICS+C (created with Revit) 92
Figure 62 – Comparison of Baseline and Proposed Case Study EC1 Results for GWP 95
Figure 63 – Proposed Case Study Life Cycle Carbon Model, GWP Breakdown by Life-Cycle Stage 96
Figure 64 – Case Study Integrated Scoring for EC1 (created with Miro) 97
Figure 65 – Case Study Integrated Scoring for EC3 (created with Miro) 100
Figure 66 – Case Study Analysis Block-Level Score; Embodied Carbon (created with Miro) 100
Figure 67 – Case Study Baseline Energy Model Validation (Herrero et al., 2025) 101
Figure 68 – Case Study Integrated Scoring for OC1 (created with Miro) 104
Figure 69 – Case Study Integrated Scoring for OC3 (created with Miro) 105
Figure 70 – Annual Share of Energy from Renewable Sources per EU Member State (Eurostat, 2026) 106
Figure 71 – Case Study Integrated Scoring for OC4 (created with Miro) 106
Figure 72 – Case Study Analysis Block-Level Score; Operational Carbon (created with Miro) 107
Figure 73 – Case Study Daylight Model Room Layout, Ground Level (created with Revit) 108
Figure 74 – Case Study Daylight Model Room Layout, Level 1 (created with Revit) 108
Figure 75 – Location of Case Study Special Glazing Assembly; Ground Level (Left), Level 1 (Right) 109
Figure 76 – Case Study Typical Glazing Assembly (Guardian Glass, n.d.) 110
Figure 77 – Other Case Study Glazing Assemblies (Guardian Glass, n.d.) 110
Figure 78 – Structures Adjacent to Case Study Building, Modeled in Daylight Simulation; Adapted from Google Maps with Bluebeam Revu 111
Figure 79 – Case Study LightStanza Daylight Simulation Model (LightStanza, n.d.-b) 111

Figure 80 – Case Study Daylight Simulation Results (LightStanza, n.d.-b), Ground Level; 112
Figure 81 – Case Study Daylight Simulation Results (LightStanza, n.d.-b), Level 1; sDA (Left), ASE (Right) 112
Figure 82 – Case Study Integrated Scoring for IEQ1 (created with Miro) 113
Figure 83 – Case Study Heating- & Cooling-mode Setpoints and Seasonal Operation (Herrero et al., 2025) 113
Figure 84 – Case Study PMV Thermal Comfort Results; Heating-Mode (Tartarini et al., 2020) 114
Figure 85 – Case Study PMV Thermal Comfort Results; Cooling-Mode (Tartarini et al., 2020) 114
Figure 86 – Case Study Integrated Scoring for IEQ2 (created with Miro) 115
Figure 87 – Case Study Integrated Scoring for IEQ3 (created with Miro) 116
Figure 88 – Case Study Analysis Block-Level Score; IEQ (created with Miro) 117
Figure 89 – Case Study Integrated Scoring for RAI1 (created with Miro) 119
Figure 90 – Case Study Presence of Axis Composition & Hierarchy 120
Figure 91 – Case Study Presence of Transformation 120
Figure 92 – Case Study Presence of Rhythm / Repetition 121
Figure 93 – Case Study Presence of Lines and Spaces & Materials 121
Figure 94 – Case Study Presence of Surfaces and Apertures 121
Figure 95 – Case Study Presence of Openings towards natural areas 122
Figure 96 – Case Study Presence of Play of Light and Shadow; 123
Figure 97 – Case Study Presence of Light-Shadow Effects; 123
Figure 98 – Case Study Integrated Scoring for RAI2 (created with Miro) 124
Figure 99 – Case Study Integrated Scoring for RAI3 (created with Miro) 125
Figure 100 – Case Study Analysis Block-Level Score; RAI (created with Miro) 125
Figure 101 – Project Level Score for the Case Study Building (created with Miro) 126
Figure 102 – Recs for Case Study Daylight Access, Ground Floor; Adapted from (LightStanza, n.d.-b) 129
Figure 103 – Recs for Case Study Daylight Access, Level 1; Adapted from (LightStanza, n.d.-b) 129
Figure 104 – Case Study Standard Window Sizes (Revit) 130
Figure 105 – Impact of Recs on sDA, Partial Floor Plans, Ground Level; Adapted from (LightStanza, n.d.-b) 131
Figure 106 – Impact of Recs on sDA, Partial Floor Plans, Level 1; Adapted from (LightStanza, n.d.-b) .. 131
Figure 107 – Case Study PMV Heating-Mode Sensitivity Check (Tartarini et al., 2020) 132
Figure 108 – Case Study PMV Heating-Mode Compliance with Proposed Recs (Tartarini et al., 2020) 133
Figure 109 – Case Study PMV Cooling-Mode Air Speed Sensitivity Check (Tartarini et al., 2020) 133
Figure 110 – Year-Round Relative Humidity in Case Study Classrooms, Pre-Renovation (TECNALIA) ... 134
Figure 111 – Standard PV Panels GWP Benchmark (One Click LCA, 2015) 135
Figure 112 – Comparison of Baseline, Proposed, and Further Recommendation Case Study EC1 Results 137
Figure 113 – NEB-SAM Performance Class Thresholds: Indicators vs Dimension Discrepancy Example; 140
Figure 114 – Room Numbers; Ground Level 168
Figure 115 – Room Numbers; Level One 168

INDEX OF TABLES

Table 1 – List of AEGIR Circularity KPI (Zabek et al., 2023) 10
Table 2 – Additional Level(s)-based KPI relevant to AEGIR (Zabek et al., 2023) 10
Table 3 – Guiding Framework Indicators, Prerequisites, and Credits; 17
Table 4 – Integrated Measure Composition for Embodied Carbon; 37
Table 5 – Average Material Quantities in Composite Elements; Adapted from (One Click LCA, n.d.-a) 39
Table 6 – Average Quantities of Reinforcement in Concrete; Adapted from (One Click LCA, n.d.-b) 39
Table 7 – NEB-side Scoring for EC1; Adapted from (Lourenco et al., 2024) 40
Table 8 – LEED-side Scoring for EC1; Adapted from (Lourenco et al., 2024; USGBC, 2025) 40
Table 9 – Scoring Thresholds for Responsible Sourcing 42
Table 10 – Integrated Measure Composition for Operational Carbon; 44
Table 11 – Scoring Thresholds for Operational Emissions and Current Source Energy Performance; 45
Table 12 - ASHRAE 90.1-2019: Equivalent Building Performance Factors for a Future Source Energy Metric; Defined in EAc3: Enhanced Energy Efficiency (USGBC, 2025) 46
Table 13 – EAc1 Scoring Distribution; Adapted from EAc1: Electrification (USGBC, 2025) 47
Table 14 – EC2, OC2 Scoring Distribution; Adapted from (Bienert et al., 2023) 49
Table 15 – Renewable Energy Supply Scoring Distribution; 51
Table 16 - Integrated Measure Composition for IEQ; Adapted from (Lourenco et al., 2024; USGBC, 2025) 53
Table 17 – Default Surface Light Reflectance Values (DiLaura et al., 2011) 54
Table 18 – Daylight Simulation Scoring Thresholds; 55
Table 19 – Daylight Design Strategies Scoring Thresholds; 55
Table 20 – Thermal Comfort Requirements for Naturally Conditioned Spaces; 57
Table 21 – Thermal Zoning Scoring Thresholds; Adapted from T03: Thermal Zoning (IWBI, 2025) 57
Table 22 – Air Pollutant Scoring; Adapted from (Lourenco et al., 2024) 59
Table 23 – Filtration Compliance Criteria; Defined in EQp2: Fundamental Air Quality (USGBC, 2025) 60
Table 24 – Enhanced Ventilation Scoring; Adapted from EQc1: Enhanced Air Quality (USGBC, 2025) 60
Table 25 - Additional Pollutant Design Limits; Defined in EQc1: Enhanced Air Quality (USGBC, 2025) 60
Table 26 - Pollutant Design Limits Scoring Thresholds 61
Table 27 – Integrated Measure Composition for RAI; Adapted from (Lourenco et al., 2024; USGBC, 2025) 62
Table 28 – Example NEB-SAM Indicator Weighting Redistribution; Adapted from (Lourenco et al., 2024) 68
Table 29 – Determination of THRIVE Integrated Measure Weighting in IEQ 70
Table 30 – THRIVE Integrated Measure Weighting per Analysis Block 71
Table 31 – Iterative Determination of THRIVE Analysis Block Weighting 71
Table 32 – Case Study Window Replacement Breakdown 78
Table 33 – Differences Between Baseline and Proposed Life Cycle Carbon Assessment Models; 93
Table 34 – Summary of Baseline and Proposed Total GWP results 95
Table 35 – Proposed Case Study Life Cycle Carbon Results, Highest-Contributing Cradle-to-Gate Components; Adapted from (One Click LCA, 2015) 96
Table 36 – Case Study Circularity of Material Calculations 97
Table 37 – Comparison of Case Study Energy Consumption Pre- and Post-Reno; 101
Table 38 – Case Study Energy Balance Pre-Renovation; Adapted from (Herrero et al., 2025) 102
Table 39 – Case Study Energy Balance Post-Renovation; Adapted from (Herrero et al., 2025) 102

Table 40 – Case Study Peak Thermal Load Reduction; Adapted from (Herrero et al., 2025) 104
Table 41 – Case Study Solar Contribution to Energy Demand; Adapted from (Herrero et al., 2025) 105
Table 42 – Visible Light Properties of Case Study Glazing Assemblies (Guardian Glass, n.d.) 109
Table 43 – Case Study Envelope Fire and Water Resistance Results Summary 118
Table 44 – Summary of THRIVE Results for the Case Study Building 126
Table 45 – Impact of Recommendations on Daylight Simulation Results 130
Table 46 – Recommended Standard PV Panel Alternatives for the Case Study Building; 135
Table 47 – Case Study ETICS Insulation Comparison with Recommended Alternative; 136
Table 48 – GWP Impact of Embodied Carbon Case Study Recommendations 136
Table 49 – Cumulative Impact of Proposed Recommendations for Improvement 137

SYMBOLS, ACRONYMS AND ABBREVIATIONS

AEC – Architecture, Engineering, and Construction

AHU – Air Handling Unit

AI – Artificial Intelligence

APF – Active, Prefabricated Facades

ASHRAE – American Society of Heating, Refrigerating and Air-conditioning Engineers

BD+C – Building Design and Construction

BIM – Building Information Modeling

BIPV – Building-Integrated Photovoltaics

BMS – Building Management System

BOD – Basis of Design

BoQ – Bill of Quantities

BPF – Building Performance Factor

BRP – Building Renovation Passport

CML – Centre for Environmental Studies

CO2 – Carbon Dioxide

CO_2e – Carbon Dioxide Equivalent

COP – Coefficient of Performance

CTE-DB-SI – Spanish Technical Building Code Basic Document on Fire Safety

DHW – Domestic Water Heating

EPD – Environmental Product Declaration

ETICS – External Thermal Insulation Composite System

EU – European Union

GHG – Greenhouse Gas

GWP – Global Warming Potential

HPL – High-Pressure Laminate

HVAC – Heating, Ventilation, and Air Conditioning

IAQ – Indoor Air Quality

ID+C – Interior Design and Construction

IEQ – Indoor Environmental Quality

IWBI – International WELL Building Institute

JRC – Joint Research Centre

KPI – Key Performance Indicator

LCA – Life Cycle Assessment

LCCA – Life Cycle Cost Assessment

LEEDv5 – Leadership in Energy and Environmental Design, Version 5

MAS – Multi-Attribute Score

MCDA – Multi-Criteria Decision Analysis

MEP – Mechanical, Electrical, and Plumbing

MERV – Minimum Efficiency Reporting Value

MFA – Material Flow Analysis

NEB – New European Bauhaus

NEB-SAM – New European Bauhaus Self-Assessment Method

NZEB – Nearly Zero Energy Building

OSB – Oriented Strand Board

O+M – Operations and Maintenance

PEF – Primary Energy Factor

PMV – Predicted Mean Vote

PV – Photovoltaic

PVT – Photovoltaic Thermal

RAI – Resilience, Aesthetics, and Inclusiveness

RH – Relative Humidity

RSL – Reference Service Life

RSR – Responsible Sourcing Ratio

SWH – Service Water Heating

TRACI – Tool for the Reduction and Assessment of Chemical and other Environmental Impacts

UK – United Kingdom

US – United States

USGBC – US Green Building Council

VAV – Variable Air Volume

VLT – Visible Light Transmittance

VOC – Volatile Organic Compound

VRP – Ventilation Rate Procedure

WBLCA – Whole-Building Life Cycle Assessment

kg – Kilograms

m – Meters

cm – Centimeters

mm – Millimeters

m^2 – Square meters

m^3 – Cubic meters

lbs – Pounds

ft – Feet

ft^2 – Square feet

ft^3 – Cubic feet

m/s – Meters per second

kWh – Kilowatt-hour

pa – Pascal

Wp – Watt-peak

m^2K/W – Square meters kelvin per watt

ppm – Parts per million

Arch - Architectural

Demo - Demonstration

Eq. - Equation

E.g. - For example,

Recs - Recommendations

Reno - Renovation

1

INTRODUCTION

1.1. GENERAL DISCLAIMERS

Artificial Intelligence

Throughout this MBUILD final dissertation work, Artificial Intelligence (AI) was used to facilitate brainstorming, structure first drafts, organize literature review sources, and streamline the analysis of pertinent data and information. Specifically, the following tools were used for designated purposes:

- ***Perplexity, Pro version*** – The primary AI tool used throughout this MBUILD dissertation. Assisted in structuring first drafts, analyzing technical documents, formulating assumptions where necessary, and polishing text. Also used to generate certain images, noted in the figure caption where applicable (e.g. Adapted from (*Source*) with AI).
- ***Elicit, Free version*** – Used to organize sources and assist in extracting key information for the State of the Art literature review.
- ***ChatGPT, Free version*** – Used for more creative brainstorming tasks, for example, when naming the proposed assessment framework.

Sources provided or referenced by AI have been reviewed for validity by the author to ensure accuracy and that no hallucinations compromise the research.

Confidentiality

All information supporting this MBUILD final dissertation is either publicly available or, regarding the AEGIR case study project, supplied by TECNALIA Research and Innovation, the lead research partner for the project consortium. As a publicly funded EU Horizon project, any AEGIR project (Grant agreement ID: 101079961) data referred to herein is either already publicly available or intended by the project consortium to be made publicly available. Thus, to the best of the author's knowledge, no confidential or proprietary information not intended for public disclosure is included.

Citation

All citations in this MBUILD final dissertation follow APA Style 7th edition. In-text, author-date format citations are provided in parentheses immediately following the relevant statement or quotation (e.g. Author, Date). In the absence of a known author, the source title is indicated in its place. The absence of a known publication date is indicated by "n.d.". Figures and tables reproduced or adapted from external sources include in-caption citations following the same format. A bibliography with full details on each source is included in the References section at the end of the document.

References are managed using the software Mendeley Cite, which automatically generates the in-text and in-caption citations as well as the bibliography according to the outlined citation style. The author remains responsible for checking the accuracy and completeness of all citations and references.

Custom Figures and Tables

Throughout this MBUILD final dissertation, there are many instances of flow chart figures depicting the overall THRIVE methodology, the integration of assessments inspired by each of the guiding frameworks, as well as the aggregation of scores through each THRIVE level of granularity, including:

- Individual assessments into integrated measure
- Integrated measures into analysis block
- Analysis blocks into project score

These figures are created by the author using Miro, a web-based AI innovation workspace. All have been made manually using basic shapes, connectors, and text within the Miro board. No AI features have been used.

As outlined in Section 4.2, certain figures are enhanced for clarity using the PDF application Bluebeam Revu (e.g. highlighting or marking up key elements within the figure). As noted in the AI disclaimer, certain figures, indicated in the figure caption, are generated with AI.

There are several instances of tables developed by the author to communicate the New European Bauhaus Self-Assessment Method (NEB-SAM) indicators and Leadership in Environmental and Energy Design, version 5 (LEEDv5) credits and prerequisites which are integrated to guide the development of THRIVE. In the absence of an in-caption citation, these tables should be understood to be adapted from *A practical guide to the NEW EUROPEAN BAUHAUS self-assessment method and tool* (Lourenco et al., 2024) as well as the LEED credit library for the LEEDv5 building design and construction (BD+C) rating system (USGBC, 2025).

Numeric Formatting and Decimal Notation

Throughout this MBUILD final dissertation, numeric values follow American formatting. Specifically, a comma is used as the thousands separator and a full stop (period) is used as the decimal marker (e.g. “one-thousand two-hundred point five” would be written as 1,200.5). This convention is applied consistently to all quantities, measurements, and statistical results, regardless of local or regional formatting practices for source data.

1.2. STRUCTURE OF DISSERTATION

This MBUILD final dissertation is divided into the following six chapters:

Chapter 1: Introduction to the research topic including context, motivation, and problem statement. Includes relevant background information on the AEGIR renovation system, as well as NEB and LEEDv5 as guiding frameworks, including their relevance to decarbonization and well-being. Presents the core research question and outlines the primary objectives.

Chapter 2: Literature review encompassing current transatlantic deep renovation strategies, industrialized façade systems with circular components, IEQ in existing buildings, and the application of sustainability certification schemes, highlighting gaps to be addressed.

Chapter 3: Detailed methodology, introducing an overview of THRIVE which is then broken into analysis blocks (embodied carbon, operational carbon, IEQ, RAI), integrated measures, and individual assessments. Indicates which NEB-SAM indicators and LEEDv5 credits influence each integrated measure and its corresponding assessments. Data requirements, analytical procedures, and scoring logic are specified for each assessment. Details the flow across levels of granularity (individual assessment, integrated measure, analysis block, project), including the logic behind the weighting schemes used to aggregate scores and deliver results at each level. Aligns numeric scores to qualitative performance classes at integrated measure, analysis block, and project level.

Chapter 4: Showcases the THRIVE framework via application to the AEGIR Spain demo building case study project. Includes background information on the project, data collection methods, and utilized software tools. Discloses uncertainty, assumptions, and limitations regarding the results to follow.

Chapter 5: Report of the case study results, organized into analysis blocks followed by project-level performance. Interprets these findings in relation to modern industry standards and AEGIR KPI. Proposes targeted recommendations for further improvement of the case study project. Finally, presents reflections on THRIVE and the guiding frameworks, considering achievement of the defined research objectives, limitations, and potential for future influence on the construction industry.

Chapter 6: Final conclusion directly addressing the core research question. Summarizes key findings, case study recommendations, and lessons learned. Outlines suggested directions for future research based on the identified gaps and limitations.

1.3. CONTEXT & MOTIVATION

1.3.1. THE PROBLEM

Buildings account for roughly 40% of global carbon emissions, with 28% coming from operations to heat, cool, ventilate, and power the building, and the remainder embodied in materials and construction. The global population is projected to reach 10 billion in the next 60 years, with the current global building stock doubling in size to accommodate this growth (*Embodied Carbon - World Green Building Council*, n.d.). Thus, it is critical that the construction industry adopts a holistic approach to building decarbonization to mitigate climate impact while maintaining livable, healthy spaces for the growing population.

In the coming years, as electric grids are decarbonized and design teams become increasingly capable of creating efficient building systems, the majority share of emissions, and therefore the priority for innovation, is expected to shift from operational towards embodied sources (European Commission, 2026). As represented in Figure 1, by 2050, nearly half of the carbon footprint of new construction is projected to come from embodied carbon. Countries such as Canada, Sweden, and Norway, which are leading the way in renewable energy adoption, are already approaching this 50/50 split (Carrol, 2025). A common phrase among the green building community is "the most sustainable building is the one that already exists", highlighting the substantial upfront embodied carbon emitted via demolition and new construction. This adage now carries more urgency than ever for decarbonization solutions anchored in existing building stock as the construction industry aims to meet ambitious targets amid a growing global population.

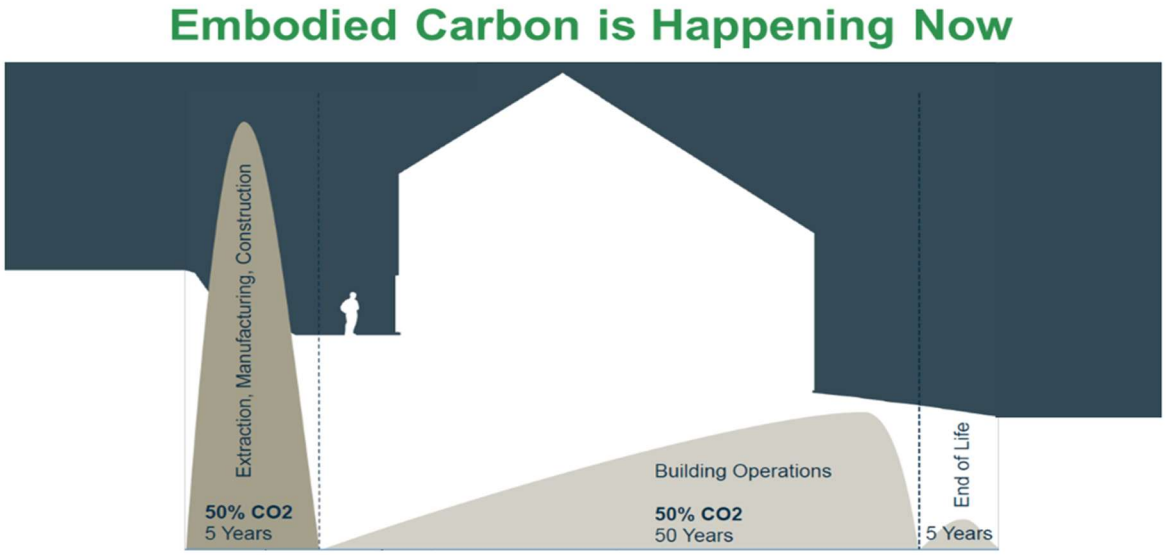


Figure 1 – Projected Whole-life Carbon Source Breakdown for New Buildings by 2050 (Carrol, 2025)

One study of European Union (EU) building stock found it to be collectively responsible for 808 million tonnes CO2e of whole-life (embodied + operational) carbon emissions per year, with most of the embodied emissions coming from new construction. Detailed in Figure 2, as much as 18% of these emissions are embodied in new construction, despite the fact that new construction made up only 1% of the total floor area studied. By comparison, renovation, which also constituted 1% of the floor area studied, embodies only 3% of the total whole-life emissions for the baseline year (European Commission, 2026).

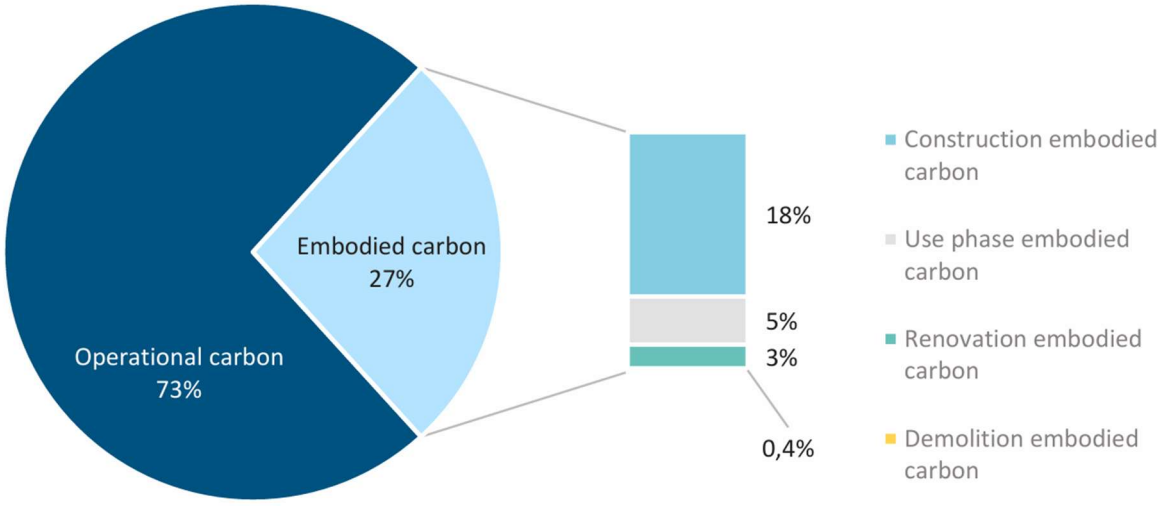


Figure 2 – Greenhouse gas Emission Distribution by Building Stock Activity, Baseline year 2020 (European Commission, 2026)

The EU is largely leading the way in the decarbonization movement, with European Climate Law setting ambitious targets for greenhouse gas (GHG) reduction by 2030 and 2040, before achieving net-zero emissions by 2050. Considering the comparatively heavy embodied carbon cost of new construction, a key initiative to meet these goals is the EU Renovation Wave. The Renovation Wave aims to achieve an annual renovation rate of 2% of existing building stock from 2020 to 2030, consisting of upgrades to energy performance, heating/cooling efficiency, and emissions cuts (*A Renovation Wave for Europe | European Hydrogen Observatory*, 2025). Over 85% of this building stock was constructed prior to 2001, with low or no energy standard criteria (*Home - AEGIR*, 2022). However, retrofit projects often require a higher level of complexity in design & construction solutions compared to new builds and present unique challenges. Thus, the demand for streamlined, cost-effective, and adaptable renovation systems is high.

Since withdrawing from the Paris Agreement, the United States (US) has abandoned the major, nationwide climate targets established by the previous administration, including emissions reductions targets for 2030, 2035, and 2050. Between this move and other various Trump administration actions slowing emissions reductions, the Climate Action Tracker has rated the US "Critically Insufficient" in terms of targets, policies, and climate finance (*USA Country Summary*, 2025). Nevertheless, many states, cities, and companies maintain their own climate targets, and coalitions like the US Climate Alliance commit to upholding Paris Agreement objectives. Thus, the US still has the history, resources, and potential to serve as a global leader in sustainable building development.

Similar to the EU, the US faces the challenges of an aging building stock. Roughly 46% of all commercial buildings in the US were built prior to 1980, meaning they predate modern energy codes and standards, with up to 75% being constructed before 2000 (Christiansen, 2026). This trend is similarly reflected in residential construction, with 48% of housing stock dating to the 1980s and earlier as shown in Figure 3 (Zhao, 2025). Therefore, the potential demand for scalable renovation systems is high, and the need to learn from EU initiatives such as the Renovation Wave great.

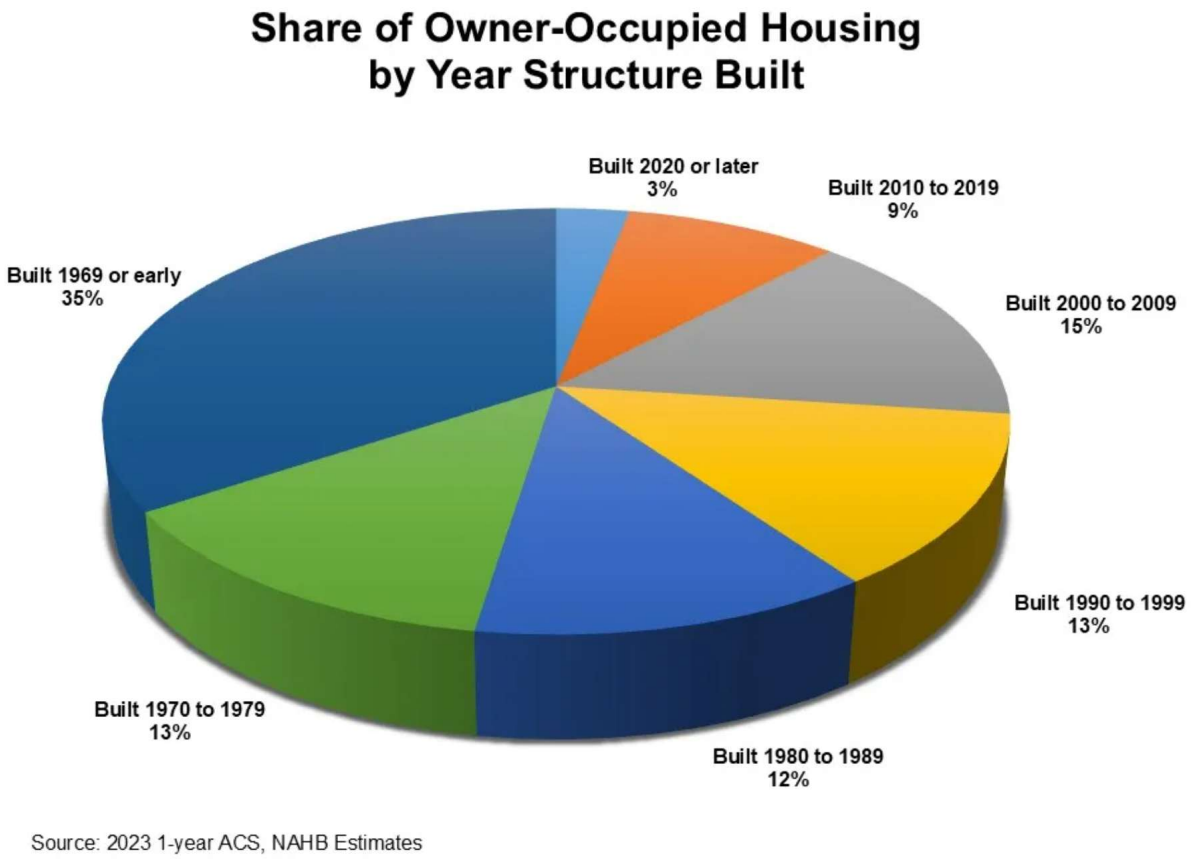


Figure 3 – US Owner-Occupied Housing Stock Share by Year Built (Zhao, 2025)

Beyond poor energy performance and its associated carbon impact, older buildings also tend to fall short compared to modern standards for indoor environmental quality (IEQ), including air purity, access to natural light, thermal comfort, and acoustics. These elements are critical to the health and productivity of building occupants, and are often compromised by leaky envelopes, poor ventilation, insufficient fenestration, and outdated insulation (Christiansen, 2026). To revitalize existing buildings into places that are not only efficient but desirable, these factors must not be neglected.

1.3.2 THE DEEP RENOVATION SOLUTION

For undertaking deep renovation at scale, systems anchored in industrialized, prefabricated envelopes have emerged as a promising approach. When integrated with key energy system upgrades, these envelopes enable significant building performance improvements while maintaining much of the original structure. Components are designed, engineered, and manufactured off-site in a controlled factory environment, then transported to the building for installation as large modules or panels. Once delivered to site, these prefabricated elements are relatively quick and simple to install compared to conventional renovation, reducing construction time and minimizing disruption for occupants. By standardizing key components while allowing for project-specific adaptation, these systems have the potential to simultaneously to upgrade energy performance, indoor comfort, resilience, and aesthetics in a way that is repeatable, cost-effective, and compatible with the diverse conditions of existing building stock.

One such system under development is AEGIR (Grant agreement ID: 101079961), a Horizon Europe-funded research project launched in 2022 to develop modular, renewable, and industrialized smart-envelope systems for energy-focused renovation of existing buildings. Intended to support scaling of the EU Renovation Wave, the systems target nearly zero-energy standards while minimizing costs and on-site execution time. Further points of emphasis include improvements to building living conditions, sustainability, and circularity. The project consists of 30 diverse partners spread across nine EU countries and managed by TECNALIA, a Spain-based private center of applied research and technology, who is also a key contributor to facilitate this MBUILD final dissertation.

Per Jay Arnaud & Astudillo Larraz (2023), elements of the AEGIR system can largely be grouped into two types: Physical and Digital. The physical solution is anchored in a scalable and customizable envelope package applicable to building facades and roofs. It also encompasses energetic systems including heat pumps, ventilation, photovoltaic (PV), and photovoltaic thermal (PVT). The differing typologies depicted in Figure 4 are made up of the following components:

Modular Façade / Roof

- Bio-composite wood-based profiles
- Bio-based insulation
- Fabric insulation
- Customizable cladding

Energetic Systems

- Heat pump connection (for heating/cooling)
- Standard integrated PV module
- Flexible integrated PV module
- Hybrid PVT module
- Smart windows with automated ventilation
- Ventilation system
- Second-life battery

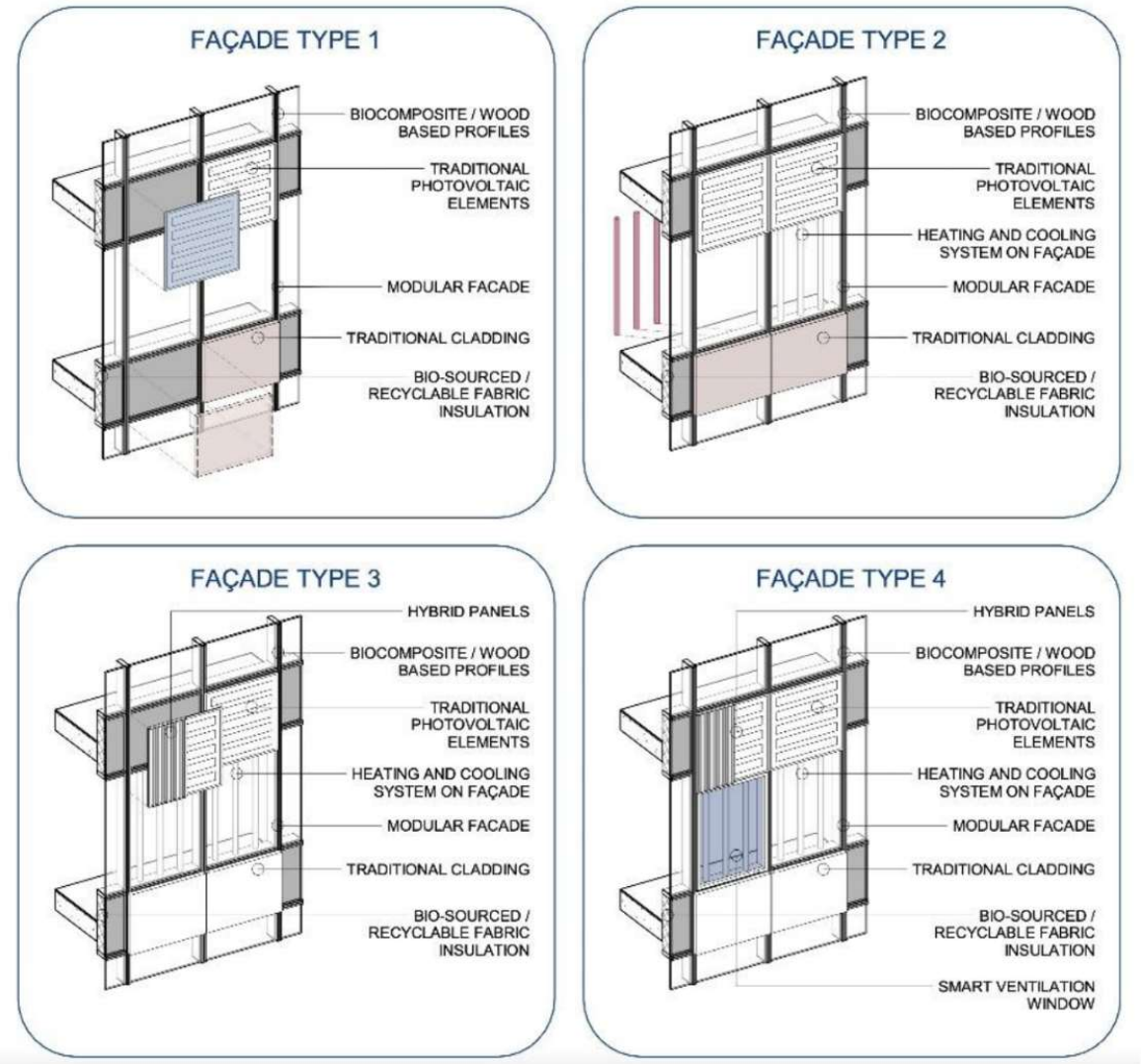


Figure 4 – AEGIR Industrialized Envelope System Typologies (Jay Arnaud & Astudillo Larraz, 2023)

The digital solution includes the use of building information modeling (BIM), energy simulations, digital twins, wireless smart integration, augmented reality, and user-friendly interfaces to streamline design, production, and operation.

AEGIR tests its solution across four real-life demonstration (demo) buildings of differing typologies in diverse climates. These include an educational building in Spain (to serve as the case study for this MBUILD final dissertation), a multi-family residential building in Denmark, a mixed-use seniors' residence in France, and a single-family home in Romania (see Figure 5). The plug & play nature of AEGIR enables solutions uniquely adapted to each demo site, but the overarching objectives of improving energy efficiency, integrating renewable energy production, enhancing indoor comfort, and utilizing sustainable & circular materials with advanced technologies remain the same.

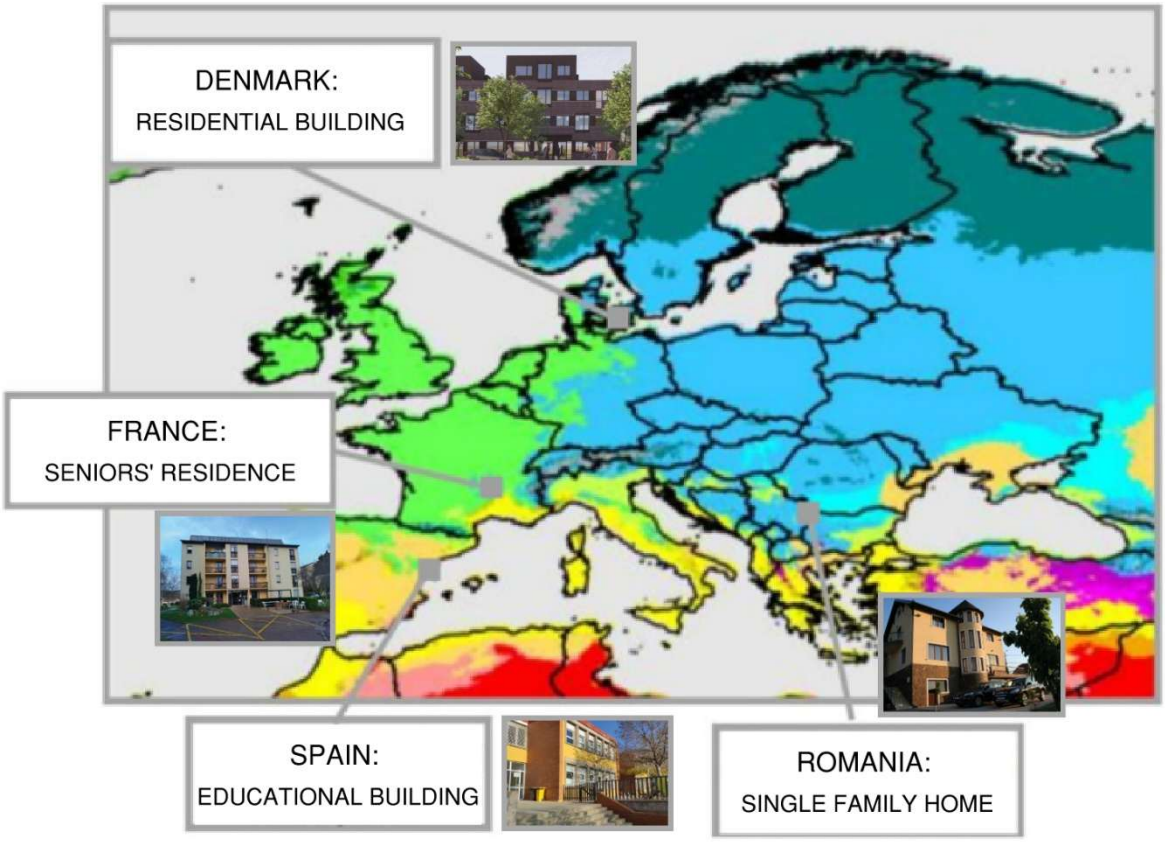


Figure 5 – Map of AEGIR Demonstration Buildings;
Adapted from (Home - AEGIR, 2022; Jay Arnaud & Astudillo Larraz, 2023)

Listed in Table 1, the project consortium has developed sustainable key performance indicators (KPI) to measure the circularity of AEGIR. These are based on European standards (prEN15978-1: 2021, EN 15804:2012+A2:2019 Sustainability of construction works - Environmental product declarations), also considering principles of the *Level(s)*, *R-strategies*, and *Cradle-to-Cradle Model* frameworks (Zabek et al., 2023). Several of these KPI will also be addressed within the scope of this MBUILD final dissertation, though approached through the lens of different frameworks.

Table 1 – List of AEGIR Circularity KPI (Zabek et al., 2023)

Most Relevant to Address	
Global Warming Potential (kg CO2e)*	Embodied energy (nonrenewable primary energy) (MJ)*
The use of renewable energy (MJ)*	Waste (hazardous substances) (kg)
Use of secondary material (reuse or recycling content) (kg)*	Future recycling or reuse strategy (kg)*
Additional Core Indicators	
Use of renewable resources (kg)*	Modularity
Durability/Lifespan/Maintenance/Warranty (years)*	Local Material*
Bill of quantities*	Low-Tech
Demountability, reversibility (type of installation)	Material Purity
Financial concept for multiple life circles (Take-back system or leasing)	Compostability

* = addressed within the proposed methodology of this MBUILD final dissertation

Additional indicators within the Level(s) framework identified as relevant by the AEGIR project consortium are shown in Table 2.

Table 2 – Additional Level(s)-based KPI relevant to AEGIR (Zabek et al., 2023)

Indicators	
Construction & demolition waste and materials	Time outside of thermal comfort range*
Use stage water consumption	Protection of occupier health and thermal comfort*
Use stage energy performance*	Increased risk of extreme weather events*
Indoor air quality*	Increased risk of flood events*

* = addressed within the proposed methodology of this MBUILD final dissertation

Deep renovation systems like AEGIR offer a scalable solution to the Renovation Wave challenge. Leveraging new bio-based materials, renewable technologies, and modern digital systems, this sort of renovation package can be a powerful tool for meeting climate targets amid evolving comprehensive standards for building health and sustainability. However, the full extent to which this is possible remains to be seen.

1.3.3 SUSTAINABILITY FRAMEWORKS

Today there exists a wide range of sustainability certification schemes and assessment tools to promote innovation, best practice, and track progress for nearly any type of project. With shifting priorities for climate management in the built environment, many of these have evolved from energy- and resource-focused origins to holistic frameworks balancing decarbonization, resilience, well-being, and inclusiveness. Nevertheless, each framework is unique, influenced by its place of origin, targeted projected types, and specific priorities within sustainable construction. The European Union (EU) and United States (US) are leaders in the development of sustainable building frameworks, consistently pushing the boundaries of what can be expected from modern design and construction. Thus, a study incorporating schemes from both regions in an attempt to capture the best of each while highlighting

potential gaps or conflicts could be of value to the industry and academic community. Two of the most recent frameworks released under this context are the New European Bauhaus (NEB) from the EU and LEEDv5 from the US.

Initially launched in January 2021, the New European Bauhaus is an EU program for green transition in the built environment anchored in three core values or "dimensions", **beautiful**, **sustainable**, and **together**. Since launch, NEB has gone through many iterative stages of growth and developed several tools to support implementation. The initiative complements the European Green Deal by promoting built environment projects that are not only sustainable, but also aesthetic and inclusive, linking climate goals with more experiential cultural and social qualities. It frames the green transition as something that should be enjoyable and meaningful in everyday places, aiming to enhance well-being and a sense of belonging while respecting local contexts, traditions, and landscapes.

"Beautiful" encompasses the activation of artistic and cultural assets to support mental and physical well-being and create a strong sense of place; "Sustainable" covers reduced environmental impact, circularity, and giving more back to nature; and "Together" emphasizes accessibility, affordability, social justice, and solidarity. Depicted in Figure 6, the dimensions are facilitated by three NEB working principles: **participatory processes**, **multi-level engagement**, and a **transdisciplinary approach**. Participatory processes empower communities to be involved in decision-making and self-govern the resulting spaces. Transdisciplinary initiatives consider the input of knowledge holders from a diverse range of backgrounds, including local, traditional, technical, and academic. Multi-level engagement implies the formation of bottom-up solutions tailored specifically to local problems while also considering the wider global impact.

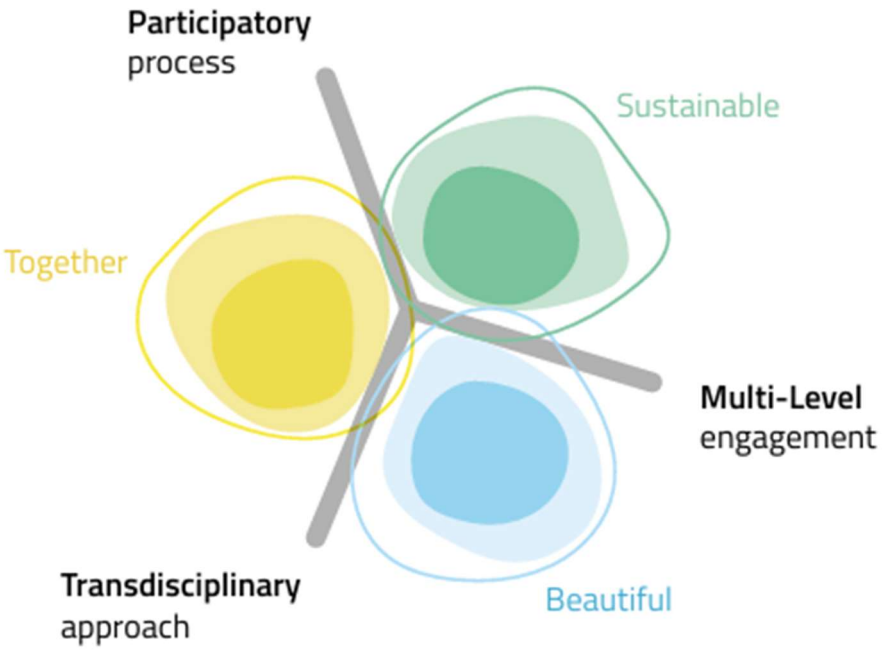


Figure 6 – NEB Dimensions and Working Principles (New European Bauhaus Compass, n.d.)

First published in late-2022, the NEB Compass (New European Bauhaus Compass, n.d.) was designed to translate these ideas into a structured tool decision makers can apply to projects. The compass defines three levels of ambition for each dimension and working principle (see Figure 7). The first level sets a

baseline a project must reach to be considered "NEB-ish," while the following levels describe increasingly aspirational states. For example, moving from preservation and impact reduction to regenerative interventions that restore ecosystems and reshape behaviors. It is structured in such a way that trade-off between the values and principles is not possible but rather they reinforce one another, encouraging integration of all aspects.

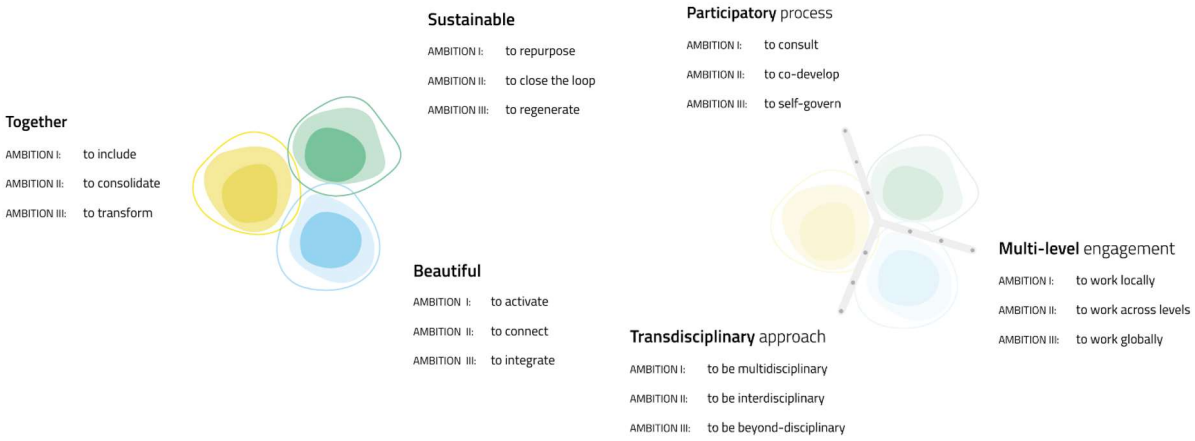


Figure 7 – NEB Levels of Ambition for; Dimensions (Left), Working Principles (Right) (New European Bauhaus Compass, n.d.)

At the next level of granularity, the NEB Self-Assessment Method (NEB-SAM), developed by the EU Commission Joint Research Centre (JRC), serves as a comprehensive tool for the application and assessment of NEB in established projects (Lourenco et al., 2024). Released in 2024, this tool structures assessment across the three NEB core values, using a hierarchy of indicators, KPIs, and final dimension (core value) scores, each normalized to a 0–100 range. At the indicator level, it captures specific attributes such as primary energy demand, embodied GWP, indoor air quality, or risks of social segregation, using either quantitative calculations or qualitative assessments depending on the indicator.

Within each dimension, indicators are aggregated into KPIs via weighted averages, and KPI scores are then translated into qualitative performance classes (Low, Acceptable, Good, Excellent). Next, these are converted back into standardized "performance-class scores" to manage uncertainty and avoid a false sense of precision across heterogeneous data types. Dimension scores are finally obtained as weighted combinations of these KPI performance-class scores and again are mapped onto qualitative dimension-level performance bands (see Figure 8). These bands provide an overall indication of how well a project meets NEB ambitions in Sustainability, Beauty, and Togetherness. Unlike the Checklist, the method intentionally stops at separate dimension scores rather than producing a single overall NEB result, such that the tool is not directly applied in a competitive or rating system-type context. Furthermore, this decision emphasizes the importance of each core value by preventing strong results in one dimension from overriding serious deficiencies in another.

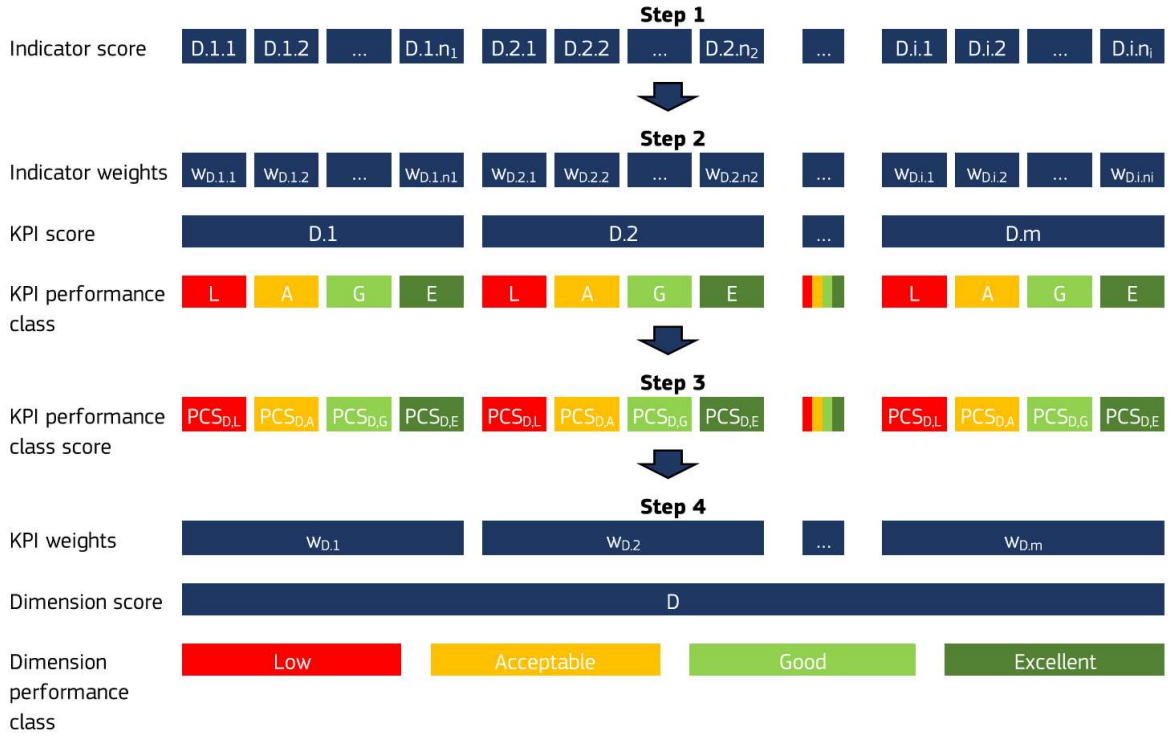


Figure 8 – Overview of NEB Self-Assessment Method Workflow (Lourenco et al., 2024)

Certain indicators in the NEB-SAM link to the WELL healthy-building standard, a US-based framework managed by the International WELL Building Institute (IWBI). Originally launched in 2014 and currently on version 2, this rating system focuses exclusively on the impact of buildings on human health and well-being and thus guides NEB indicators relevant to these issues. The framework is divided into 10 concepts depicted in Figure 9, consisting of features covering distinct health issues, including required prerequisites and elective optimizations.



Figure 9 – WELLv2 Concepts (IWBI, 2025)

One high profile project showcasing NEB is the future JRC site in Seville, Spain, designed to be the EU Commission's first net-positive energy building. With groundbreaking in June 2025, construction is currently still ongoing. Inspired to be a flagship example of NEB principles, the design team was guided by the attempt "to allow the sustainable performance of the building to drive an architectural aesthetic that not only makes the building perform better but also makes it more inhabitable and more beautiful" (*New European Bauhaus-Inspired Future JRC Site in Seville*, n.d.).



*Figure 10 – New NEB-inspired JRC Seville Building Rendering (*New European Bauhaus-Inspired Future JRC Site in Seville*, n.d.)*

Released in April 2025, LEEDv5 is the latest version of the globally recognized Leadership in Energy and Environmental Design (LEED) green building framework developed by the US Green Building Council (USGBC). Since the first version's launch in 1998, LEED has gone through several iterations, with versions 4 and 4.1 guiding the majority of certified projects for the past decade. In a shift from previous versions, LEEDv5 is explicitly organized around three core impact areas: **decarbonization**, **quality of life**, and **ecosystem conservation & restoration**. Within this structure, all prerequisites and credits are tagged to show which impact areas they influence, facilitating project teams' ability to understand and communicate how their design and operational strategies contribute to climate, health, and resource outcomes.

LEED ratings systems are comprised of required prerequisites setting minimum baselines, and elective credits that yield points towards certification. Similar to previous versions, LEEDv5 awards up to 110 points with the level of certification dictated as follows:

- Certified: 40–49 points
- Silver: 50–59 points
- Gold: 60–79 points
- Platinum: 80+ points (plus required decarbonization thresholds)

LEED has developed several rating systems depending on the project type, including Building Design and Construction (BD+C), Interior Design and Construction (ID+C), and Operations and Maintenance (O+M), among others. Deep renovation, including significant modifications to the envelope and core mechanical, electrical, and plumbing (MEP) system, is considered a "major renovation" and thus falls

under the BD+C rating system. BD+C is therefore the LEEDv5 system from which this MBUILD final dissertation draws as a guiding framework. However, it is a noted limitation that there is no LEED rating system designed specifically to assess deep renovation projects.

Given its very recent launch, at the time of writing there has yet to be any real-world projects certified under LEEDv5 BD+C. However, due to relatively faster processing times and a beta version released in late-2023 for the O+M rating system, there are already several projects which have achieved this certification. These early adopter projects span the globe, including North and South America, Europe, and Asia (*USGBC Announces First Projects Certified Under LEED V5*, 2025). Notable examples include Gianni Giorgi-Alberti, an office building located in Frascati, Italy as the first certified project in Europe (Heather Benjamin, 2025a), and Ascent MKE, a mass timber multifamily apartment building located in Milwaukee, Wisconsin as the first certified project in the US (Heather Benjamin, 2025b).



Figure 11 – Certified LEEDv5 O+M Projects;
Gianni Giorgi-Alberti (Heather Benjamin, 2025a, Left), Ascent MKE (Heather Benjamin, 2025b)

The emphasis on **decarbonization** is the most radical change from previous versions, with 50% of all credits tied to this pillar. LEEDv5 expands requirements and incentives for both operational and embodied carbon, mandating operational carbon projections, decarbonization plans, and quantifying embodied GWP while incentivizing the use of tools such as energy modeling and whole-building life cycle assessment (WBLCA). In BD+C, prerequisites such as *Operational Carbon Projection and Decarbonization Plan*, *Minimum Energy Efficiency*, and *Quantify and Assess Embodied Carbon* are paired with credits for electrification, reduced peak thermal loads, enhanced energy efficiency, renewable energy, and reduced embodied carbon, as well as planning for zero-waste operations. Improved building envelopes, electrified heating systems, and circular practices are noted among intrinsic design strategies key to whole-building decarbonization (DECARBONIZATION IN LEED V5, n.d.).

While previous versions of LEED included credits related to IEQ, much more weight was allocated to outcomes for the natural environment (e.g. energy, water, and resource consumption) than those for the human occupants. The **quality of life** impact area in LEEDv5 places new emphasis on human health, expanding its scope to encompass resilience and social value, and allocating 25% of all credits to this pillar. Prerequisites and credits spanning *Location and Transportation*, *Sustainable Sites*, and *Materials and Resources* categories address equitable and compact development, accessible outdoor space, and low-emitting materials. IEQ requirements and credits cover design air quality, occupant experience (lighting, sound, thermal comfort, adaptability, biophilia), accessibility and inclusion, resilient spaces, and

post-construction air quality testing and monitoring. These criteria serve to promote overall wellbeing through long-term comfort, satisfaction, and health outcomes (QUALITY OF LIFE IN LEED V5, n.d.).

The third impact area, **ecological conservation and restoration**, constitutes the remaining 25% of credits and focuses on protecting and restoring ecosystems so that buildings coexist more harmoniously with nature. It emphasizes strategies such as minimizing site disturbance, preserving or enhancing biodiverse habitats, low-impact management of rainwater on-site, prioritizing native vegetation, and reducing pollution from artificial light and construction waste. Though largely outside the scope of this MBUILD final dissertation, it remains an important part of the overall LEEDv5 framework that shapes how relevant credits are structured and weighted.

An overarching theme of this paper is to bridge the author's background in the US architecture, engineering, and construction (AEC) industry with the knowledge and experience gained from MBUILD, a 2-year master program in sustainable design, construction, and management of the built environment spanning three European countries: Portugal, Germany, and Spain. This has been a primary driver for the selection of NEB and LEED as the guiding frameworks for this MBULD final dissertation over other globally recognized options. Other notable frameworks include Level(s) from the EU, BREEAM from the United Kingdom (UK), DGNB from Germany, HQE from France, and CASBEE from Japan. The decision to represent the European side with NEB rather than Level(s) is rooted in the more holistic, qualitative assessment offered by NEB. Furthermore, LEED and Level(s) are already deeply aligned, making an integrated framework between the two in many cases redundant. In recent years LEED has developed alternative compliance paths for certain credits via recognition of Level(s) achievement and released updates to European market criteria to mirror key areas of Level(s) (Directorate-General for Environment, 2025).

Thus, for this dissertation, NEB provides a holistic set of principles bridging technical and experiential criteria rooted in EU vision and values. LEEDv5 offers a more established, structured benchmark as the dominant international system connecting EU projects with North American and global practice. The integration of these frameworks in the context of deep energy retrofits has the potential to produce a tailored, holistic approach to deep renovation project assessment. The full list of NEB-SAM indicators and LEEDv5 credits influencing the study can be seen in Table 3. Note that regarding the LEEDv5 tags "p" indicates a required perquisite while "c" indicates an elective credit (e.g. EQp2 = prerequisite, EQc1 = credit). Specific indicators, credits, and KPIs central to each analysis are detailed respectively in Chapter 3 – Methodology.

Table 3 – Guiding Framework Indicators, Prerequisites, and Credits; Adapted from (Lourenco et al., 2024; USGBC, 2025)

NEB Self-Assessment Method	LEEDv5
Sustainability	**Materials & Resources (MR)**
S.1.1 - Primary Energy Demand	MRp2 - Quantify and Assess Embodied Carbon
S.1.2 - Electricity Peak Demand	MRc2 - Reduce Embodied Carbon
S.2.1 - Share of Renewables	MRc4 - Building Product Selection and Procurement
S.2.2 - Energy Storage	**Energy & Atmosphere (EA)**
S.3.1 - Operational GHG Emissions	EAp2 - Min Energy Efficiency
S.3.2 - Embodied GHG Emissions	EAc1 - Electrification
S.5.1 - Indoor Air Quality	EAc2 - Reduce Peak Thermal Loads; Option 4
S.9.1 - Secondary, Bio-Based, Recycled Material	EAc3 - Enhanced Energy Efficiency
Beauty	EAc4 - Renewable Energy
B.2.2 - Responsible Material Sourcing	**Indoor Environmental Quality (IEQ)**
B.3.2 - Hazard Resilient Design	EQp2 - Fundamental Air Quality
B.4.2 - Lighting Environment	EQc1 - Enhanced Air Quality
B.4.3 - Thermal Comfort	EQc2 - Occupant Experience; Option 1, PATH 2
B.5.1 - Ease of Circulation	EQc2 - Occupant Experience; Option 3
B.5.2 - Safe Wayfinding	EQc2 - Occupant Experience; Option 5, PATH 1 & 4
B.7.1 - Visual Experience of Architecture and Space	EQc3 - Accessibility and Inclusion
	EQc4 - Resilient Spaces; Option 4

1.4. OBJECTIVES

This paper proposes a novel **T**ransatlantic, **H**olistic **R**enovation assessment framework for decarbonization, **I**ndoor environmental quality, and **E**quity (THRIVE). THRIVE seeks to quantify the potential of decarbonization and occupant well-being outcomes for deep renovation projects and promote further improvement. THRIVE is demonstrated via application to the AEGIR demonstration building in Spain as a case study. The study both holistically assesses the project's level of achievement regarding decarbonization and occupant well-being and provides a backdrop for reflection on the interoperability of the NEB Self-Assessment Method and LEEDv5 as guiding frameworks for THRIVE.

The core research question guiding the work is: *To what extent can the deep renovation of existing buildings achieve holistic, modern global standards for both decarbonization and human health & well-being criteria?*

To address this question, the following objectives have been established:

i. Develop a transatlantic framework specifically for deep renovation projects integrating principles and procedures from the EU-based NEB-SAM and US-based LEEDv5.

ii. Quantify the impact of a deep renovation solution on whole-life carbon emissions (embodied + operational) by comparing pre-renovation, post-renovation, and generic baseline conditions.

iii. Quantify the impact of a deep renovation solution on key indoor environmental quality indicators, including daylight access, thermal comfort, and indoor air quality (IAQ).

iv. Quantify the impact of a deep renovation solution on key livability indicators, including resilience, aesthetics, and inclusiveness (RAI).

v. Clearly communicate performance at varying levels of detail, identify strengths and weaknesses, and facilitate recommendations for design or implementation measures to improve performance.

2

STATE OF THE ART

2.1. LITERATURE REVIEW

2.1.1. APPROACHES TO DEEP RENOVATION IN EUROPE & THE US

As "Deep Renovation" has become an increasingly used term, it is important to establish for it a globally recognized definition. Based on an analysis of completed projects and recent EU guidance conducted by the International Energy Agency's *Energy in Buildings and Communities Program*, the following definition for a "Deep Energy Retrofit" has been proposed: "Deep Energy Retrofit is a major building renovation project in which site energy use intensity (including plug loads) has been reduced by at least 50% from the pre-renovation baseline with a corresponding improvement in indoor environmental quality and comfort" (Zhivov & Lohse, 2021). According to the study, energy use requirements in the US have improved over 50% since the 1980s, highlighting the degree of potential inefficiency among older building stock. Furthermore, it finds that regular degradation of buildings tends to reduce their energy performance by a minimum of 10%. Zhivov & Lohse emphasize the importance of whole-building analysis and an integrative design process when undertaking a Deep Energy Retrofit. These measures are commonly promoted or required by popular sustainable building frameworks and rating systems.

The EU's commitment to carbon neutrality by 2050 has positioned building renovation as a critical intervention strategy. The previously mentioned EU Renovation Wave initiative, launched in October 2020, aims to double Europe's current renovation rate, building upon the foundation established by the Energy Performance of Buildings Directive (EPBD) in 2002 (Sesana et al., 2021). The implementation of these EU-wide policies has led to considerable variation in national approaches and performance. Member countries have been found to exhibit markedly different levels of strategic development and ambition regarding EU-wide climate objectives. A comprehensive analysis has been performed encompassing CO_2 emission reductions, renovation rates, energy savings, investment requirements, and overall strategy quality. Finland, Spain, and the Netherlands were noted as high-performers while Bulgaria and Poland demonstrated challenges in achieving EU targets (Plebankiewicz & Grącki, 2025).

The diversity of European contexts has prompted the development of sophisticated approaches to renovation strategy selection with the flexibility to account for regional variance. In a scenario-based robustness assessment for six different European contexts (Walker et al., 2022), it was demonstrated that retrofit strategy decarbonization effectiveness varies significantly based on climate, electric grids, and typical building typologies. Greenhouse gas (GHG) emission intensity of the grid was found to be the driving factor in optimizing heating & electrical systems. Secondary factors include the integration of photovoltaic (PV) and battery systems. Building typology primarily influenced the robustness of envelope solutions. The differing temperatures across climates were found to be already well considered in retrofit measures and thus had minimal effect on robustness. For most investigated European contexts where electricity grid GHG emission intensity exceeds 300-400 g CO_2-eq/kWh, grid decarbonization is

highlighted as the highest priority for decarbonizing at the building-level. In contexts with lower grid emission intensities, embodied emissions of renovation materials become the dominating factor for retrofit decisions. These findings align with the sentiment of growing importance of embodied carbon as global electric grids are gradually cleaned.

Thus, current EU methodological approaches to deep renovation have evolved toward multi-criteria frameworks that integrate energy- and resource-based environmental criteria along with economic considerations. One such approach is the ALDREN project (Sesana et al., 2021), designed to support decision-making through systematic protocols that assess energy performance, indoor environmental quality (IEQ), and financial value both before and after renovation. The framework consists of step-by-step implementation modules tailored for non-residential buildings, with demonstrated application to Italian office buildings. The project also employs and develops the novel Building Renovation Passport (BRP), introduced under EU directive 2018/844 in response to recent EU climate policy evolution. The BRP is an empowering decision-making tool which provides reliable, independent information on energy savings potential tied to building renovation. The stamps shown in Figure 12 represent "stops" on the building's renovation journey which also correspond to the ALDREN BRP structure. Ultimately, ALDREN represents a shift toward comprehensive evaluation methodologies that extend beyond traditional energy performance metrics.



Figure 12 – Each ALDREN BRP Module (M) with Specific Passport Stamp (Sesana et al., 2021)

Beyond energy efficiency and operational emissions, life cycle thinking has been increasingly incorporated in the evaluation of renovation strategies. Life cycle strategies consider the embodied carbon impact and end-of-life considerations for building products and materials. Nevertheless, many current decarbonization strategies still primarily focus on operational energy efficiency while overlooking the emissions embodied in the production, construction, and retrofitting phases (Leichter et al., 2025).

There are several common key components that can be found across deep renovation solutions for energy efficiency. These include improved envelope insulation and airtightness, heat pump systems, heat recovery ventilation, and the integration of renewables such as on-site PV and batteries. With the diverse range of contexts that can be found across Europe regarding climate and the existing built environment, it is important to verify the effectiveness of solutions standardized around such components. This verification should be performed across projects of differing backgrounds, needs, and priorities. An energy performance study of two common renovation concepts applied to residential construction in three different geographical settings – Germany, Italy and Estonia – has demonstrated that similar renovation approaches can be successfully implemented across diverse European contexts. This study provides a base for the further development of standardized solutions (Võsa et al., 2023).

However, the research also reveals a critical limitation in the current assessment capabilities of national energy calculation methodologies. While the standard Estonian, German, and Italian approaches demonstrate good accuracy for pre-renovation building performance, all three fail to adequately calculate nearly-zero energy building (NZEB) renovation concepts that integrate heat pumps and PV systems. Furthermore, the results show that highly energy efficient buildings tend to be more sensitive to the calculation methods imposed when assessing energy performance. This highlights the importance

of robust assessment frameworks to address modern standards of sustainable construction (Võsa et al., 2023).

The development of comprehensive key performance indicators (KPI) for industrialized renovation has facilitated evaluating the holistic performance of solutions. Beyond traditional metrics of cost and energy performance, these KPI encompass economic, environmental, energy, social, and technological dimensions. The EU Horizon project INPERSO has devised a KPI list via a multi-criteria decision analysis (MCDA), enabling a systematic assessment of renovation outcomes. Depicted in Figure 13, these KPI were developed considering the following criteria: Frequency of appearance in current literature; Alignment with case study project objectives; and User-centric emphasis. Critically, they seek to balance technological advancement with human comfort and experience. However, challenges common among industrialized deep renovation projects including administrative reluctance and user disruption still present significant barriers to widespread adoption of this type of solution (Secondo-Maglia et al., 2024).

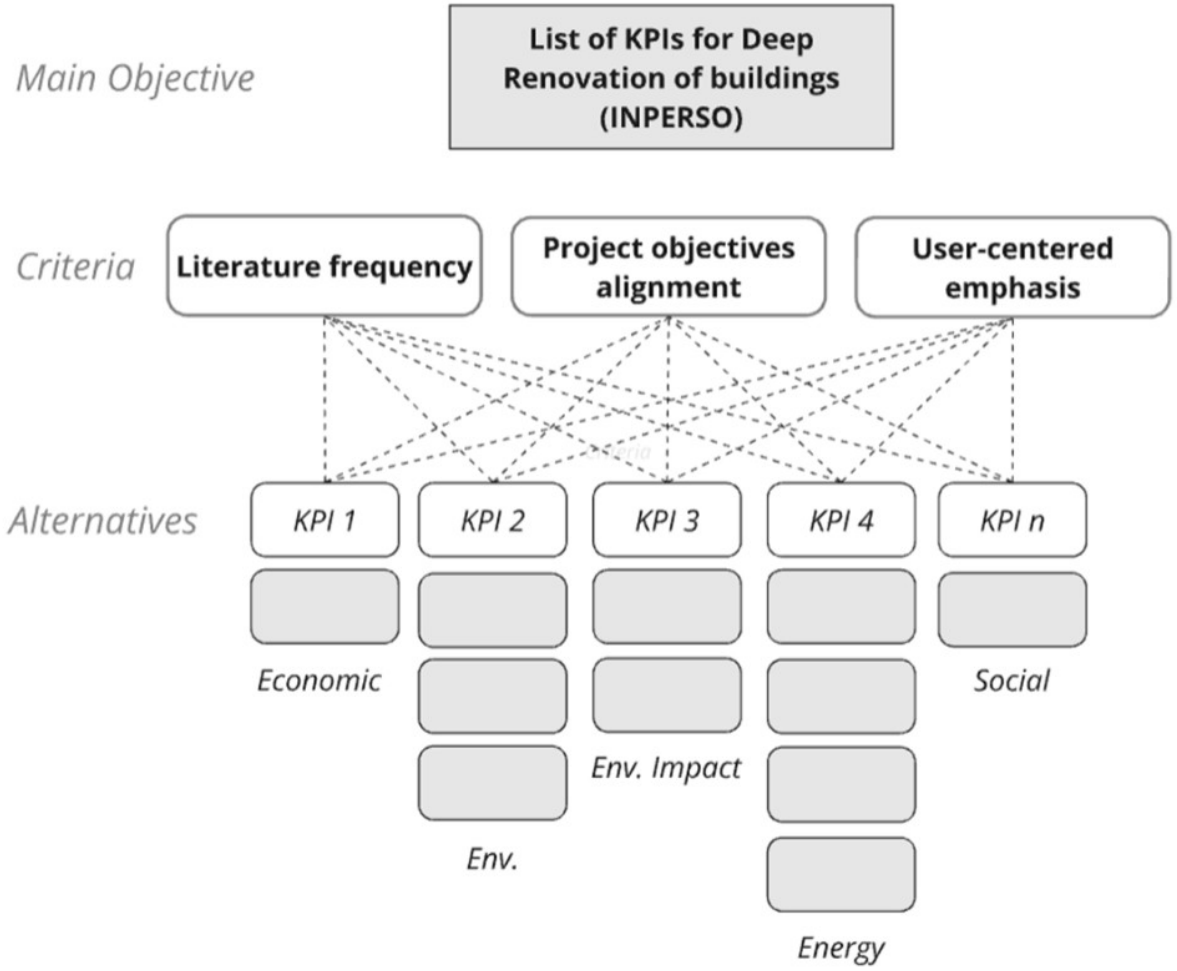


Figure 13 – INPERSO KPI Selection Methodology (Secondo-Maglia et al., 2024)

Though lacking the extensive research on the topic available from the European market, the US has also studied the consequences of aging building stock and strategies for deep renovation as a solution. Drawing from *Commercial Building Energy Consumption Survey* data, it has been proposed that US commercial buildings pre-dating 1980s modern energy codes (nearly half of the current stock) typically use 2–3 times more heating and cooling energy per square foot than code-compliant contemporary buildings (Christiansen, 2026).

Christiansen identifies several envelope-based measures among the highest return on investment (ROI) improvements for these older buildings, including air sealing, roof & wall insulation, and window upgrades, with payback periods primarily ranging from 4-10 years. The article further estimates envelope retrofits are capable of reducing heating/cooling energy by 30-50%. Major market drivers in the US for this type of solution include building performance & carbon reduction mandates, as well as associated tax credits & rebates (Christiansen, 2026). Given the decrease in federal support under the current presidential administration, the drivers are now emerging at the level of states and major cities/municipalities.

Going deeper from energy performance to whole-life carbon assessment of US commercial buildings, another study quantifies both operational and embodied emissions for eleven archetype building typologies, listed in Figure 14. The study spans all life-cycle stages and benchmarks the results against carbon budgets of 1.5°C and 2°C above pre-industrial levels. Results show that under the current trajectory, the 1.5°C carbon budget will be exceeded well before 2050. Again, noting the large share of older building stock, the paper highlights the importance of material efficiency and renovation over new construction (Ghorbany et al., 2025).

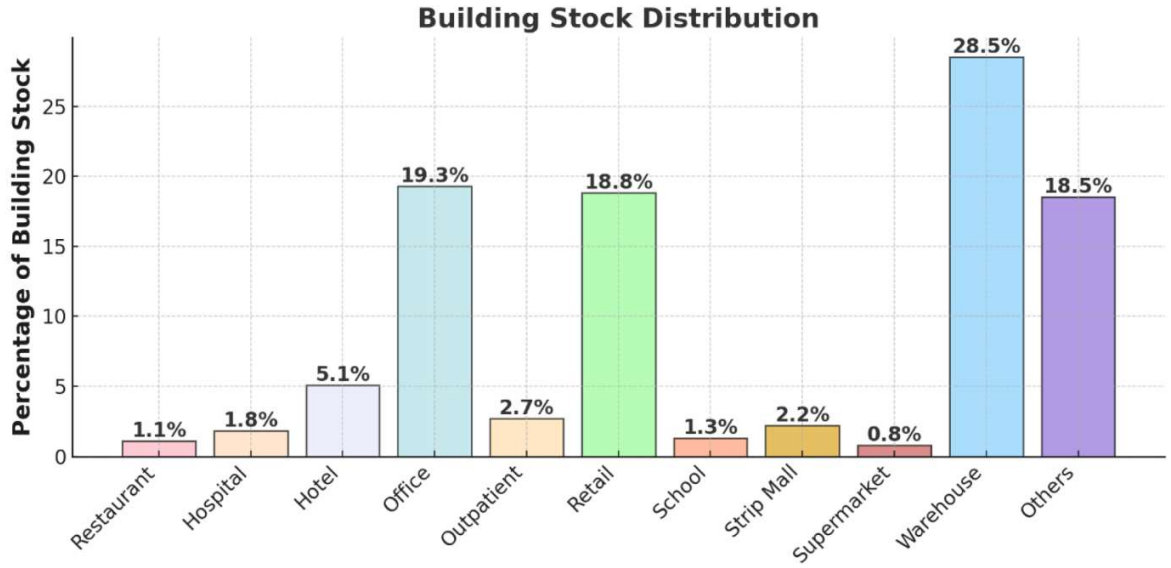


Figure 14 – US Commercial Building Stock Distribution by Typology (Ghorbany et al., 2025)

As an alternative to the current trajectory, a "green economy" scenario is proposed, where no new commercial buildings are constructed, but instead, existing ones renovated to meet new demands. Under this scenario, the 1.5°C carbon budget was calculated to last 253 years, and the 2°C budget 607 years, showcasing the massive potential impact of prioritizing renovation over new construction (Ghorbany et al., 2025). While this idealized scenario is not realistic in practice, recommended policy measures can serve to bridge the gap with current reality. These include mandating embodied carbon limits (as seen in Sweden), advancing low-carbon materials and circular economy strategies, and developing regional carbon reduction strategies, especially in larger, high-emission states.

Focusing deeper on the regionality of emissions mitigation in the US, another study quantifies the impacts of various strategies for both existing and new buildings through 2050. A bottom-up approach was employed starting with the modeling of reference buildings across different US climactic regions. The results were then scaled up to regional networks and finally the entire country. This enabled the exploration of key impact drivers which guided the study to prioritize strategies for different regions and

building types. The overall results confirm that operational use-phase emissions remain the largest contributor. Nevertheless, embodied carbon in new construction still represents a significant portion of cumulative emissions through 2050, with the extent varying by region and building typology. For example, GHG emission shares suggest that incentives for embodied-impact reduction should prioritize residential projects in Western states and commercial construction in the Southeast (Vahidi et al., 2021).

Furthermore, the study identifies strong regional differentiation for mitigation leverage. Due to relatively clean grids and strict codes already in place in the Western and New England regions, these areas have minimal potential for GHG reduction. In contrast, Central and Midwest have much greater opportunities to lower life-cycle GHG emissions with targeted investment in measures such as grid decarbonization, appliance/lighting efficiency, and improved thermal envelopes (Vahidi et al., 2021). The regional sensitivity displayed in this study highlights the national need for solutions that are not only easily scalable but adaptable to various local contexts.

The current state of EU & US deep renovation approaches presents both significant progress and persistent challenges. Policy frameworks increasingly emphasize holistic, standardized solutions and sophisticated optimization tools demonstrating the potential for near-complete decarbonization. However, there remains much room for improvement in existing assessment methodologies for evaluating advanced renovation techniques and integrated building systems that are essential for achieving long-term global climate targets.

2.1.2. DECARBONIZATION VIA DEEP RENOVATION WITH PREFABRICATED ENVELOPE SYSTEMS

The evolution of industrialized, prefabricated envelope systems as a key component of deep building renovation represents one of the most significant technological advances in contemporary sustainable construction. Growth has been driven by the urgent need to meet climate targets and the imperative to scale renovation solutions across aging building stock. The construction industry's historically low productivity compared to manufacturing sectors has created a high demand for technological and methodological innovations that can deliver the scale and speed required to meet climate targets while maintaining economic viability and user acceptance (Secondo-Maglia et al., 2024). Within this context, prefabricated envelopes have emerged as a particularly promising solution, offering the potential to combine factory-based quality control and efficiency with on-site installation speed and minimal occupant disruption.

The conceptual evolution of building envelopes from passive protective barriers to active, multifunctional building systems represents a fundamental shift in the AEC industry's approach to building performance. Traditional envelope renovation approaches, characterized by sequential installation of individual components and extensive on-site labor, are increasingly being replaced by integrated systems that combine multiple functions within prefabricated assemblies designed for rapid installation and superior performance. Research activity in this field has experienced remarkable growth, with publications on Active Prefabricated Façades (APF) increasing approximately 3.5 times over the past decade across major academic databases. This signals both the maturation of available technologies and the intensifying demand for renovation approaches based on industrialized envelope systems (Salvalai & Zhao, 2025).

Components now available within prefabricated envelope assemblies include renewable energy generation, cutting edge insulation, heating, ventilation, & air conditioning (HVAC) distribution, and intelligent control systems. Such systems require the convergence of multiple technological domains, including building physics, renewable energy technology, advanced materials science, and digital control systems. The integration of Building-Integrated Photovoltaics (BIPV) within these systems has emerged as a particularly significant development. APF with BIPV technologies offer dual benefits of on-site

energy generation and enhanced envelope thermal regulation, supported by a comprehensive review of life cycle assessment (LCA) and life cycle cost assessment (LCCA) perspectives (Salvalai & Zhao, 2025).

The LCA perspective is crucial to true whole-life decarbonization. Thus, proposed technologies should be situated within comprehensive frameworks that account for both operational and embodied carbon impacts throughout the building lifecycle. The relationship between these two sources presents complex trade-offs that require careful analysis and optimization. The substantial operational carbon reductions achievable through improved energy performance renovation must be balanced against the embodied carbon associated with the required materials and manufacturing processes. This is especially true today, as studies indicate that new buildings constructed between 2020 and 2050 will have embodied emissions surpassing operational emissions, both in the first ten years and throughout their life cycle (Udisi et al., 2024).

One study on life cycle carbon emissions optimization in prefabricated envelope systems leveraging Structural Equation Modeling (SEM) simulations found a reduction of nearly 17% possible through optimal material and component selection. Simulation results demonstrated that material selection and thickness significantly impact carbon emissions, with thicker envelope materials resulting in higher embodied carbon emissions during the production phase but lower operational carbon emissions (Chen et al., 2025). Despite embodied emissions trending toward higher significance, this study still found 73–91% of the total lifecycle emissions attributable to operational carbon, while embodied carbon contributed the remaining 9–27%.

Research examining diverse, widely-used envelope assemblies reveals considerable variation in embodied carbon intensity (ECI), driven primarily by cladding materials, insulation layers, and backup structures (Udisi et al., 2024). The same study also identifies floor systems as having relatively high ECI when compared to wall or roof assemblies, as well as the lowest variability in ECI across different assembly options. These findings further support deep renovation via envelope retrofit as an optimal strategy for decarbonization, due to its ability to significantly impact operational performance without requiring floor system modifications. Additionally, the results highlight the critical importance of material selection, as well as the complexity of assessing negative ECI for wood-based products due to their carbon sequestration.

The potential for envelope solutions that improve energy efficiency while incorporating bio-based components is demonstrated in the SmartWall modular system. SmartWall is a versatile, "Plug-and-Play" prefabricated envelope including a timber-based prefabricated panel, high-performance glazing, and decentralized fan-coil HVAC units. Each layer of the SmartWall assembly can be seen in Figure 15. The application of SmartWall to a typical single-family residence in Berlin has been studied in multiple phases: first to assess energy performance and embodied energy at the component and building level (Katsigiannis et al., 2022), and later expanded to consider three bio-based insulation alternatives, tracking their impact on thermal and environmental outcomes (Katsigiannis et al., 2025).

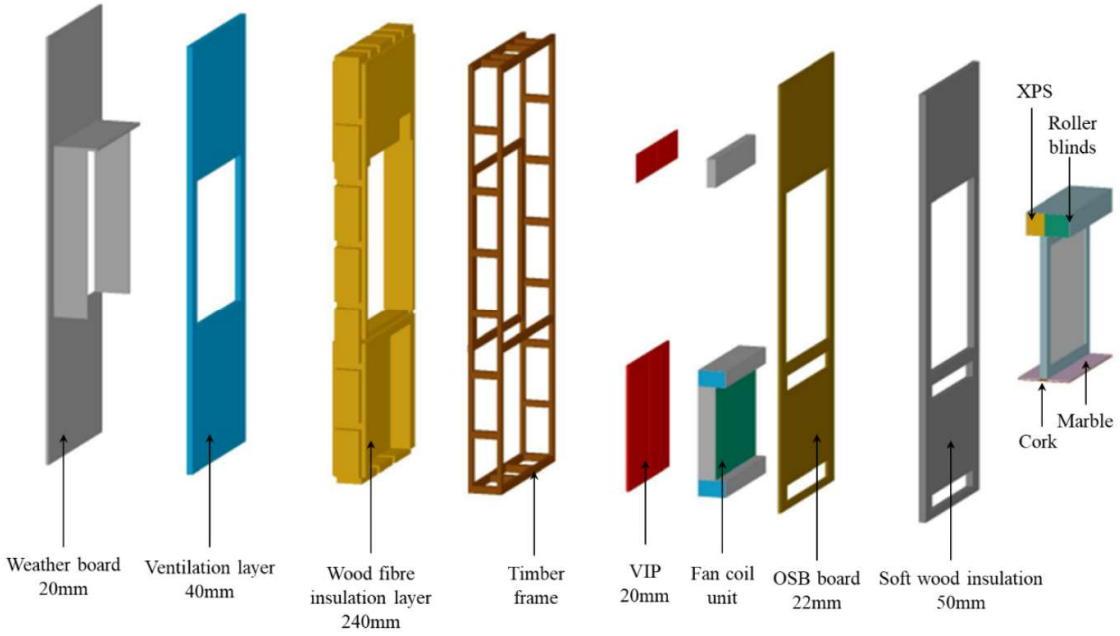


Figure 15 – Layered configuration of SmartWall Assembly (Katsigiannis et al., 2022)

The initial 2022 study demonstrates the ability of SmartWall to upgrade both the envelope and the HVAC systems without impacting aesthetics. While the capital expense of the envelope's embodied carbon is significant, this is counterbalanced by the operational energy savings within the first few years after implementation as it facilitates a NZEB state (Katsigiannis et al., 2022). The 2025 study refines these results with a more robust LCA and updated electricity mix data. It also includes a sensitivity analysis across three bio-based insulation options, the baseline wood fiber along with rice straw and expanded perlite alternatives. While thermal performance across the three options remained similar, straw panel emerged as the most favorable option for embodied carbon footprint, despite the initial carbon sequestration potential of the wood fiber (Katsigiannis et al., 2025). These results underline the importance of holistic, life cycle–based evaluation frameworks for assessing envelope solutions which include proper consideration of biogenic material outcomes.

Circularity of envelope products is emerging as another key strategy towards achieving ambitious EU climate neutrality goals. Within the AEGIR project, the consortium has developed a set of qualitative and quantitative KPI for evaluating the circularity of building products, with an emphasis on façade components (Zabek et al., 2024). These KPI are grounded in LCA, the EU Level(s) framework and circular-economy concepts (e.g. modularity, demountability, local materials, purity, compostability). The study applies material flow analysis (MFA) at the component level to nine facade-related product groups, including insulation and PV panels. The insulation case study contrasts recycled-cotton and cellulose panels with similar thermal properties but different life-cycle behaviors. Both use 80–90% secondary material, yet the cellulose product shows net carbon uptake in A1–A3, while fire-retardant additives and lack of recycling systems currently push both products toward landfill or incineration at end of life.

For active components, the paper compares a conventional crystalline silicon PV module with a flexible, thin-film PV optimized for façade integration. The results show that the thin-film option can reduce embodied GWP in the product stage by up to 80%. However, this comes at the cost of substantially lower power density and persistent recycling challenges due to glass, aluminum, and trace metals. The authors argue that existing tools such as LCA and Level(s) do not fully capture circularity performance. Thus, MFA-based visualization of primary/secondary flows, combined with a structured KPI set, can

better inform early design decisions and product selection for industrialized façade renovation (Zabek et al., 2024). In the context of SmartWall and similar prefabricated systems, this work pushes the state of the art from "low-carbon, NZEB-ready façades" toward façade products that are also designed for closed material loops. Highlighted issues include such as fire-protection additives, demountability, and realistic end-of-life pathways that are largely absent from retrofit studies focused on primarily on energy and cradle-to-gate embodied carbon. Furthermore, the use of qualitative approaches in conjunction with standardized methods like MFA is recommended for achieving holistic solution, an aspect of often neglected in building sustainability assessment frameworks.

2.1.3. INDOOR ENVIRONMENTAL QUALITY

Encompassing the physical conditions within buildings that directly impact occupant health, wellbeing, and satisfaction, indoor environmental quality (IEQ) represents a critical and often under-prioritized dimension of building performance. Given that inhabitants spend approximately 90% of their time indoors, the quality of indoor environments has profound implications for human health outcomes (Saadoon Abdulaali et al., 2020). The fundamental parameters of IEQ include indoor air quality (IAQ), thermal comfort, lighting quality, and acoustic conditions.

Detailed in Figure 16, research demonstrates clear linkages between poor IEQ and adverse health outcomes, including Sick Building Syndrome (SBS), respiratory conditions, and reduced cognitive performance. Immediate physical symptoms such as respiratory irritation and headaches have been demonstrated, as well as long-term psychological health impacts including depression, anxiety and stress, ultimately affecting inhabitants' confidence, strength, and motivation (Saadoon Abdulaali et al., 2020). Particularly concerning are chemical contaminants such as volatile organic compounds (VOC), particulate matter, and traffic-related pollutants.

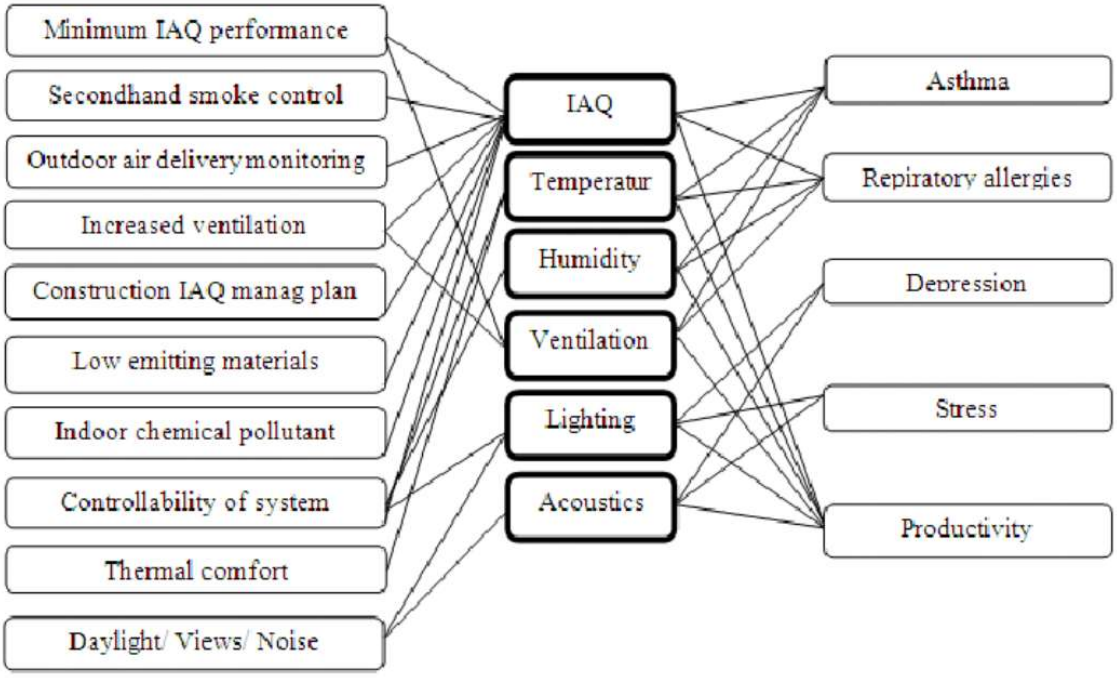


Figure 16 – Inhabitant Wellbeing and Productivity Framework (Saadoon Abdulaali et al., 2020)

A review of numerous studies affirmed that green buildings perform more efficiently in generating a healthy IEQ environment than non-green buildings based on both human and physical factors, leading to higher satisfaction for inhabitants (Saadoon Abdulaali et al., 2020). Furthermore, reduced costs from absenteeism and health care along with benefits to cognitive performance and productivity demonstrate direct economic benefits yielded by investment in IEQ.

In the post-COVID era, topics critical to human health and well-being have gained mounting international attention, including within the realms of green building and sustainable renovation. Nevertheless, a systematic review of global research reveals a concerning imbalance in renovation priorities. Analysis of 450 scholarly outputs on sustainable building renovation shows that energy efficiency receives significantly higher research attention at 59 publications than topics of IAQ with 12, reflecting a larger industry trend of more concern for energy efficiency at the expense of other sustainable parameters (Ismaeel, 2022). The study concluded that there remains variance across countries regarding the exact definition of a "Sustainable Building Renovation", and that practitioners are looking for frameworks and guidelines to support timely and efficient renovations. These frameworks should consider energy efficiency, IAQ, material efficiency, and resources to minimize waste.

A critical challenge lies in the inherent conflicts that can present themselves between energy efficiency objectives and desired IEQ outcomes. A comprehensive case study of a UK school campus has demonstrated that "if the building design focus primarily remains on energy, unintended consequence of indoor environmental quality underperformance may occur where there are conflicts between energy and indoor environmental quality objectives" (Jain et al., 2020). This finding is particularly significant given current policy-driven emphasis on energy performance in building regulations and assessment frameworks.



Figure 17 - Case Study School (Jain et al., 2020); Entrance – West Façade (Left), Central Courtyard (Right)

Some observed conflicts include: 1. airtight envelopes for energy efficiency exacerbating issues of hotspot overheating in certain areas and 2. inadequate ventilation as well as thermal mass requirements driving a pour acoustic environment. Specific challenges which compromised both energy and IEQ performance for the school campus include: 1. inadequate ventilation control strategies, 2. poor commissioning of automated lighting systems, and 3. operational inefficiencies. One provided example for how to holistically balance energy and IEQ considerations is the consideration of acoustic comfort and external pollution in the design of natural and mechanical ventilation systems (Jain et al., 2020).

IEQ challenges presented during building renovation activities can significantly impact occupant health during and after construction processes. The relatively vulnerable occupant base of education buildings makes them a particularly important typology for which to address these issues. Another study of a university building in Egypt has been conducted providing detailed evidence of how renovation activities in educational buildings can cause both short- and long-term health effects through elevated pollutant

emissions (Sameh et al., 2021). Assessing the application of new finishes throughout the regularly occupied spaces, wall painting activities were demonstrated to have the greatest impact on IAQ.

The research reveals that renovation impacts vary significantly based on space characteristics, occupancy patterns, and ventilation systems. Full-time occupants experienced different symptom patterns compared to transient occupants, with symptoms of SBS developing based exposure duration at a varying rate depending on space size and ventilation adequacy. Importantly, the study found that "using green materials and products may not be enough to guarantee a sustainable renovation activity if the best practices used still follow the traditional renovation methods" (Sameh et al., 2021). Though this study focused only on interior renovation, the discussed dual emphasis on material selection and construction best practices to ensure healthy IAQ is relevant to renovation projects at any scale.

Research on green-certified buildings provides insights into the relationship between IEQ performance and occupant satisfaction. Adopted from LEED, Malaysia's Green Building Index (GBI) was developed to promote a sustainable built environment within the country. Analysis of a GBI Platinum-rated office building via a questionnaire validated by PLS-SEM (Partial Least Squares Structural Equation Modeling) demonstrates that thermal comfort, visual comfort, and indoor air quality significantly influence occupant satisfaction, which in turn affects self-reported productivity (Hamimi et al., 2017). Interestingly, acoustic comfort showed no significant relationship with occupant satisfaction. These findings support the economic case for prioritizing IEQ in building design and renovation decisions, especially regarding thermal comfort, lighting and IAQ.

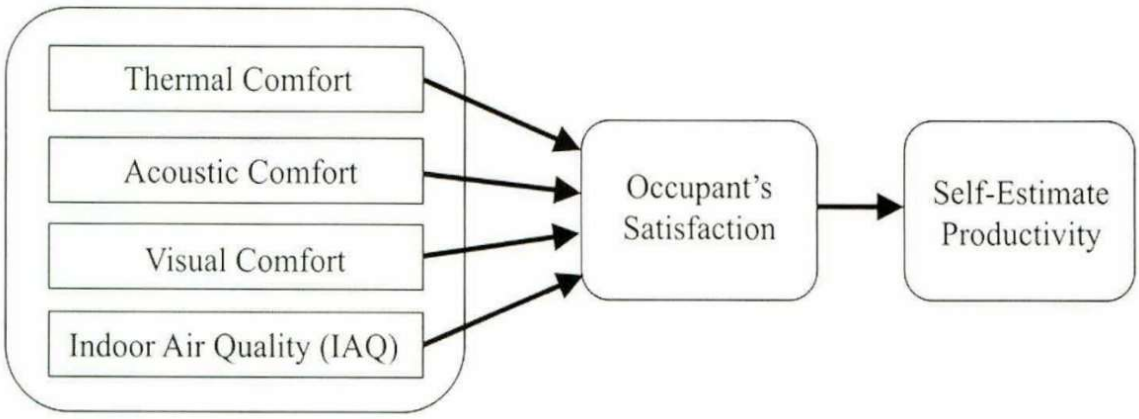


Figure 18 – IEQ Impact on Satisfaction & Productivity, Conceptual Research Model (Hamimi et al., 2017)

2.1.4. APPLICATION OF SUSTAINBILITY FRAMEWORKS

The assessment of sustainability in the built environment has evolved significantly in recent decades, driven by growing recognition of the construction sector's environmental impact and the need for comprehensive evaluation frameworks. Building sustainability assessment is typically the primary driver for these frameworks and has become a critical tool for achieving sustainable development goals in the construction sector, fostering integrative project team cooperation and informed decision-making. As such, the development of frameworks has been undertaken and studied by a wide range of global institutions for application to various types of building projects. Among the most popular assessment frameworks for green building include LEED from the US, BREEAM from the UK, and Level(s) developed by the EU.

Inspired by their local context, each framework has its own unique priorities and ideal applications. Thus, the development of novel, integrated assessment frameworks within the academic community for specific or underserved applications has been attempted. In recent years there has been growing

emphasis on holistic sustainability assessment, evidenced by one proposed framework employing a comprehensive life-cycle thinking approach that integrates environmental, economic, and social dimensions of sustainability rather than assessing these dimensions independently (Tran et al., 2023). Designed to be applicable across different building types, this framework serves as a practical tool for construction investment project stakeholders as well as a reference for future research regarding sustainability assessment models optimized for different types of projects.

Building on these foundational concepts, the New European Bauhaus (NEB) initiative launched in 2021 represents a broader cultural transformation in how sustainability is conceptualized and implemented. One critical study positions NEB as an innovation ecosystem that transcends traditional disciplinary boundaries, emphasizing symbiosis between art, technology, and science. The initiative responds to the overwhelming cultural consequences of prior and current Industrial Revolutions, aiming toward environmental, social, and cultural sustainability while also maintaining aesthetic considerations (Rosado-García et al., 2021). This approach to transversality is represented in Figure 19 through the visual tool, CATI. The paper argues that this integrated vision for sustainable development requires unprecedented coordination among government, industry, academia, society, and the natural environment. This coordination will foster collective intelligence and human-machine collaboration in sustainable construction practices.

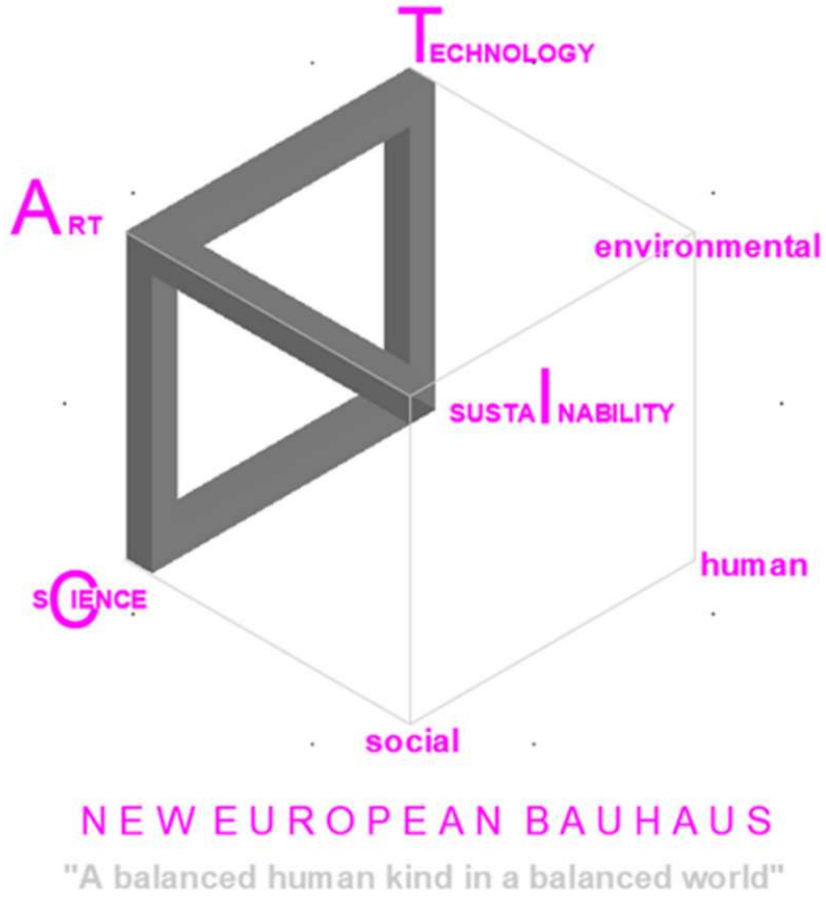


Figure 19 – CATI: A New Sustainability Culture (Rosado-García et al., 2021)

At the regional level, the EU has made significant strides in implementing LCA methodologies through specific frameworks. As the primary policy frameworks driving sustainable built environments in Europe, Level(s) and NEB both play a key role. Recent updates to Level(s) have expanded its scope, integrating

more comprehensive guidelines for embodied carbon calculation and improving alignment with EPDs. NEB promotes life cycle thinking via circular design principles and interdisciplinary, collaborative platforms. Research has been conducted analyzing these two frameworks for gaps and synergies, emphasizing the promotion of LCA to achieve sustainability objectives (Fokaides, 2025).

With a focus on identifying how LCA indicators are applied during the design phase, (Fokaides, 2025) organizes data between integration of LCA in design and construction, data management practices, stakeholder engagement, and policy alignment. Level(s) excels in promoting the calculation of embodied carbon, encouraging the use of EPDs, and providing standard guidelines for stakeholder engagement. Unlike Level(s), NEB currently offers the opportunity for the funding of projects deploying NEB principles via NEB Facility. Qualifications for this funding promote the use of bio-based materials, common data exchange formats, and adoption of community-driven approaches which engage local stakeholders. Furthermore, while Level(s) is primarily applicable for use within the AEC sector, NEB contributes to mainstreaming LCA across industries, integrating architectural design, material science, and environmental assessment within a single framework (Fokaides, 2025).

A recent, practical application of modern sustainability frameworks in the context of renovation projects has been demonstrated through the planned deep renovation and expansion of the EU Commission's Joint Research Center (JRC) in Belgium. The project follows NEB-aligned participatory and multidisciplinary processes as outlined by the NEB Compass and applies the Level(s) framework for assessment (Bektasiadou, 2024). Though construction is not complete, this approach has resulted in a distinct and innovative design process illustrating the potential for integrating multiple frameworks in real-world projects.



Figure 20 – JRC Geel Site (Bektasiadou, 2024); Current Condition (Left), Post-Reno Rendering (Right)

Beginning with a NEB-inspired bottom-up approach to design, JRC staff were engaged via workshops and surveys as a key project stakeholder. Level(s) indicators for pre-design and part of the design phase were then implemented. Included among these is an LCA comparison of various assembly options at the building envelope level. A Belgian LCA method for construction products and buildings was employed which considers a broad list of environmental indicators in line with the EN15804+A1 standard. The impacts are expressed in an aggregated single score, represented by a monetary value reflecting the "cost to prevent or repair the environmental damage" in €/m^2 (Bektasiadou, 2024). The results highlight the value of deep renovation as an alternative to demolition and new construction, with the chosen renovation option outperforming the option of an entirely new building envelope in terms of life cycle cost, LCA, and upfront investment cost.

Alignment with NEB included the pursuit of the highest level of ambition for each working principle. For sustainability, this meant going beyond the application of Level(s) by disseminating findings to provide a role model for future renovation projects. Regarding beauty, the implementation of Level(s) also facilitated extra care given to IEQ factors including light, shading, thermal & visual comfort, and air quality. Material selection and flexible space layout were further analyzed under a NEB-inspired lens. Inclusivity considerations include carefully designed circulation areas, an accessible green roof terrace, and the delivery of diverse spaces for stakeholders to collaborate and interact (Bektasiadou, 2024). As

this assessment is purely qualitative at the NEB Compass level, there remains room for deeper study via application of the NEB Self-Assessment Method (NEB-SAM).

The LEED rating system has also evolved substantially since its inception in 1998, having undergone several significant revisions in which the expectations needed to achieve the desired certification level were clarified and updated. Generally, these updates considered the adoption of new technologies and increasingly stringent energy standards, leading to the perception that higher certification levels are more challenging to obtain in each subsequent version of LEED. This perception has been verified via a comprehensive analysis of LEED versions 2.1, 2.2, and 3.0. The study developed both strict and interpretative conversion matrices to compare projects across these different LEED versions on a credit-by-credit basis (Madson et al., 2022).

Results verified an increase in difficulty to achieve the various levels of certification in successive versions of LEED, though only from a slight to moderate extent. After conversion, most sampled projects decreased by one to two certification levels, for example, from Silver to Certified, Gold to Silver, or even Gold to Certified (Madson et al., 2022). Though this study does not include the more recent LEED versions 4, 4.1, and 5, it is reasonable to assume this evidence for increasing sustainability demands of LEED buildings from 2006 to 2017 extends forward to present day. An opportunity for future work noted in the study is the comparison of LEED individual credit changes against other rating systems to serve as a verification for the trajectory of sustainable buildings. Such a comparison presents the opportunity to add a layer of global context to the discussion as the majority share of LEED projects are located in the US.

An example of a LEED-adapted rating system applied to building retrofit can be seen in the restoration of a historical heritage high school in Italy. The project employed the Italian Green Building Council's Historic Building protocol to adapt LEED categories and credits to protected historic buildings, blending technical and aesthetic considerations via a single modified rating system. The primary objectives consist of energy savings, preservation of historic architecture, and improvement of IEQ for building occupants (Baggio et al., 2017). Through a credit-by-credit analysis, the study maps realistically attainable and relevant credits to each objective, with calculated results verified wherever possible based on available data and present state of project construction. Summarized in Figure 21, solid lines indicate credits for which verification was possible while dashed lines indicate calculation only.

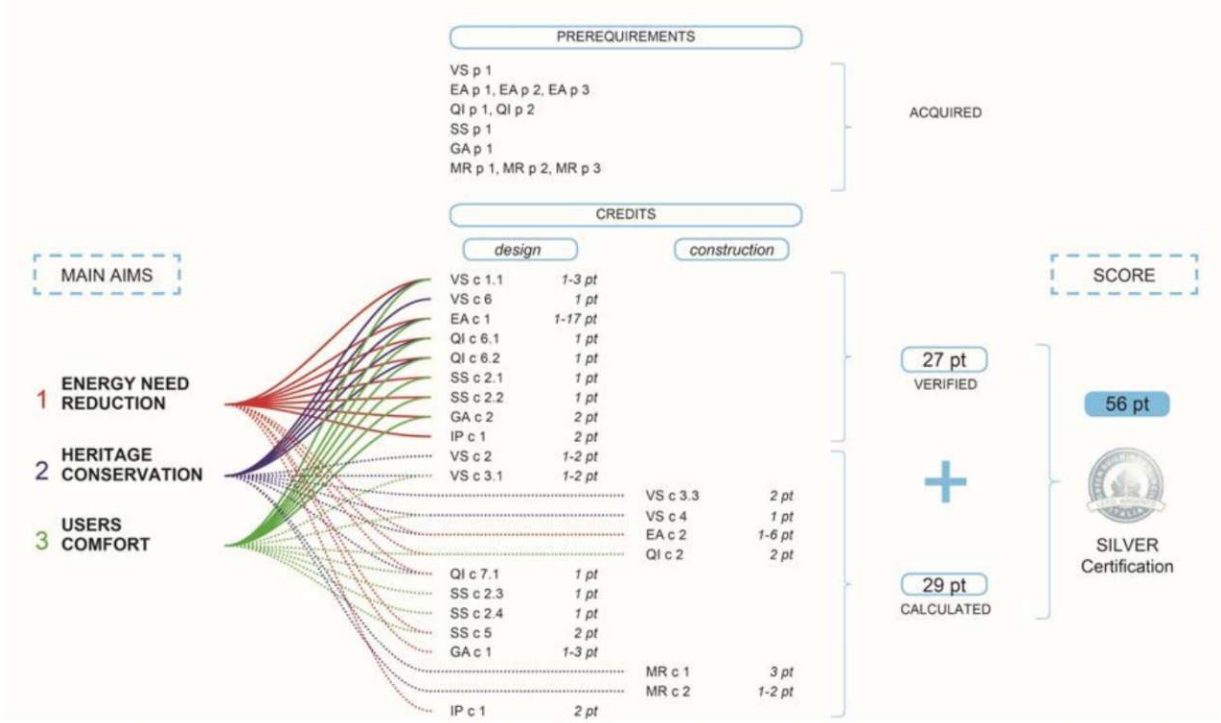


Figure 21 – Relationship between Historical Reno Project Aims, LEED-adapted Credits, and Final Score (Baggio et al., 2017)

Along with a projected LEED Silver certification, the project demonstrated the potential for 39% reduction in energy consumption while maintaining historical conservation and thermal comfort goals. Ultimately, the study validates the adaptation potential for LEED to serve as a decision-support tool for balancing more qualitative, cultural objectives with energy and environmental concerns applied to deep renovation. However, released in 2017, this particular application does not reflect the most recent developments to the LEED, and further lacks valuable context from the holistic, culturally-informed perspective of emerging European initiatives such as NEB.

2.2. EXISTING RESEACH GAPS & LIMITATIONS

In response to the literature review, the following key gaps and limitations have been identified:

- **Consideration of Whole Life Carbon Trade-offs with IEQ:** Previous studies have explored trade-offs between energy efficiency (and by extension, operational carbon) with embodied carbon and IEQ performance respectively. However, the current state of the art lacks research balancing all three elements in real construction and renovation projects.
- **Holistic Assessment of Deep Renovation Systems Beyond Residential Applications:** As concluded by (Ismaeel, 2022), practitioners are looking for holistic frameworks and guidelines to support a timely and efficient sustainable building renovation. These should include energy efficiency, material efficiency, IAQ, and minimization of waste. Previous research that has attempted to bridge the assessment of energy & carbon with IEQ and social considerations into a single renovation framework has been limited to residential case study applications. The INPERSO project has noted further studies should investigate how to adapt these KPIs for further building types and climates (Secondo-Maglia et al., 2024).
- **Impact of Building Envelope on IEQ:** With the demands produced by the EU Renovation Wave, envelope retrofits have become one of the primary solutions. Several studies were identified with a focus on energy efficiency and life cycle carbon impact of envelope packages; however, research coupling these considerations with IEQ metrics including lighting quality, thermal comfort, and IAQ is limited.
- **Cross-continental framework integration:** While studies were identified analyzing synergies and gaps between NEB and Level(s), this sort of research has not been expanded to consider NEB with a building sustainability framework from outside the EU, such as LEED. Such an analysis presents the opportunity to bridge innovative NEB principles beyond the EU sphere of influence. Research regarding NEB and LEEDv5 individually also presents its own limitations. Previous case studies incorporating NEB have done so only at a qualitative level following principles of the NEB Compass, lacking the quantitative depth offered via the Self-Assessment Method. With its recent release in 2025, minimal formal research of any kind has been identified addressing this newest version of LEED.

Any effort to address these limitations will be valuable to the widespread adoption of sustainable renovation projects to address the climate and construction targets established by the EU Renovation Wave and beyond. This MBUILD final dissertation proposes THRIVE: a holistic, transatlantic sustainability framework to validate and measure decarbonization and occupant well-being outcomes in deep renovation. THRIVE is developed through the integration of the NEB Self-Assessment Method and LEEDv5 BD+C rating system and further builds upon these guiding frameworks with novel contributions. Application to a demonstration project for the AEGIR deep renovation system demonstrates the logic behind THRIVE and offers insights to strengths and areas for targeted improvement for the case study project. The desired result is a clear, practical example that could further developed by application to similar renovation projects throughout the globe.

3

METHODOLOGY

3.1. OVERVIEW

The proposed **T**ransatlantic, **H**olistic **R**enovation assessment framework for decarbonization, **I**ndoor environmental quality, and **E**quity (THRIVE) methodology is broken into four analysis blocks encompassing whole-life decarbonization and diverse metrics for occupant well-being. Detailed in the following sections, these include:

- Embodied carbon
- Operational carbon
- Indoor environmental quality (IEQ)
- Resilience, aesthetics, & inclusiveness (RAI)

Each analysis block is made up of integrated measures which in turn are built on individual assessments guided by NEB Self-Assessment Method (NEB-SAM) indicators and LEEDv5 Building Design and Construction (BD+C) prerequisites and credits identified as relevant. Additionally, THRIVE expands on these frameworks with the introduction of the novel "Carbon Payback" measure spanning both the Embodied and Operational Carbon analysis blocks.

Following the rationale of the NEB-SAM, each induvial assessment is assigned a 0-100 score, which are aggregated first into integrated measure scores, then analysis block scores, and finally a single overall THIRVE score for the project.

An overview of the THRIVE structure is shown in Figure 22. Detailed procedures for the individual assessments outlined in Sections 3.2 – 3.5. The logic behind integrating the NEB-SAM and LEEDv5 BD+C, the weighting and aggregation to deliver analysis block- and project-level scores, and the determination of corresponding performance classes are detailed in Section 3.6.

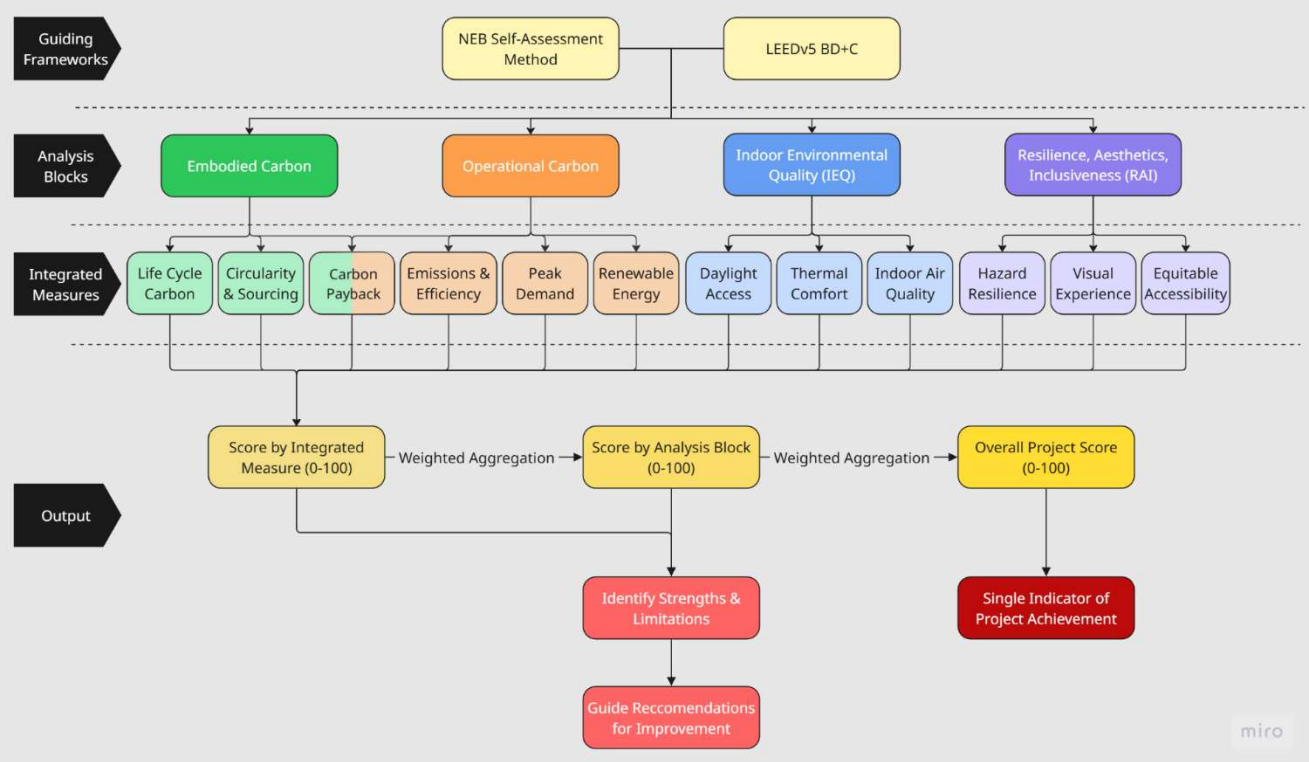


*Figure 22 – Proposed **T**ransatlantic, **H**olistic **R**enovation assessment framework for decarbonization, **I**ndoor en**V**ironmental quality, and **E**quity (THRIVE) Methodology Structure (created with Miro)*

3.2. EMBODIED CARBON

The integrated measures forming this analysis block are inspired by the guiding framework indicators prerequisites, and credits shown in Table 4, grouped by alignment.

Table 4 – Integrated Measure Composition for Embodied Carbon; Adapted from (Lourenco et al., 2024; USGBC, 2025)

Integrated Measure	Weight	NEB-SAM	LEEDv5 BD+C
EC1 – Life Cycle Carbon	50%	S.3.2 - Embodied GHG Emissions	MRp2 - Quantify and Assess Embodied Carbon
			MRc2 - Reduce Embodied Carbon
EC2 – Carbon Payback	20%	N/A	N/A
EC3 – Circularity & Sourcing	30%	S.9.1 - Secondary, Bio-Based, Recycled Material	MRc4 - Building Product Selection & Procurement
		B.2.2 - Responsible Material Sourcing	

Life Cycle Carbon

A cradle-to-grave life cycle carbon assessment is to be conducted for new materials comprising the renovation, considering all life cycle stages stipulated by EN 15804 as shown in Figure 23, excepting stage D. The assessment should include all major envelope layers, structural components (e.g. foundations, supplementary roof framing, shading structures), and if applicable, PV systems. Smaller components such as fasteners, coatings, and adhesives may be excluded to reduce complexity considering their negligible impact on the overall results. This assessment quantifies the global warming potential (GWP) of the system in kilograms (kg) of carbon dioxide equivalent (CO_2e), representing embodied greenhouse gas (GHG) emissions for the project. To reflect the benefit of bio-based materials in delaying carbon emissions and promote circularity, biogenic storage is to be considered.

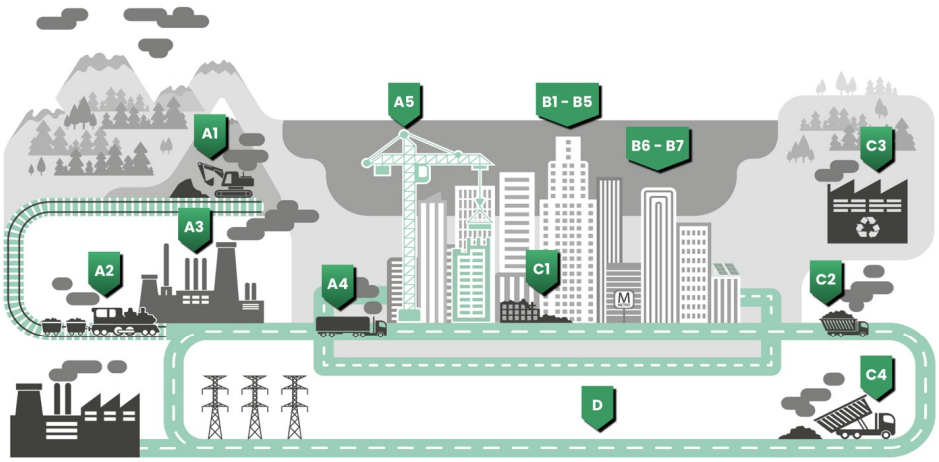


Figure 23 – Life Cycle Stages (Zahrmann, 2024)

Per S.3.2 and MRc2, a baseline scenario will be developed using industry-standard EPDs for each component of the envelope system. The GWP of the proposed renovation will be compared to the baseline to quantify improvement in the reduction of embodied carbon. The service life is to be taken as 50 years, per direction of S.3.2. The reduction calculation is shown in (Eq. 1). At a minimum, the top three sources of embodied carbon on the project should be identified to facilitate the exploration of strategies to reduce the impact of these hot spots.

$$Reduction\ (\%) = \frac{GWP_b - GWP_a}{GWP_b} * 100 \quad \text{(Eq. 1)}$$

$GWP_b =$ Baseline Embodied GHG Emissions (kg CO2e)

$GWP_p =$ Proposed Embodied GHG Emissions (kg CO2e)

The following parameters are to be kept consistent between the baseline and proposed scenarios:

- Functional units and system boundary
- Gross floor area
- Building programmatic function
- Building orientation
- Building location
- Operating energy performance

To ensure equivalent operating energy performance, care should be taken to ensure consistent R-values for thermal resistance for all insulation components between the baseline and proposed. The number of panes for all window or curtainwall glazing components should be kept consistent (e.g. double-glazed windows in the proposed scenario correspond with double-glazed windows in baseline). In the case of different R-values between baseline and proposed insulation products, the thickness (and corresponding volume) of the baseline should be adjusted to maintain consistency, as shown in (Eq. 2). Regarding renewable energy systems, the total Watt-peak capacity for PV panels should be kept consistent as shown in (Eq. 3).

$$d_b = d_p * \frac{\lambda_b}{\lambda_p} \quad \text{(Eq. 2)}$$

$d_b =$ Baseline Thickness (mm)

$d_p =$ Proposed Thickness (mm)

$\lambda_b =$ Baseline Thermal Conductivity (W/m*K)

$\lambda_p =$ Proposed Thermal Conductivity (W/m*K)

$$A_b = A_p * \frac{Wp_p}{Wp_b} \quad \text{(Eq. 3)}$$

$A_b =$ Baseline Area (m^2)

$A_p =$ Proposed Area (m^2)

$Wp_b =$ Baseline Watt-peak

$Wp_p =$ Proposed Watt-peak

In the absence of detailed data regarding the quantities of individual material components within a composite element, the average material quantities in typical assemblies listed in Table 5 and reinforcement quantities in reinforced concrete elements listed in Table 6 may be used for estimation.

Table 5 – Average Material Quantities in Composite Elements; Adapted from (One Click LCA, n.d.-a)

Composite Element	Materials	Share of Entire Element (%)	Kg of Material per m²
Brick Wall	Brick / Mortar	85.00% / 15.00%	-
Steel studs in a light wall, 100 mm	Studs	-	1.73
Steel studs in a light wall, 80 mm	Studs	-	1.44
Wood studs in a light wall, 100 mm	Studs	-	6.37
Wood studs in external wall	Studs	-	10.25
Steel studs in an external wall	Studs	-	8.30
Roof trusses of wood	Wood	-	10.74*
Roof trusses of steel	Steel	-	6.30*
External plastering & plaster net	Glass fiber mesh / Plasters	1.25% / 98.75%	0.14 / 11.71
Wooden windows	Wood / Glass	-	9.50 / 21.00
Metal windows	Metal / Glass	-	12.30 / 27.50
PVC windows	PVC / Glass	-	8.70 / 18.70

*per m^2 of roof area

Table 6 – Average Quantities of Reinforcement in Concrete; Adapted from (One Click LCA, n.d.-b)

Concrete Element	Kg of Reinforcement per m^3	Steel Share of Total Structure (%)
Footings	70-100	0.9 - 4.2 %
Ground beams	230-330	2.9 - 4.2 %
Slabs – one way	75–125	1 - 1.6 %
Slabs – two way	67–135	0.9 - 1.7 %
Walls – normal	70–100	0.9 - 1.3 %
Walls – wind	90–150	1.1 - 1.9 %

The score for NEB indicator S.3.2 is determined based on the % reduction results of (Eq. 1). This percentage is converted to a 0-100 score per Table 7, which translates S.3 performance class thresholds for Renovation - Non-residential to those for the embodied carbon analysis block, informed by the overall NEB sustainability dimension (NEB-S) as shown in Figure 45. Linear interpolation is permitted.

Table 7 – NEB-side Scoring for EC1; Adapted from (Lourenco et al., 2024)

% Improvement	Converted NEB-side Score
≤ 0%	0
10%	40
35%	60
65%	80
100%	100

LEEDv5 credit MRc2 awards 2-6 points based on reduction thresholds. These points are translated into the 0-100 scale considering the THRIVE performance class thresholds for embodied carbon, informed by NEB-S (see Figure 45), as shown in Table 8. Linear interpolation is permitted for reduction values in between thresholds. The NEB-side and LEED-side converted scores are combined with 50/50 weighting to reach the score for integrated measure EC1.

Table 8 – LEED-side Scoring for EC1; Adapted from (Lourenco et al., 2024; USGBC, 2025)

GWP Reduction (%)	LEED Points	Converted LEED-side Score
Higher than Baseline (-%)	0	0
Meet Baseline (0%)	2	20
10	3	40
20	4	53
30	5	67
40	6	80
100	6	100

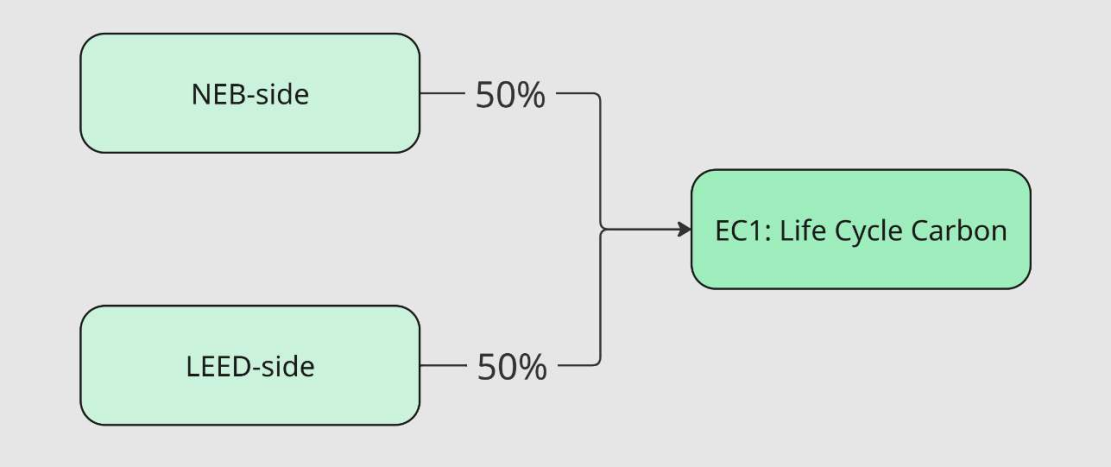


Figure 24 – Integration Flowchart and Weighting for EC1: Life Cycle Carbon (created with Miro)

Carbon Payback

The "investment" GWP value calculated for the proposed life cycle carbon model is compared to the results of the operational carbon analysis to determine a "Carbon Payback" period for the renovation. This calculation, which facilitates the score of both EC2 and OC2, is detailed in Section 3.3 – Operational Carbon.

Circularity & Sourcing

Beyond the cradle-to-grave embodied carbon impact measured by the life cycle carbon assessment, the mounting importance of circularity and responsible material sourcing in modern sustainable construction is promoted and evaluated through Integrated Measure EC3. The measure is divided into two equally weighted assessments. The first addresses the circularity of materials and products considered in EC1 as directed by S.9.1. The second covers responsible materials sourcing in regard to a holistic set of criteria, informed by both B.2.2 and MRc4.

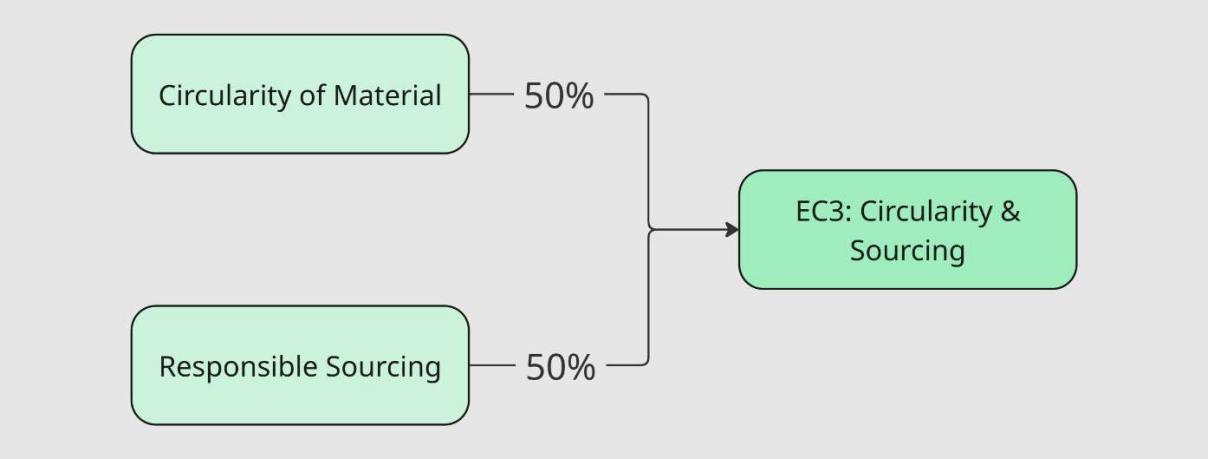


Figure 25 – Integration Flowchart and Weighting for EC3: Circularity & Sourcing (created with Miro)

Circularity of Material is first calculated as the ratio of the mass of secondary, bio-based and recycled materials to the total mass of the total amount of new materials used in the project, expressed as a percentage (CM) as shown in (Eq. 4). All components included in the life cycle carbon assessment should also be included in this calculation. The inclusion of additional components is optional at the project team's discretion. To normalize to a 0-100 assessment score, the CM metric is multiplied by a constant **k=5** per (Eq. 5). Per S.9.1, this constant reflects the assumption that the maximum realistic CM is 20% in today's construction industry, converting a 20% CM to a perfect score of 100. This assumption is based on 2022 Eurostat data for material coming from recycled waste in EU member states as well as EU 2030 circular material use rate targets (Lourenco et al., 2024).

$$CM = \frac{Mass\ of\ secondary, bio_based\ and\ recycled\ materials}{Total\ mass\ of\ materials} * 100 \quad \text{(Eq. 4)}$$

$$Score = CM * k \quad \text{(Eq. 5)}$$

Responsible Sourcing evaluates demonstrated achievement of key renovation products in the following criteria areas:

- Climate health
- Human health
- Ecosystem health
- Social health and equity
- Circular economy

Under THRIVE, at a minimum, products within the product category of Walls, Insulation, and Composite Wood (if present) should be considered for this assessment. Further product categories listed in MRc4 (e.g. paints and coatings, adhesives and sealants) may be included at the project team's discretion.

The wall panels product category includes all finish wall treatments (wall coverings, wall paneling, wall tile), gypsum, curtain walls, exterior doors and windows, non-structural wall framing, non-structural sandwich panels, CMU. Exclude products covered under composite wood from this category. The insulation product category includes all thermal and acoustic boards, batts, rolls, blankets, sound attenuation fire blankets, foamed-in place, loose-fill, blown, and sprayed insulation. The composite wood product category includes all particleboard, medium density fiberboard (both medium density and thin), hardwood plywood with veneer, composite or combination core, and wood structural panels or structural wood products.

Each product falling into these categories is assigned a LEEDv5-based multi-attribute score (MAS) according to available documentation supporting achievement in the listed criteria areas. A full list of supporting documentation and their corresponding contribution to the criteria areas can be found in Annex A.3. In addition to the documentation listed in Annex A.3, a product may earn an additional point towards its MAS by meeting the responsible sourcing criteria outline in B.2.2. That is, organizations involved at each stage of the product supply chain are certified by an accredited organization according to ISO 9001, and the products present an environmental management system certified by an accredited organization. The maximum MAS may not exceed 5 for a single product.

To assure proportional weighting of each product category (e.g. not over-inflating the importance of composite wood on a project with minimal surface area covered by composite wood products compared to walls and insulations), calculations are based on the total area of assessed products across all product categories. The surface area of each product is multiplied by its MAS to determine an adjusted responsible sourcing value. Per (Eq. 6), the responsible sourcing ratio (RSR) of the summed adjusted responsible sourcing values to the surface area of all assessed products is calculated. The RSR then determines assessment score for Responsible Sourcing according to Table 9.

$$RSR = \frac{\sum V_{adj}}{A_{tot}} \quad \text{(Eq. 6)}$$

$RSR =$ Responsible Sourcing Ratio

$V_{adj} =$ Adjusted Responsible Sourcing Value

$A_{tot} =$ Total Surface Area of Assessed Products

Table 9 – Scoring Thresholds for Responsible Sourcing

RSR	Assessment Score
0	0
0.5	40
1.0	60
2.0	80
3.0	100

The assessment score thresholds are based on NEB-S performance class thresholds governing the embodied carbon analysis block, shown in Figure 45. An R of 1.0, corresponding to a situation where, on average, each square meter of envelope is served by products that collectively achieve a MAS of 1, is deemed "good" for essentially meeting the base conditions for MRc4 across all assessed product categories. R = 0.5 is equated to "acceptable", considering points are available in MRc4 through base compliance with only some of the assessed product categories, and that 0.5 implies essentially half of

assessed product categories are compliant. At R = 2.0, the project has effectively doubled LEED's base requirement, implying widespread use of products with an MAS of 2-3, and some with an MAS of 4–5, earning an "excellent" score. While the theoretical maximum RSR is 5.0 if every product carried a MAS of 5, the thresholds are adjusted to assume R = 3.0 as an ambitious but practically achievable maximum level of achievement for responsible sourcing in today's construction industry. Linear interpolation between the scoring thresholds is permitted.

3.3. OPERATIONAL CARBON

The integrated measures forming this analysis block are inspired by the guiding framework indicators prerequisites, and credits shown in Table 10, grouped by alignment.

Table 10 – Integrated Measure Composition for Operational Carbon; Adapted from (Lourenco et al., 2024; USGBC, 2025)

Integrated Measure	Weight	NEB-SAM	LEEDv5 BD+C
OC1 – Emissions & Efficiency	50%	S.1.1 - Primary Energy Demand	EAp2 - Minimum Energy Efficiency
			EAc3 - Enhanced Energy Efficiency; Option 2
		S.3.1 - Operational GHG Emissions	EAc1 - Electrification
OC2 – Carbon Payback	20%	N/A	N/A
OC3 – Peak Demand	12%	S.1.2 - Electricity Peak Demand	EAc2 - Reduce Peak Thermal Loads; Option 4
OC4 – Renewable Energy	18%	S.2.1 - Share of Renewables	EAc4 - Renewable Energy
		S.2.2 - Energy Storage	

Emissions & Efficiency

Given the central focus and objectives centered on decarbonization, OC1 carries the heaviest weight within this analysis block, with an operatorial emissions analysis rooted in S.3.1 worth 50% of the weight for this integrated measure. The remaining 50% consists of an energy performance assessment considering both current national primary energy factors as outlined in S.1.1 and future source energy metrics guided by EA3, as well as the extent of project electrification guided by EAc1. The weighing here is split 2/3 energy performance, 1/3 electrification, considering the ratio of potential LEED points for each relevant credit to the combined total (EAc3 = up to 10 points, EAc1 = up to 5 points).

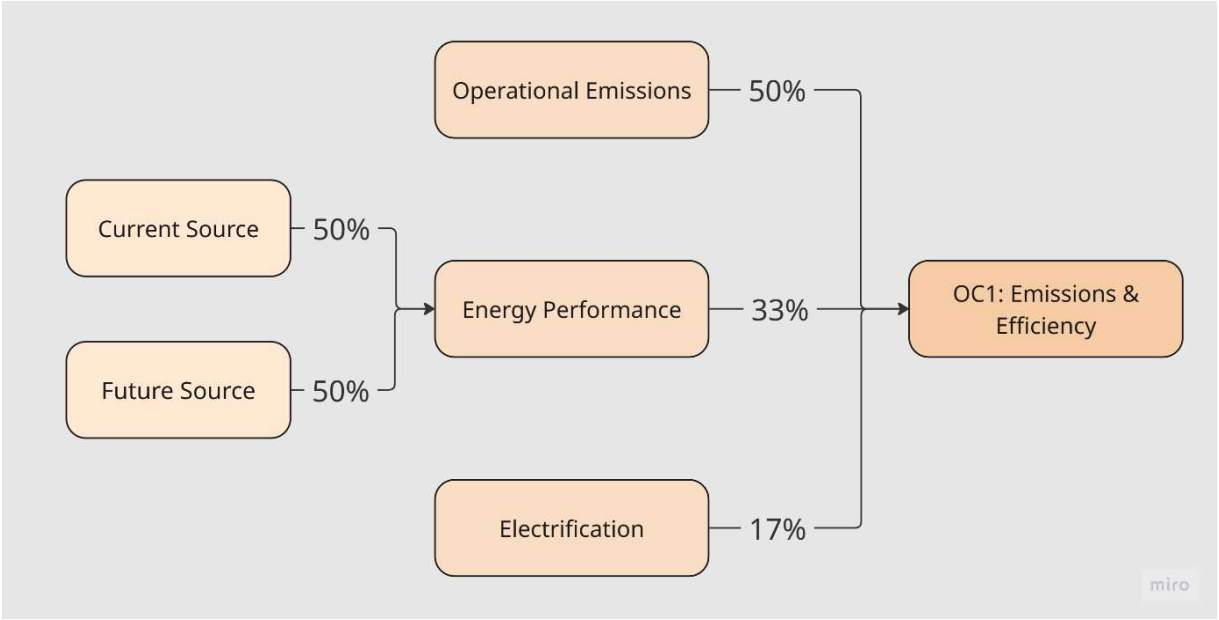


Figure 26 – Integration Flowchart and Weighting for OC1: Emissions & Efficiency (created with Miro)

The operational emissions and energy performance assessments are conducted via energy simulations representing the pre- and post-renovation state of the project. Projected annual net energy use in kilowatt hours (kWh), considering on-site renewable energy if present, will be utilized with carbon emissions factors, primary energy factors (PEF), and future source energy metrics based on the most current and local data available.

Calculations for operational emissions, and current source energy performance are described respectively in (Eq. 7) and (Eq. 8). The 0-100 score for each corresponds to the percent improvement between the pre- and post- renovation models, converted to align with THRIVE operational carbon performance class thresholds, informed by NEB-S (see Figure 45), as shown in Table 11. In the case of a negative value where the post-renovation state has higher emissions than pre-renovation, the score will be 0.

$$Reduction\ (\%) = 1.0 - \frac{\sum_{i=1}^{n} E_{post,i} * f_i}{\sum_{i=1}^{n} E_{pre,i} * f_i} \quad \text{(Eq. 7)}$$

E_{pre} = Annual Net Energy Consumption, pre-renovation, per energy carrier; i (kWh/year)

E_{post} = Annual Net Energy Consumption, post-renovation, per energy carrier; i (kWh/year)

f = Carbon Emissions Factor per energy carrier; i (kg CO2e/kWh)

n = number of different energy carriers in the project with unique carbon emissions factors

$$Reduction\ (\%) = 1.0 - \frac{\sum_{i=1}^{n} E_{post,i} * PEF_i}{\sum_{i=1}^{n} E_{pre,i} * PEF_i} \quad \text{(Eq. 8)}$$

E_{pre} = Annual Net Energy Consumption, pre-renovation, per energy carrier; i (kWh/year)

E_{post} = Annual Net Energy Consumption, post-renovation, per energy carrier; i (kWh/year)

PEF = Primary Energy Factor per energy carrier; i

n = number of different energy carriers in the project with unique primary energy factors

Table 11 – Scoring Thresholds for Operational Emissions and Current Source Energy Performance; Adapted from (Lourenco et al., 2024)

% Reduction	Converted Score
≤ 0%	0
10%	40
35%	60
65%	80
100%	100

To assess future source energy performance, the building performance factor (BPF) future source energy metric is derived from ASHRAE based on the project's climate zone and building typology. The tabulated metric should be multiplied by a 1.05 major building renovation factor per EAc3 instruction. Furthermore, energy consumption must be quantified in terms of regulated (e.g. space heating, cooling, ventilation, pumps, service hot water, interior lighting) and unregulated (e.g. equipment, appliances, servers) loads as defined in ASHRAE 90.1 *(ASHRAE & IES, 2022)*. The calculations then proceed as outlined in (Eq. 9), (Eq. 10), and (Eq. 11). The 0-100 score for this assessment corresponds directly to % Reduction.

$$Reduction\ (\%) = 1.0 - \frac{PI}{PI_t} \quad \text{(Eq. 11)}$$

Table 12 - ASHRAE 90.1-2019: Equivalent Building Performance Factors for a Future Source Energy Metric; Defined in EAc3: Enhanced Energy Efficiency (USGBC, 2025)

Building type	Climate zone																		
	0A	0B	1A	1B	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7	8
Multifamily	0.74	0.69	0.73	0.70	0.73	0.70	0.71	0.70	0.63	0.70	0.71	0.69	0.68	0.70	0.70	0.68	0.68	0.68	0.74
Healthcare/hospital	0.72	0.72	0.73	0.73	0.74	0.71	0.72	0.74	0.71	0.72	0.73	0.71	0.74	0.73	0.80	0.73	0.77	0.78	0.79
Hotel/motel	0.72	0.71	0.72	0.71	0.71	0.70	0.71	0.73	0.72	0.71	0.73	0.73	0.71	0.73	0.74	0.70	0.72	0.70	0.70
Office	0.62	0.63	0.61	0.62	0.58	0.60	0.57	0.62	0.55	0.55	0.61	0.57	0.58	0.61	0.59	0.58	0.60	0.54	0.58
Restaurant	0.65	0.62	0.63	0.61	0.62	0.58	0.63	0.63	0.63	0.67	0.66	0.66	0.70	0.70	0.68	0.73	0.72	0.74	0.77
Retail	0.57	0.54	0.53	0.53	0.48	0.47	0.47	0.47	0.47	0.52	0.50	0.56	0.57	0.53	0.59	0.58	0.56	0.53	0.60
School	0.57	0.57	0.58	0.57	0.55	0.54	0.57	0.51	0.49	0.48	0.51	0.52	0.51	0.53	0.51	0.53	0.50	0.51	0.58
Warehouse	0.28	0.30	0.24	0.27	0.23	0.24	0.27	0.23	0.20	0.33	0.26	0.28	0.40	0.32	0.29	0.44	0.38	0.40	0.44
All others	0.65	0.62	0.64	0.62	0.57	0.54	0.57	0.56	0.58	0.59	0.57	0.60	0.60	0.59	0.65	0.62	0.62	0.61	0.64

$$PI = \frac{E_{post}}{E_{pre}} \quad \text{(Eq. 9)}$$

$PI =$ Performance Index for Future Source Energy including On-site Renewable Contribution

$E_{pre} =$ Annual Net Energy Consumption, pre-renovation (kWh/year)

$E_{post} =$ Annual Net Energy Consumption, post-renovation (kWh/year)

$$PI_t = \frac{UE_{pre} + (BPF * RE_{pre})}{E_{pre}} \quad \text{(Eq. 10)}$$

PI_t = Performance Index Target for Future Source Energy Use

BPF = Building Performance Factor

UE_{pre} = Unregulated Energy Consumption, pre-renovation (kWh/year)

RE_{pre} = Regulated Energy Consumption, pre-renovation (kWh/year)

E_{pre} = Annual Net Energy Consumption, pre-renovation, (kWh/year)

$$Reduction\ (\%) = 1.0 - \frac{PI}{PI_t} \quad \text{(Eq. 11)}$$

PI = Performance Index for Future Source Energy including On-site Renewable Contribution

PI_t = Performance Index Target for Future Source Energy Use

The final component of OC1 comes from an assessment of the project's electrification potential, guided by EAc1. This credit awards up to 5 points under the LEEDv5 rating system, which are converted to the 0-100 scale for THRIVE. To achieve the full 5 points (or a score of 100), the project must contain no on-site combustion except for emergency support systems. Additionally, combined weighted average equipment efficiency for space heating and service water heating (SWH) must be at least 1.8 coefficient of performance (COP), with the following exceptions. Note that regarding this assessment, "low temperatures" is defined as outdoor air temperatures below -6.5°C or 20°F.

- Space heating equipment in climate zones 0–2.
- Supplemental heating equipment designed only for operation at low temperatures.
- SWH equipment in nonresidential spaces complying with the point-of-use water heater criteria in ASHRAE 90.1-2022, Section 11.5.2.3.3, W05, without exceptions.

Alternatively, up to 4 LEED points, or a converted score of 80, can be earned via a combination of strategies limiting on-site combustion to low temperatures for various end uses.

Table 13 – EAc1 Scoring Distribution; Adapted from EAc1: Electrification (USGBC, 2025)

End Use	LEEDv5 Points	Converted Score
Space Heating	2	40
Service Water Heating (SWH)	1	20
Cooking and Other Process Loads	1	20

Points are earned accordingly for each end use that is capable of operating without on-site combustion except in low temperatures, with the following additional requirements.

- Space Heating: Projects in climate zones 3 and above must have a weighted average space heating equipment efficiency of at least 1.8 COP, excluding supplemental or auxiliary heating equipment designed only for operation at low temperatures.
- Service Water Heating (SWH):
    - Projects with total SWH capacity exceeding 34,000 Btu/hr (10 kW) must have a weighted average service hot water equipment efficiency of at least 1.8 COP - or - domestic hot water solar fraction of at least 0.4.
    - SWH equipment in nonresidential spaces complying with the point-of-use water heater criteria in ASHRAE 90.1-2022, Section 11.5.2.3.3, W05, without exceptions (ASHRAE & IES, 2022) - and/or - supplemental or auxiliary heating equipment designed only for operation at low temperatures may be excluded from the COP determination.
- Cooking and Other Process Loads: Other process loads include laundry, process equipment, and on-site power generation except emergency support systems. Projects that do not have these systems automatically earn this point. Process heating equipment designed for operation at low temperatures may be excluded.

Carbon Payback

To evaluate integrated measures EC2 and OC2, the carbon payback period is calculated per (Eq. 12) as the upfront embodied carbon investment from the proposed life cycle carbon (LCC) assessment model divided by difference between the pre- and post-renovation operational emissions, both represented in kg CO2e. This novel measure is intended to further support the holistic consideration of embodied and operational carbon impacts in deep renovation decision-making beyond what is represented in the NEB-SAM or LEEDv5. The results also present a clear indicator of environmental return on investment (ROI) that can be easily communicated to the general public.

$$PP = \frac{GWP_p}{OGHG_{pre} - OGHG_{post}} \quad \text{(Eq. 12)}$$

$PP =$ Payback Period (years)

$GWP_p =$ Proposed Embodied GHG Emissions (kg CO2e)

$OGHG_{pre} =$ Annual Operational GHG Emissions, pre-renovation (kg CO2e/year)

$OGHG_{post} =$ Annual Operational GHG Emissions, post-renovation (kg CO2e/year)

The THRIVE scoring methodology is identical for EC2 and OC2, based on a 2023 report on the embodied carbon of retrofits conducted by the Carbon Risk Real Estate Monitor (CRREM) initiative. Through an in-depth analysis of 36 completed projects from all over the globe, the study identified the average carbon payback period for a deep retrofit to be 4.4 years (see Figure 27), with a maximum payback of up to 8 years (Bienert et al., 2023). All retrofits considered in the study were considered "ecologically favorable". Therefore, a score of 40 is attributed to the 8-year maximum, setting the boundary for an "Acceptable" payback based on THRIVE embodied and operational carbon performance class thresholds, informed by NEB-S (see Figure 45). For the purposes of this measure, achieving the identified average of 1.3 years payback for a light retrofit in a deep retrofit is attributed a score of 100. Via linear extrapolation, the maximum payback period beyond which earns a score of 0 is calculated as 12.5 years. This establishes a linear scale represented in

Table *14* to interpolate points for any payback period between 1.3 and 12.5 years. By this scale, achieving the average payback period among the ecologically favorable dataset translates to a "Good" score of 72.

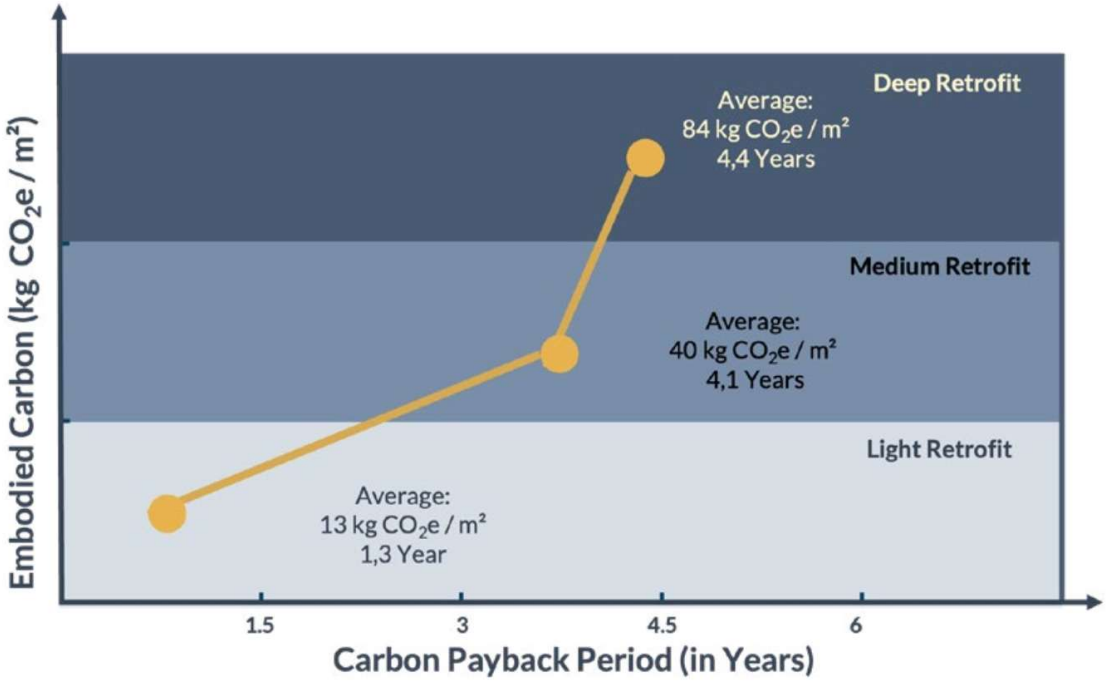


Figure 27 – Aggregated Results of Analyzed Case Studies (Bienert et al., 2023)

Table 14 – EC2, OC2 Scoring Distribution; Adapted from (Bienert et al., 2023)

Carbon Payback Period	Converted Score
1.3 Years -	100
8 Years	40
4.4 Years	72
12.5 Years +	0

Peak Demand

OC3 synthesizes requirements from S.1.2 and EAc2 into a simplified measure tailored to deep renovation. The measure consists of a direct comparison of the peak load over a full-year time period to maintain thermal setpoints between the pre- and post-renovation condition of the project. Design simulation results or recorded energy demand data may be used for each condition depending on what is available for the project. This assessment recieves a 0-100 score corresponding directly to the % decrease in peak load. Furthermore, an assessment of ventilaiton rates is conducted to assure the tight building envelopes necessary for low peak loads do not come at the cost of compromised IAQ. Compliance with balanced ventilation is achieved via ventilation and exhaust airflows within 10% of each other, earning 100 points if met and 0 if not. Weighting is established according to the relative potential point value of Peak Thermal Load Reductions (3 Points) and Balanced Ventilation (1 Point) per EAc2.

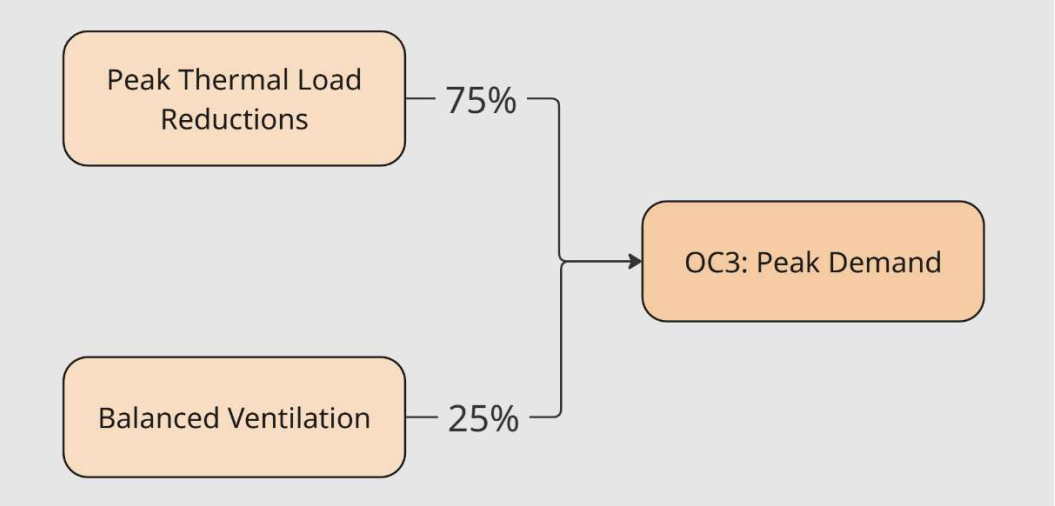


Figure 28 – Integration Flowchart and Weighting for OC3: Peak Demand (created with Miro)

Renewable Energy

OC4 directly addresses and quantifies the impact of renewable energy technologies incorporated in the project. NEB and LEED methodologies are weighted equally, with individual NEB indicators weighted per Self-Assessment Method guidance for non-residential building renovations.

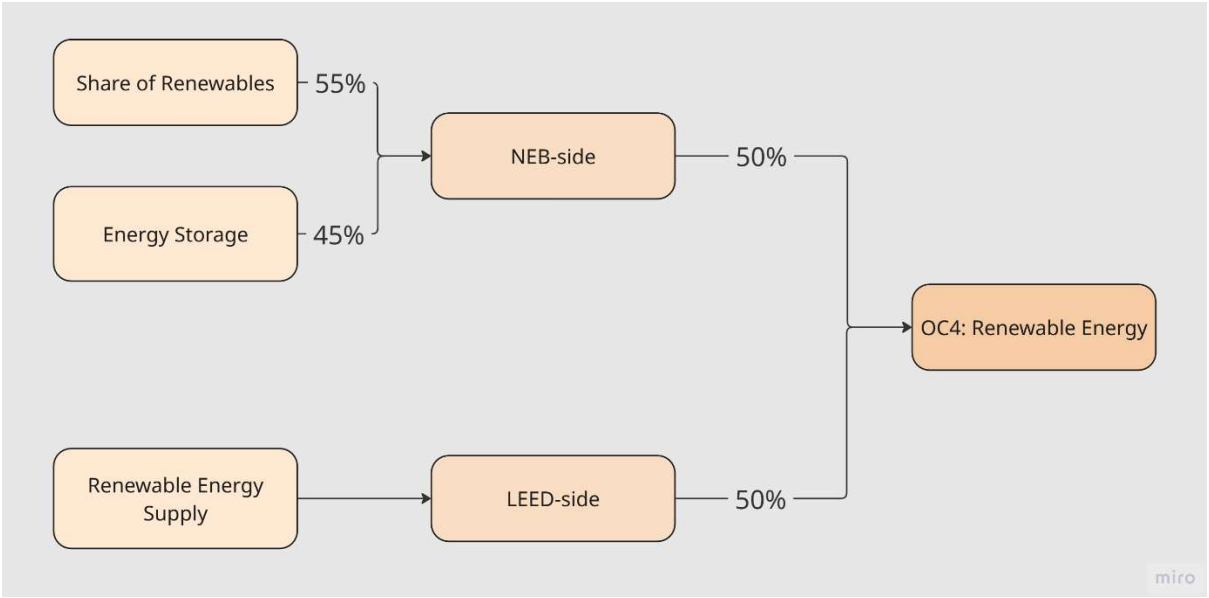


Figure 29 – Integration Flowchart and Weighting for OC4: Renewable Energy (created with Miro)

The "Share of Renewables" and "Renewable Energy Supply" assessments compare annual project energy demand against renewable energy generated on-site to meet this demand. In the case of the Renewable Energy Supply assessment, guided by EAc4, the calculation is a direct ratio between the two. Points are awarded based on the percentage of energy demand covered by renewable energy as shown in Table 15. Linear interpolation is permitted for percent coverage between listed thresholds.

Table 15 – Renewable Energy Supply Scoring Distribution; Adapted from EAc4: Renewable Energy (USGBC, 2025)

Percent of Energy Demand Covered by Renewables	LEEDv5 Points	Converted Points
5%	1	20
10%	2	40
20%	3	60
35%	4	80
100%	5	100

Share of Renewables, guided by S.2.1, assesses the same energy generation to demand ratio against a baseline metric determined at the local, national, or EU level. The baseline metric will vary depending on the project's context. For projects in the EU, the current practice for the share of renewables on the final energy consumption in EU-27 Member States is available from Eurostat. Thus, projects may use the most current and local data to assume a baseline. Other global projects should make reasonable assumptions using comparable databases where available. The generation : demand ratio is then measured against the chosen baseline to yield a 0-100 score based on (Eq. 13).

$$S.2.1 = \frac{\frac{RE}{ED} - T_b}{T_b} * 100 \quad \text{(Eq. 13)}$$

$S.2.1 =$ Share of Renewables Score (0-100)

$RE =$ On-Site Generated Renewable Energy (kWh/year)

$DE =$ Annual Energy Demand (kWh/year)

$T_b =$ Baseline Share of Renewables Metric (%)

The Energy Storage assessment, guided by S.2.2, quantifies the effect of energy storage solutions on the flexibility requirements of the energy system. First, flexibility requirements over a given time period are determined by comparing load at a given time step against the average load over all time steps within the time period per (Eq. 14).

$$FR^T = \sum_T \frac{1}{2} \sum_t |RL_t - \overline{RL_t}| \quad \text{(Eq. 14)}$$

$FR^T =$ Flexibility Requirements over Time Period

$T =$ Time Period

$t =$ Time Step

$RL_t =$ Load at Time Step

$\overline{RL_t} =$ Average Load over all Time Steps

The impact of energy storage solutions is then determined by subtracting the energy supplied by the energy storage systems from the standard load curve and comparing this value to the system's flexibility

requirements per (Eq. 15). Accordingly, the correlation can be updated to evaluate the effectiveness of the energy storage technologies in meeting the changing demands of the power system.

$$FR^{T,es} = FR^{T} - \sum_{T} \frac{1}{2} \sum_{t} \left| (RL_t - EP_t^{es}) - (\overline{RL_t - EP_t^{es}}) \right| \quad \text{(Eq. 15)}$$

$FR^{T,es}$ = Contribution of Energy Storage to Flexibility Requirements over Time Period

FR^{T} = Flexibility Requirements over Time Period

T = Time Period

t = Time Step

RL_t = Load at Time Step

EP_t^{es} = Energy Supplied by Energy Storage at Time Step t

Finally, a 0-100 score for this assessment is calculated by comparing the energy storage factor, which is the ratio of the contribution of energy storage to the flexibility requirements ($FR^{T,es}$) to the flexibility requirements of the system in case of absence of any energy storage system (FR^{T}), against a baseline metric for energy storage impact on flexibility requirements, per (Eq. 16). The baseline metric can be based on a report issued by European Commission Joint Research Center (JRC) covering flexibility requirements and the role of energy storage in power systems (Koolen et al., 2023).

$$\text{S. 2.2} = 0 \leq \frac{\frac{FR^{T,es}}{FR^{T}} - T_b}{T_b} \leq 100 \quad \text{(Eq. 16)}$$

$S.2.2$ = Energy Storage Score

$FR^{T,es}$ = Contribution of Energy Storage to Flexibility Requirements over Time Period

FR^{T} = Flexibility Requirements over Time Period

T_b = Baseline Energy Storage Factor (%)

T_b = Baseline Flexibility Requirements Metric (%)

3.4. INDOOR ENVIRONMENTAL QUALITY (IEQ)

The integrated measures forming this analysis block are inspired by the guiding framework indicators prerequisites, and credits shown in Table 16, grouped by alignment.

Table 16 - Integrated Measure Composition for IEQ; Adapted from (Lourenco et al., 2024; USGBC, 2025)

Integrated Measure	Weight	NEB-SAM	LEEDv5 BD+C
IEQ1 – Daylight Access	40.0%	B.4.2 - Lighting Environment	EQc2 - Occupant Experience; Option 5, PATH 1 & 4
IEQ2 – Thermal Comfort	22.5%	B.4.3 - Thermal Comfort	EQc2 - Occupant Experience; Option 3
IEQ3 – Indoor Air Quality	37.5%	S.5.1 - Indoor Air Quality	EQp2 - Fundamental Air Quality
			EQc1 - Enhanced Air Quality

3.4.1. DAYLIGHT ACCESS

Analysis of Daylight Access consists of a daylight simulation (incorporated in both B.4.2 and EQc2), an assessment of design strategies including specified glazing properties, the ratio glazing area to floor area, and shading devices per B.4.2, and a review of glare-control devices per EQc2. Each individual assessment delivers a score on a 0-100 scale, which are then aggregated to determine the score for IEQ1.

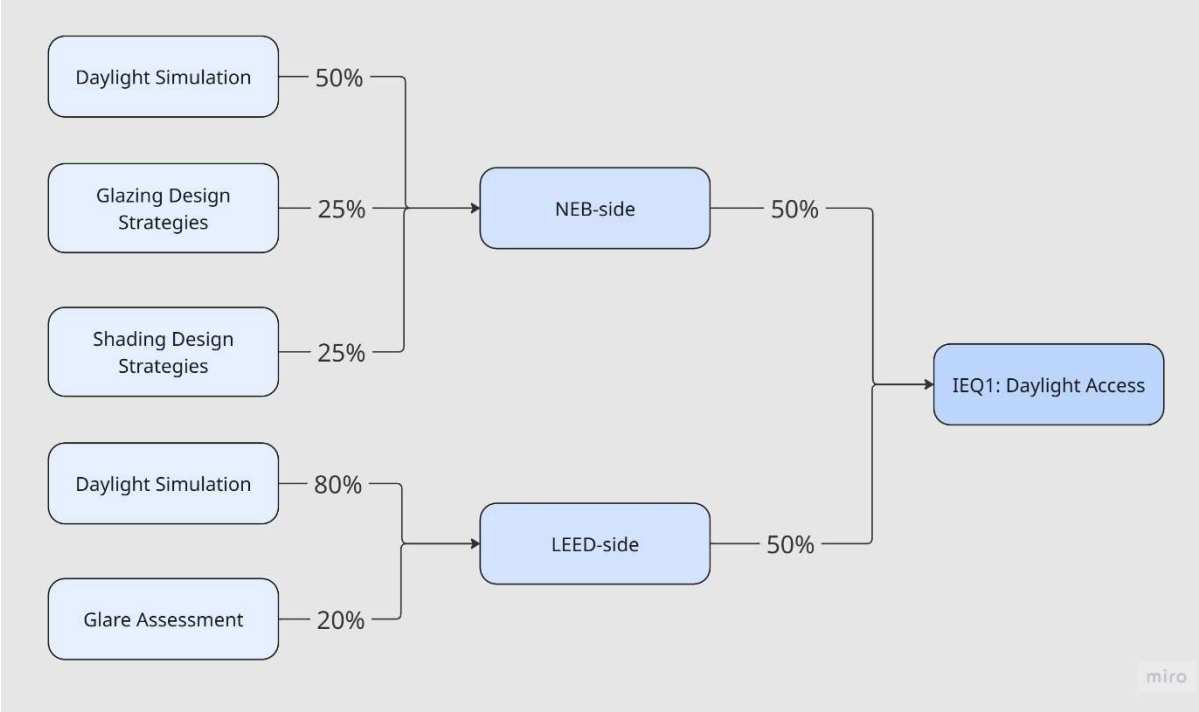


Figure 30 – Integration Flowchart and Weighting for IEQ1: Daylight Access (created with Miro)

The daylight simulation is to be conducted following calculation protocols outlined by the Illuminating Engineering Society (IES) in standard IES LM-83-23 (Illuminating Engineering Society, 2023), specifically, calculating spatial daylight autonomy (sDA) and annual sunlight exposure (ASE) for all regularly occupied spaces in the project building. sDA describes the percentage of space that receives "sufficient" sunlight

over the course of a year. For this analysis, "sufficient" is defined as $sDA_{300/50\%}$, meaning the space receives a minimum of 300 lux for at least 50% of the building's operating hours. ASE quantifies the potential for glare and overhearing via excessive direct sunlight. For this analysis, ASE is defined as the percentage of space exceeding 1000 lux for more than 250 occupied hours per year. Spaces are determined to be "regularly occupied" according to the LEED definition of those that when in use, are continuously occupied for approximately one hour or more.

The analysis should use the most up-to-date and thorough .epw weather files available from the weather station closest to the project site. Care should be taken to ensure the accurate representation of visible light transmittance (VLT) for all glass elements and reflectance for all opaque (non-glass) elements. VLT is a metric expressed on a scale from 0% to 100% measuring the percentage of visible light that can pass through glazing. In the context of daylight, reflectance is a metric measuring the percentage of incident visible light reflected back by a material surface rather than absorbed. In the absence of detailed information on the reflectivity of ceiling, wall and floor finishes, the standard industry assumptions shown in Table 17 can be assumed as recommended in the IES Lighting Handbook (DiLaura et al., 2011).

Table 17 – Default Surface Light Reflectance Values (DiLaura et al., 2011)

Surface	Default Reflectance
Ceilings	80%
Walls	50%
Floors	20%

Neighboring buildings or other obstructions of significant size and proximity to potentially impact shading should be modeled using simple geometric shapes. At a minimum, this is to include adjacent objects with a height greater than the distance from the building under consideration for daylight analysis. Surface reflectance of these shapes may be set to 50% to match the Walls default. Additionally, a ground plane should be modeled following the guidance shown in Figure 31 (note imperial units may need to be converted to metric). In the absence of reflectance data for the surrounding paving materials, a default reflectance of 20% can be assumed for the ground plane matching the default floor value.

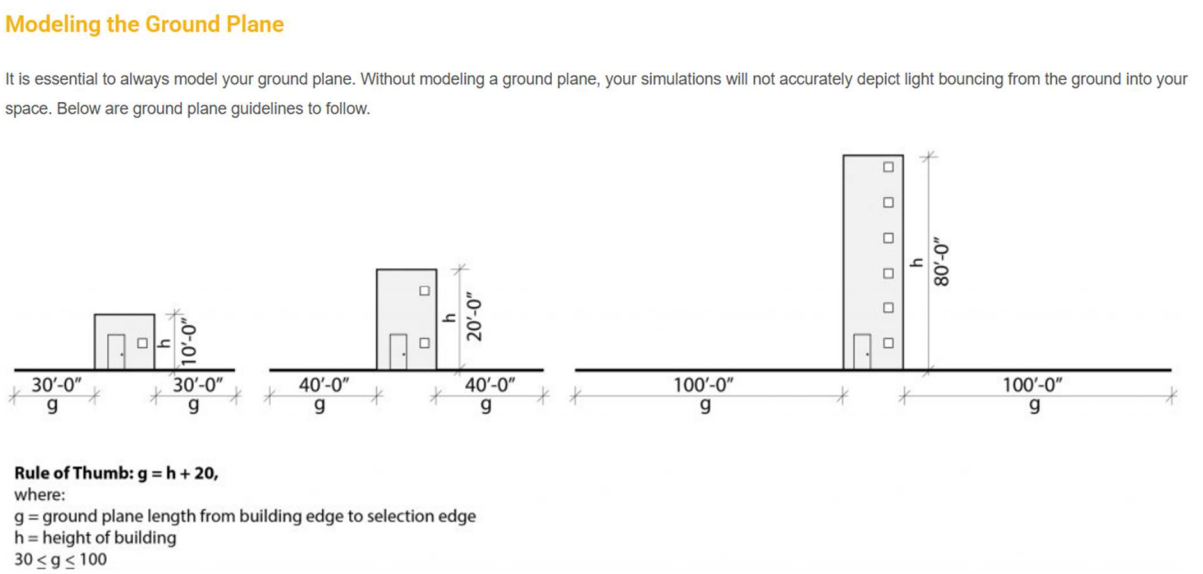


Figure 31 – Daylight Simulation Ground Plane Modeling Guidance (LightStanza, n.d.-a)

The assessment score is based on the sDA result as shown in Table 18 with the prerequisite of maintaining an overall average ASE below 20% to earn a score above 0. The scale is established by mapping the performance class thresholds for IEQ, governed by NEB-B, (see Figure 45) onto the LEED thresholds stipulated in EQc2 – Option 5, PATH 4. Daylight simulation under B.4.2 has less thresholds than LEED, but they align directly. Linear interpolation is permitted for sDA values between listed thresholds.

Table 18 – Daylight Simulation Scoring Thresholds;
Adapted from L06: Daylight Simulation (IWBI, 2025) and EQc2: Occupant Experience (USGBC, 2025)

NEB sDA Threshold	LEED sDA Threshold	Assessment Score
0	0	0
-	≥ 40%	40
≥ 55%	≥ 55%	65
-	≥ 65%	85
≥ 75%	≥ 75%	100

The next phase of the analysis reviews design strategies related to daylight and lighting comfort, covering glazing and shading. To earn any points for the glazing portion of this assessment, all glazing serving regularly occupied spaces must be confirmed to have a minimum VLT of 40%. With this confirmed, level of achievement is based on the ratio of total envelope glazing to regularly occupied floor area in the project. Regarding shading, all glazing serving regularly occupied spaces must have shading devices to earn any points. Level of achievement is determined by whether this shading is manually operable or automated to prevent glare. The converted score for these assessments is based on the NEB-SAM score for each threshold relative to the maximum possible score for the assessment as depicted in Table 19.

Table 19 – Daylight Design Strategies Scoring Thresholds;
Adapted from L05: Daylight Design Strategies (IWBI, 2025)

Envelope Glazing : Regularly Occupied Floor Area	Type of Shading	NEB-SAM Score	Converted Score
≥ 15%	Manual	5.0 / 7.5	67
≥ 25%	Automatic	7.5 / 7.5	100

Finally, a pass-fail check (worth 0 or 100 points) for manually operable or automatic glare control devices at all glazing serving regularly occupied spaces is conducted, carrying 20% weight in the LEED-side score integration.

3.4.2. THERMAL COMFORT

B.4.3 links to features from the WELLv2 healthy building standard under the Thermal Comfort concept. Those directly relevant to deep building renovation have been extracted and adapted for THRIVE integrated measure IEQ2. These consist of a PMV- or adaptive method-based compliance check for thermal comfort in both heating and cooling mode, an assessment of zoning and thermal comfort control, implementation checks for radiant thermal comfort solutions, and assessment of humidity control parameters. For EQc2 alignment, compliance with ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy is assessed via the same procedure as the PMV/adaptive method compliance check.

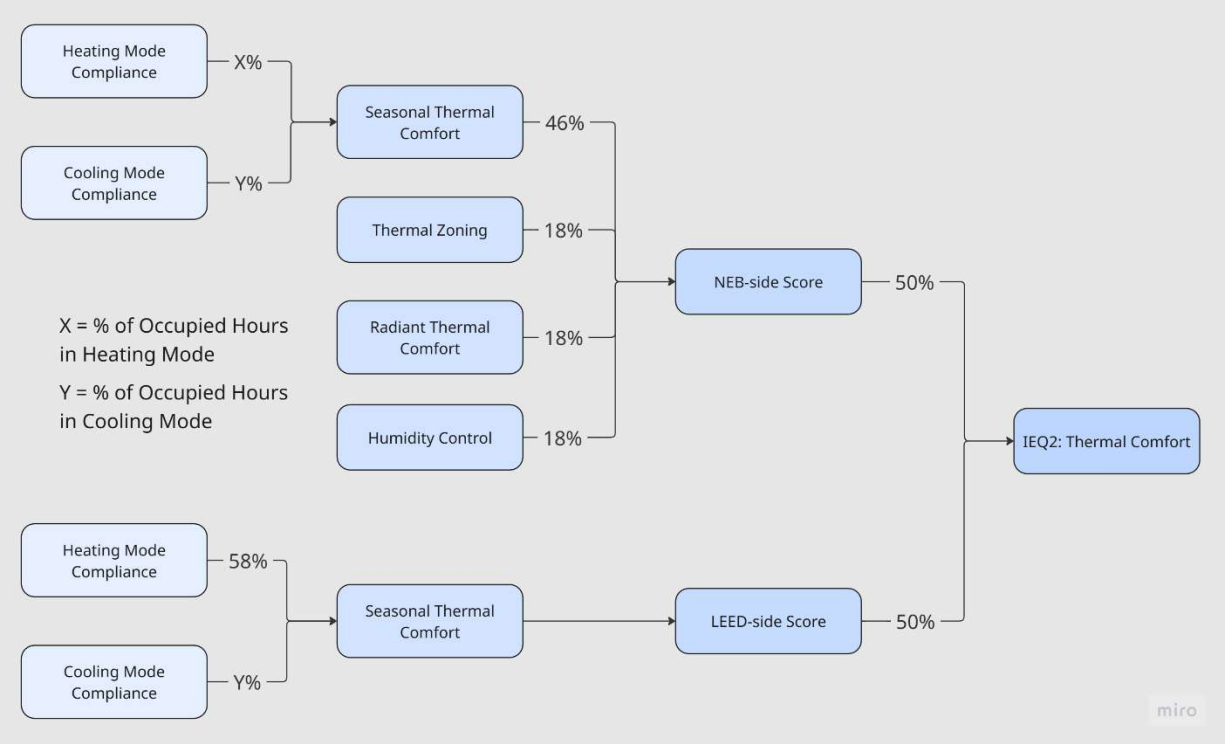


Figure 32 – Integration Flowchart and Weighting for IEQ2: Thermal Comfort (created with Miro)

To help normalize across different climates, weighting for compliance with heating and cooling mode thermal comfort is determined by the percentage of occupied time the building is designed to operate in each mode. For naturally conditioned spaces, this translates to percentage of occupied time during summer vs winter conditions. Weighting for each assessment within the NEB-side score is determined by the fraction of points it contributes to B.4.3 over the sum of points for all assessments considered for IEQ2, highlighted in Figure 33. Note that "T08 Enhanced Operable Windows" is not included to avoid double-counting as THRIVE addresses the topic of operable windows under the Resilience, Aesthetics, and Inclusiveness analysis block.

Metric	**Score**
Select single value below:	
The project does not comply with any of the following WELL v2 (IWBI, 2020) criteria.	B.4.3 = 0. No further points to be added.
The project complies with the following WELL v2 criteria	*Check next metrics.*
WELL v2 criteria (multiple selections allowed):	
T01 Thermal performance – Part 1	+40
T03 Thermal zoning	+15
T05 Radiant thermal comfort	+15
T07 Humidity control	+15
T08 Enhanced operable windows	+15
T09 Outdoor thermal comfort – Part 1	+15
Indicator score = Σ(metric scores)	**≤ 100**

Figure 33 – B.4.3 Indicator Scoring; Adapted from (Lourenco et al., 2024)

The seasonal thermal comfort assessment confirms compliance with ASHRAE Standard 55-2023 for all occupied interior spaces (storage and MEP equipment rooms may be excluded), in both winter (heating mode) and summer (cooling mode) conditions. This assessment follows the PMV method for mechanically conditioned spaces and the adaptive method for naturally conditioned spaces. Mechanically conditioned spaces should maintain thermal comfort conditions of PMV +/- 0.5 for at least 90% of occupied hours. Naturally conditioned spaces should meet the conditions detailed in Table 20.

Table 20 – Thermal Comfort Requirements for Naturally Conditioned Spaces; Adapted from T01: Thermal Performance (IWBI, 2025)

	Prevailing Mean Outdoor Temperature, $t_{pma(out)}$	**Indoor Operative Temperature**
Minimum	10.0°C / 50.0°F	$t_{pma(out)}$ × 0.31 + 14.3°C $t_{pma(out)}$ × 0.31 + 47.9°F
Maximum*	33.3°C / 92.0°F	$t_{pma(out)}$ × 0.31 + 21.3°C $t_{pma(out)}$ × 0.31 + 60.5°F

*Occupant-controlled elevated air speed may be used to increase this maximum per ASHRAE 55

Studies have shown mean radiant temperature to be essentially the same as the dry-bulb temperature across a range of evaluations using globe and infrared measured surface temperatures (Int-Hout; Dan, 2014). Therefore, in the absence of detailed data design regarding radiant temperature, operative temperature may be assumed to be equal to dry-bulb temperature for the purpose of these calculations. When following the PMV method, reasonable assumptions can be made regarding the activity level (and corresponding metabolic rate) and clothing level of occupants based on project climate, building typology, and space function. The 0-100 score for these assessments corresponds to the percent of regularly occupied spaces compliant for heating and cooling mode.

For the thermal zoning assessment, the project must first meet the prerequisite of providing temperature control devices in at least 90% of all regularly occupied spaces (as defined in Section 3.4.1). Furthermore, the maximum size of each thermal zone is not to exceed 60 m^2 (650 ft^2) or 10 occupants, whichever allows a larger zone, for at least 90% of all zones serving regularly occupied spaces. Failing to meet these prerequisites results in an assessment score of 0. Once met, assessment score is determined based on the thresholds in Table 21 for the total number of thermal zones serving regularly occupied space. Linear interpolation is permitted for a number of zones between the listed thresholds.

Table 21 – Thermal Zoning Scoring Thresholds; Adapted from T03: Thermal Zoning (IWBI, 2025)

Number of Zones		**Number of Zones**	**Converted Score**
One per 60 m^2 One per 650 ft^2	OR	One per 10 occupants	50
One per 30 m^2 One per 320 ft^2	OR	One per 5 occupants	100

The radiant thermal comfort assessment awards projects for the implementation of radiant heating and cooling systems through radiant ceilings, walls, or floors (or panels covering a majority of these surfaces). Studies have shown occupants have a 50% chance of experiencing a higher temperature satisfaction rating in spaces with radiant systems, compared to conventional "all-air" systems (Karmann et al., 2017). Installing radiant systems as described above to condition at least 50% of all regularly occupied floor area with either heating **OR** cooling translates to an assessment score of **50**, while radiant systems

conditioning at least 50% of all regularly occupied floor area with heating **AND** cooling earns a score of **100**.

The humidity control assessment is a pass/fail check yielding a score of 0 or 100. For projects with mechanical humidity control systems, compliance may be achieved with a system capable of maintaining relative humidity (RH) between 30%-60% at all times in all regularly occupied spaces, verified by the design engineer or performance testing. Alternatively, any project may comply via humidity modeling or sensor data showing RH levels between 30%-60% in all regularly occupied spaces for at least 98% of hours in which the building is in use throughout the year.

3.4.3. INDOOR AIR QUALITY

The IAQ analysis consists of a comparative assessment of air pollutant concentration levels rooted in the NEB-SAM, as well as LEEDv5-based checks on filtration, entryway systems, ventilation rates, and additional pollutant design limits. Represented in Figure 34, the assessments based on prerequisite compliance with LEEDv5 EQp2 (Entryway Systems, Filtration, Ventilation) are weighted double compared to those based on compliance with the voluntary EQc1 credit (Enhanced Ventilation, Pollutant Design Limits).

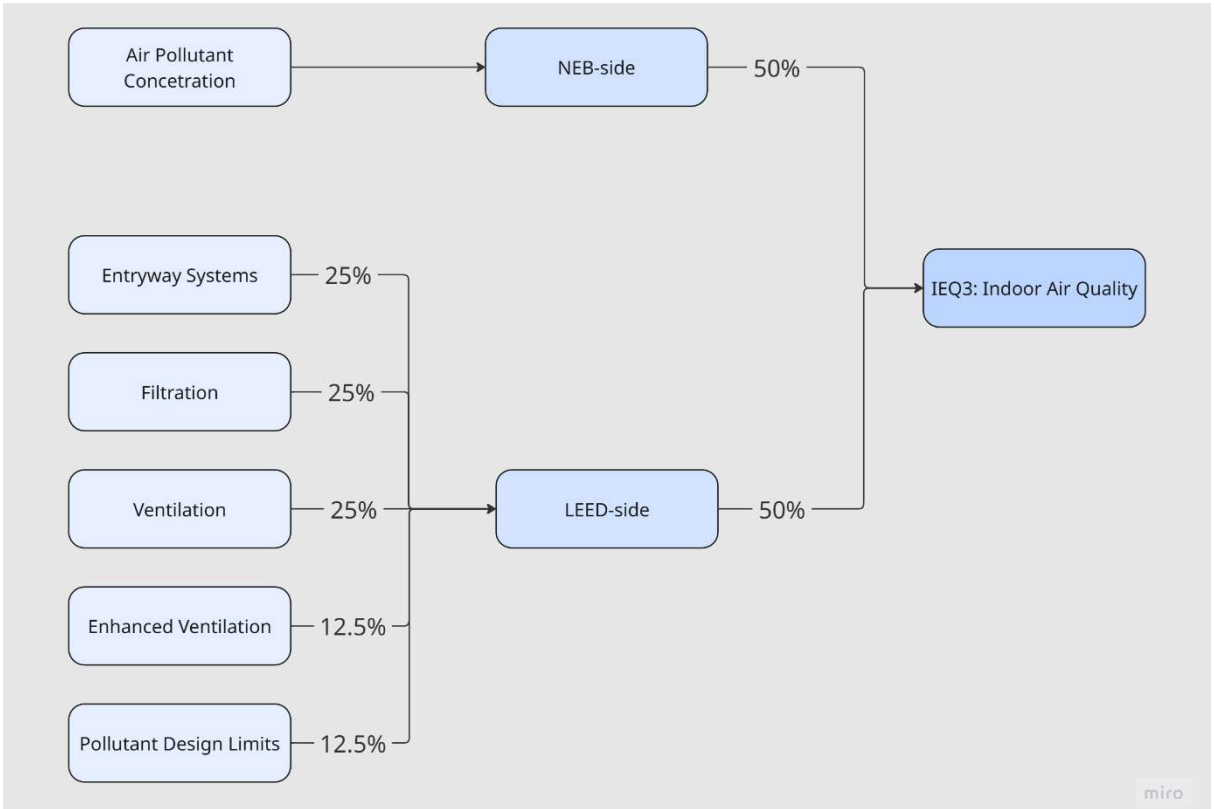


Figure 34 – Integration Flowchart and Weighting for IEQ3: Indoor Air Quality (created with Miro)

At a minimum, Air Pollutant Concentration must consider CO2. Further pollutants (e.g. VOC, formaldehyde) may be considered based on available data and project priorities. Baseline pollutant concentration metrics should be taken as the maximum concentration from measurements taken pre-renovation. The measurements should cover at least full-year of building operation. Per S.5.1, a typical baseline metric for CO2 concentration is 1000 parts per million (ppm), which may be used as an

alternative to pre-renovation measurements. The baseline is evaluated against the maximum projected or measured post-renovation concentration level for each considered pollutant to determine percentage improvement as shown in (Eq. 17).

$$\%\ Improvement = \frac{C_b - C_p}{C_b} * 100 \quad \text{(Eq. 17)}$$

$C_b =$ Baseline pollutant concentration

$C_p =$ Projected or measured pollutant concentration

This percentage then converted into a "pollutant score" on a scale established by translating the NEB-SAM building-scale indicator performance class thresholds for "Renovation - Non-residential" under S.5 (See Figure 35) to those for THRIVE IEQ, governed by NEB-B (See Figure 45). Pollutant score is determined via
Table 22 with linear interpolation permitted.

Performance class:	Low	Acceptable	Good	Excellent
S.5 thresholds ($t_{S.5}$):	$0 \leq$	$t_{S.5,\ Acceptable}$	$t_{S.5,\ Good}$	$t_{S.5,\ Excellent}$ ≤ 100
Newbuild - Residential		≥ 5	≥ 10	≥ 35
Newbuild - Non-residential		≥ 5	≥ 15	≥ 35
Renovation - Residential		≥ 5	≥ 10	≥ 35
Renovation - Non-residential		≥ 5	≥ 15	≥ 35

Figure 35 – S.5 Building-Scale Performance Class Thresholds (Lourenco et al., 2024)

Table 22 – Air Pollutant Scoring; Adapted from (Lourenco et al., 2024)

% Improvement	Pollutant Score
≤ 0%	0
5%	40
15%	60
35%	80
100%	100

In cases where only CO2 is considered, the 0-100 score for the assessment directly corresponds to the pollutant score. Where other pollutants are considered, the final score is an average with each pollutant weighted equally, per (Eq. 18).

$$S_{APC} = \frac{1}{N}\sum_{i=1}^{N} S_{p,i} \quad \text{(Eq. 18)}$$

$S_{APC} =$ Air Pollutant Concentration assessment score

$S_p =$ Pollutant score

$N =$ Number of assessed pollutants

The Entryway Systems score corresponds to the percentage of primary building entrances that have permanently installed entryway systems (e.g. walk-off mats) within the building to capture dirt and particulates.

Filtration is assessed via review of filter quality at each HVAC system that supplies outdoor air and/or recirculated air to regularly occupied spaces. Filters can comply via the filtration media class as defined by ISO 16890-2016, Particulate Air Filters for General Ventilation — Determination of the Filtration Performance, or the minimum efficiency reporting value (MERV) rating of filters. The score of this assessment corresponds to the percent of pertinent HVAC systems meeting the filter criteria in Table 23.

Table 23 – Filtration Compliance Criteria; Defined in EQp2: Fundamental Air Quality (USGBC, 2025)

Filtration Media Class	MERV Rating
ePM1 50%	13

Alternatively, an HVAC system not meeting these thresholds may show compliance via testing for effectiveness and safety per ASHRAE Standard 241-2023, Section 7.4, and Normative Appendix A (ASHRAE, 2023), or through the installation of in-room air cleaning systems in every regularly occupied space served by the HVAC system. For projects without mechanical ventilation, the Filtration score may be taken as 100 provided an investigation of outdoor air quality proves compliance with regional requirements for natural ventilation.

Ventilation is scored on the percentage of HVAC systems compliant with minimum ventilation rates established by ASHRAE Standard 62.1-2022, Section 6 (ASHRAE, 2022). These minimums may be calculated with the ventilation rate procedure (VRP), the IAQ procedure, the natural ventilation procedure, or a combination thereof. For Enhanced Ventilation, exceeding the minimum outdoor air ventilation rates for all HVAC systems serving > 5% of all regularly occupied spaces translates to a score on the scale established by Table 24, with linear interpolation permitted for intermediate values.

Table 24 – Enhanced Ventilation Scoring; Adapted from EQc1: Enhanced Air Quality (USGBC, 2025)

Provided Outdoor Air Intake	Enhanced Ventilation Score
≤ Minimum Ventilation Rate	0
+ 15%	50
+ 30%	100

The Pollutant Design Limits assessment is scored on the number of pollutants listed in Table 25 that do not exceed the corresponding limits as defined by EQc1, per Table 26. Compliance may be shown via system specifications or post-renovation measurements.

Table 25 - Additional Pollutant Design Limits; Defined in EQc1: Enhanced Air Quality (USGBC, 2025)

Design Compound or PM2.5	Enhanced IAQ Design Limit
PM2.5	10 µg/m^3
Formaldehyde	20 µg/m^3
Ozone	10 ppb*

*Note: ppb = parts per billion

Table 26 - Pollutant Design Limits Scoring Thresholds

# of Compounds Meeting Design Limit	Score
0	0
1	33
2	67
3	100

3.5. RESILIENCE, AESTHETICS, & INCLUSIVENESS

The integrated measures forming this analysis block are inspired by the guiding framework indicators and credits shown in Table 27, grouped by alignment.

Table 27 – Integrated Measure Composition for RAI; Adapted from (Lourenco et al., 2024; USGBC, 2025)

Integrated Measure	Weight	NEB-SAM	LEEDv5 BD+C
RAI1 – Hazard Resilience	40%	B.3.2 - Hazard Resilient Design	EQc4 - Resilient Spaces; Option 4
RAI2 – Visual Experience	35%	B.7.1 - Visual Experience of Architecture and Space	EQc2 - Occupant Experience; Option 1, PATH 2
RAI3 – Equitable Accessibility	25%	B.5.1 - Ease of Circulation	EQc3 - Accessibility and Inclusion
		B.5.2 - Safe Wayfinding	

Hazard Resilience

The Hazard Resilience measure encompasses the assessment of strategies to protect against primary forces of nature, selected from among B.3.2 and EQc4 pathways deemed most relevant to envelope-focused deep renovation projects. Three B.3.2 assessments covering envelope-centric resilience to different natural elements are supplemented by an EQc4-based assessment (Operable Windows) promoting adaptability, with each having equal weight.

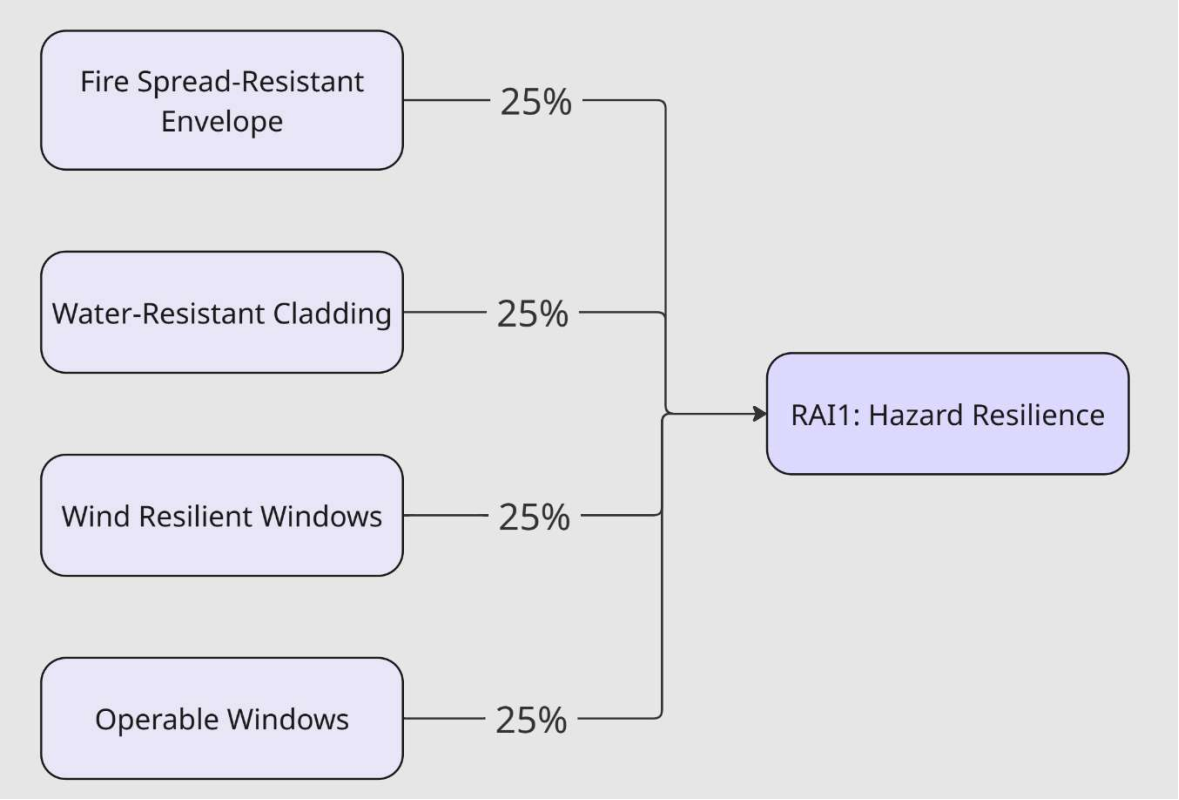


Figure 36 – Integrated Flowchart and Weighting for RAI1: Hazard Resilience (created with Miro)

Fire Spread-Resistant Envelope is based on compliance with the UK Department for Levelling Up, Housing & Communities (DLUHC) statutory guidance on fire safety: Approved Document B (HM Government, 2019). Specifically, Section 10(12): Resisting fire spread over external walls (see Figure 37)

and Section 12(14): Resisting fire spread over roof coverings (see Figure 38). Note the section number varies whether using volume 1: Dwellings or (volume 2: Buildings other than dwellings). The 0-100 score is equal to the percentage of combined wall and roof area meeting the applicable fire spread criteria. Specifically, at a minimum, the applicable criteria shown in the following figures must be met for the outmost layer of the envelope assembly to be considered "fire-resistant". Consult (HM Government, 2019) for additional notes.

Building type	Building height	Less than 1000mm from the relevant boundary	1000mm or more from the relevant boundary
'Relevant buildings' as defined in regulation 7(4) (see paragraph 12.15)		Class A2-s1, d0[1] or better	Class A2-s1, d0[1] or better
All 'residential' purpose groups (purpose groups 1 and 2)	More than 11m	Class A2-s1, d0[2] or better	Class A2-s1, d0[2] or better
	11m or less	Class B-s3, d2[2] or better	No provisions
Assembly and recreation	More than 18m	Class B-s3, d2[2] or better	From ground level to 18m: class C-s3, d2[3] or better
			From 18m in height and above: class B-s3, d2[2] or better
	18m or less	Class B-s3, d2[2] or better	Up to 10m above ground level: class C-s3, d2[3] or better
			Up to 10m above a roof or any part of the building to which the public have access: class C-s3, d2[3] or better[4]
			From 10m in height and above: no minimum performance
Any other building	More than 18m	Class B-s3, d2[2] or better	From ground level to 18m: class C-s3, d2[3] or better
			From 18m in height and above: class B-s3, d2[2] or better
	18m or less	Class B-s3, d2[2] or better	No provisions

Figure 37 – Wall External Surface Requirements for Fire Spread (HM Government, 2019)

Designation[1] of covering of roof or part of roof	Distance from any point on relevant boundary			
	Less than 6m	At least 6m	At least 12m	At least 20m
BROOF(t4)	●	●	●	●
CROOF(t4)	○	●	●	●
DROOF(t4)	○	●[2][3]	●[2]	●
EROOF(t4)	○	●[2][3]	●[2]	●[2]
FROOF(t4)	○	○	○	●[2][3]

● Acceptable. ○ Not acceptable.

Figure 38 – Roof Covering Requirements for Fire Spread (HM Government, 2019)

Water-Resistant Cladding supports resilience against flooding and other heavy-rainfall events. This assessment considers the material selection for the outermost layer of the building facades and its innate ability to limit water ingress. The 0-100 score is equal to the percentage of façade surface area with an outer layer constructed of low-absorption, flood-resistant material or assemblies detailed to limit water penetration. This can be met through any of the following listed criteria. Alternative compliance methods

may be submitted with a justification of the water-resistance of the outer layer based on guidance from the British Standard BS 85500 (British Standards Institution (BSI), 2025)on flood resilient construction.

- Cladding made of concrete or rendered masonry.
- ETICS with closed-cell insulation or insulation otherwise rated as flood-resistance via third party verification.
- Dense, non-porous external panels (e.g. metal, HPL, fiber-cement) that are fixed and sealed to prevent significant water ingress.

Wind Resilient Windows supports mindful selection of window systems with wind resistance ratings that meet or exceed the requirements governed by the project's design wind pressures. Compliant window systems must have their wind rating verified by a third party standard and testing regime locally or globally recognized within the construction industry. The 0-100 score is equal to the percentage of compliant windows.

Operable windows provide valuable access to outdoor air during heat waves or localized power outages, protecting occupant health and comfort. The 0-100 score for this assessment equals the percentage of windows on the project that can be manually opened and closed or are automated with a manual override which occupants can use as desired.

Visual Experience

With aesthetic considerations of the building itself being unique to the NEB-SAM as a guiding framework, the Visual Experience integrated measure is primarily structured around NEB-SAM indicator B.7.1, supplemented in small part by the Quality Views criteria under LEEDv5 credit EQc2. B.7.1 is comprised of two metrics, visual richness and attractiveness of circulation. Considering the inherently limited impact of envelope and energy renovations to circulation, only visual richness is adapted for THRIVE. Visual richness is evaluated as the weighted average of four sub-metrics, each serving as a THRIVE assessment as shown in Figure 39 with weights matching those stipulated by B.7.1.

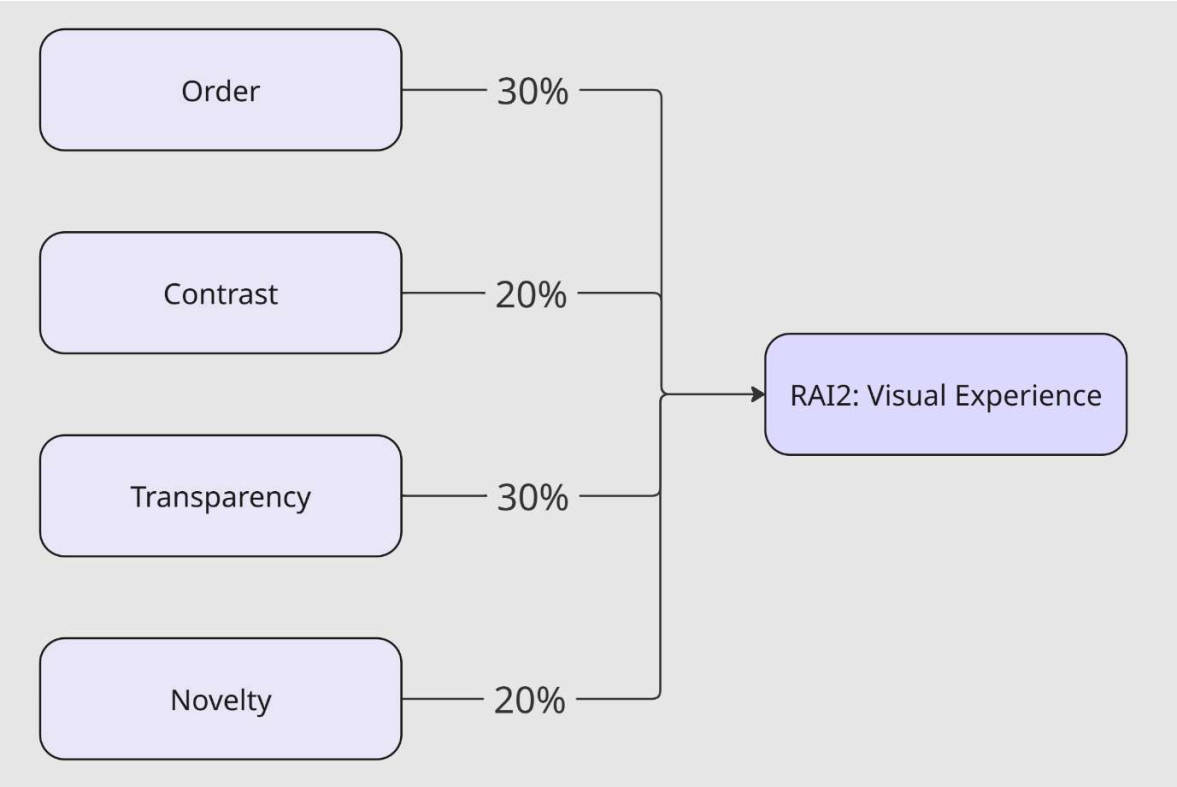


Figure 39 – Integrated Flowchart and Weighting for RAI2: Visual Experience (created with Miro)

Order consists of four principles: axis composition, hierarchy, transformation, and rhythm/repetition, exemplified in Figure 40. Full NEB definitions of each principle can be found in Annex A.7. The presence of each principle is worth 25 points towards the 0-100 assessment score.

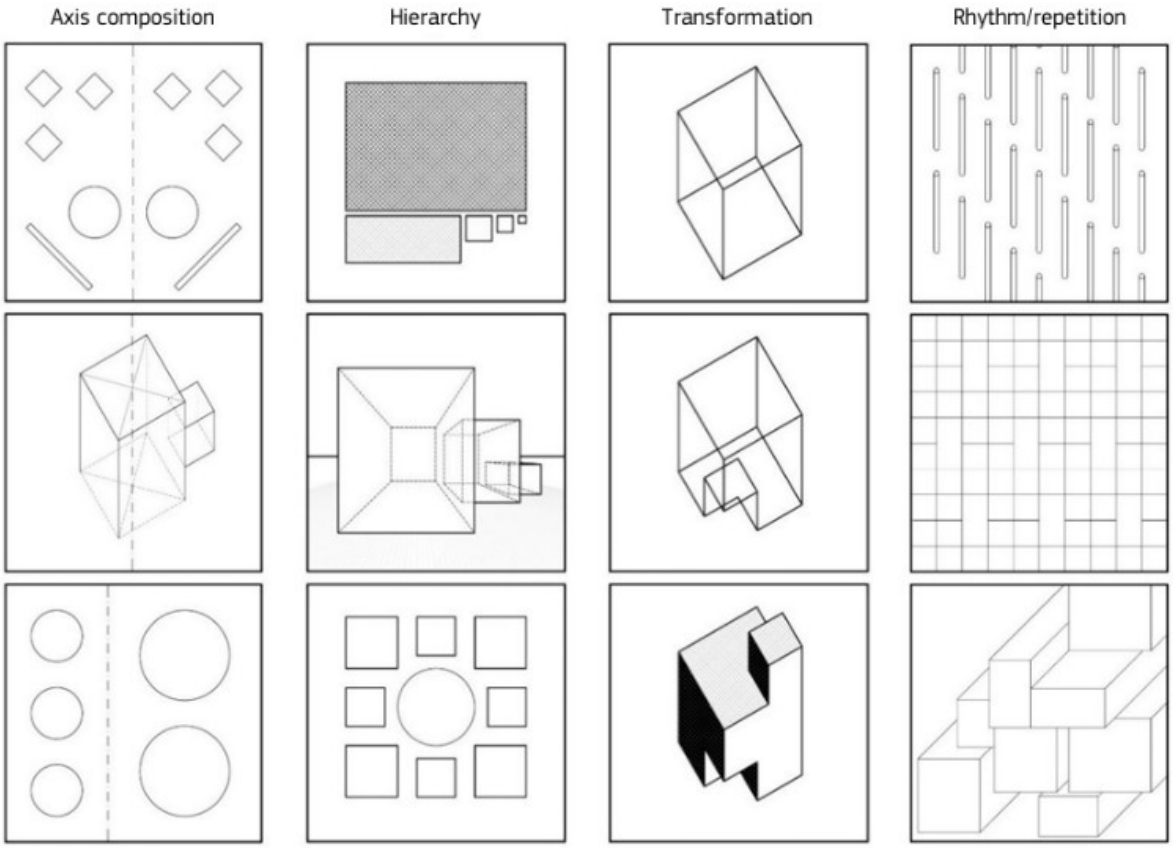


Figure 40 – Examples of the Four Order Principles for Visual Richness (Lourenco et al., 2024)

Contrast assumes the inclusion of contrast as a positive factor enhancing the experience of pleasure in the perception of architecture and space. Similar to Order, this assessment measures the inclusion of four principles exemplified in Figure 41, each worth 25 points towards the 0-100 assessment score: massing (e.g. 'light' and 'heavy' volumes), lines & spaces, surfaces & apertures, (e.g. light and dark surfaces), and materials. Supporting definitions for each principle can be found in Annex A.7.

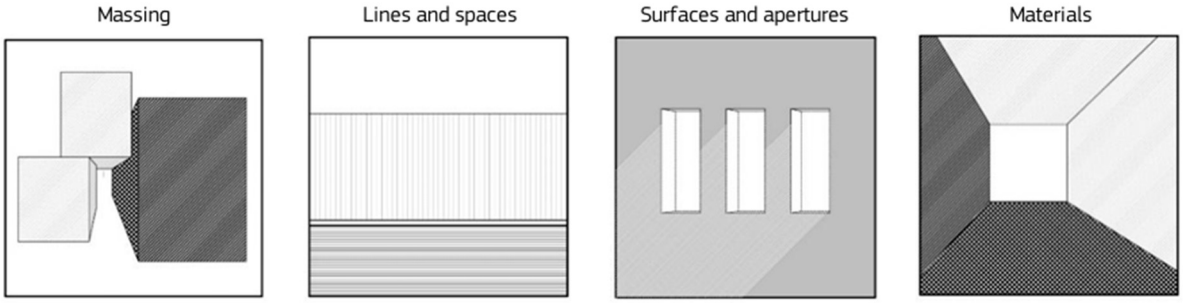


Figure 41 – Examples of the four Contrast Principles for Visual Richness (Lourenco et al., 2024)

Transparency, in the context of envelope-focused deep energy renovations, relies on the ability of façade glazing to facilitate interior-exterior visual interaction and provide views of the surrounding landscape, as well as the façade as a whole to optimize the effects of light and shadow. B.7.1 again addresses transparency via four principles exemplified in Figure 42. Compliance with each of the four principles contributes 25 points towards the 0-100 assessment score for Transparency.

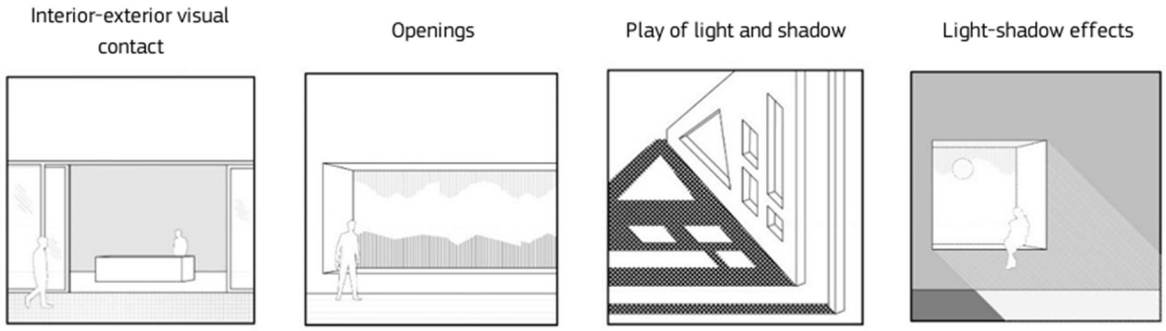


Figure 42 – Examples of the four Transparency Principles for Visual Richness (Lourenco et al., 2024)

Interior-exterior visual contact reviews for the presence of transparent ground-floor glazing to promote openness and interaction. Openings awards the presence of quality views for building occupants by proving openings towards surrounding natural areas, such as greenery, water reservoirs, fields, meadows, hills, etc. Alternatively, projects in completely urban areas with no surrounding natural landscape may claim compliance with this requirement if:

- Every floor of the building has transparent openings on at least two opposite facades.
- These openings provide views to sky, urban landmarks, art, or other objects of visual interest located at least 7.5m away from the exterior of the glazing.

Play of light and shadow is demonstrated through an envelope designed to allow the sun and sky to produce changing patterns of brightness and shade that articulate form, material and depth over time. Some strategies to achieve this effect include deep reveals and frames around openings, vertical fins and side screens, and layered, perforated, or otherwise textured cladding. Additional strategies may be proposed with supporting narrative and visual evidence provided by the design team.

Light-shadow effect checks for the presence of strategies to modulate incident sunlight at the interior of the façade, supporting visual comfort for building occupants. Strategies to achieve this effect include recessed or protruding panels around glazing, overhangs, fins, and shading with perforated or slated elements. Additional strategies may be proposed with supporting narrative and visual evidence provided by the design team.

Novelty promotes innovation and exploration beyond established architectural norms. Two principles comprise this assessment, the first being the expression of novelty through **meaningful artwork** integrated into the project, and the second the use of **aesthetic pioneering solutions**. Pioneering solutions in aesthetics can include, for example, the use of structures that result from visionary construction systems, the application of completely new materials (structural, decorative, other) or known materials in unobvious, surprising ways, the incorporation of scientific achievements or the latest socio-cultural trends in the shaping of architectural and urban forms (Lourenco et al., 2024).

As these principles are particularly abstract and variable project-to-project, methods of compliance should be uniquely presented and justified with a supporting narrative by the design team. The presence of each principle is worth 50 points towards the 0-100 assessment score for Novelty. Projects in which there is no interiors or landscape architecture scope to facilitate the inclusion of artwork alternatively may be exempt from meaningful artwork and carry all 100 points through aesthetic pioneering solutions.

Equitable Accessibility

The Equitable Accessibility measure seeks to evaluate the extent to which the project design provides ease of physical access and promotes widespread usability to a diverse range of potential occupants. Within the context of envelope-forward deep renovations, THRIVE addresses this measure through the assessment of building entrances and where applicable, signage and wayfinding. It is understood that signage can often fall outside the scope of deep renovation projects, therefore the sign-related assessments are optional. Projects may pursue these assessments if the addition of signage is within the project scope or the building has existing signage sufficient to deliver a score. The weight of each assessment for this measure is equally distributed according to the total number of assessments pursued.

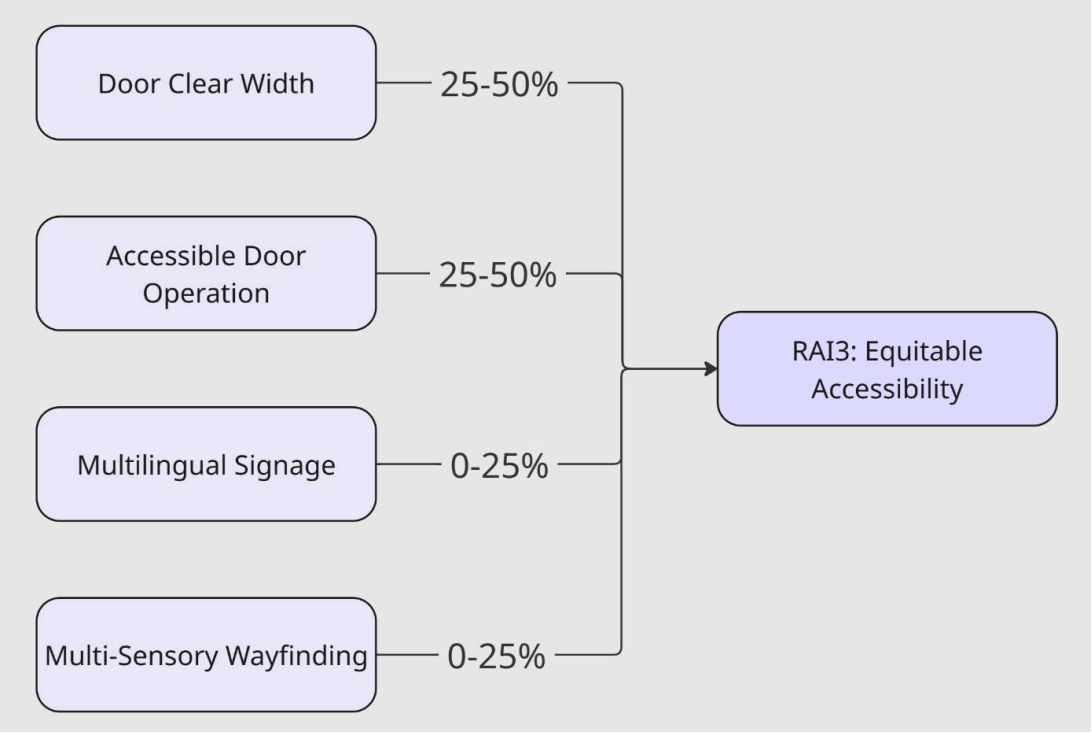


Figure 43 – Integrated Flowchart and Weighting for RAI3: Equitable Accessibility (created with Miro)

Per B.5.1, all main exterior entrance doors of the project, as well as their associated interior entrance lobby doors, if applicable, will be checked against a minimum clear width of 1.0 m. The 0-100 score for Door Clear Width corresponds to the percentage of doors compliant. Per EQc3, all main exterior entrance doors will also be reviewed for accessible means of operation, including wave-to-open, vertical hand press, or foot press features. The 0-100 score for Accessible Door Operation corresponds to the percentage of applicable doors with at least one of these features. Multilingual Signage should only be pursued by projects located in regions where multiple languages are spoken by more than 5% of the local population. In such cases, the 0-100 score for this assessment corresponds to the percentage of signs presented in all languages spoken by >5% of the local population. Signs that communicate only the name of a room or space with no further information may be excluded. Multi-Sensory Wayfinding is scored according to the percentage of all wayfinding signage on the project that communicates information in at least two sensory formats, including visual, audible, and tactile. Projects which do not include signage in their scope may omit Multilingual Signage and Multi-Sensory Wayfinding with the weighting for RAI3 equally distributed between the remaining assessments. Existing-to-remain signage may be considered for these assessments, but it must be all or nothing.

3.6. THRIVE INTEGRATED SCORING LOGIC

NEB and LEED represent fundamentally different approaches to sustainability assessment in the built environment. While LEED is a certification system focused strictly on quantifiable performance and awarding levels of certification based on prerequisite and credit compliance, NEB is a policy initiative with supportive tools for assessment but does not award formal certification labels. Thus, the "scoring" methods between the two are quite different, with NEB scoring dependent on the utilized tool (Compass, Self-Assessment Method). In response to the core research question of this MBUILD final dissertation and its associated objectives, the NEB Self-Assessment Method (NEB-SAM) tool is integrated with the LEEDv5 BD+C scorecard to produce a scoring logic unique to THRIVE.

As detailed in the previous methodology sections, THRIVE is divided into 4 analysis blocks, each of which contain novel measures developed via the integration of relevant NEB-SAM indicators and LEEDv5 credits and prerequisites. Following a similar workflow outlined in the NEB-SAM, each analysis block receives a block score based on the weighted results of the integrated measures within the block, which in turn receive their score based on the weighted results of individual assessments within the measure. The blocks are also assigned weights and aggregated into a project-level THRIVE score.

The integrated measure weights have been determined via a multi-step calculation procedure. First, the full lists of KPI and indicators from the NEB-SAM, with assigned weights, are filtered to include only those serving THRIVE. In cases where not all of the indicators under a given KPI contribute to THRIVE, the weighting is proportionately redistributed to the remaining indicators per (Eq. 19). See Table 28 for an example in which S.1.3 is outside the scope of THRIVE.

$$w_{a,i} = \frac{w_{o,i}}{\sum_1^K w_{o,i}} \quad \text{(Eq. 19)}$$

$w_{a,i} = Adjusted\ Indicator\ Weight$

$w_{o,i} = Original\ Indicator\ Weight$

$K = number\ of\ indicators\ within\ KPI\ in\ filtered\ list$

Table 28 – Example NEB-SAM Indicator Weighting Redistribution; Adapted from (Lourenco et al., 2024)

KPI	Indicator	Scale, Type, Main Use	NEB-SAM Weight	Adjusted THRIVE Weight
Minimize the use of fossil fuels in the built environment (S.1)	Primary energy demand (S.1.1)	Building, Renovation, Non-residential	0.500	0.667
	Electricity peak demand (S.1.2)		0.250	0.333
	Smart readiness (S.1.3)		0.250	-

Next, adjusted KPI weights are determined based on their originally assigned weights and the total number remaining in the filtered list as shown in (Eq. 20). These adjusted KPI weights are then used to determine the weight of individual indicators within the entire dimension as shown in (Eq. 21). To maintain the NEB-SAM intention of keeping dimensions separate, the weights are not further aggregated at this stage. As THRIVE does not incorporate any indicators from the inclusiveness dimension, this only involves keeping the sustainability and beauty weightings separate.

$$w_{a,k} = \frac{w_{o,k}}{\sum_1^D w_{o,k}} \quad \text{(Eq. 20)}$$

$w_{a,k} = Adjusted\ KPI\ Weight$

$w_{o,k} = Original\ KPI\ Weight$

$D = number\ of\ KPI\ within\ Dimension\ in\ filtered\ list$

$$w_{d,i} = w_{a,k} * w_{a,i} \quad \text{(Eq. 21)}$$

$w_{d,i} = Dimension\text{-}level\ Indicator\ Weight$

$w_{a,k} = Adjusted\ KPI\ Weight$

$w_{a,i} = Adjusted\ Indicator\ Weight$

On the LEEDv5 side, the weight of each credit is determined by dividing the possible points available for the credit by the total possible points available from all credits contributing to THRIVE. Some credits include multiple options and pathways for compliance that offer differing numbers of points. In this case, only points available from options and paths contributing to THRIVE are included in the calculations. For example, up to 5 points are available under credit EAc2 – Reduce Peak Thermal Loads; however, only Option 1 – Infiltration and Balanced Ventilation (1 point) and Option 4 – Peak Thermal Load Reductions (1-3 points), contribute to THRIVE integrated measures. Therefore, a maximum of 4 possible points will be considered for this credit. Regarding prerequisites, only those which stipulate a minimum threshold (EAp2, EQp2) are assigned points, excluding MRp2 which only requires measurement and reporting. 1 point is considered for meeting baseline compliance with EAp2, and 2 points for are considered for EQp2 following the logic outlined in Section 3.4.3.

The weighted NEB indicators and LEED credits are then grouped into integrated measures for each analysis block as outlined in the tables in the previous methodology sections. Calculations per (Eq. 22) and (Eq. 23) determine the NEB-side and LEED-side contribution.

$$w_{N,m} = \frac{\sum_1^{N_i} w_{d,i}}{\sum_1^{AB_i} w_{d,i}} \quad \text{(Eq. 22)}$$

$w_{N,m} = NEB\text{-}side\ Integrated\ Measure\ Weight$

$w_{d,i} = Dimension\text{-}level\ Indicator\ Weight$

$N_i = Number\ of\ Indicators\ within\ Integrated\ Measure$

$AB_i = Number\ of\ Indicators\ within\ Analysis\ Block$

$$w_{L,m} = \frac{\sum_1^{N_c} w_c}{\sum_1^{AB_c} w_c} \quad \text{(Eq. 23)}$$

$w_{L,m} = LEED\text{-}side\ Integrated\ Measure\ Weight$

$w_c = Credit\ Weight$

$N_c = Number\ of\ Credits\ within\ Integrated\ Measure$

$AB_c = Number\ of\ Credits\ within\ Analysis\ Block$

The two sides ($w_{N,m}$, $w_{L,m,}$) are averaged to produce the final weight for each integrated measure, shown in Table 30. However, the Embodied Carbon and Indoor Environmental Quality (IEQ) analysis blocks contain NEB-SAM indicators from both the sustainability and beauty dimensions, making it impossible to calculate a single, NEB-side weight. For these blocks, initial weighting is based solely on the LEED-side with the following adjustments.

- Embodied Carbon is adjusted for the addition of Carbon Payback as detailed in the next paragraph.
- Within IEQ, Daylight Access and Thermal Comfort are adjusted based on a weighted average reflecting the equal weight between lighting (B.4.2) and thermal comfort (B.4.3) considered by the NEB-SAM (see Table 29).

Table 29 – Determination of THRIVE Integrated Measure Weighting in IEQ

Integrated Measure	LEED-side Weight	NEB-side Weight	THRIVE Weight
Daylight Access	50.0%	50.0%	40.0%
Thermal Comfort	12.5%	50.0%	22.5%
Indoor Air Quality	37.5%	-	37.5%

Within the Embodied and Operational Carbon analysis blocks, the Carbon Payback measure is assigned a weight of 20%, and the weights of the remaining measures in the blocks proportionately redistributed while maintaining a minimum 50% weight for EC1 and OC1. This distribution respects EC1 and OC1 as the main outcome drivers while providing Carbon Payback a sufficient share to influence design decisions and reinforce the objective of analyzing embodied and operational carbon as a coupled system rather than in isolation.

Table 30 – THRIVE Integrated Measure Weighting per Analysis Block

Analysis Block	Integrated Measure		Weight	
Embodied Carbon	EC1	LCA	50.0%	100%
	EC2	Carbon Payback	20.0%	
	EC3	Circularity & Sourcing	30.0%	
Operational Carbon	OC1	Emissions & Efficiency	50.0%	100%
	OC2	Carbon Payback	20.0%	
	OC3	Peak Demand	12.0%	
	OC4	Renewable Energy	18.0%	
Indoor Environmental Quality	IEQ1	Daylight Access	40.0%	100%
	IEQ2	Thermal Comfort	22.5%	
	IEQ3	Indoor Air Quality	37.5%	
Resilience, Aesthetics, Inclusiveness	RAI1	Hazard Resilience	40.0%	100%
	RAI2	Visual Experience	35.0%	
	RAI3	Equitable Accessibility	25.0%	

An iterative process was followed to determine the weight of each analysis block within the overall THRIVE score. Initial determination of the weight of each block within was calculated via an adjusted average of each block's contribution to the total scores for the NEB sustainability dimension (NEB-S), the NEB beauty dimension (NEB-B), and LEEDv5 - *Iteration 1*. However, for the Embodied Carbon and IEQ blocks, which contain indicators from both NEB-S and NEB-B, this approach over-estimates the impact of NEB as double that of LEED. Thus, the weights for these blocks were adjusted to ensure equal impact between the two guiding frameworks (NEB-S, NEB-B, 2*LEED) - *Iteration 2*. Final adjustments were made according to the following considerations.

- Resilience, Aesthetics, Inclusiveness (RAI) is capped at 20% due to the inherently more qualitative nature and higher uncertainty in many of its assessments. This cap avoids giving interpretive assessments greater weight than the more established and accurately quantifiable assessments in other analysis blocks, while still allowing RAI to have significant influence on the overall score.
- The difference between embodied and operational carbon is slightly reduced while establishing a round 60% total weight for decarbonization performance. The 60% total reflects the strong emphasis LEEDv5 places on decarbonization, assigning it the most credit points of any of its core goals. The 25/35 split reflects state of art findings that operational emissions still dominate the life cycle emissions of most building renovation projects, but the gap is narrowing as energy grids become cleaner and building systems more efficient.
- IEQ is increased to carry equal weight with RAI, guided by NEB ideology that sustainability, beauty, and inclusiveness should be pursued in balance without one dimension overshadowing another. This parity promotes both established metrics for occupant well-being and broader experiential and social qualities without incentivizing trade-offs or steering project teams to prioritize one over the other.

Table 31 – Iterative Determination of THRIVE Analysis Block Weighting

Analysis Block	Iteration 1	Iteration 2	Final
Embodied Carbon	17%	21%	25%
Operational Carbon	42%	38%	35%
Indoor Environmental Quality	14%	17%	20%
Resilience, Aesthetics, Inclusiveness	27%	24%	20%

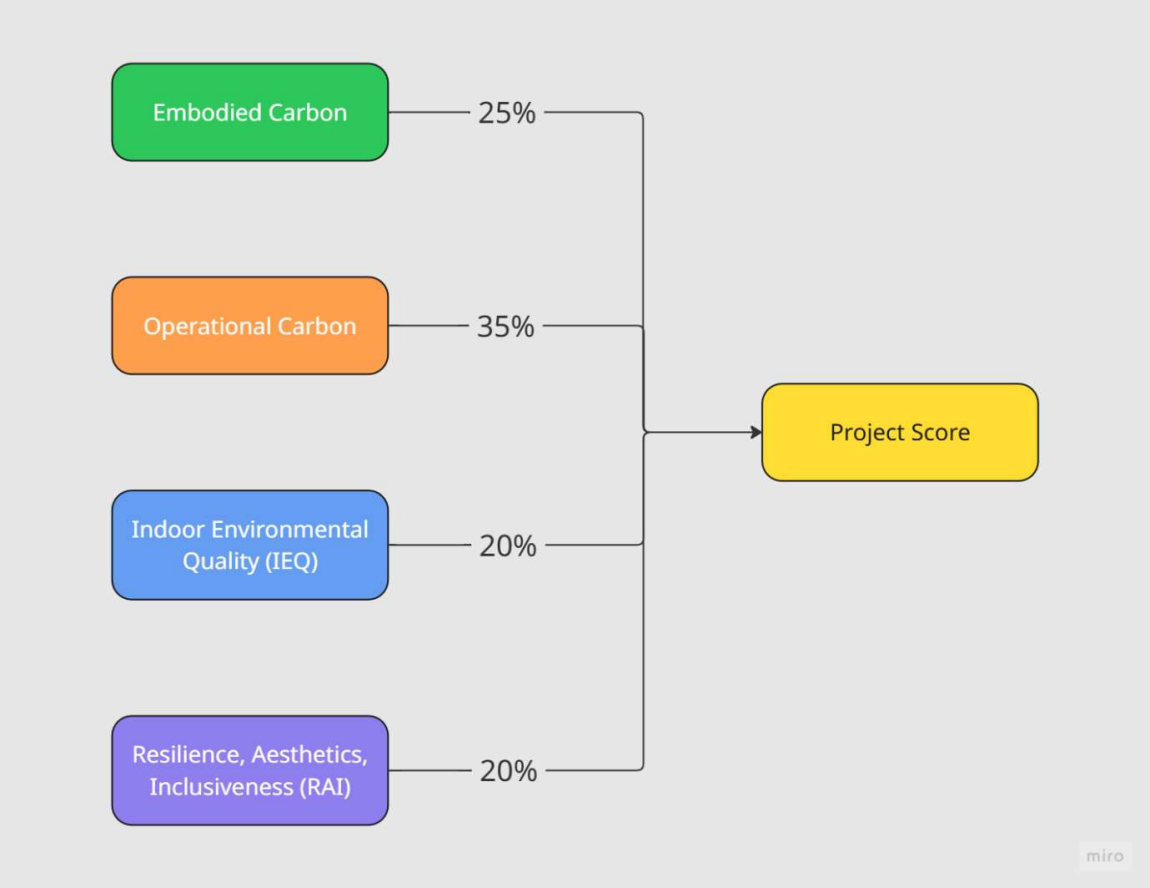


Figure 44 – Analysis Block Weighting for Project Level Score (created with Miro)

The numerical (0-100) THRIVE results for each integrated measure, analysis block, and the overall project are translated to user-friendly performance classes to clearly communicate level of achievement. The four classes (Low, Acceptable, Good, Excellent) and their corresponding thresholds shown in Figure 45 are derived from the NEB-SAM dimension thresholds. From the NEB-side, the Embodied Cabron and Operational Carbon analysis blocks are built primarily on NEB sustainability dimension (NEB-S) indicators, while IEQ and RAI are built primarily on NEB beauty dimension (NEB-B) indicators. Therefore, Embodied Cabron and Operational Carbon, as well as all integrated measures within these blocks, correspond to NEB-S performance class thresholds. IEQ and RAI along with all their integrated measures correspond to NEB-B performance class thresholds. At the project level, THRIVE performance classes are calculated as a weighted average based on the established 60/40 split between decarbonization (NEB-S) and well-being (NEB-B) blocks.

	Low	Acceptable	Good	Excellent
	$0 \leq$	$t_{S,\,Acceptable}$	$t_{S,\,Good}$	$t_{S,\,Excellent}$ ≤ 100
Embodied & Operational Carbon:		≥ 40	≥ 60	≥ 80
IEQ & RAI:		≥ 40	≥ 65	≥ 85
Project-level:		≥ 40	≥ 62	≥ 82

Figure 45 – THRIVE Performance Class Thresholds; Adapted from (Lourenco et al., 2024) with AI

To maintain the NEB intention of not allowing excellence in one dimension to overshadow poor performance in another, the following criteria also apply to the determination of project-level performance class:

- To achieve "Acceptable", at least 3 of the 4 analysis block scores must correspond to "Acceptable" or better.
- To achieve "Good", at least 2 of the 4 analysis block scores must correspond to "Good" or better, with none below "Acceptable".
- To achieve "Excellent", at least 2 of the 4 analysis block scores must correspond to "Excellent", with at least 3 of the 4 corresponding to "Good" or better, and none below "Acceptable".

4

CASE STUDY DEMONSTRATION OF THRIVE

4.1. AEGIR SPAIN DEMO BUILDING – BACKGROUND

For the purposes of this MBUILD final dissertation, the AEGIR Spain building will serve as a case study through which THRIVE is demonstrated. Located just outside of Barcelona in Malgrat de Mar (see Figure 46), it is an existing public school facility for infant and primary education. Constructed in 1970, the building is regularly occupied by students, faculty, and staff throughout the school year. The two-story, flat-roof building has a total gross floor area of roughly 2,660 square meters and is generally rectangular in shape, fragmented by interior and exterior courtyards, with the long faces running northeast to southwest (see Figure 47). The programming layout consists of classrooms, offices, faculty rooms, and a cafeteria on the ground floor with additional classrooms, arts rooms, and a library on the upper level. The climate is coastal Mediterranean, combing mild, wet winters with hot, dry summers. The building is in an urban area, though it does not receive shading from any surrounding structures.



Figure 46 – Case Study Building Geographic Location;
Adapted from (Home - AEGIR, 2022; Jay Arnaud & Astudillo Larraz, 2023) with AI



Figure 47 – Case Study Building; Orientation (Left), Satellite View (Right)

The existing facade consists of uninsulated, 15-centimeter brick over an air chamber and internal partition wall. The roof is also uninsulated and consists of a concrete deck with a ventilated cavity and clay finish. The primary structural system of the building is made of concrete, with aluminum-frame windows built into prefabricated concrete frames. Rooms are heated via gas boilers and radiators, and only manual ventilation is available via operable windows. There is no existing cooling system. As part of the AEGIR renovation, the following updates are to be implemented:

- Industrialized envelope with enhanced bio-based and fabric thermal insulation
- Mechanical ventilation system with smart controls
- Smart windows with automated ventilation
- Upgraded manually operable windows
- Ground source heat pump (GSHP) for efficient heating/cooling
- Roof photovoltaic (PV) and photovoltaic-thermal (PVT) panels to generate electricity and hot water
- Second life battery for energy storage



Figure 48 – Case Study Building (Herrero et al., 2025);
Pre-Renovation Condition (Left), Post-Renovation Rendering (Right)

The envelope renovation consists of three panel typologies applied over the existing structure, depicted in Figure 49. These include the AEGIR modular prefabricated panel, which is applied to 6 facades, an External Thermal Insulation Composite System (ETICS), and ETICS with additional cladding. Furthermore, detailed in Table 32, many of the existing windows will be removed and replaced.

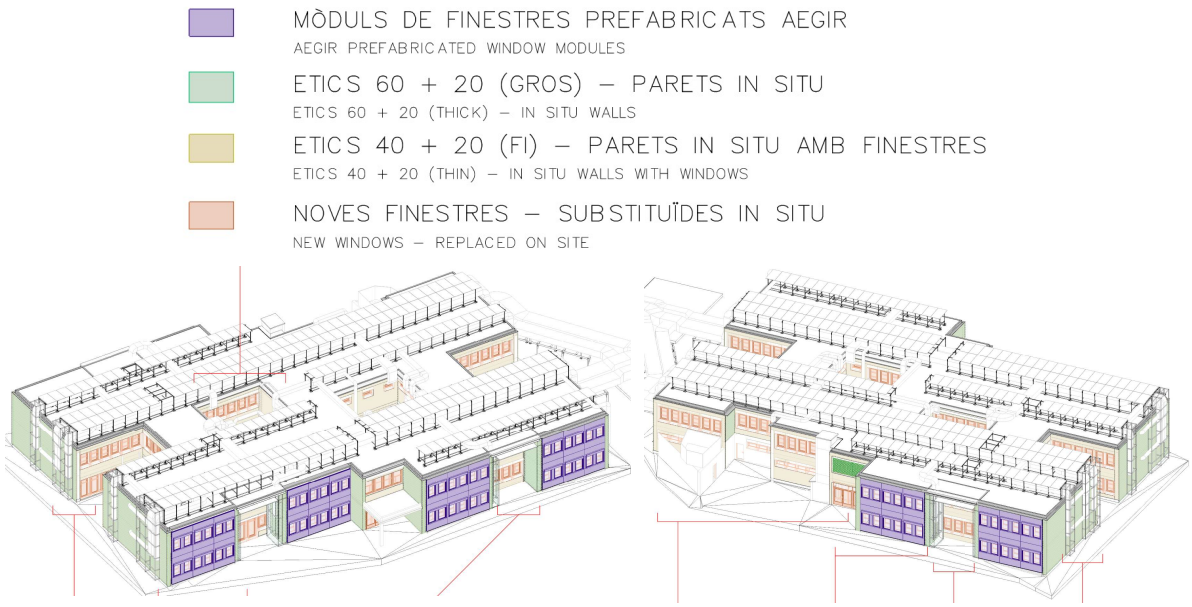


Figure 49 – Panel Typology Distribution; North-facing (Left), South-facing (Right)

The AEGIR facades are comprised of:

- Mineral wool insulation infill, approximately 120mm thick, between the existing brick exterior layer and the new prefabricated facade panel.
- AEGIR self-supporting industrialized sandwich panel:
  - S275 steel structural profiles (first layer = 15mm thick, second layer = 10mm thick)
  - Two 75mm thick wood fiber insulation panels
  - Two 12mm thick oriented strand board (OSB) panels
- Automated Venetian blind integrated into the air gap between the AEGIR panel and the finished surface
- High-pressure laminate (HPL) or composite cladding finishes
- At Windows:
  - New aluminum joinery with thermal break
  - Double glazing with air chamber
  - Exterior venetian blinds



Figure 50 – AEGIR Panel Concept (United Network Studio, 2026)

The ETICS facades are composed of:

- Fire-resistant rock wool insulation layer
- Adhesive mortar
- Waterproof mortar
- Fiberglass mesh reinforcement at the base of the wall and perimeters of openings
- HPL, reclaimed wood, or composite cladding layer (where applicable)
- At Windows:
  - New aluminum joinery with thermal break
  - Double glazing with air chamber
  - Exterior venetian blinds

All new windows on the project use aluminum joinery with a thermal break. The typical double glazing assembly consists of a monolithic outer pane, 6.0 mm thick, with low-emissivity coating on the inside surface, an 18.0 mm argon-filled cavity with black spacer, and laminated inner pane, 5.0+5.2 mm thick. Further details on glazing assemblies are shown in Section 5.4.1.

Table 32 – Case Study Window Replacement Breakdown

Total Window Count = 239	
Existing to Remain	67
New Automated Windows	63
New Manually Operable Windows	109

The mechanical ventilation system is serviced by a single air handling unit (AHU) including a heat exchanger for recovering energy from exhaust air, a mixing box, heating and cooling coils and supply and exhaust fans. This unit serves multiple thermal zones via a variable air volume (VAV) system, supplying air through overhead ducts with ceiling diffusers. The new heat pump system assumes the majority of the building's thermal demand, allowing the existing biomass boiler to be relegated to use only during particularly low-temperature conditions. The PV and PVT panels are primarily used to generate solar energy for instantaneous use since the hours of occupation of the building coincide with the hours of maximum solar radiation. The battery use is generally limited to the early hours of the week with energy generated and stored over the weekend.

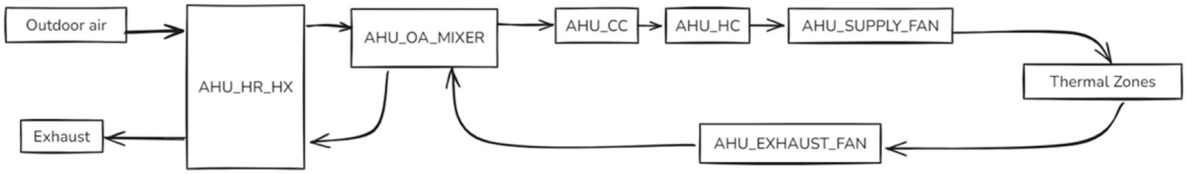


Figure 51 – Case Study Air Handling Unit System Scheme (Herrero et al., 2025)

Fire resistance is a critical safety consideration for the renovation. The existing brick facade, rehabilitated using the AEGIR industrialized system, has been confirmed to meet the external propagation requirements of the Spanish Technical Building Code Basic Document on Fire Safety (CTE-DB-SI). Furthermore, the stone wool insulation included with the ETICS facades is an intrinsically fire-resistant material. The fire resistance of the AEGIR facade is considered to guarantee a reduction in the risk of external fire spread. Further details regarding fire resistance properties of the AEGIR system can be found in Section 5.5. Regarding accessibility, the dimensional parameters of minimum width, clear height, and load-bearing capacity of the approach road have been considered, as well as fire department access.

Construction officially began in December 2025 over the school's Christmas holidays and work is projected to be complete prior to the start of the new school year in September 2026. Given this timeline, all case study assessments are based on the final design of the project and do not reflect as-built conditions.

4.2. DATA COLLECTION AND SUPPORTING TOOLS

The data for the Spain demo building comes from two primary sources: 1) deliverables made available to the public via the AEGIR official project website, and 2) drawings, models in Autodesk Revit, renderings, schedules, reports, energy simulation results, product cut sheets, environmental product declarations (EPD), and bill of quantities (BoQ) provided by TECNALIA. The data will be processed via qualitative and quantitative assessment methods to reach outlined objectives of this MBUILD final dissertation, with the assistance of specialized software for certain analyses. In certain cases, such as the Life Cycle Carbon assessment, data available from the utilized software tools is used to supplement project data where necessary.

The methodology is intentionally written to allow for the user's choice of software for conducting assessments under THRIVE. The following tools have been chosen to facilitate certain analyses for the AEGIR Spain demo building case study.

General – Google Earth
Google Earth is a free geospatial visualization tool that offers access to satellite and aerial imagery, as well as 3D terrain through an interactive digital platform. Key features utilized for the case study are the ability to measure distances and areas as well as conduct a visual assessment of the project site.

General – Bluebeam Revu
Bluebeam Revu is a specialized PDF tool for architecture, engineering, and construction (AEC) to enhance efficiency and collaboration. It includes precise measurement tools as well as robust markup and editing features. For this MBUILD final dissertation, an educational license of Bluebeam Revu is used to facilitate material quantity takeoffs from scaled drawings and enhance certain figures through its editing and markup functions.

General – Autodesk Revit
Autodesk Revit is a building information modeling (BIM) software used to design, document, visualize, and deliver AEC projects. For this MBUILD final dissertation, the 2022 and 2024 versions of Revit are used with provided case study models to assist in material quantity takeoffs, build a simplified, custom model for daylight simulation, and draft simplified cross sections depicting components relevant to the Life Cycle Carbon assessment for each façade typology.

Life Cycle Carbon – One Click LCA
The software used to carry out the Life Cycle Carbon assessment is One Click LCA, Level(s) life-cycle carbon (EN15804 +A1/+A2) tool. Though LEED-based tools within One Click LCA are available, the educational license used for this MBUILD final dissertation limits access to Level(s)-based tools. However, the difference here merely influences the formatting of outputs, and thus will not fundamentally impact assessment results. One Click LCA has been third party verified by ITB for compliancy with the following LCA standards: EN 15978, ISO 21931–1 and ISO 21929, and data requirements of ISO 14040 and EN 15804 (Building Research Institute (ITB), 2015). ITB is a certification organization and a Notified Body (EC registration nr. 1488) to the European Commission designated for construction product certification. (One Click LCA, 2015).

Daylight Simulation – Guardian Glass Performance Calculator
The Performance Calculator, part of the Guardian Glass "Glass Analytics" suite, is a free, web-based tool for modeling thermal and optical properties of assemblies made with Guardian glazing. The tool allows for the definition of substrates, coatings, interlayers, and cavity configurations and returns performance values for the assembly using standardized calculation procedures (e.g. EN 410:2011 / EN 673:2011). For the case study project, this tool is used specifically to determine visual light transmittance (VLT) values for the specified glazing assemblies (Guardian Glass, n.d.).

Daylight Simulation – LightStanza

LightStanza is a web-based, radiance-powered daylight and lighting simulation platform that runs calculations in the cloud and is widely used for LEED/WELL/EN 17037 compliant climate-based daylight analysis. The platform integrates with BIM and 3D modeling tools such as Revit and is capable of importing geometry and materials for direct use in daylight simulations. For this MBUILD final dissertation, a free-trial version of LightStanza is used in conjunction with its Revit plugin is used to facilitate the Daylight Simulation assessment. (LightStanza, n.d.-b).

Seasonal Thermal Comfort – CBE Thermal Comfort Tool

The CBE Thermal Comfort Tool is a free, web-based application developed by the Center for the Built Environment at University of California Berkeley. The tool performs thermal comfort calculations and visualizations in accordance with major international standards, including ASHRAE 55-2023, ISO 7730:2005, and EN 16798-1:2019. The tool facilitates calculations via the predicted mean vote (PMV) and adaptive comfort methods, with possible inputs of operative temperature, air speed, relative humidity, activity level/metabolic rate, clothing level, and prevailing mean outdoor temperature depending on the method used. The tool automatically calculates the relative air speed and the dynamic clothing insulation. Output is used to directly confirm compliance with NEB-SAM- and LEEDv5-based thermal comfort criteria in both heating and cooling mode. (Tartarini et al., 2020).

4.3. UNCERTAINTY, LIMITATIONS, & ASSUMPTIONS FOR THIS WORK

Throughout the case study demonstration, the author encountered a variety of limitations or issues generating uncertainty, which in some cases required the development of certain assumptions. Here these are disclosed and organized into those spanning the entire case study project, followed by more granular instances affecting each analysis block.

The following apply at the project level:

- Considering construction of the case study building is currently ongoing, all analysis is based on final (or near-final) design information. Within the timeline of this MBUILD final dissertation, it is impossible to verify certain THRIVE analyses with as-built data and post-renovation testing.
- Information regarding the existing building is generally limited or available at a low level of detail. This generates the need for various assumptions detailed under the applicable analysis blocks.

The following are specifically relevant to the assessments within Embodied Carbon:

- Regarding life cycle carbon:
    - Due to a limited level of detail in the provided Revit models, most material quantities for the life cycle carbon assessment are estimated via simplified take-offs and hand calculations based on construction drawings rather than direct export from the model.
    - For simplicity, components of the envelope system such as fasteners, furring, sub-framing, and perforated fins are excluded considering lack of accurate detailed quantities and the minimal carbon impact of these elements in relation to the rest of the system.
    - At the time of writing, a specific ETICS product has yet to be selected by the contractor. The "basis of design" (BOD) product specified by the design team is StoTherm Mineral, meaning the final selection should be this product or something similar. Therefore, StoTherm Mineral is the assumed ETICS product for the case study. Figure 52 shows the component layers of this product, note that "Sto Product 4" for the Mineral Wool Insulation Board = Owens Corning Thermafiber.

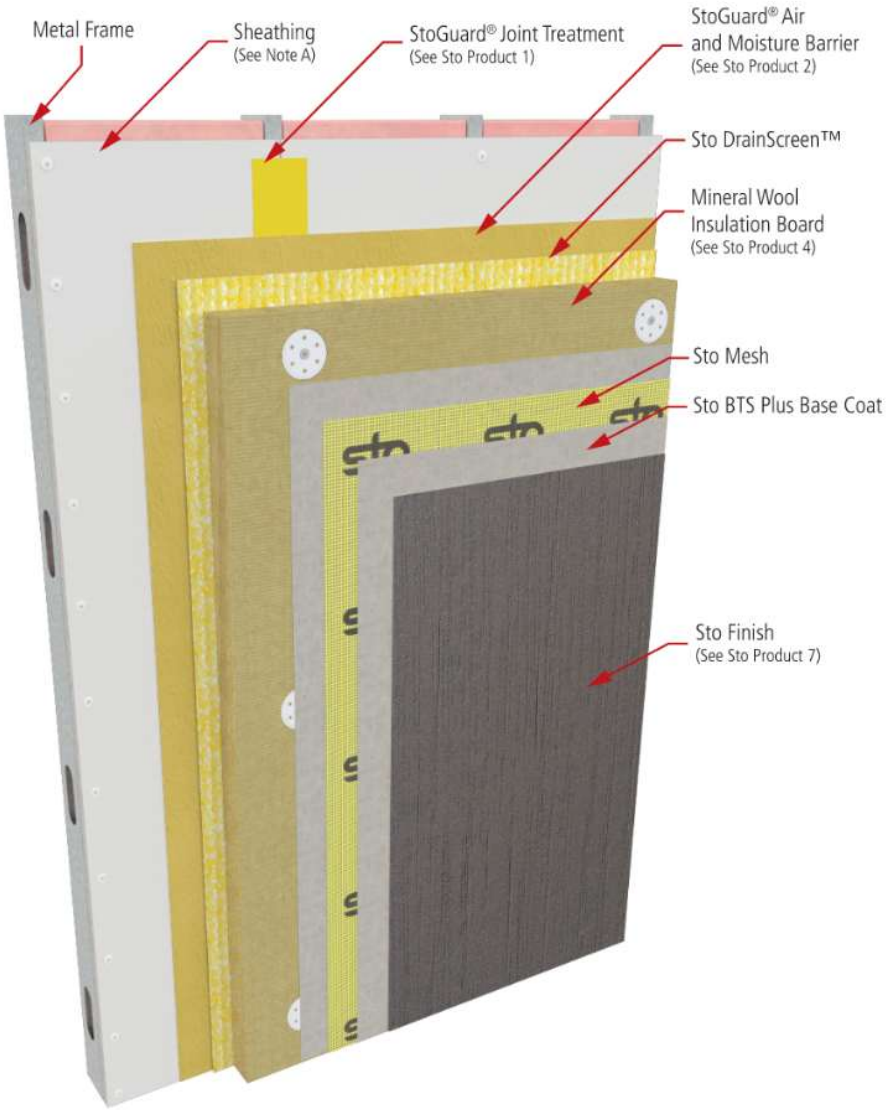


Figure 52 – StoTherm Mineral Assembly Components (Sto, 2020)

- Some of the analyzed components either have yet to be specified for the final design or lack product-specific environmental data. For these components (listed below) the generic EPD chosen for the baseline was kept consistent in the proposed model.
  - **Concrete** – No mix-specific submittals or EPD are available.
  - **Rebar** – Product-specific data has not been provided.
  - **ETICS** – The final product is yet to be specified. A generic EPD has been selected that includes the BOD product among its representative dataset for a family of ETICS systems with stone wool insulation.
  - **OSB** – No EPD is available for specified product.
  - **Steel doors** – Product-specific data has not been provided.
  - **Reclaimed wood cladding** – Product-specific data has not been provided.
  - **Flexible PV Panels** – No EPD is available for specified product.
- The most recent EPD available for the proposed wood fiber insulation, Soprema – Pavawall Smart, expired November 2025. As a currently valid EPD for this product could not be located, the data in the expired version is used.

- With the educational One Click LCA license used for this assessment, access is limited to the Level(s) assessment tools. While a LEED-based assessment tool would be a more natural fit given the position of LEEDv5 as a guiding framework, the scope and boundaries of the One Click LCA models have been established as outlined in Section 3.2 following LEED guidance. Thus, the only difference is the default structure and formatting of results, and the tool choice does not affect the outcome of the results themselves.
- Sufficient product data regarding transport distance (life cycle stage A4) and typical percentage of construction site wastage (life cycle stage A5) is not available for input in the LCA. Thus, these values are left as the One Click LCA defaults for each component.
- It should be noted that there is inherent uncertainty in life cycle assessment methodologies, with research documenting variations of ±20% in embodied carbon values reflecting both methodological limitations and data quality issues, exacerbated by limited availability of EPDs for bio-based and innovative materials (B Udisi et al., 2024). The LCA largely relies on the One Click LCA database of EPDs, with an effort to keep the EPD program data source consistent across generic EPD selections as possible. The environmental data source of each EPD is detailed in Annex A.2.

- Regarding circularity & sourcing:
  - For the purposes of the circularity of material calculation, product densities to calculate quantities by weight will be assumed to correspond with the assigned EPDs in One Click LCA where necessary due to lack of data. This approach considers an ETICS weight per area as provided by the selected EPD, neglecting the varying insulation thickness between ETICS (60 mm) and ETICS+C (80 mm), thus limiting the accuracy of the results.

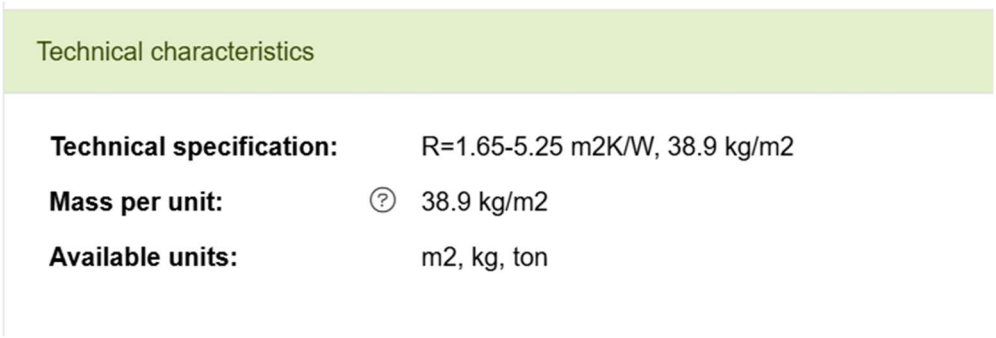


Figure 53 – ETICS Mass per Functional Unit per EPD (One Click LCA, 2015)

  - Similarly, secondary material content (percentage of secondary, bio-based, and recycled material) is assumed to match the EPD in the absence of explicitly provided data. If the EPD makes no mention of secondary content it is conservatively assumed to be 0%.
  - For simplicity, where the quantity of glazing is needed by area rather than weight for the Responsible Sourcing calculations, the full window area (including mullions) is assumed to be glass.

The following are specifically relevant to the assessments within Operational Carbon:

- Given the project timeline, all post-renovation energy data comes from energy simulations. Real consumption and generation data following construction completion would yield more accurate results and serve to either validate or contradict the projections.

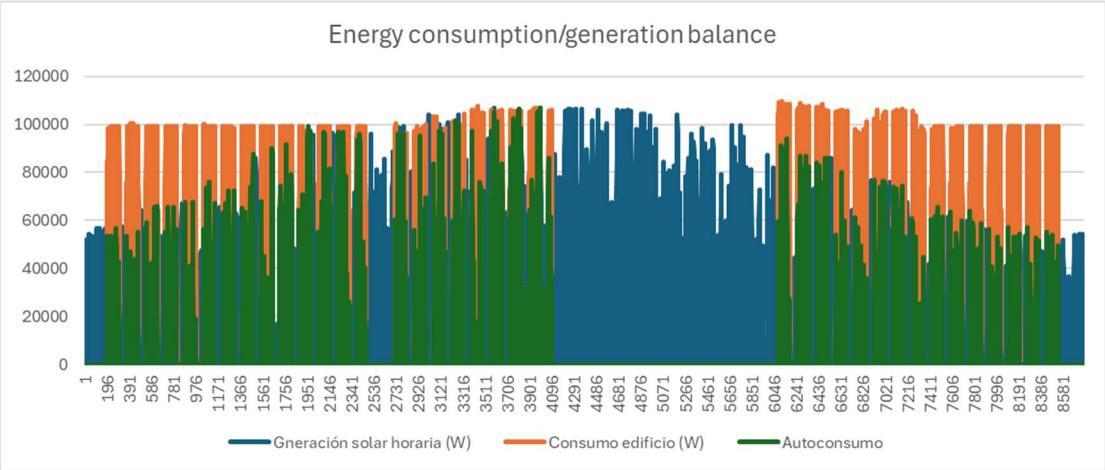


Figure 54 – Case Study Simulated Post-Renovation Energy Balance (TECNALIA)

- Regarding the energy storage assessment, as (Koolen et al., 2023) does not publish numeric values for the share of flexibility requirements covered by storage for the EU or individual Member States, the baseline metric for energy storage impact on flexibility requirements must be qualitatively assumed. The report shows that current storage capacity remains limited compared with the magnitude and growth of flexibility requirements' contribution to total electricity demand. This supports the conclusion that, at present, storage covers only a small fraction of total flexibility needs in the average European system. Based on this evidence and following NEB-SAM guidance to establish the baseline on "flexibility requirements and energy storage power" per (Koolen et al., 2023), the case study assumes a baseline energy storage factor of 5%. This order-of-magnitude estimate is consistent with the relatively small storage capacities reported for 2022 compared with flexibility requirements and considers storage's supporting role among other flexibility options such as interconnectors, dispatchable generation, and demand-side response (Koolen et al., 2023).

The following are specifically relevant to the assessments within Indoor Environmental Quality:

- Regarding daylight:
    - Due to fragmented data between existing-building and new-envelope Revit models, a custom model is built for the daylight analysis compiling necessary info. This model is built with the following assumptions/simplifications:
        - Windows on three ground-floor facades the southwest corner of the building was not sufficiently modeled in any of the provided Revit models to be compatible with the daylight analysis. Therefore, custom windows were modeled here matching the overall dimensions to capture only a level of detail necessary to have meaningful impact on the daylight results.



Figure 55 – Case Study Custom-modeled Windows, Ground Floor

        - Existing structural columns are omitted for simplicity as they are deemed to have negligible impact on daylight results.
    - Based on info the project's energy compliance certification, the existing-to-remain windows are assumed to be made of a clear, double-glazed assembly.
    - Detailed topographic data is not available to assist in accurately modeling adjacent structures. These structures were sized and placed within the daylight model as simple geometric shapes based on approximations made with Google Earth measurement tools.
    - IES Standard LM-83-23 outlines fixed analysis hours of 8am-6pm for every day of an entire year. LightStanza does not allow for the custom definition of operating hours within the daylight model or operating hour variability by space type. Thus, while the analysis follows LM-83-23 as directed in Section 3.4.1, it is restricted from a more accurate analysis considering the real operating hours of the case study building (e.g. not operational in summer, cafeteria only used mid-day, 12:30-3).
- Regrading thermal comfort:
    - For the seasonal thermal comfort assessment, the following assumptions have been made regarding inputs to the CBE Tool, following the PMV method:
        - Due to a lack of specific data regarding the design mean radiant temperature, the operative temperature is assumed to be equal to the mechanical system set points for dry-bulb temperature, as outlined and justified under Section 3.4.2.
        - Due to a lack of specified relative humidity control setpoints for the mechanical system, the following are assumed according to best-practice typically recommended per ASHRAE of 30% for winter design and 50-60% for summer design (ASHRAE 55 and 61: Guidelines, n.d.).
            - Heating mode, RH = 30%
            - Cooling mode, RH = 50% (conservative end of range)

- The input MET value is based on a study of the metabolic rate in children and adolescents for common activities (Gao et al., 2023). The MET for children between the ages of 6-12 during "Computer Games", the reported activity deemed closest to schoolwork, ranges from 1.3-1.1. Therefore, a median value of 1.2 is assumed for the case study.

Table 3
The metabolic rate for common activities in children and adolescents in met (1 met equal to 58.2 W/m^2, data show mean (SD)).

Activity	Age (year)							
	6–9		10–12		13–15		16–18	
	M	F	M	F	M	F	M	F
TV	0.9 (0.2)	0.9 (0.2)	1.0 (0.3)	1.0 (0.2)	1.0 (0.2)	0.9 (0.2)	1.0 (0.1)	0.9 (0.2)
Computer Games	1.3 (0.2)	1.3 (0.4)	1.2 (0.2)	1.1 (0.2)	1.2 (0.2)	1.0 (0.2)	1.0 (0.2)	0.9 (0.1)
Wii play	2.5 (0.5)	2.2 (0.7)	2.6 (1.0)	2.1 (0.6)	2.5 (0.8)	1.9 (0.8)	2.0 (0.3)	1.8 (0.4)
Sweeping	3.2 (0.7)	3.1 (0.6)	3.1 (0.9)	2.8 (0.6)	2.8 (0.5)	2.5 (0.4)	2.5 (0.6)	2.4 (0.7)
Dance	2.7 (0.8)	2.6 (0.6)	3.0 (1.1)	2.9 (0.6)	3.5 (1.2)	2.9 (0.9)	2.9 (0.8)	2.5 (0.5)
Aerobics	3.2 (1.0)	3.5 (1.1)	3.6 (1.1)	3.4 (1.0)	3.8 (1.2)	3.4 (1.0)	3.4 (0.9)	3.3 (0.7)
Basketball	5.3 (1.5)	4.5 (1.0)	6.3 (1.1)	5.5 (1.1)	6.6 (1.3)	5.4 (1.3)	7.8 (2.3)	4.9 (1.4)
Rope Skip	5.9 (1.4)	6.3 (0.9)	6.5 (1.1)	6.1 (1.2)	7.3 (1.3)	6.2 (1.3)	7.4 (1.7)	5.9 (1.7)
Walk 4.0 km/h	3.1 (0.7)	2.9 (0.8)	3.2 (0.5)	3.0 (0.5)	3.2 (0.6)	3.0 (0.5)	2.8 (0.4)	2.6 (0.4)
Walk 4.8 km/h	3.8 (0.7)	3.9 (0.5)	3.6 (0.6)	3.5 (0.5)	3.7 (0.8)	3.5 (0.5)	4.1 (1.4)	3.3 (0.7)
Run 7.2 km/h	5.5 (1.2)	4.9 (1.1)	6.5 (0.9)	6.2 (0.9)	7.4 (1.0)	6.2 (0.6)	6.1 (0.6)	6.1 (0.8)
Run 8.0 km/h	6.6 (0.9)	6.4 (0.6)	6.9 (0.9)	6.7 (0.8)	7.3 (0.9)	7.0 (0.9)	7.2 (1.1)	6.8 (1.0)
Cycling 16 km/h	4.0 (1.4)	3.6 (1.3)	5.5 (0.9)	4.9 (1.1)	4.9 (0.9)	4.6 (0.8)	4.7 (0.7)	4.8 (0.6)
Housework	–	–	2.8 (0.6)	2.5 (0.3)	3.0 (0.6)	2.7 (0.7)	–	–

Figure 56 – Metabolic Rate for Common Activities in Children and Adolescents (Gao et al., 2023)

- For the cooling mode assessment, the clothing level is set to 0.50 clo as the CBE Tool default for "typical indoor summer clothing". For the heating assessment, the CBE Tool default of 1.00 "typical indoor winter clothing" was deemed to overestimate the amount of clothing worn by children in a Mediterranean climate with mild winters. Thus, 0.74 clo is assumed based on the CBE Tool default for "sweatpants, long-sleeve sweatshirt".

- Regarding indoor air quality:
  - In the absence of post-construction sensor data, the CO2 concentration assessment uses the design specifications to meet Spanish RITE code requirements for IDA 2 to determine a post-renovation CO2 concentration value. The specifications mandate a maximum CO2 concentration of outdoor CO2 levels +500 ppm. The assumed maximum outdoor CO2 concentration is based on data available from the Metropolitan Area of Barcelona Urban Greenhouse Gas Network (Villalba Mendez et al., 2025). Specifically, data from the ICM station is used as the most geographically and climatologically representative station of Malgrat de Mar.
  - The most recent full year of monthly mean CO2 data is averaged to determine an annual mean of 439 ppm, which serves as representative assumption for the outdoor CO2 concentration.
  - For the ventilation calculations following the ASHRAE VRP, a zone air distribution effectiveness of Ez = 1.0 is assumed for all zones. Derived from ASHRAE Standard 62, Table 6.2, this assumption considers the overhead (ceiling) supply of air, and a lack of detailed information regarding diffuser throw patterns or anticipated differences between supply and space temperatures to warrant a modified Ez value (ASHRAE, 2003).

The following are specifically relevant to the assessments within Resilience, Aesthetics, and Inclusiveness:

- Regarding hazard resilience:
    - For the DLUHC-based fire resistance assessment, for simplicity and to maintain a conservative benchmark, all external walls are considered as less than 1,000mm from the "relevant boundary". This means applying the most stringent reaction-to-fire class requirement for external surfaces across the entirety of all façades. Similarly, the full roof area is assumed to be less than 6m from any point on the relevant boundary to conservatively require the most stringent fire criteria.
    - Considering the lack of available data regarding the reclaimed wood cladding, it is conservatively assumed to not meet fire-resistant or water-resistant criteria for the purposes of assessments within this analysis block.
    - Specific product data for the existing roof construction is not available; thus, its external fire resistance class cannot be verified. As both the clay external surface and the concrete deck are inherently non-combustible, the risk of fire spread is considered low, and the roof is expected to offer performance consistent with the criteria for $B_{ROOF}(t4)$ classification (Vaczi, 2022). Therefore, the roof is assumed to be fire-resistant for the purposes of the Fire Spread-Resistant Envelope assessment despite the lack of formal EN 13501-5 classification.
- Regarding aesthetics and visual experience:
    - The visual experience assessments are inherently qualitative and based on the interpretation of the reviewer or professional conducting the assessment. Coming from an engineering background, the author of this MBUILD final dissertation is not a subject-matter expert in the architectural principles assessed. An architectural coordinator for the case study project was consulted regarding these assessments to mitigate this lack of expertise and expand the "sample size" of input on which these assessments are based. Though polling a larger base of subject-matter expert reviewers would be ideal, time-constraints inhibit this approach.
    - Considering the timeline of construction, the visual experience assessments are based on renderings rather than the actual as-built condition.
- Regarding inclusiveness and equitable accessibility:
    - Given a lack of as-built shop drawings considering the construction timeline, entry door clear widths have been determined based on scaled measurements from door detail elevations (see Figure 57). While this provides a reasonable level of confidence, the accuracy is limited compared to shop drawings or product cut sheets as the preferred source of data.

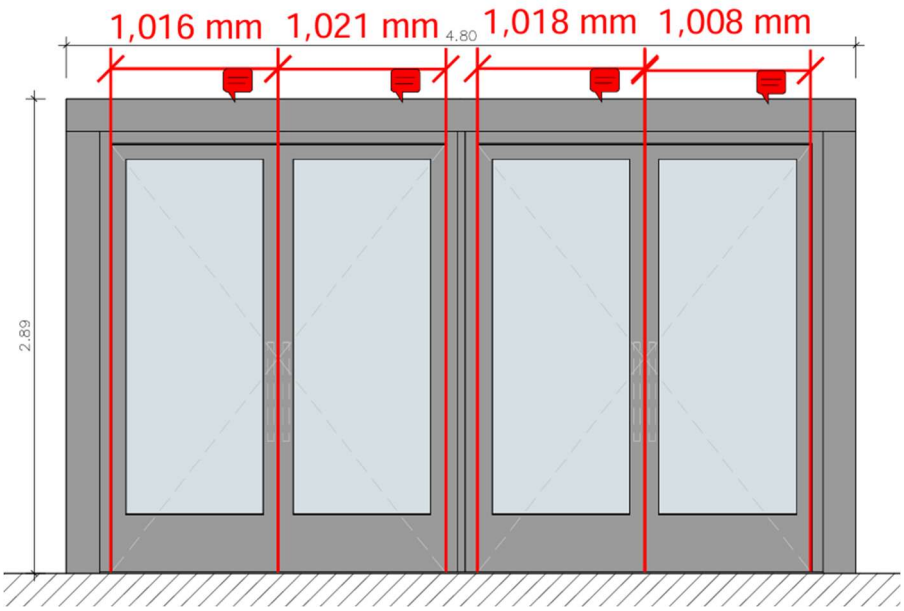


Figure 57 – Case Study Main Entrance Clear Widths; Adapted from Arch Drawings with Bluebeam Revu

- Design scope regarding signage is not clear. After discussions with the project architectural coordinator, a conservative approach of including the signage-based assessments but considering the project fully non-compliant has been chosen.

5

RESULTS AND DISCUSSION

5.1. STRUCTURE OF RESULTS

THRIVE results are delivered at four levels of granularity:

- Individual assessment
- Integrated measure
- Analysis block
- Project

The chapter is first organized into analysis blocks following the same sequence as the methodology (Sections 5.2 – 5.5). The outcome of each individual assessment and integrated measure for the AEGIR Spain demo building is reported along with all input data and analytical procedures specific to the case study. The analysis block score and corresponding performance class is reported at the end of each respective section. Section 5.6 then reports the project-level THRIVE score along with a summary of the results, communicating score and performance class at the integrated measure, analysis block, and project level.

Section 5.7 follows with interpretation of the case study results, elaborating on performance class significance, identifying areas of strength and weakness, and proposing targeted recommendations for the project to improve its THRIVE performance. Section 5.8 reflects on the effectiveness of THRIVE in addressing the core research question and associated objectives. Strengths and limitations are explored along with suggestions for further development of the framework. Finally, this section provides commentary on the NEB-SAM and LEEDv5 as drivers for sustainability in the built environment and the potential of THRIVE to serve as a foundation for future influence on the approach to deep renovation in the construction industry.

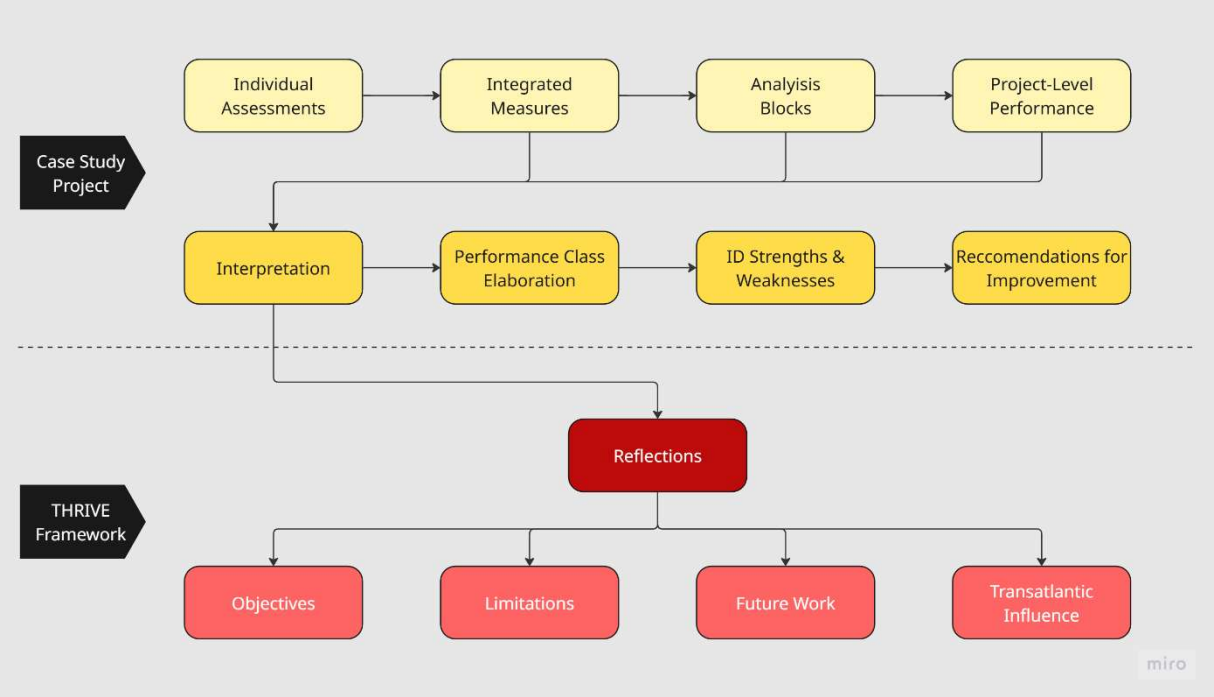


Figure 58 – Structure of Results and Discussion (created with Miro)

5.2. EMBODIED CARBON RESULTS

The following material components were considered in the embodied carbon assessments:

AEGIR Panels

- Mineral wool infill layer (R=3.5 m2K/W)
- Oriented strand board (OSB) panels
- Primary structural framing – Steel profiles
- Secondary structural framing – Aluminum profiles
- Wood fiber insulation (R=4.1 m2K/W)
- Waterproofing membrane
- Window glazing
- Window framing – Aluminum profiles
- High pressure laminate (HPL) cladding
- Aluminum composite cladding

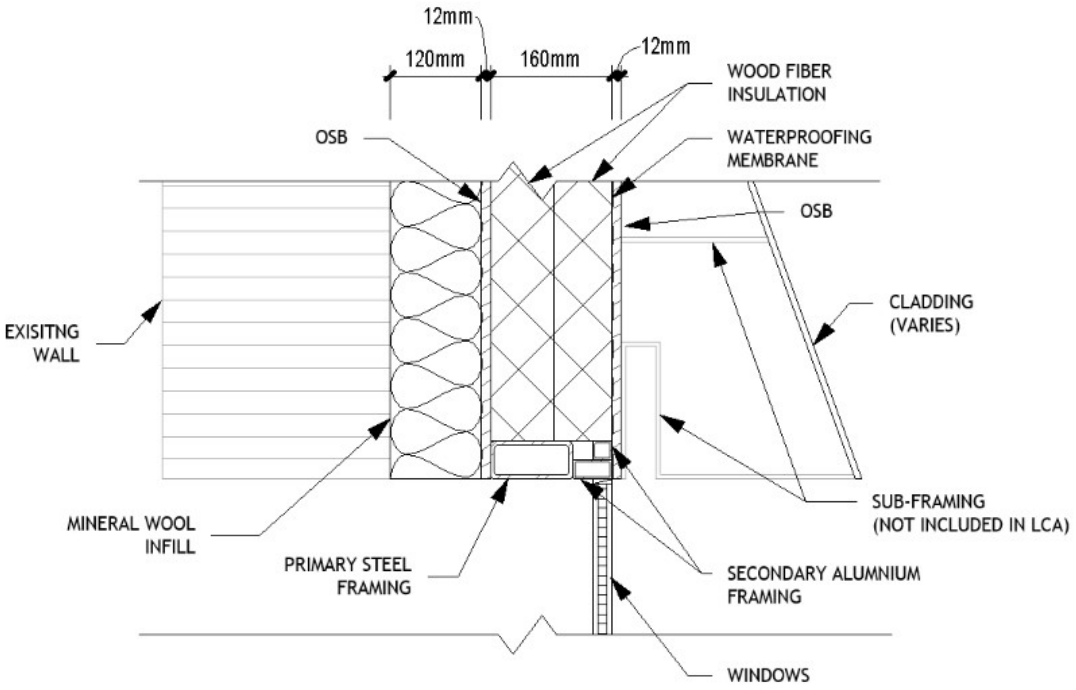


Figure 59 – Simplified Cross Section for Embodied Carbon Assessments; AEGIR Panel (created with Revit)

ETICS Panels

- ETICS with stone wool insulation (R = 1.14 m^2K/W)
- Window glazing
- Window framing – Aluminum profiles
- Glass door glazing
- Glass door framing – Steel profiles
- Steel doors with mineral wool core

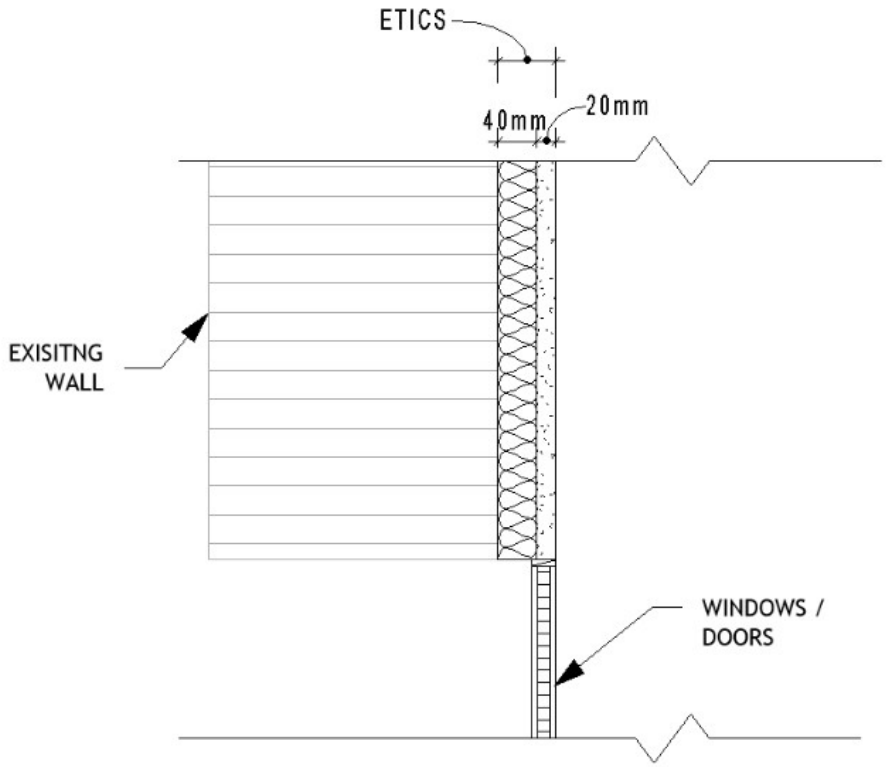


Figure 60 – Simplified Cross Section for Embodied Carbon Assessments; ETICS (created with Revit)

ETICS Panels with Cladding (ETICS+C)

- ETICS with stone wool insulation (R = 1.71 m^2K/W)
- High pressure laminate (HPL) cladding
- Timber cladding
- Aluminum composite cladding

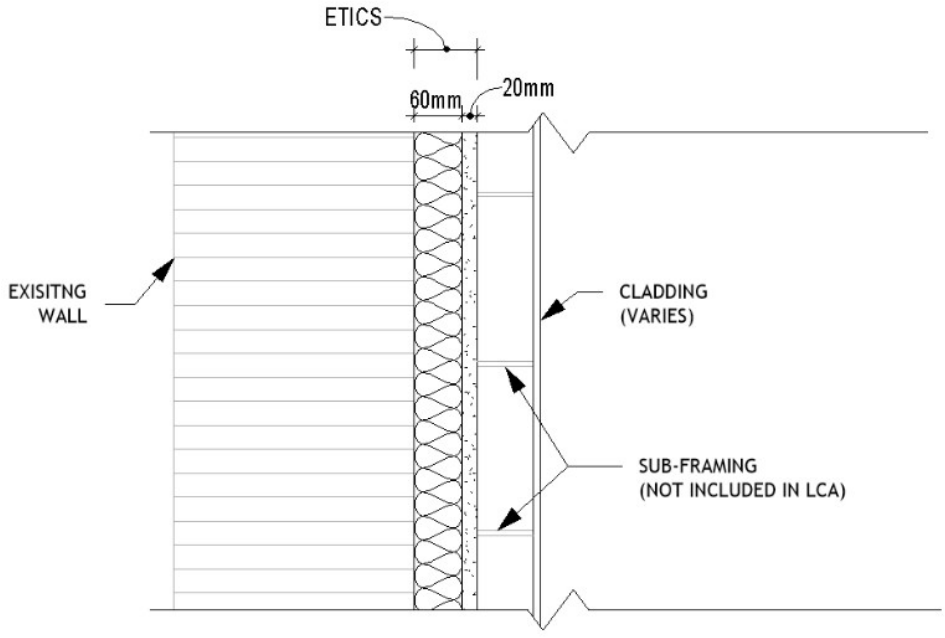


Figure 61 – Simplified Cross Section for Embodied Carbon Assessments; ETICS+C (created with Revit)

Support Structure
- AEGIR panel footings – Concrete
- AEGIR panel footings – Rebar
- AHU and battery support slabs – Concrete
- AHU and battery support slabs – Rebar

Roof PV
- Standard PV Panels
- Flexible PV Module

Component specifications and quantity data come from drawings, Revit models, and BoQ for the case study project provided by TECNALIA. Detailed quantities for each component can be found in Annex A.1. Breaking down quantities for composite elements was addressed as follows. The weight of glazing in kg/m^2 for each type window of assembly (detailed in Section 5.4.1) was calculated with Guardian Glass Performance Calculator and used to calculate the total weight of glazing based on window area. The weight of metal framing in windows and glass doors was estimated using the 12.3 kg/m^2 assumption from Table 5. For reinforced concrete elements, reinforcement quantities were estimated by assuming the average steel share of total structure % from Table 6 (e.g. Slabs – one way = 1.0 – 1.6%, thus 1.3% steel is assumed).

Life-Cycle Carbon

The baseline model was constructed using generic EPDs from the One Click LCA database, tailored to Spain where possible. All baseline quantities match the quantities gathered from the provided project data, with the exception of wood fiber insulation within the AEGIR panel, which was adjusted to account for a slightly differing R-value between the baseline and proposed EPDs. Transport distance and method from manufacturing to construction site for each product are left as the One Click default values, based on regional typical values for the product type. One Click default values were also used for the baseline service life of each product, with the notable exception of HPL cladding. The One Click default of 15 years for this product, corresponding to 3 replacements over the building's service life was deemed unrealistic and led to a disproportionately large impact on the overall system. Thus, this value was updated to 30 years (1 replacement) as a conservative assumption based on the typical lifespan of HPL panels in the current European market (Pops Facades, n.d.). End of life (EOL) processing and the percentage of construction site wastage was also set to One Click defaults.

For the Proposed model, generic EPDs were replaced with product-specific EPDs for all components with sufficient data available. Due to a lack of sufficient data, transportation distances and site wastage were kept consistent between the baseline and proposed for all components. All differences between the Baseline and Proposed building and the evidence for equivalent energy performance are explained in Table 33. Full EPD assignments for the Baseline and Proposed models are detailed in Annex A.2.1. and A.2.2 respectively.

Table 33 – Differences Between Baseline and Proposed Life Cycle Carbon Assessment Models; Adapted from (One Click LCA, 2015)

Baseline Material Assignment	Proposed Material Assignment	Details
Stone wool (mineral wool) insulation, unfaced, L = 0.031 W/mK, R = 1 m2K/W, 31mm, 1.86 kg/m2, 60 kg/m3, (Range: 51-65kg/m3), 22% slag content (One Click LCA)	Stone wool insulation, unfaced, L= 0.034 W/mK, R= 1 m2K/W, 34 mm, 1.73 kg/m2, 51 kg/m3, Ventirock Duo (ROCKWOOL Peninsular S.A.U.)	Same application, quantities, service life, and EOL process. Thickness in the baseline model adjusted to 109 mm to match thermal performance of 120 mm in proposed model. Project-specific product assigned for the proposed.

Baseline Material Assignment	Proposed Material Assignment	Details
Float glass, single pane, 4 mm, 10 kg/m2, 2500 kg/m3 (One Click LCA)	Uncoated flat glass, 2500 kg/m3, Guardian ExtraClear™, Guardian UltraClear™ (Guardian Europe)	Same application, quantities, service life, and EOL process. Quantities expressed in kg to normalize for thickness. Project-specific product assigned for the proposed.
Extruded aluminium profiles for window and door frames, generic, 60% recycled content, average world aluminium manufacturing technology (One Click LCA)	Aluminium profiles, 2700 kg/m3 (Gesamtverband der Aluminiumindustrie e.V.)	Same application, quantities, service life, and EOL process. Project-specific product assigned for the proposed.
Wood fibre weather resistant insulation for walls and roof, L = 0.043 W/mK, 180 kg/m3, average World wood pulp manufacturing technology, Lambda=0.043 W/(m.K) (One Click LCA)	Wood fiber insulation panel, biogenic CO2 not subtracted (for CML), L=0.039 W/mK, R=4.1 m2K/W, 160 mm, 18.4 kg/m2, 115 kg/m3, Lambda=0.039 W/(m.K), PAVAWALL® SMART 160 mm (SOPREMA SAS)	Same application, service life, and EOL process. Project-specific product assigned for the proposed. Volume of material used in baseline adjusted to maintain equivalent thermal performance of proposed product.
Steel hot dip galvanised Europe 2022, blast furnace route, production mix, at plant, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm (WorldSteel 2023)	Hot-dip galvanized steel profiles and accessories for plasterboard, 7850 kg/m3 (Gyproc Saint Gobain (2022))	Same application, quantities, service life, and EOL process. Project-specific product assigned for the proposed.
HPL laminate cladding, 8.1 mm, 11.6 kg/m2 (KBOB)	High pressure laminate (HPL) panels, 8 mm, 11.2 kg/m2, Trespa® Meteon EDF (Nemho)	Same application and quantities. Project-specific product assigned for the proposed. Service life adjusted from 30 to 50 years based on documented technical service life of the proposed product. EOL scenario adjusted from “plastic-based material incineration” to “reuse as material” based on established manufacturer Second Life program for the proposed product.
Timber cladding for walls and ceilings, 31.699 kg/m2, 700 kg/m3 (FRAPONT S.A.)	Timber cladding for walls and ceilings, 31.699 kg/m2, 700 kg/m3 (FRAPONT S.A.)	Same application, quantities, service life, and EOL process. Same generic EPD. Component flagged as “Reused Material” in the proposed to reflect the use of reclaimed wood.

Baseline Material Assignment	Proposed Material Assignment	Details
Aluminium sandwich panel with thermoplastic core, 4 mm, 7.04 kg/m2 (Aluminium Deutschland)	Composite panel with double sided aluminium sheet and mineral filled polymer core, 4 mm, 7.6 kg/m2, ALUCOBOND A2 (3A Composites GmbH)	Same application, quantities, service life, and EOL process. Project-specific product assigned for the proposed.
PP underlay sheet, 0.15 kg/m2, EN15804+A2, ref. year 2022	Waterproof membrane from nonwoven HDPE for roof and wall underlay, 0.175 mm, 145 g/m2, DuPont™ Tyvek® 2507B (DuPont)	Same application, quantities, service life, and EOL process. Project-specific product assigned for the proposed.
Photovoltaic systems, calculated average for Spain, 14.5 kg/m2, P=500 Wp (One Click LCA)	Mono-crystalline photovoltaic module, per m2, 12.70 kg/m2 (Phono Solar Technology Co.,Ltd)	Same application, service life, and EOL process. Project-specific product assigned for the proposed. Volume of material used in baseline adjusted to maintain equivalent energy performance of proposed product.

The resulting embodied carbon impact of each scenario, represented as total GWP measured in kg CO2e, is shown in Table 34 and represented visually in Figure 62.

Table 34 – Summary of Baseline and Proposed Total GWP results

Baseline Result	Proposed Result	Reduction
318,012 kg CO2e	254,877 kg CO2e	19.9%

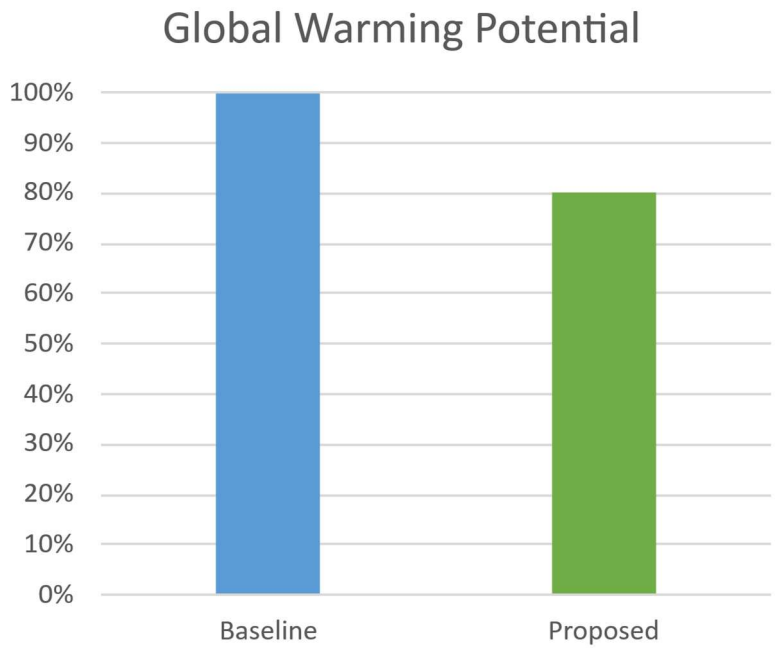


Figure 62 – Comparison of Baseline and Proposed Case Study EC1 Results for GWP

Detailed in Figure 63, the majority of the impact comes from the A1-A3 production stages, followed by B4-B5 replacement and A5 construction. Therefore, identifying the highest-contributing materials within the A1-A3 stage can aid in prioritizing investments and providing recommendations for further improvement to GWP reduction. The top 5 highest contributors to A1-A3 are detailed in Table 35. The overall GWP reduction of 19.9% corresponds to the THRIVE scores shown in Figure 64.

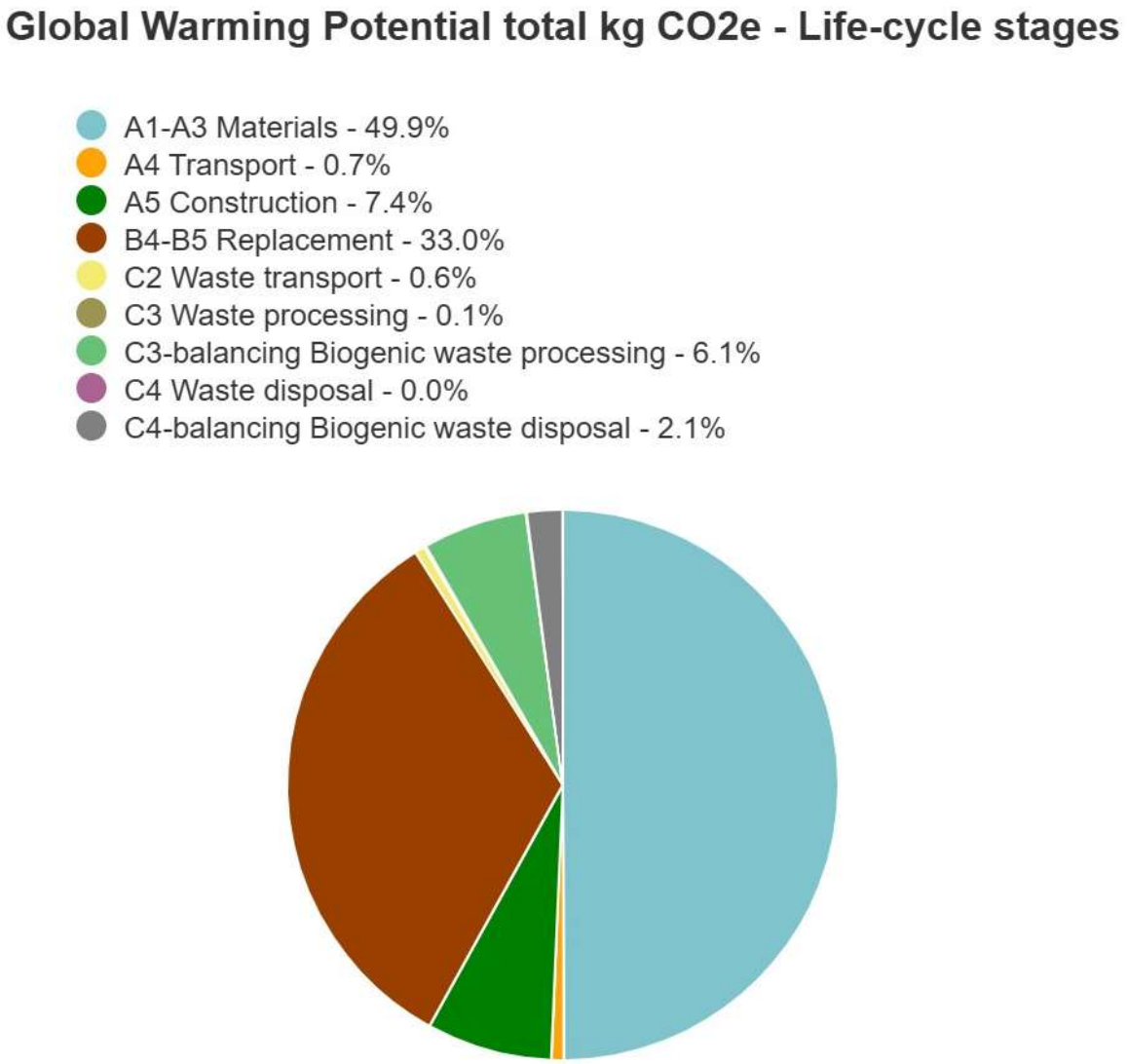


Figure 63 – Proposed Case Study Life Cycle Carbon Model, GWP Breakdown by Life-Cycle Stage

Table 35 – Proposed Case Study Life Cycle Carbon Results, Highest-Contributing Cradle-to-Gate Components; Adapted from (One Click LCA, 2015)

No.	Resource	Cradle to Gate Impact (A1-A3)	% of Total Impact (A1-A3)
1	Mono-crystalline photovoltaic panel (Standard)	63,000 kg CO2e	39.4
2	ETICS with stone wool insulation	25,000 kg CO2e	15.4
3	Aluminum profiles	20,000 kg CO2e	12.3
4	Guardian ExtraClear flat glass	14,000 kg CO2e	8.6
5	High pressure laminate (HPL) panels	10,000 kg CO2e	6.4

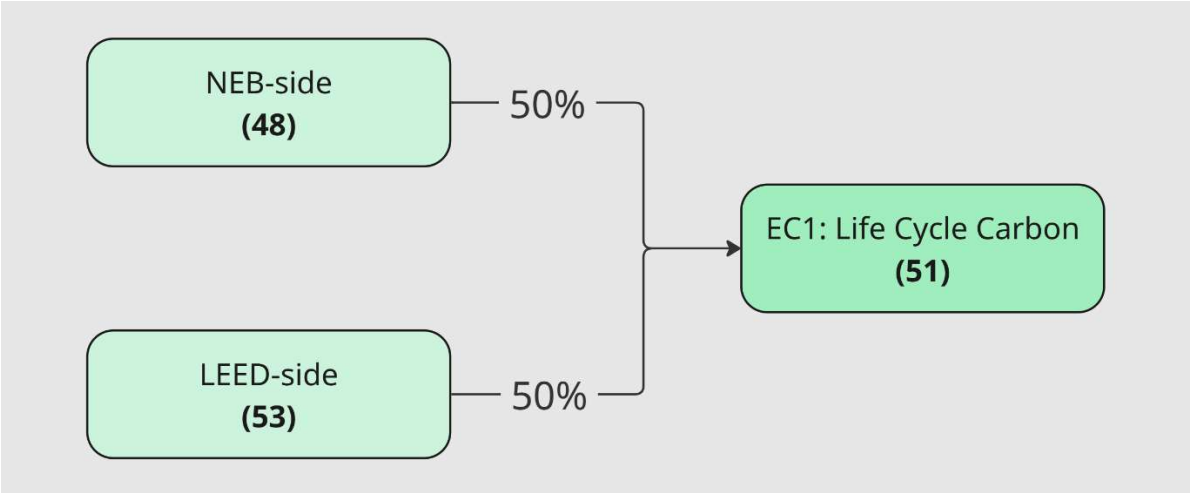


Figure 64 – Case Study Integrated Scoring for EC1 (created with Miro)

Carbon Payback

The carbon "investment" value for the project corresponds to the proposed GPW of 260,042 kg CO2e. The results of EC2 – Carbon Payback are shown in Section 5.3.

Circularity & Sourcing

To calculate Circularity of Material, mass quantities are taken either directly from the material takeoffs performed for the life cycle carbon assessment or converted from area/volume quantities. The percentage of circular material (secondary, bio-based and recycled material) came from the BoQ provided by TECNALIA and product data sheets. Calculations are summarized in Table 36. Assumptions outlined in Section 4.3 for product densities and circular material percentage have been used where necessary.

Table 36 – Case Study Circularity of Material Calculations

Material/Product	Total Area (m2)	Mass per FU (kg/m2)	Total Volume (m3)	Density (kg/m3)	Total mass (kg)	Circular %	Circular mass (kg)
Rockwool Insulation			22.3	51	1137.3	61.0%	693.8
OSB			4.5	613	2727.9	0.0%	0.0
Steel Framing					2609.3	0.0%	0.0
Aluminum Framing					3483.2	77.0%	2682.1
Wood Fiber Insulation			29.7	115	3415.5	95.0%	3244.7
Waterproofing	185.5	0.15			26.9	2.8%	0.7
HPL Cladding			3.4	1400	4802.0	61.0%	2929.2
Aluminum Composite Cladding	89.3	7.60			678.7	17.8%	120.8
Reclaimed Wood Cladding	118.7	31.70			3761.7	100.0%	3761.7
Glazing					12747.1	0.0%	0.0
Steel Door					148.0	15.0%	22.2
ETICS	824.0	38.90			32053.6	0.0%	0.0
Concrete			38.8	2386	92576.8	10.0%	9257.7
Rebar			0.7	7850	5730.5	97.0%	5558.6
Standard PV Panels	332.3	12.70			4220.2	9.9%	417.8
Flexible PV Module	80.1	1.83			146.5	5.4%	7.9
					170265.2		**28697.2**

The results of the calculation and corresponding Circularity of Material score are summarized below:

- Total Mass = 170,265 kg
- Circular Material Mass = 28,697 kg
- CM = 17%
- k = 5
- Score = **84**

The assessed materials (Manufacturer: Product), their surface area, supporting documentation, and corresponding multi-attribute score (MAS) for responsible sourcing are as follows:

Insulation

Rockwool: Ventirock Duo

- Area = 185.5 m^2
- Supporting Documentation
  - EPD: Product-Specific Type III → **1** Point Climate Health
- MAS = 1.0
- V_{adj} = 185.5

Soprema: Pavawall Smart

- Area = 185.5 m^2
- Supporting Documentation
  - EPD: Product-Specific Type III → **1** Point Climate Health
- MAS = 1.0
- V_{adj} = 185.5

Composite Wood

OSB (manufacturer/product TBD)

- Area = 371.0 m^2
- Supporting Documentation
  - N/A
- MAS = 0.0
- V_{adj} = 0.0

Walls

Trespa: Meteon EDF

- Area = 428.9 m^2
- Supporting Documentation
  - EPD: Product-Specific Type III → **1** Point Climate Health
  - Declare (v2.0) → **1** Point Human Health
  - HPD: Pre-Checked for LEED, min 1000ppm → 1 Point Human Health (Redundant)
  - Wood Products: Legal Sourcing with Disclosure → **1** Point Ecosystem Health
- MAS = 3.0
- V_{adj} = 1,286.7

GmbH: ALUCOBOND A2

- Area = 89.3 m^2
- Supporting Documentation
  - EPD: Product-Specific Type III → **1** Point Climate Health
- MAS = 1.0
- V_{adj} = 89.3

Reclaimed Wood Cladding (manufacturer/product TBD)

- Area = 118.7 m^2
- Supporting Documentation
  - Materials Reuse (100% reused product) → **2** Points Climate Health, **1** Point Ecosystem Health, **2** Points Circular Economy
- MAS = 5.0
- V_{adj} = 593.5

DuPont: Tyvek 2507B

- Area = 185.5 m^2
- Supporting Documentation
    - EPD: Product-Specific Type III → **1** Point Climate Health
- MAS = 1.0
- V_{adj} = 185.5

Guardian Glass: Guardian ExtraClear Float Glass

- Area = 283.1 m^2
- Supporting Documentation
    - EPD: Product-Specific Type III → **1** Point Climate Health
    - Cradle to Cradle: Bronze (Version 3.1) → 1 Point Human Health (Redundant)
    - Cradle to Cradle: Material Health Certificate, Gold (v3.1/v4.0/v4.1) → **3** Points Human Health
- MAS = 4.0
- V_{adj} = 1132.4

Sto: StoTherm Mineral ETICS

- Area = 824.0 m^2
- Supporting Documentation
    - EPD: Product-Specific Type III → **1** Point Climate Health
- MAS = 1.0
- V_{adj} = 824.0

Existing-to-remain Windows (product unknown)

- Area = 235.0 m^2
- Supporting Documentation
    - N/A
- MAS = 0.0
- V_{adj} = 0.0

Overall Results

- A_{tot} = 2,906.5 m^2
- V_{adj} = 4482.4
- R = 1.54
- Assessment Score = **71**

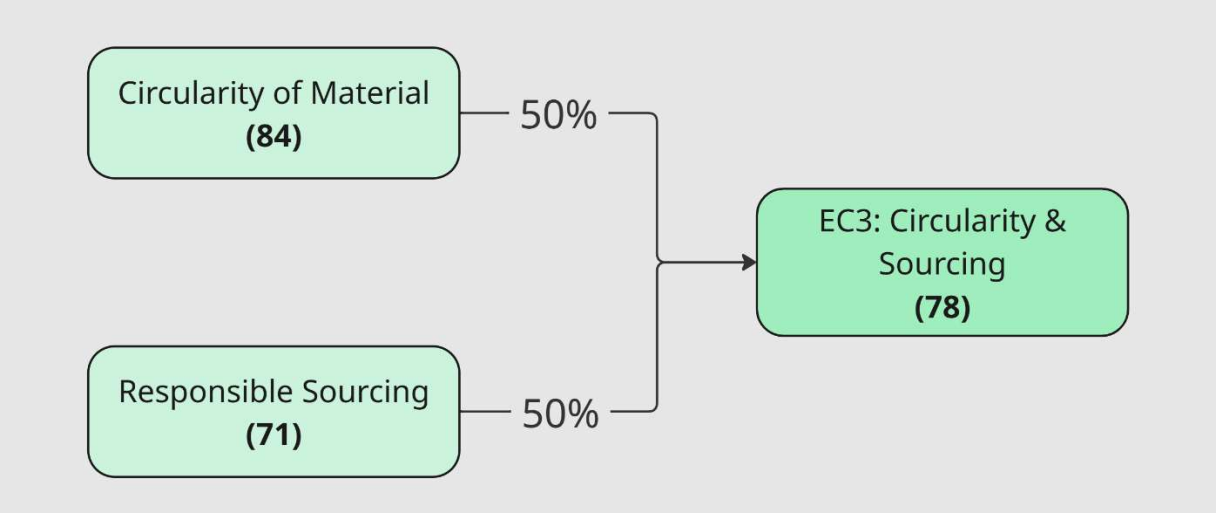


Figure 65 – Case Study Integrated Scoring for EC3 (created with Miro)

Analysis Block Score

Finally, the resulting analysis block THRIVE score for Embodied Carbon, per established integrated measure weighting, is **61 ("Good")**. Results are summarized in Figure 66.

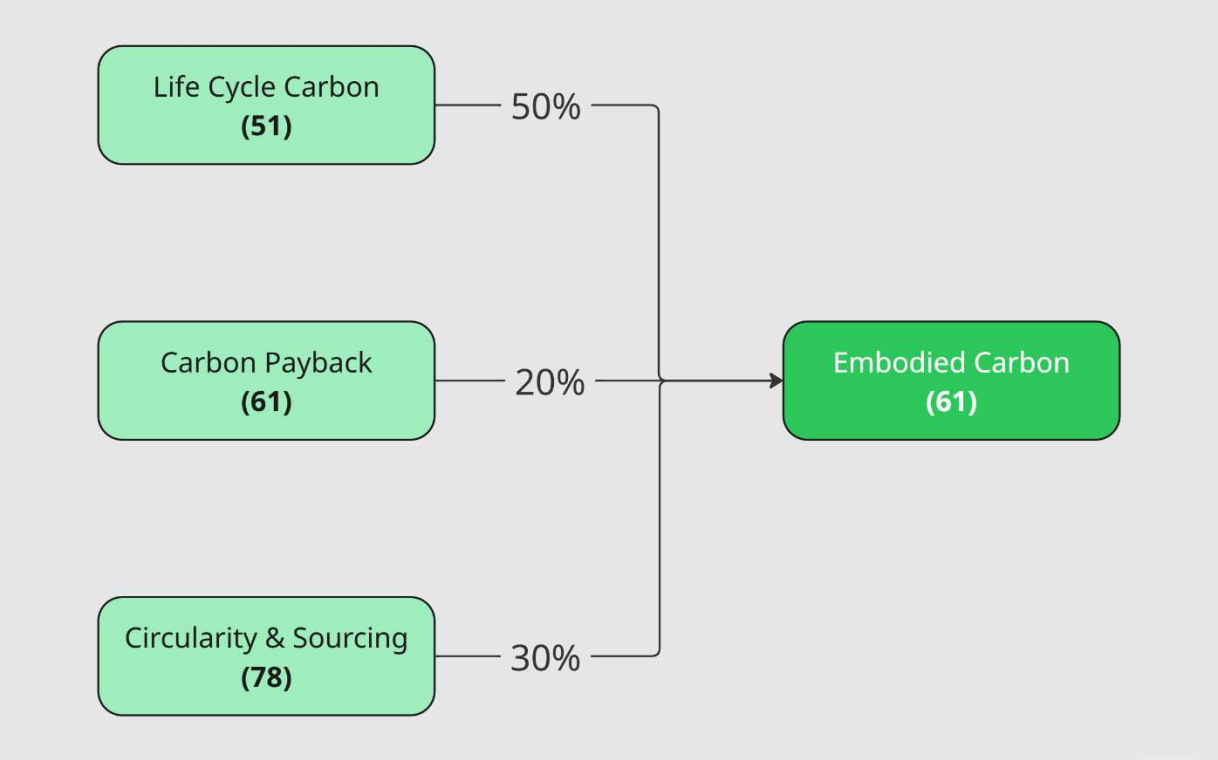


Figure 66 – Case Study Analysis Block-Level Score; Embodied Carbon (created with Miro)

5.3. OPERATIONAL CARBON RESULTS

Pre- and post- renovation energy model simulations have already been completed by the AEGIR project consortium using the software EnergyPlus, providing the necessary results for review and analysis.

Represented in Figure 67, the baseline (pre-renovation) energy model was validated against the pre-renovation building consumption data. The model achieved a remarkable accuracy, with an annual error margin of just 1%. This validation establishes a solid foundation for evaluating the impact of proposed interventions on the building's energy performance and indoor comfort (Herrero et al., 2025).

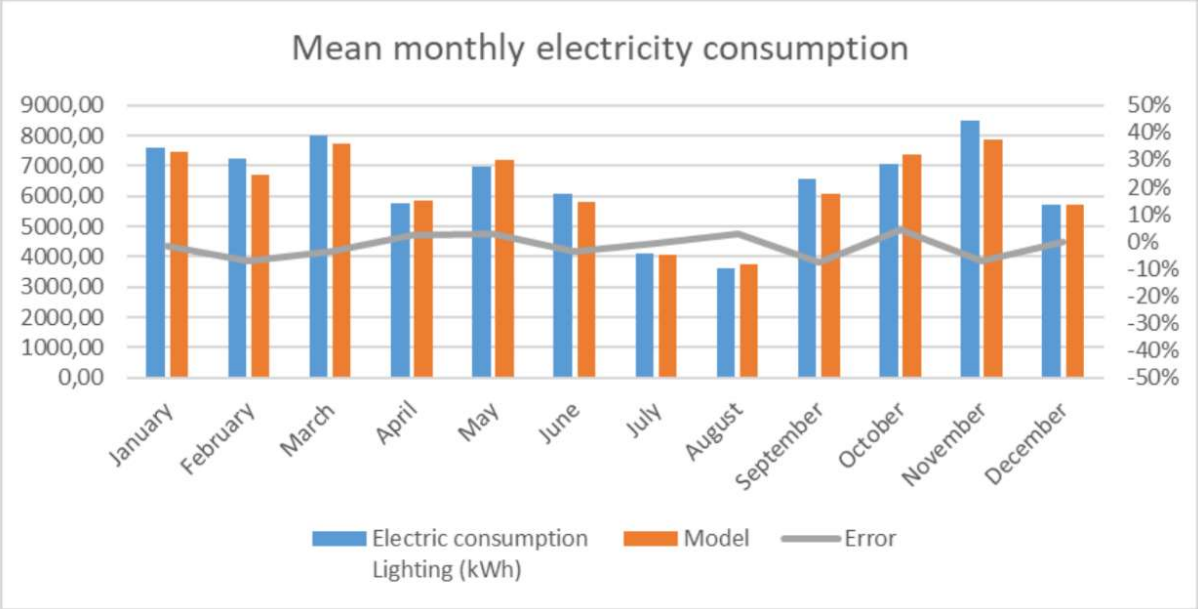


Figure 67 – Case Study Baseline Energy Model Validation (Herrero et al., 2025)

Emissions & Efficiency

Key data used for the calculation of OC1 – Emissions & Efficiency is outlined in Table 37, Table 38, and Table 39, sourced from the AEGIR "Metamodel for building operation" deliverable (Herrero et al., 2025).

Table 37 – Comparison of Case Study Energy Consumption Pre- and Post-Reno; Adapted from (Herrero et al., 2025)

Parameter	Before AEGIR	After AEGIR	% Reduction
Biomass Boiler Consumption (kWh)	145,724.00	14,629.61	90%
Heat Pump Consumption (kWh)	-	11,986.89	-
Ventilation (kWh)	-	55,983.39	-
Lighting and Equipment (kWh)	85,088.54	85,088.54	0%
Instantaneous Renewable Use (kWh)	-	78,069.19	-
Total Consumption (kWh)	230,812.54	89,619.24	61%

Table 38 – Case Study Energy Balance Pre-Renovation; Adapted from (Herrero et al., 2025)

End Use	Energy Source	kWh / Year	Primary Energy (kWh / Year)
CONSUMPTION			
Heating boiler	Biomass	133,093.1	148,119.1
DHW	Biomass	12,630.9	14,047.3
Heat Pump	Electric	-	-
Ventilation	Electric	-	-
Lighting	Electric	49,928.5	94,837.3
Appliances	Electric	35,160.0	66,791.6
GENERATION			
Solar Panels	-	-	-
NET ENERGY			
Total Electricity (ele)		85,088.5	161,628.9
Total Biomass (bm)		145,724.0	162,166.3
Total Energy		230,812.5	323,795.2

Table 39 – Case Study Energy Balance Post-Renovation; Adapted from (Herrero et al., 2025)

End Use	Energy Source	kWh / Year	Primary Energy (kWh / Year)
CONSUMPTION			
Heating boiler	Biomass	1,186.8	1,319.2
DHW	Biomass	12,630.9	14,047.3
Heat Pump	Electric	10,650.2	20,228.0
Ventilation	Electric	55,983.4	106,343.8
Lighting	Electric	49,928.5	94,837.3
Appliances	Electric	35,160.0	66,791.6
GENERATION			
Solar Panels		165,539.9	303,567.2
NET ENERGY			
Total Electricity (ele)		73,665.0	139,910.6
Total Biomass (bm)		13,817.8	15,366.5
Total Energy		87,482.8	155,277.1

Following the most recent guidance from the Catalan Office for Climate Change, the operational emissions calculations utilize an electric grid emissions factor of **0.283 kg CO2e/kWh** (Oficina Catalana del Canvi Climátic, 2025) for Malgrat del Mar. The biomass boiler is understood to use wood-based fuel, corresponding to an emissions factor of **0.320 kg CO2e/kWh** per GHG inventories established by the US Environmental Protection Agency (EPA Center for Corporate Climate Leadership, 2025).

Operational Emissions:

$E_{pre,ele}$ = 85,088.5	kWh/year	Pre-Reno Emissions = 70,711.7 kg CO2e/year
$E_{pre,bm}$ = 145,724.0	kWh/year	Post-Reno Emissions = 25,268.9 kg CO2e/year
$E_{post,ele}$ = 73,665.0	kWh/year	
$E_{post,bm}$ = 13,817.8	kWh/year	
f_{ele} = 0.283 kg	CO2e/kWh	**% Reduction = 64.3%**
f_{bm} = 0.320 kg	CO2e/kWh	**Converted Score = 79**

As the primary energy for each end use was computed as part of the consortium's energy simulations, improvement in current source energy performance could be calculated directly.

Current Source Energy Performance:

Pre-Reno Primary Energy = 323,795.2 kWh/year	**% Reduction = 52.0%**
Post-Reno Primary Energy = 155,277.1 kWh/year	**Converted Score = 71**

For the future source energy performance calculations, Malgrat de Mar's mediterranean climate most closely aligns with ASHRAE Climate Zone 3C, which translates to a BPF of **0.515** considering the school typology and 1.05 major renovation factor.

Future Source Energy Performance:

E_{pre} = 230,812.5	kWh/year	PI = 0.379
E_{post} = 87,482.8	kWh/year	PI_t = 0.588
BPF = 0.515		**% Reduction = 35.6%**
UE_{pre} = 35,160.0	kWh/year	**Converted Score = 36**
RE_{pre} = 195,652.5	kWh/year	

Regarding electrification, while the biomass boiler is designed to supplement the heat pump system for space heating only in colder temperatures, it kicks on starting at < 15°C, making the project ineligible for the full 100 points or any partial points via space heating. Energy simulation results also show the biomass boiler fueling domestic hot water (DHW), making it ineligible for the service water heating points. Modifications to the kitchen are not included in the scope of the renovation, meaning it still runs on combustion and is also not eligible for any points.

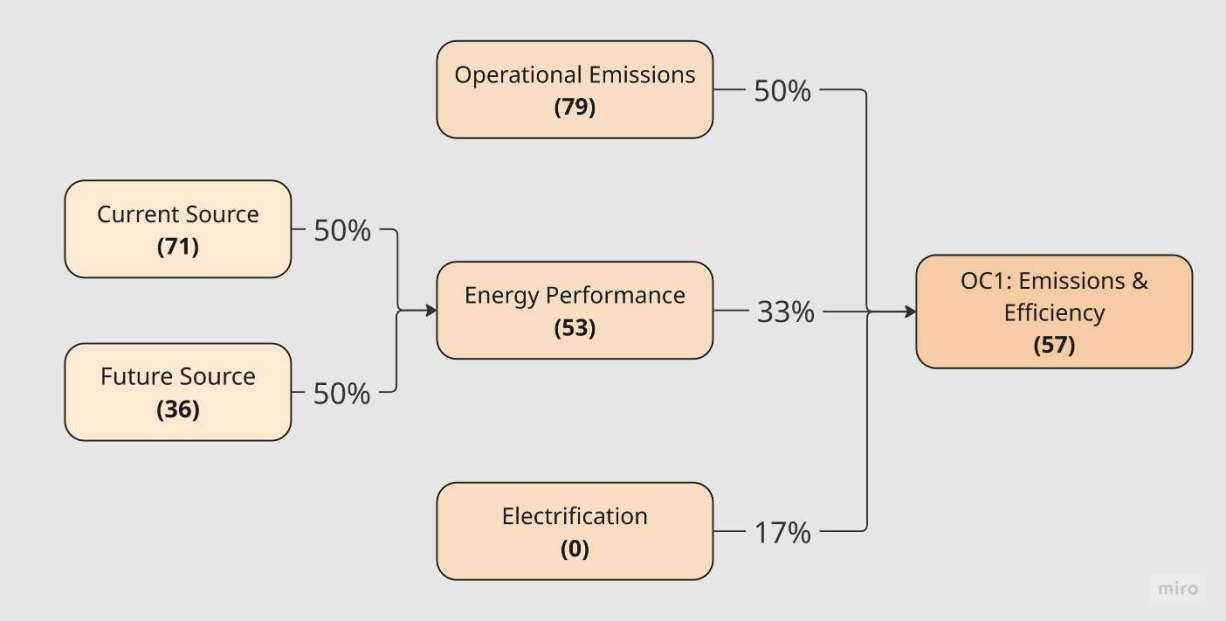


Figure 68 – Case Study Integrated Scoring for OC1 (created with Miro)

Carbon Payback

With a proposed embodied carbon investment of **254,877 kg CO2e** and a net operational carbon reduction of **45,443 kg CO2e / year**, the project achieved a carbon payback period of **5.6 years**, translating to a score of **61** for EC2 and OC2.

Peak Demand

Pre- and post-renovation peak loads for maintaining thermal setpoints were provided by energy simulation results and pre-renovation design schematics for the biomass boiler. Detailed in Table 40, the corresponding reduction in peak demand is **69.8%**.

Table 40 – Case Study Peak Thermal Load Reduction; Adapted from (Herrero et al., 2025)

	Before AEGIR	After AEGIR	% Reduction
Biomass Boiler	200.00 kW	10.95 kW	94.5%
Heat Pump	-	49.48 kW	-
Total	200.00 kW	60.43 kW	69.8%

Balanced ventilation compliance was confirmed via correspondence with a representative from the AEGIR project consortium, thus returning a score of 100. Final OC3 scoring is summarized in Figure 69.

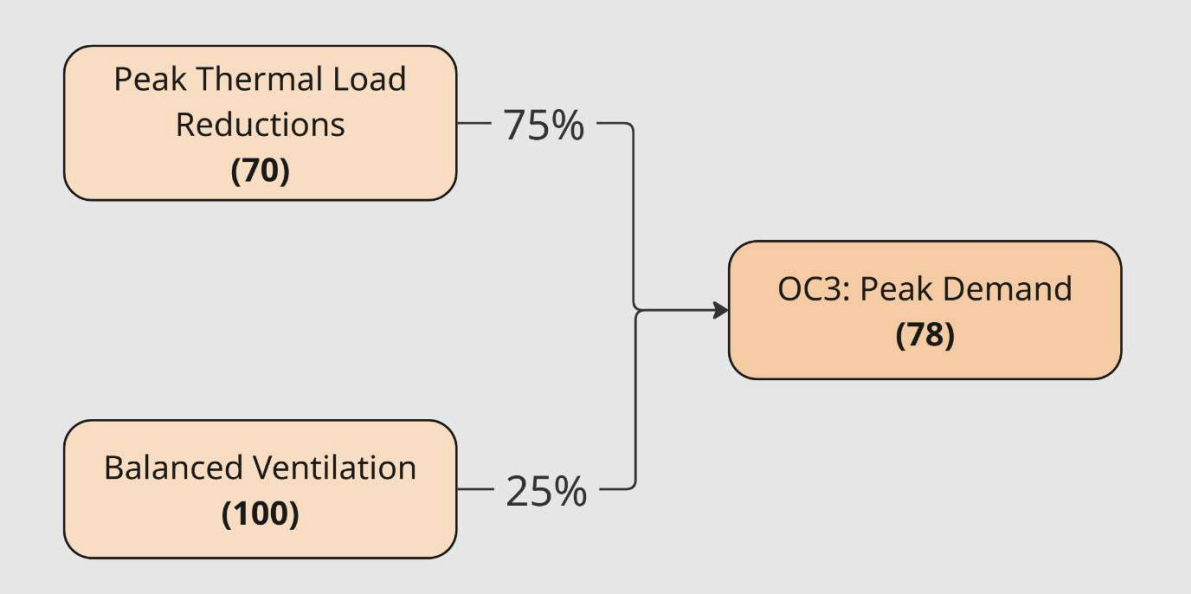


Figure 69 – Case Study Integrated Scoring for OC3 (created with Miro)

Renewable Energy

Key data used for the calculation of OC4 – Renewable Energy comes from the energy simulation results provided by TECNALIA, including energy consumption and generation at hourly time steps for a full year. Key parameters are summarized in Table 41.

Table 41 – Case Study Solar Contribution to Energy Demand; Adapted from (Herrero et al., 2025)

Parameter	Value
Electricity Consumption (kWh/year)	162,307.77
Instantaneous Renewable Use (kWh/year)	72,068.19
Instantaneous Non-renewable Use (kWh/year)	78,069.19
Percentage of Energy Covered by PV (%)	44.4%
Annual Hours of PV Use (hours)	2,006
Annual Hours Covered by PV (hours)	324

44.4% of energy consumption covered by on-site renewables corresponds to 4 raw LEEDv5 points under EAc4 and a converted score of **83** for the renewable energy supply assessment. The baseline metric for the S.2.1-based share of renewables assessment is taken as **25.4%** based on the most recent Eurostat data available for Spain (see Figure 70), translating to a score of **75**.

TIME / GEO	2022	2023	2024
Spain	21.837	24.981	25.417
France	20.330	22.462	23.229
Croatia	28.088	28.088	26.477
Italy	18.826	19.179	19.385
Cyprus	19.427	20.213	20.844
Latvia	43.786	43.250	45.535
Lithuania	29.599	31.927	35.408
Luxembourg	14.286	14.312	14.742
Hungary	15.128	17.117	18.264
Malta	14.040	15.437	17.210
Netherlands	15.291	17.588	20.180
Austria	34.057	41.600	42.951

Figure 70 – Annual Share of Energy from Renewable Sources per EU Member State (Eurostat, 2026)

For the S.2.2-based energy storage assessment, flexibility requirements were calculated for a period of 1 year at an hourly time step based on the available energy simulation results, with an outcome of **86,879 kWh/year**. Considering energy supplied by the installed battery, the contribution of energy storage technology to project flexibility requirements was calculated to be **15,310 kWh/year**. Thus, the energy storage factor = **17.6%**. Considering this calculated value against the 5% baseline, assumed as outlined in Section 4.3, yields a S.2.2 result of **252**, comfortably corresponding to an energy storage score of **100**.

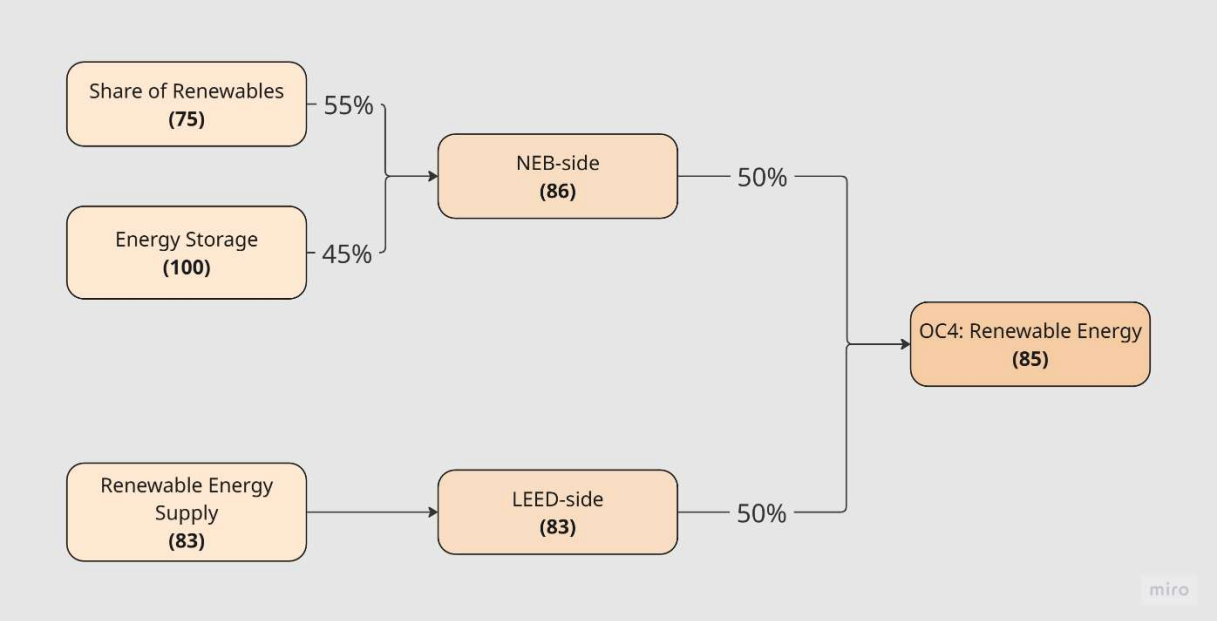


Figure 71 – Case Study Integrated Scoring for OC4 (created with Miro)

Analysis Block Score

Finally, the resulting analysis block THRIVE score for Operational Carbon, per established integrated measure weighting, is **65 ("Good")**. Results are summarized in Figure 72.

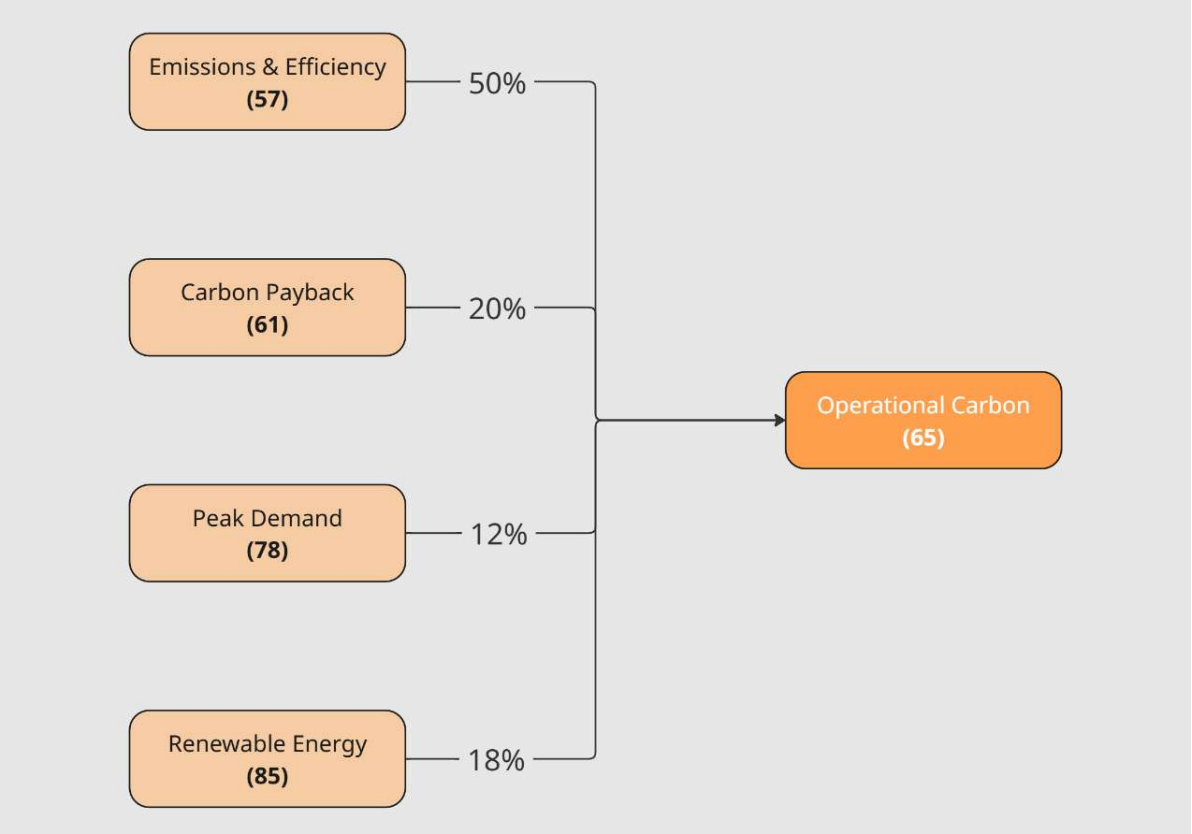


Figure 72 – Case Study Analysis Block-Level Score; Operational Carbon (created with Miro)

5.4. IEQ OUTCOMES

5.4.1. DAYLIGHT RESULTS

A dedicated Revit model for daylight analysis was built compiling case study data from individual Revit models for the existing building and new façade, as well as the most current design drawings. This simplified model is made up of flat walls, floors, roof, and windows to represent only the level of detail necessary for significant daylight implications.

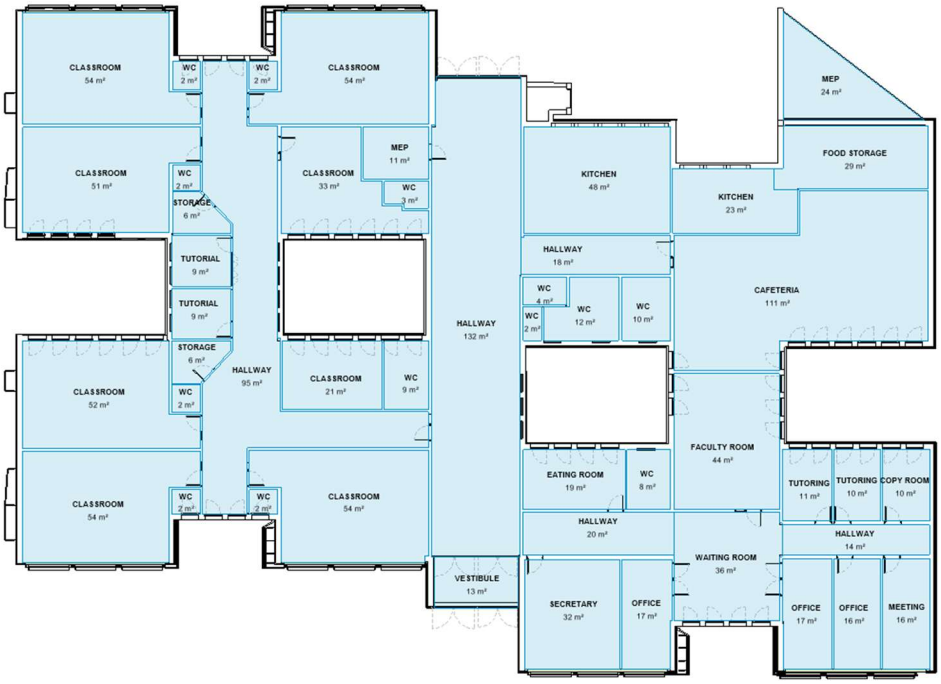


Figure 73 – Case Study Daylight Model Room Layout, Ground Level (created with Revit)

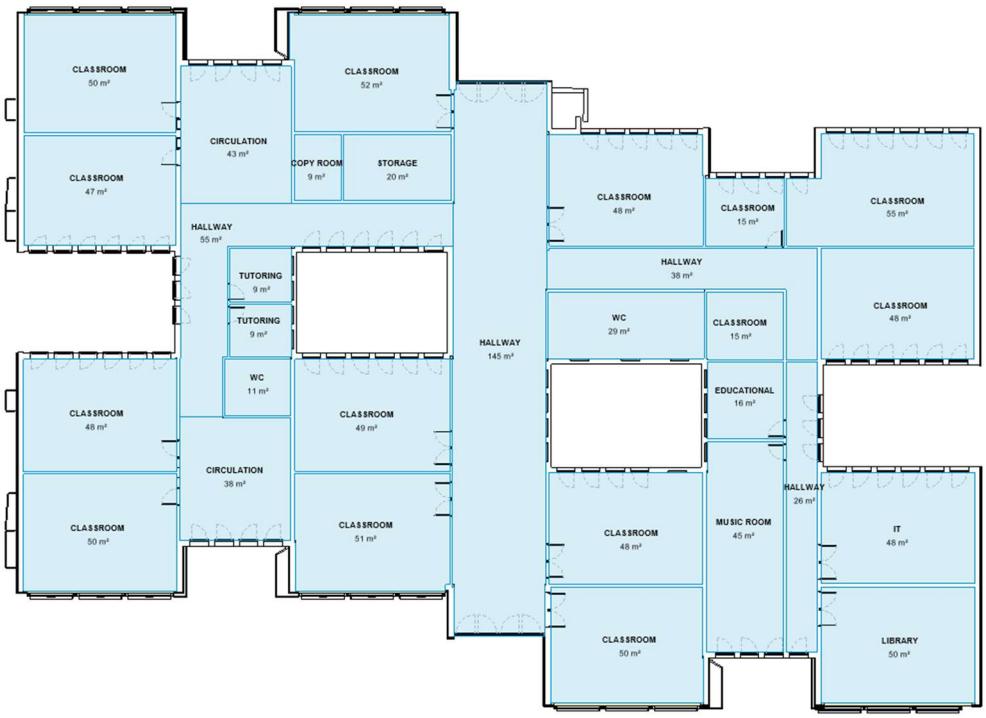


Figure 74 – Case Study Daylight Model Room Layout, Level 1 (created with Revit)

All rooms shown in Figure 73 and Figure 74 are considered regularly occupied with the exception of toilets (WC), hallways, circulation spaces, vestibules, waiting areas, copy rooms, storage rooms (including food storage), and MEP equipment rooms. A full list of rooms with their designation as regularly or non-regularly occupied can be found in Annex A.4.

Using glazing assembly data provided by TECNALIA and considering Guardian ExtraClear (CE) as the specified glass, the VLT of each glazing assembly was calculated using the Guardian Glass Performance Calculator, with results highlighted in Table 42. The layers of each assembly are detailed in Figure 76 and Figure 77.

Table 42 – Visible Light Properties of Case Study Glazing Assemblies (Guardian Glass, n.d.)

GUARDIAN GLASS SUNGUARD | PERFORMANCE CALCULATOR

28.April.2026
By Clark, Tanner

KIWA confirms to have verified the calculation engine of the software Guardian Performance Calculator 4.1 to be compliant to EN 410 and EN 673. TESTED BY kiwa

Spain AEGIR Demo

Make-up Name	Glass 1 & Coating	Glass 2 & Coating	Glass 3 & Coating	Glass 4 & Coating	Visible Light		
					Transmittance	Reflectance	
					Visible (τ_V %)	ρ_V % out	ρ_V % in
Typical	ClimaGuard® 1.0+ (CE) on Guardian ExtraClear (CE)	Guardian ExtraClear (CE)	Guardian ExtraClear (CE)	N/A	73.6	18.0	17.0
Special	Guardian ExtraClear (CE)	SunGuard® SNX 60 (CE) on Guardian ExtraClear (CE)	Guardian ExtraClear (CE)	Guardian ExtraClear (CE)	57.6	12.6	12.5
Doors	Guardian ExtraClear (CE)	SunGuard® SNX 60 (CE) on Guardian ExtraClear (CE)	Guardian ExtraClear (CE)	Guardian ExtraClear (CE)	57.3	12.6	12.5

Calculation Standard: EN 410:2011 / EN 673:2011

The "Special" glazing assembly is found at only facades for the main building entrances as well as the ground-floor vestibule (see Figure 75). The assumed clear, double-glazed assembly for the existing-to-remain windows is understood to generally correspond to a VLT value similar to the "Typical" assembly for new windows. Thus, all remaining windows are represented by the "Typical" assembly, and all exterior doors with glazing by the "Doors" assembly.

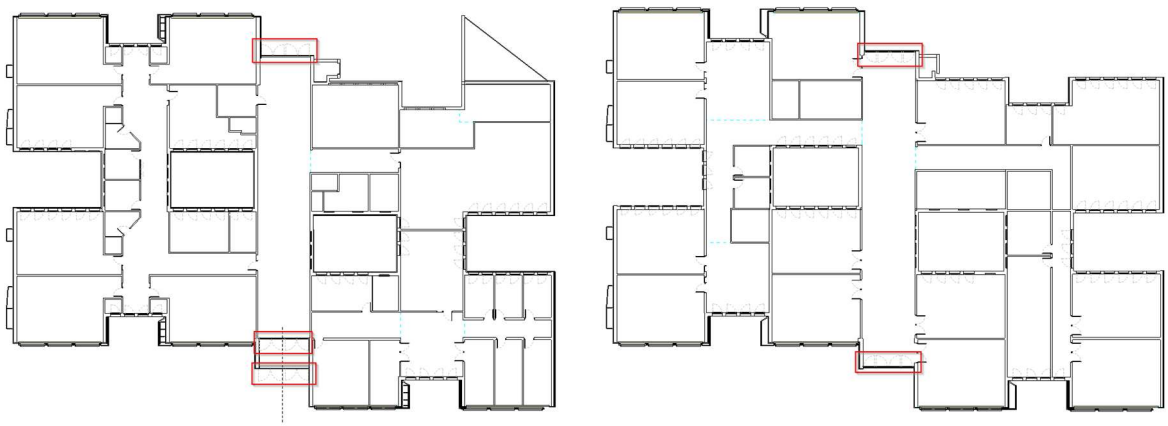


Figure 75 – Location of Case Study Special Glazing Assembly; Ground Level (Left), Level 1 (Right)

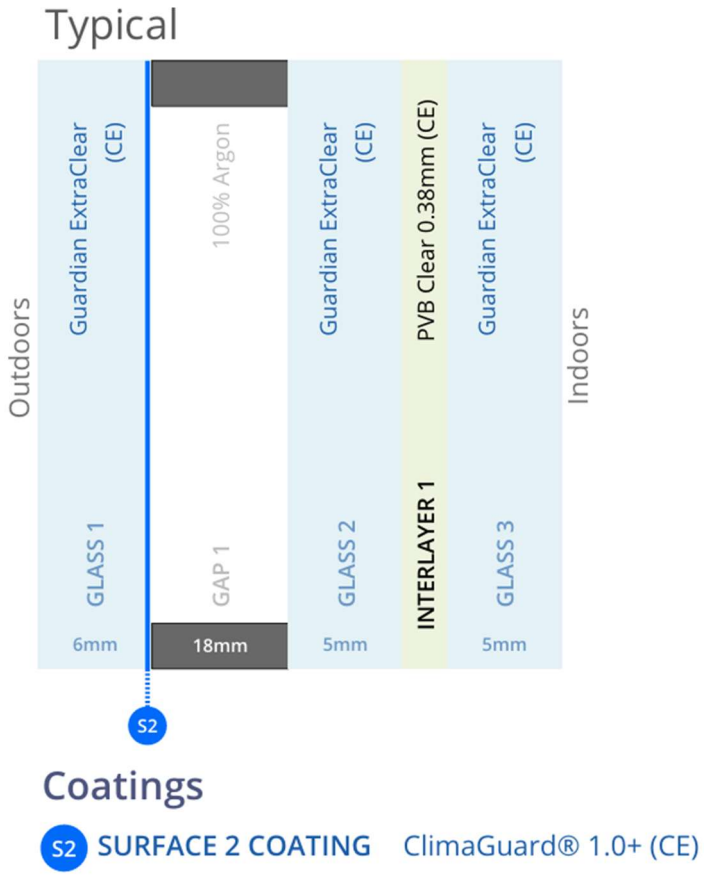


Figure 76 – Case Study Typical Glazing Assembly (Guardian Glass, n.d.)



Figure 77 – Other Case Study Glazing Assemblies (Guardian Glass, n.d.)

Through visual inspection of the surrounding development via Google Maps and Google Earth, the structures highlighted in Figure 78 were identified to have potential shading impact and thus modeled in LightStanza using simple block geometry with a 50% reflectance. Length and width dimensions for the blocks as well as placement relative to the case study building were estimated using measurements from Google Earth. Block heights were estimated via visual inspection of the number of stories in each building assuming 3.0-3.5 meters per story.



Figure 78 – Structures Adjacent to Case Study Building, Modeled in Daylight Simulation; Adapted from Google Maps with Bluebeam Revu

Default surface reflectance values were used for all walls, ceilings, and floors, as well as the modeled ground plane. Climate data for Girona available through LightStanza was employed considering it is the nearest available station and matches what was used by the AEGIR project consortium for energy simulations.



Figure 79 – Case Study LightStanza Daylight Simulation Model (LightStanza, n.d.-b)

Overall results of the daylight simulation consist of: **sDA = 30.5%** | **ASE = 7.0%**, corresponding to a THRIVE score of **31**. Sensitivity checks removing the adjacent structure block geometry and setting the blinds to always-open had minimal impact on the results. Breakdown by floor is represented in Figure 80 and Figure 81. Room-by-room results can be found in Annex A.5.

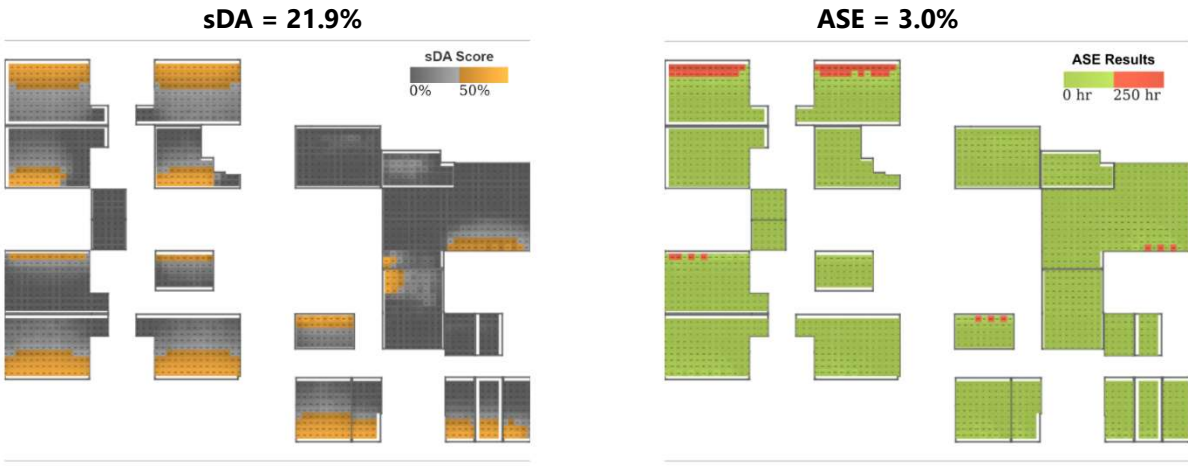


Figure 80 – Case Study Daylight Simulation Results (LightStanza, n.d.-b), Ground Level; sDA (Left), ASE (Right)

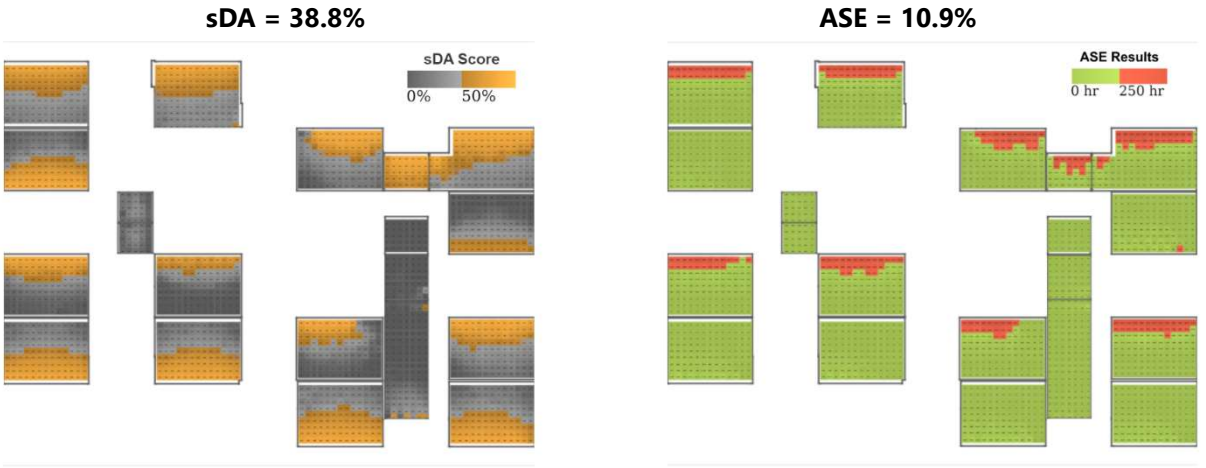


Figure 81 – Case Study Daylight Simulation Results (LightStanza, n.d.-b), Level 1; sDA (Left), ASE (Right)

The total regularly occupied floor area for the project, per data exported from the daylight simulation Revit model, is 1,558 m^2. Comparing this value to the 348 m^2 of total window area calculated from material quantity takeoffs as part of the embodied carbon analysis results in a glazing : floor area ratio of **22.3%**, translating to a Glazing Design Strategies score of **67**. Furthermore, the project was verified to include **manually operable** shading at all windows serving regularly occupied spaces to address glare, translating to a Shading Design Strategies score of **67** and a Glare Assessment pass for a score of **100**.

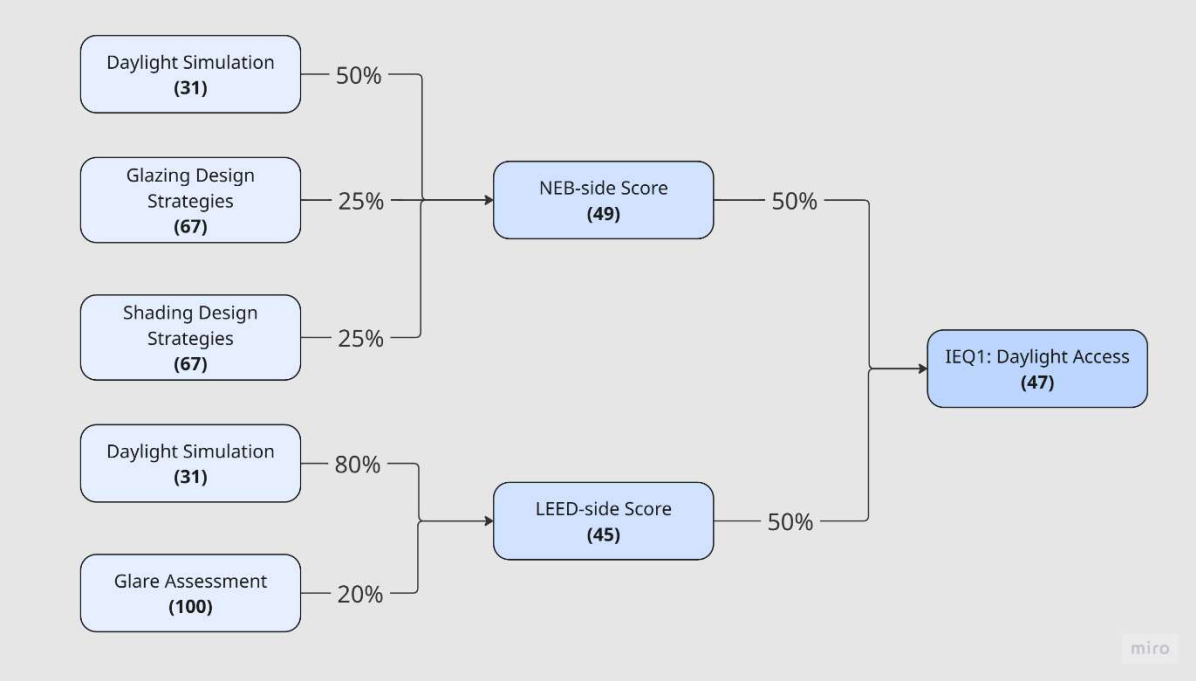


Figure 82 – Case Study Integrated Scoring for IEQ1 (created with Miro)

5.4.2. THERMAL COMFORT RESULTS

Considering the mixed-mode ventilation strategies employed by the post-renovation building, which include mechanical heating in winter and mechanical cooling in summer, the predicted mean vote (PMV) method has been followed to assess Seasonal Thermal Comfort. Inputs are based on the following case study design data and assumptions outlined in Section 4.3. The results show compliance under cooling-mode conditions, but not heating-mode. As all spaces in the building operate under the same design conditions, this corresponds to a score of 100 for cooling-mode compliance and 0 for heating-mode compliance. Based on roughly 5.5 months spent in heating mode and 4.0 months in cooling mode under the same hourly schedule, with the remaining 2.5 months un-operational during summer, heating-mode compliance is weighted at 58% and cooling-mode compliance at 42%. Time of operation and setpoints for each mode are shown in Figure 83.

	Heating	Cooling
Availability	From 1st January to 15th April and from 31st October to 31st December	From 15th of April to 20th June and from 8th September to 31st October
Setpoint	21°C from 8am to 6 pm	25°C from 8 am to 6 pm

Figure 83 – Case Study Heating- & Cooling-mode Setpoints and Seasonal Operation (Herrero et al., 2025)

Per the project's HVAC Executive Report, maximum air speed in occupied zones = 0.25 m/s (TESCOR Enginyeria, 2025). Remaining inputs for PMV calculations with the CBE Thermal Comfort Tool have been determined as outlined in Section 4.3. Results for heating and cooling mode are shown in Figure 84 and Figure 85, respectively.

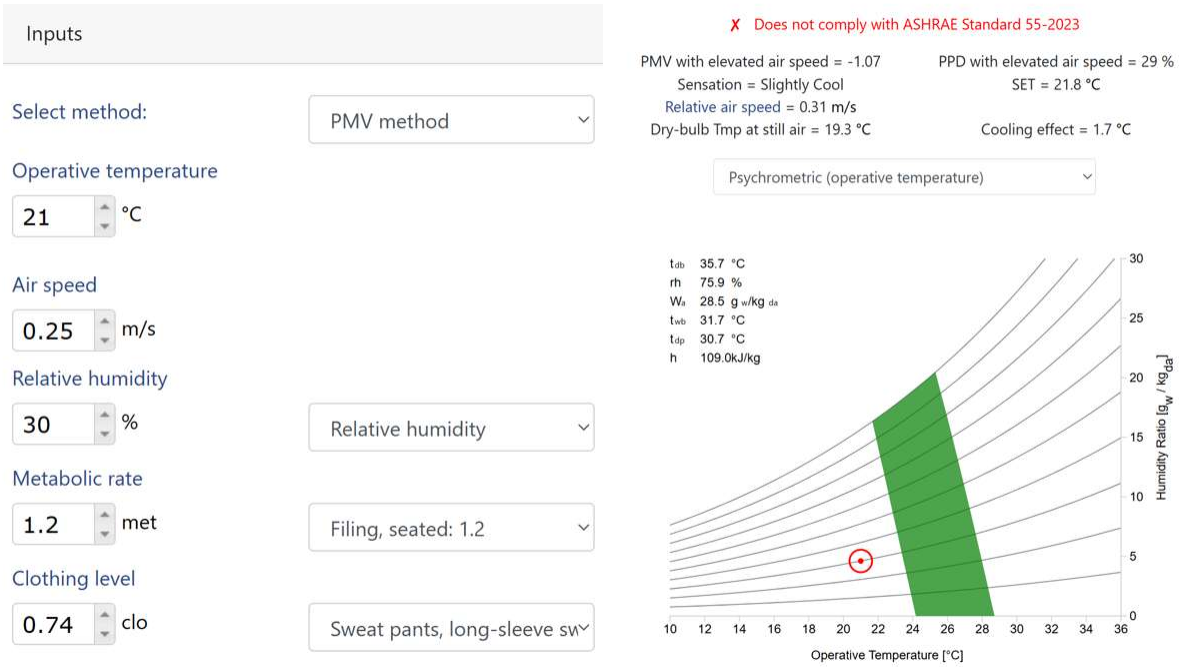


Figure 84 – Case Study PMV Thermal Comfort Results; Heating-Mode (Tartarini et al., 2020)

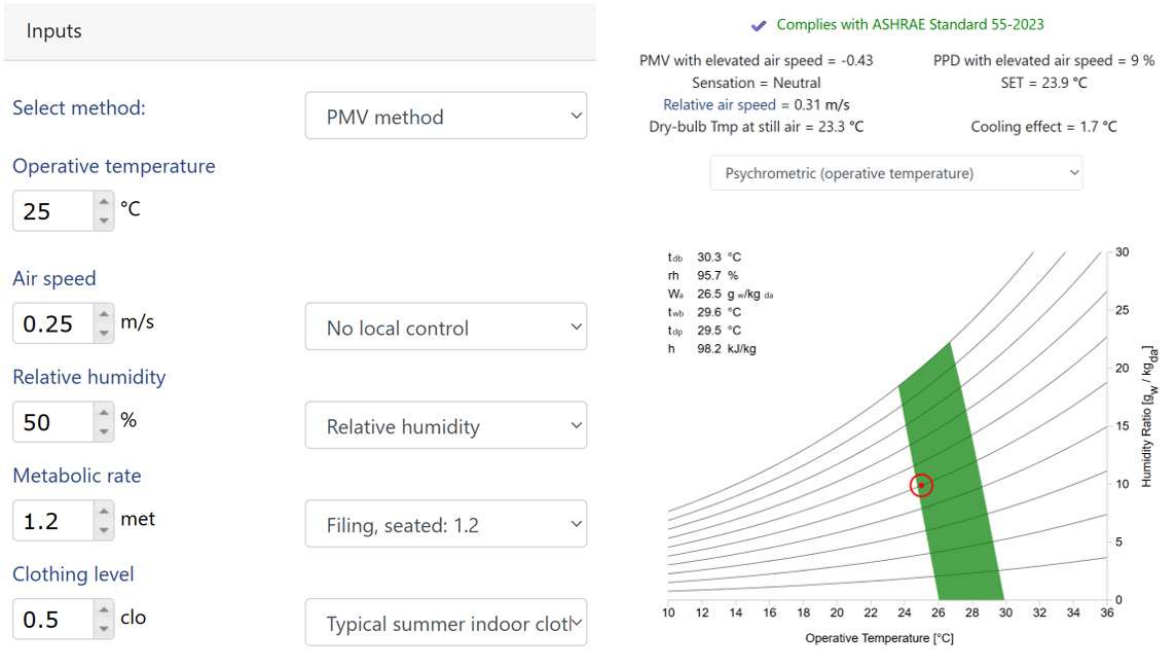


Figure 85 – Case Study PMV Thermal Comfort Results; Cooling-Mode (Tartarini et al., 2020)

Via a review of the building management system (BMS) installation plans, 38 out of the 42 total regularly occupied spaces were identified to have temperature control devices (90.4%) via either pre-existing radiators, airflow control devices installed as part of AEGIR, or both. A room-by-room list for the temperature control device check can be found in Annex A.4. A review of the MEP plans identified 40 thermal zones serving regularly occupied spaces, of which only 1 (serving the cafeteria) exceeds 60 m^2,

translating to 97.5% of zones compliant and meeting the assessment prerequisites. The total area of regularly occupied space within the building is 1,558 m^2, which when divided by 40 zones yields a value of **one zone per 39 m^2** and a corresponding thermal zoning score of **85**.

As the project does not employ any radiant heating or cooling systems, the score for radiant thermal comfort is **0**. Furthermore, the mechanical ventilation system lacks humidity control capabilities compliant with the humidity control assessment. As the necessary tools and data to conduct humidity modeling are not available for this MBUILD final dissertation or the case study project, and post-reno sensor measurements not possible considering the project timeline, the humidity score is also **0**.

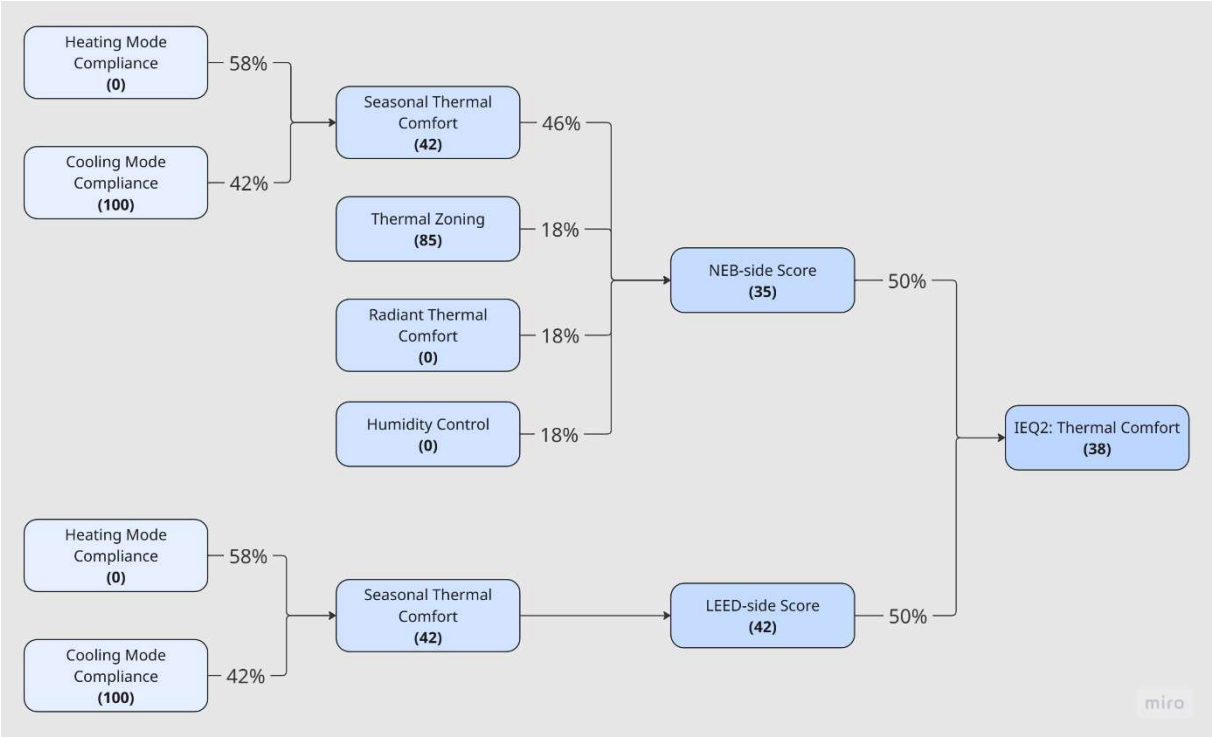


Figure 86 – Case Study Integrated Scoring for IEQ2 (created with Miro)

5.4.3. INDOOR AIR QUALITY RESULTS

The IAQ analysis is conducted via a review of the mechanical drawings and specifications, pre-renovation sensor data, as well as the results of ventilation and design pollutant calculations already completed by the AEGIR project consortium.

Considering the project has only pre-renovation concentration data for CO2, no other pollutants are considered as part of the Air Pollutant Concentration assessment. Data from pre-renovation sensors identifies highest CO_2 concentrations during the winter months, suggesting that ventilation is reduced to preserve indoor thermal comfort. Multiple CO2 concentration measurements exceeding 4,000 ppm are observed during these months. Therefore 4,000 ppm is taken as the baseline value for CO2 concentration.

As outlined in Section 4.3, the post-renovation maximum indoor CO2 concentration is calculated as an assumed representative outdoor concentration of 439 ppm, plus 500 ppm. The results are summarized as follows:

- C_b = 4,000 ppm
- C_p = 939 ppm
- % Improvement = 76.5%
- Pollutant Score = Air Pollutant Concentration Score = **93**

Via correspondence with design team members from the AEGIR project consortium, the project was verified to have existing walk-off mats to remain at all primary building entrances, earning an Entryway Systems score of **100**.

The single HVAC air handling unit (AHU) serving the project has a filtration media class rating of **ePM1: 89%**, exceeding the minimum threshold and earning a Filtration score of **100**. The AHU was sized to meet Spanish RITE code requirements for indoor air quality under category IDA 2, with a nominal outdoor air intake of 26,700 m^3/h or 7,417 L/s. Airflow to individual zones is controlled by variable air volume (VAV) modules responding to CO_2 and temperature sensors. Zone-by-zone calculations per ASHRAE Standard 62.1, Section 6, ventilation rate procedure (VRP), result in a minimum outdoor air intake of 6,592 L/s for the building. Thus, the provided 7,417 L/s exceeds this value by **12.5%**, yielding a score of **100** for Ventilation and **42** for Enhanced Ventilation. Inputs for the VRP calculations can be found in Annex A.6.

The project has no design specifications or sensors in place for pollutants besides CO2, and the construction timeline does not allow for post-renovation testing as part of this MBUILD final dissertation. Therefore, the project receives as score of **0** for Pollutant Design Limits.

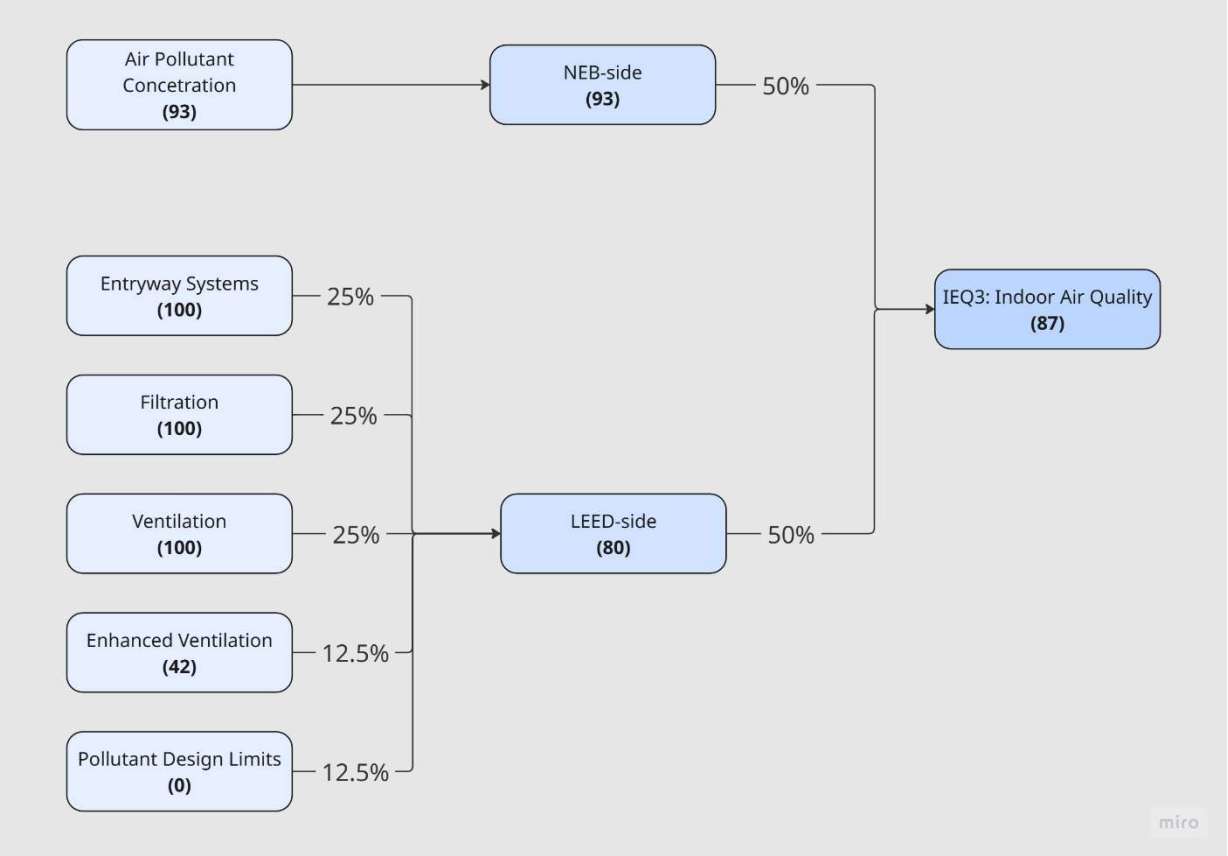


Figure 87 – Case Study Integrated Scoring for IEQ3 (created with Miro)

Analysis Block Score

Finally, the resulting analysis block THRIVE score for Indoor Environmental Quality, per established integrated measure weighting, is **60 ("Acceptable")**. Results are summarized in Figure 88.

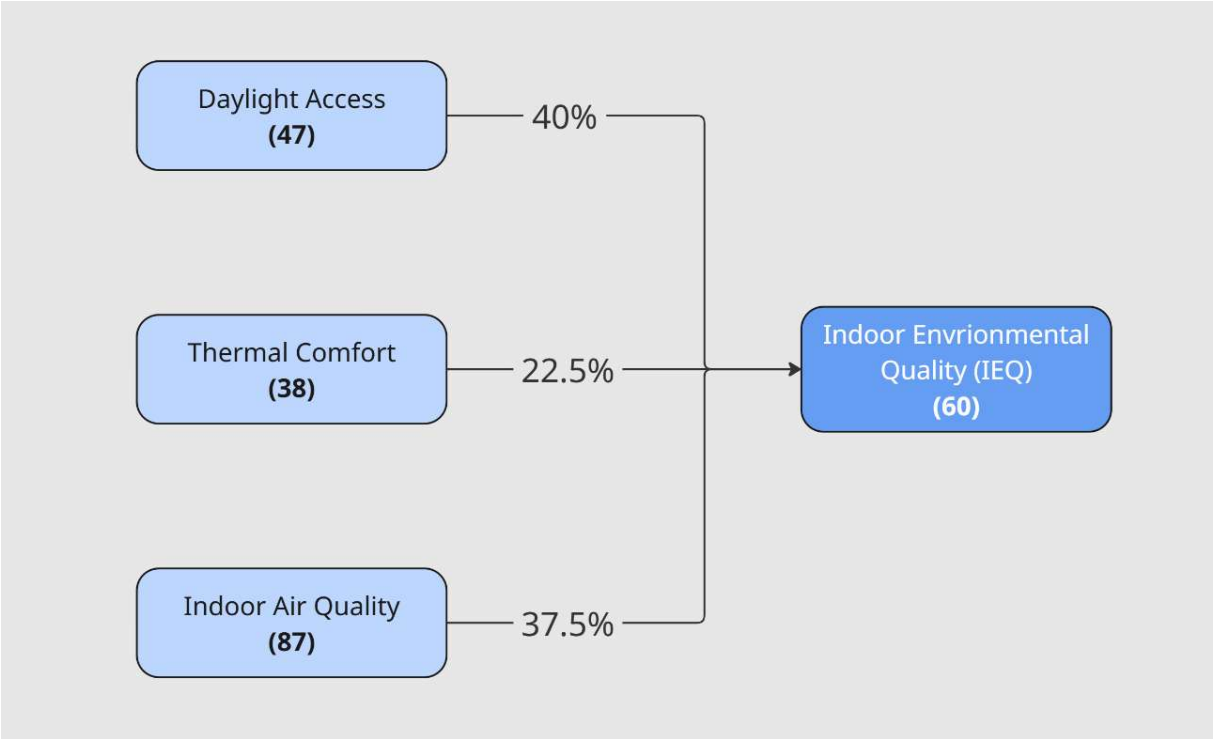


Figure 88 – Case Study Analysis Block-Level Score; IEQ (created with Miro)

5.5. RESILIENCE, AESTHETICS, & INCLUSIVENESS RESULTS

Hazard Resilience

Using the same cladding area values gathered via quantity takeoffs for the Embodied Carbon assessments, existing roof area from the provided Revit model, and available product data, the fire and water resistance results are determined as outlined in Table 43. Based on building height and typology, the minimum threshold for fire-resistant compliance among the outer wall layers is Class B-s3, d2. Product data for the HPL Cladding, Composite Cladding, and ETICS were available to verify the criteria. The existing roof is considered fire-resistant based on the assumptions outlined in Section 4.3. The HPL and Composite cladding are deemed water-resistant as "dense, non-porous external panels (e.g. *metal*, *HPL*, fiber-cement) that are fixed and sealed to prevent significant water ingress". As the ETICS is made with mineral wool, an open-cell insulation material, it cannot be deemed water-resistant. Results for the Reclaimed Wood Cladding are per assumptions outlined in Section 4.3.

Table 43 – Case Study Envelope Fire and Water Resistance Results Summary

Wall Typology – Outer Layer	Area (m2)	Fire-Resistance Compliance | Rating	Water-Resistant?
AEGIR - HPL Cladding[a]	186.9	Yes | B-s1, d0	Yes
AEGIR - Composite Cladding[b]	16.9	Yes | A2-s1, d0	Yes
ETICS+C - HPL Cladding[a]	483.9	Yes | B-s1, d0	Yes
ETICS+C - Reclaimed Wood Cladding	237.3	No | Unknown	No
ETICS+C - Composite Cladding[b]	72.5	Yes | A2-s1, d0	Yes
ETICS - Uncovered[c]	422.0	Yes | A2-s1, d0	No
Roof Covering	**Area (m2)**	**Fire-Resistant?**	**Water-Resistant?**
Existing Clay Finish	1,263.7	Yes	-
Results			
Total Façade Area		1,419.5 m^2	
Water-Resistant Façade Area		760.1 m^2	
% Water Resistant		**53.6%**	
Total Envelope Area (Façade + Roof)		2,683.2 m^2	
Fire-Resistant Envelope Area		2,445.8 m^2	
% Fire Resistant		**91.2%**	

a) TRESPA METEON EDF (TRESPA METEON MATERIAL PROPERTY DATASHEET, 2022).

B) ALUCOBOND A2 (3A Composites, 2026)

c) StoTherm Mineral (Sto, 2026)

The typical assembly for all new windows is the COR 70 Industrial system by Cortizo, which has been verified to have a Class C5 wind resistance rating (CORTIZO, n.d.). Corresponding to resistance against a 2000 Pa test pressure, the system comfortably exceeds the following design wind pressures for the project calculated by the AEGIR project consortium (Curiel Martín, 2025).

- Wind suction at corner: -970.7 Pa
- Wind suction in typical area: -660.0 Pa
- Wind pressure in typical area: 652.3 Pa

Thus, all new windows on the project (172 in total) are considered to meet the wind resilience criteria. Considering a lack of product data for the existing to remain windows (67), these are conservatively

assumed to not meet the wind resilience criteria, resulting in **72.0%** compliance for the Wind Resilient Windows assessment. Via correspondence with a representative from the AEGIR project consortium, all existing windows were confirmed to be manually operable. Furthermore, the new automated windows were verified to have manual control in addition to the operation by the BMS. With the remaining new windows also manually operable, the project achieves 100% compliance for the Operable Windows assessment.

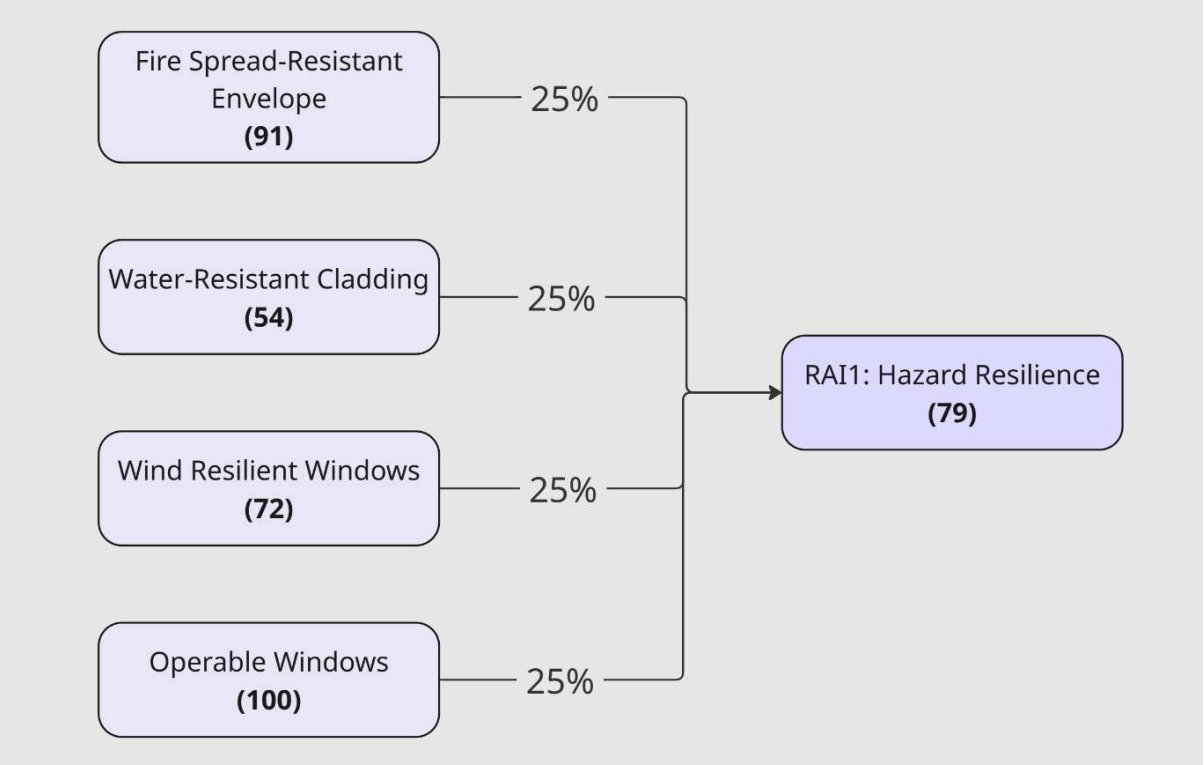


Figure 89 – Case Study Integrated Scoring for RAI1 (created with Miro)

Visual Experience

Considering construction of the case study project is ongoing at the time of this MBUILD final dissertation, the Visual Experience assessment is conducted via a review of renderings provided by TECNALIA. This review first identified the presence of each of the four Order principles, yielding an assessment score of **100**.

Axis composition can be most clearly seen across the front façade with the symmetric alignment of glazed openings on each side of the main building entrance. The entrance block also serves as a focus point for the use of hierarchy. Centered, slightly projected, and with prominent signage, allows the entrance block to dominate over the repeated classroom wings. The recessed timber-clad "portals" to each side serve as secondary focal points, interrupting the white HPL horizontal bars and marking important lateral secondary circulation nodes. Zooming in, transformation can be seen within each window bay, where white-clad window modules are all based on the same rectangular form but are stretched and modulated differently at corners and edges while keeping a coherent pattern of recessed openings. Furthermore, each timber-lined portal is essentially further transformation of a typical window bay, pulled deeper and wrapped in a different material while following the same structural rhythm. Examples of rhythm and repetition can be seen throughout the renderings, as this principle is inherently present in the prefabricated panel approach to renovation. One particularly clear example unique to the case study project is the use of perforated aluminum mesh fins of a consistent size and shape but varied spacing to create intriguing architectural rhythm.

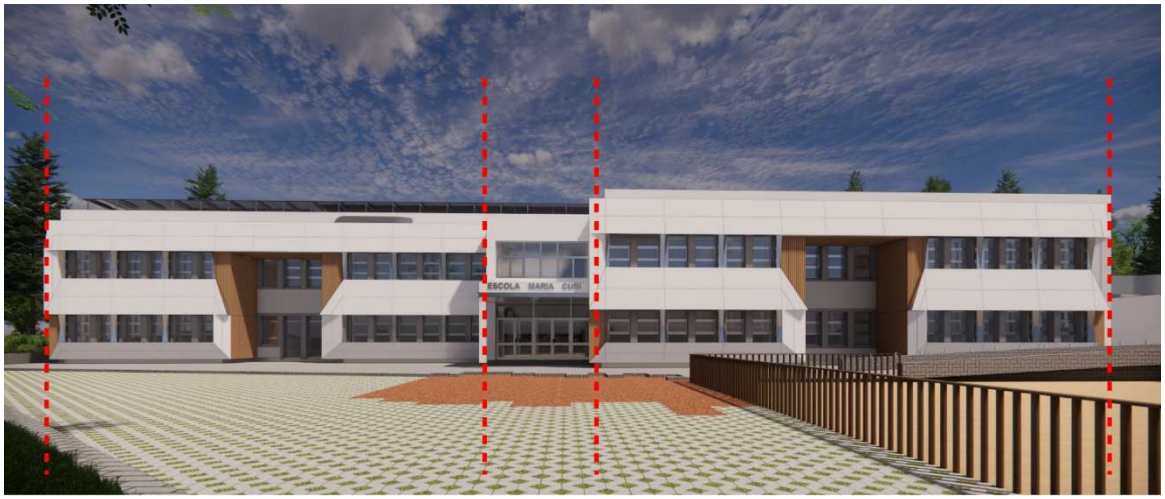


Figure 90 – Case Study Presence of Axis Composition & Hierarchy



Figure 91 – Case Study Presence of Transformation



Figure 92 – Case Study Presence of Rhythm / Repetition

The review identified the presence of three out of the four Contrast principles, yielding an assessment score of **75**. As the building largely consists of similar masses, using a lighter color pallet, consistent glazing, and repetitive volumes throughout, there was not deemed to be sufficient presence of the massing principle to award the associated points.

The contrast of vertical and horizontal lines is present throughout the envelope, particularly noticeable at the scale of an individual panel. Here, the vertical lines of the reclaimed timber cladding are clearly set against the horizontal or angled breaks in the white HPL panels wrapping around the recessed openings. The distinct color and texture between the timber and HPL seen here also exhibits the presence of the materials principle. Regarding the contrast of surfaces & apertures, the recessed openings of the AEGIR panels most clearly support the presence of this principle.



Figure 93 – Case Study Presence of Lines and Spaces & Materials



Figure 94 – Case Study Presence of Surfaces and Apertures

The review identified the presence of each of the four Transparency principles, yielding an assessment score of **100**.

Transparent ground floor glazing used at all building facades and providing views to the surrounding landscaping verifies the presence of both the interior-exterior visual contact and opening principles. Transparency was verified through the glazing VLT as calculated in Section 5.4.1, rather than a purely visual review of the renderings.

Regarding play of light and shadow, the differing textures between cladding types along with recessed openings and portals facilitate aesthetic variation in the appearance of light and shadow across the exterior envelope over the course of a day and throughout the year.

The presence of light-shadow effects is demonstrated through various strategies to modulate incident sunlight in the renovated envelope. Namely, the recessed openings, main entrance canopy overhangs created by the roof and angled HPL cladding, serve to improve interior conditions near the façade through mitigated glare. A sun study analysis was conducted by the AEGIR project consortium considering different inclinations for the HPL cladding, informing the final orientation optimized for shading performance.



Figure 95 – Case Study Presence of Openings towards natural areas



Figure 96 – Case Study Presence of Play of Light and Shadow; Rendering (Left), Varying Cladding Textures (Right)

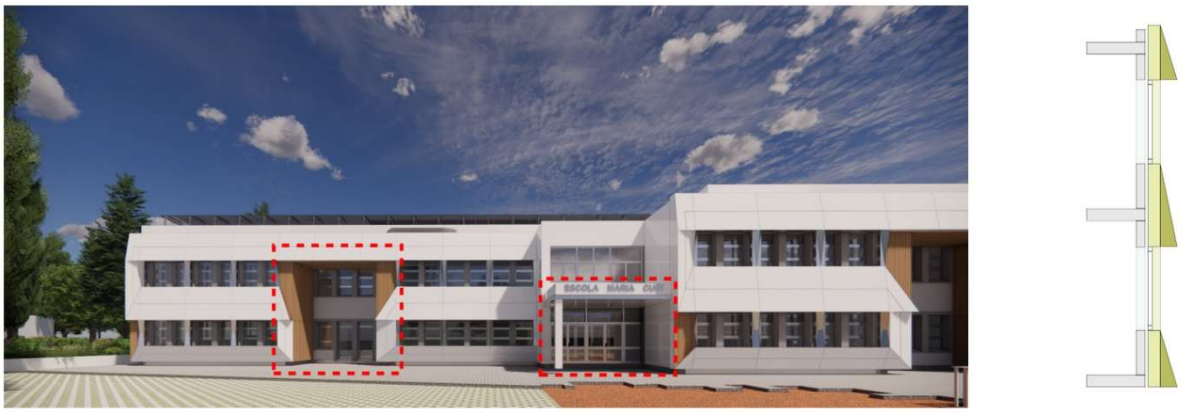


Figure 97 – Case Study Presence of Light-Shadow Effects; Canopies/Overhangs (Left), Angled Cladding (Right)

The Novelty review, particularly aided by conversations with the project architectural coordinator from TECNALIA, verified the presence of aesthetic pioneering solutions but not meaningfully integrated artwork, resulting in an assessment score of **50**.

The project has interior and potentially art-related scope still in development, but no clear plan for "meaningfully-integrated" artwork. Thus, the conservative decision was made to not exempt meaningful artwork from the novelty assessment or claim any points for it. Regarding aesthetic pioneering, the following strategies have been identified:

- The use of angled cladding to create forms capable of hiding the inherently fragmented nature of prefabricated panel construction and create a homogenous appearance across the envelope.
- The layout of windows within the AEGIR panel diverges from standard practice by combining what is typically two separate frames into a single, larger opening. This creates a more continuous, open face towards the public, a key benefit for the perception of a school facility.
- The façade and roof PV packages where designed and integrated under a single architectural vision.

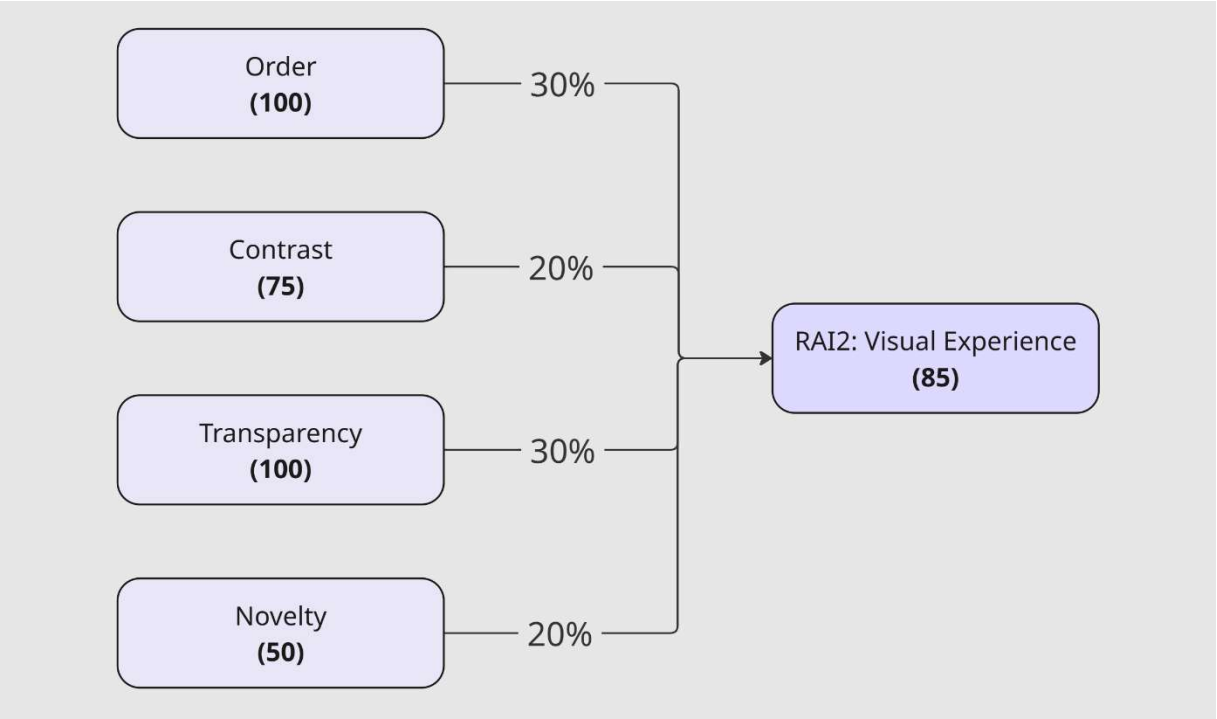


Figure 98 – Case Study Integrated Scoring for RAI2 (created with Miro)

Equitable Accessibility

Provided BoQ data confirmed each leaf of the main entrance doors to have a 1.2 m nominal width and 1.5 mm thick cold-rolled steel profiles. Between this data and scaled measurements from door detail elevations showing greater than 1.0 m for internal frame-to-frame width (see Section 4.3), these doors were deemed to meet the Door Clear Width requirement. As the project has only one typology for main entrance doors this compliance translates to a score of **100**.

The doors are not designed to include wave-to-open, vertical hand press, or foot press features compliant with Accessible Door Operation. Regarding signage and wayfinding, discussions with the project architectural coordinator guided the decision to include these assessments in the case study despite not meeting compliance. Along with the official languages of Catalan and Spanish in Malgrat de Mar, there are also significant English- and Arabic-speaking populations. No applicable signs within the project are expected to communicate information in each of these languages. Furthermore, no applicable signs are expected to include a secondary sensory format such as audible or tactile to communicate information. Thus, the remaining Equitable Accessibility assessments yield a score of 0. Results for the measure are summarized in Figure 99.

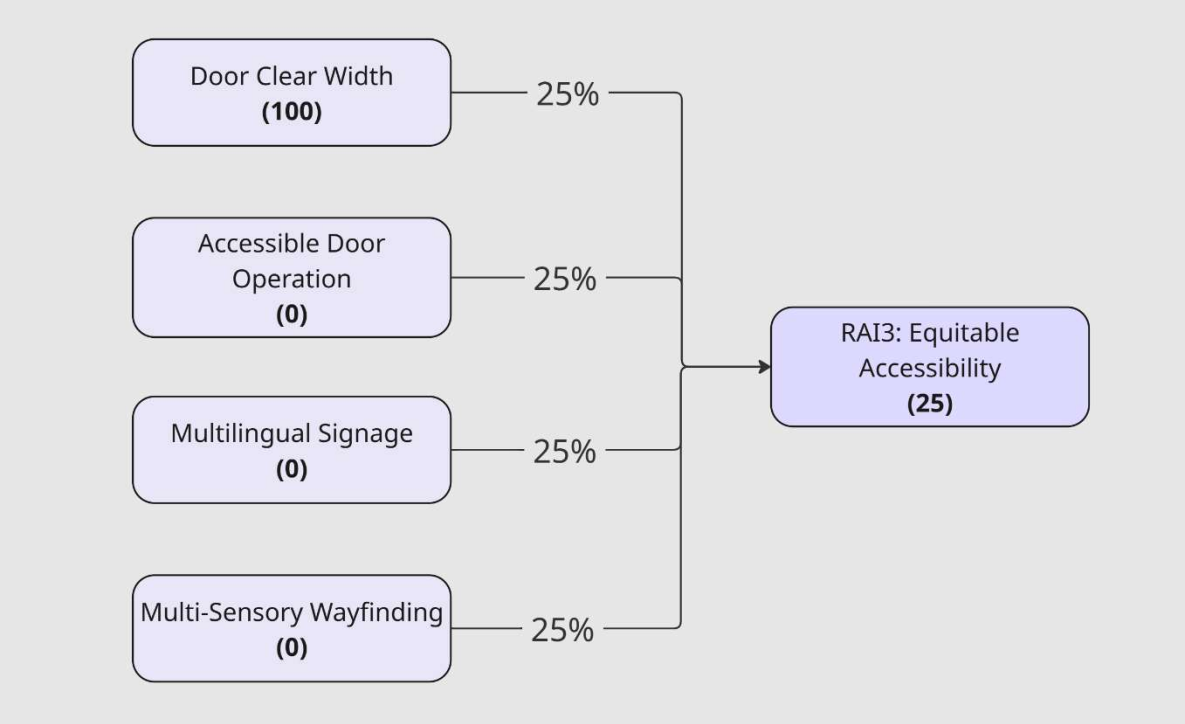


Figure 99 – Case Study Integrated Scoring for RAI3 (created with Miro)

Analysis Block Score

Finally, the resulting analysis block THRIVE score for Resilience, Aesthetics, and Inclusiveness, per established integrated measure weighting, is **68 ("Good")**. Results are summarized in Figure 100.

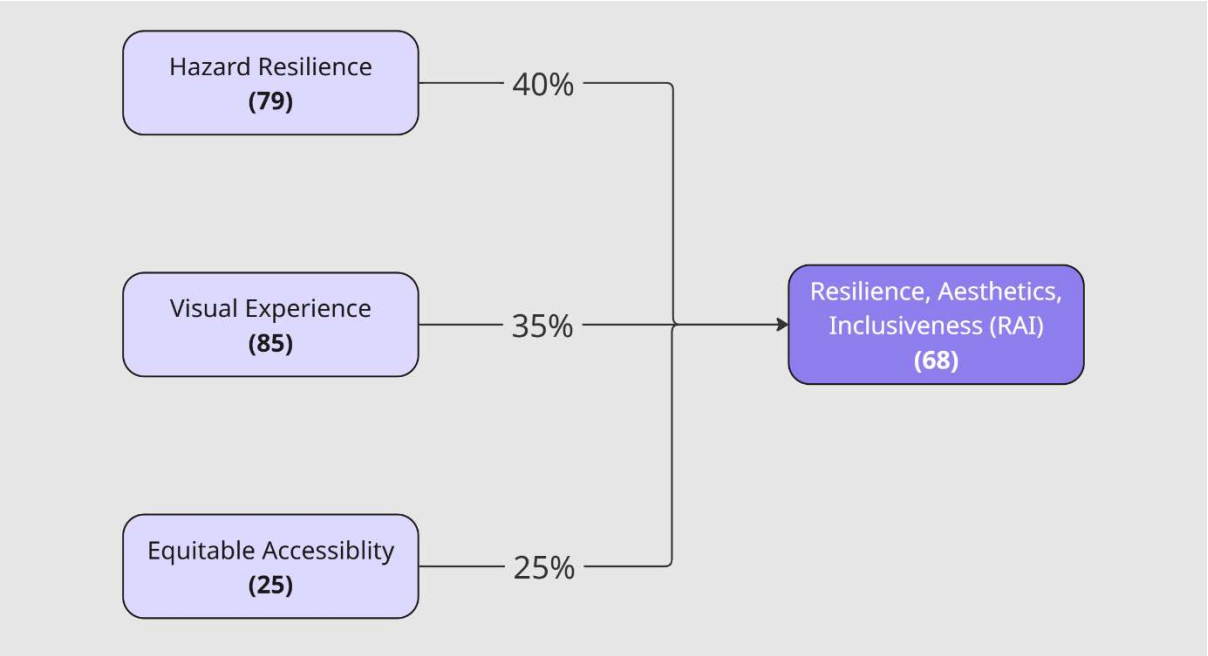


Figure 100 – Case Study Analysis Block-Level Score; RAI (created with Miro)

5.6. PROJECT RESULTS

Overall Project Performance

Per established analysis block weighting, the AEGIR Spain Demo Building project achieves an overall THRIVE score of **64 ("Good")**, represented in Figure 101 and detailed across the integrated measure, analysis block and project levels in Table 44.

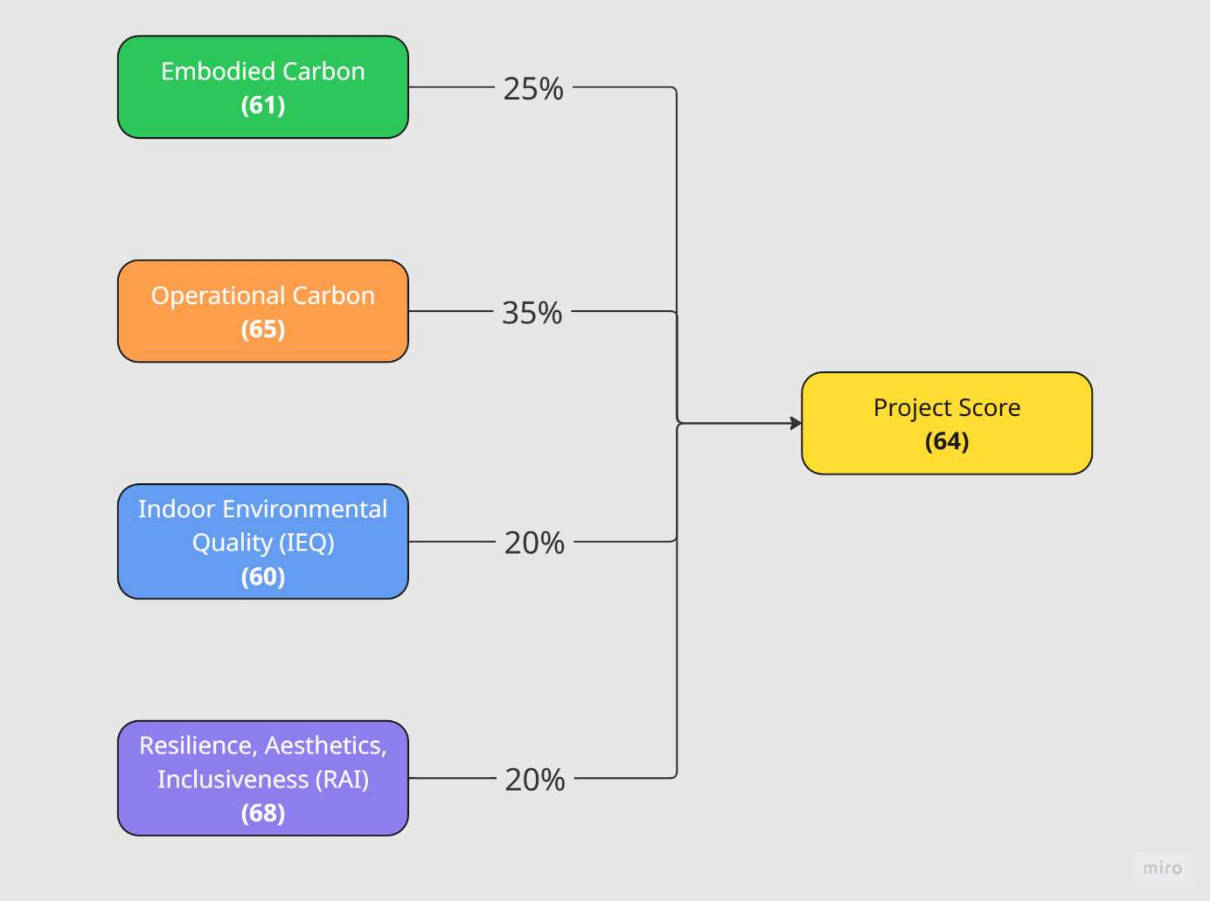


Figure 101 – Project Level Score for the Case Study Building (created with Miro)

Table 44 – Summary of THRIVE Results for the Case Study Building

Integrated Measure		Score	Class	Analysis Block	Score	Class	Project	Score	Class
EC1	Life Cycle Carbon	51	Acceptable	Embodied Carbon	61	Good	AEGIR Spain Demo Building	64	Good
EC2	Carbon Payback	61	Good						
EC3	Circularity & Sourcing	78	Good						
OC1	Emissions & Efficiency	57	Acceptable	Operational Carbon	65	Good			
OC2	Carbon Payback	61	Good						
OC3	Peak Demand	78	Good						
OC4	Renewable Energy	85	Excellent						
IEQ1	Daylight Access	47	Acceptable	Indoor Environmental Qualtiy	60	Acceptable			
IEQ2	Thermal Comfort	38	Low						
IEQ3	Indoor Air Quality	87	Excellent						
RAI1	Hazard Resilience	79	Good	Resilience, Aesthetics, & Inclusiveness	68	Good			
RAI2	Visual Experience	85	Excellent						
RAI3	Equitable Accessiblity	25	Low						

5.7. DISCUSSION: CASE STUDY INTERPRETATION & RECOMMENDATIONS

Interpretation – Performance Classes

The results indicate an overall "Good" level of performance for the case study project. Performance is generally consistent across analysis blocks. At the integrated measure level, a wide range of performance is seen ranging from "Low" to "Excellent".

In the context of modern standards and best practice for sustainable building renovation as defined by NEB and LEED, each performance class can generally be interpreted as follows:

- **Low** – Clearly below THRIVE aspirations. Outcomes in line with what would be expected from an industry average renovation project without considerations for decarbonization and well-being. At the integrated measure and analysis block levels, results in this class should trigger a warning, signaling where to prioritize design upgrades to achieve Acceptable at a minimum. At the project level, this performance class indicates an overall lack of alignment with THRIVE principles and a failure to deliver a healthy, low-carbon renovation by modern standards.
- **Acceptable** – Meets the minimum performance thresholds for compliance with THRIVE principles. At the integrated measure level, indicates sufficient design strategies to achieve the desired intent. At the analysis block level, indicates better carbon performance than an industry average renovation and/or adequate occupant well-being outcomes. At the project level, delivers what can be considered a healthy and low-carbon building by mainstream modern standards, but leaves significant room for improvement and should not be the endpoint for ambitious projects.
- **Good** – Firmly above the minimum performance thresholds for compliance with THRIVE principles. At the integrated measure and analysis block levels, this class shows clear integration of technical and qualitative THRIVE design strategies. While further improvement can be pursued, measures and blocks in lower performing classes should generally be prioritized for targeted intervention to achieve a more balanced project. At the project level, delivers a well-rounded, sustainable building in line with modern best practice.
- **Excellent** – Above and beyond THRIVE aspirations. At the integrated measure and analysis block levels, indicates exceptional performance aligned with the most innovative and ambitious sustainable renovation projects in today's construction industry. At the project level, delivers a highly carbon-efficient and desirable building that serves as an example of what is possible when sustainable renovation practices are fully embraced. Projects in this performance band drive the future of building renovation, bridging the best practice of today with the standard practice of tomorrow.

Interpretation – Strengths

The project has integrated measures spanning all four analysis blocks which stand out as clear strengths, notably:

- EC3 - Circularity & Souring
- OC3 - Peak Demand
- OC4 - Renewable Energy
- IEQ3 - Indoor Air Quality
- RAI1 - Hazard Resilience
- RAI2 - Visual Experience

Per Table 1, several of these measures align with KPI established by the AEGIR project consortium as most relevant (Zabek et al., 2023), including:

- The use of renewable energy, corresponding to OC4
- Use of secondary material (reuse or recycling content), corresponding to EC3
- Future recycling or reuse strategy, corresponding to EC3

Per Table 2, further indicators identified from the Level(s) framework as relevant to AEGIR also align with THRIVE strong points (Zabek et al., 2023), including:

- Indoor air quality, corresponding to IEQ3
- Increased risk of extreme weather events, corresponding to RAI1
- Increased risk of flood events, corresponding to RAI1

This alignment implies that AEGIR was successful in implementing design strategies to support these KPI for the Spain demo building, validated via THRIVE as an independent assessment framework. AEGIR's overall emphasis on bio-based materials, circularity, improved ventilation, and incorporation of renewable energy generation and storage technologies is clearly reflected in its highest-achieving THRIVE integrated measures.

At the analysis block level, RAI can be considered a strong point for the project, driven by high achievement in Hazard Resilience and Visual Experience. Safety and resilience are key drivers for the development of the AEGIR system, with compliance for Construction Product Regulation (CPR) requirements for "mechanical resistance" and "stability and safety" in case of fire detailed in the solution requirements and specs (Jay Arnaud & Astudillo Larraz, 2023). These requirements ensured the detailed consideration of environmental lateral loads, fire resistance, combustibility, and water tightness when selecting materials. Regarding aesthetics, a coherent architectural vision integrated the project's energy and ventilation systems with angular envelope cladding. The result is a harmonious and appealing structure that manages to mask the typically fragmented and rigid appearance of prefabricated panel construction. The resulting achievement in Hazard Resilience and Visual Experience which carries RAI as a whole validates these efforts and serves as a testament to the value of early design considerations and integrative planning regarding these design aspects.

Interpretation – Weaknesses & Recommendations for Improvement

Among integrated measures, the lowest-scoring in the project are isolated in the occupant well-being analysis blocks.

- IEQ1 - Daylight Access (47)
- IEQ2 - Thermal Comfort (38)
- RAI1 - Equitable Accessibility (25)

With integrated roof canopies and operable shading devices and all openings at all windows supporting the supplementary design strategy assessments, performance in IEQ1 is driven down by daylight simulation sDA results. It should be noted that envelope-focused deep renovations may be inherently limited in their ability to impact daylight access if they involve none-to-minimal modifications to the building's programming and room layout, as in the case study project. The project uses coated, high-VLT glazing at all openings to support the transmission of daylight while maintaining UV and heat protection. Thus, the low score can be attributed to the quantity and size of openings in relation to regularly occupied space.

Key rooms bringing down the simulated sDA score, considering their relatively large area and minimal daylight access, are enclosed by facades with either very small or no openings. Avoiding modifications to the room layout outside the scope of the project, the recommended course of action is to add new or expand existing openings at these facades, as noted in Figure 102 and Figure 103, to match the typical window size depicted in Figure 104. Due to anticipated relative ease and low cost, expanding existing openings is proposed as the first priority before adding new ones.

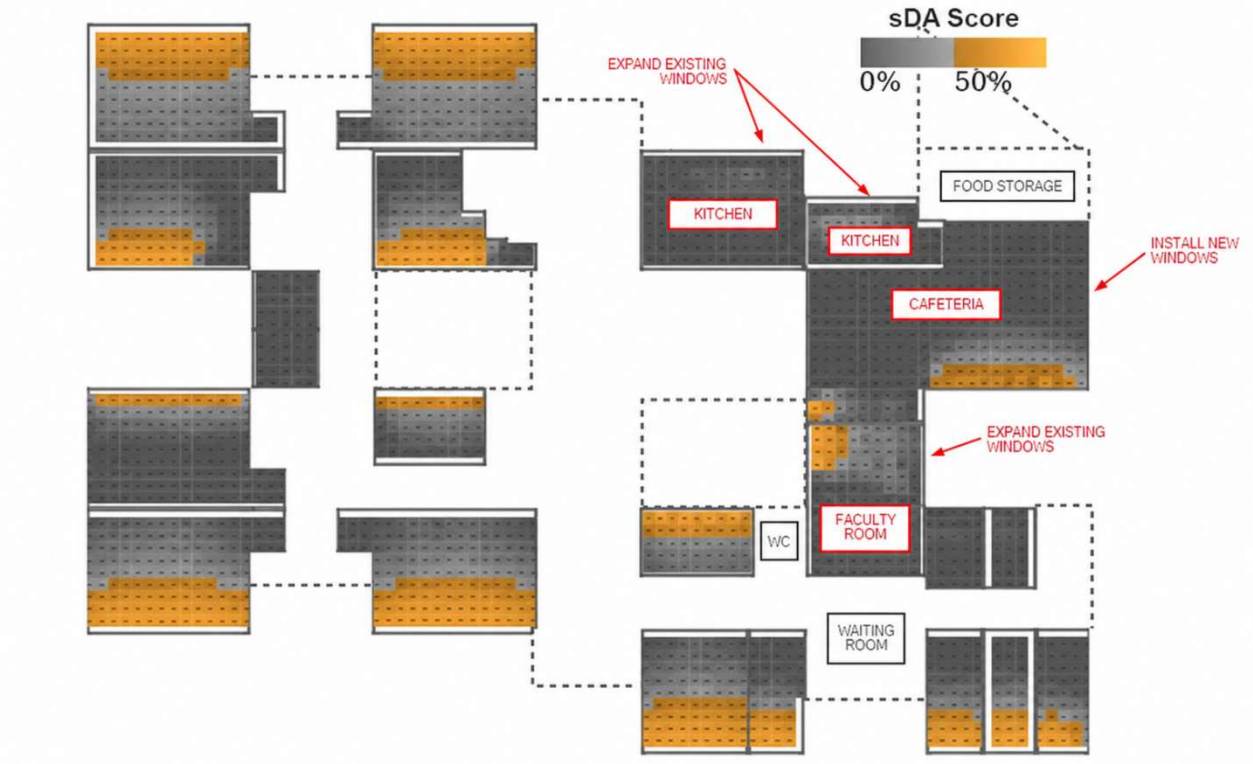


Figure 102 – Recs for Case Study Daylight Access, Ground Floor; Adapted from (LightStanza, n.d.-b)

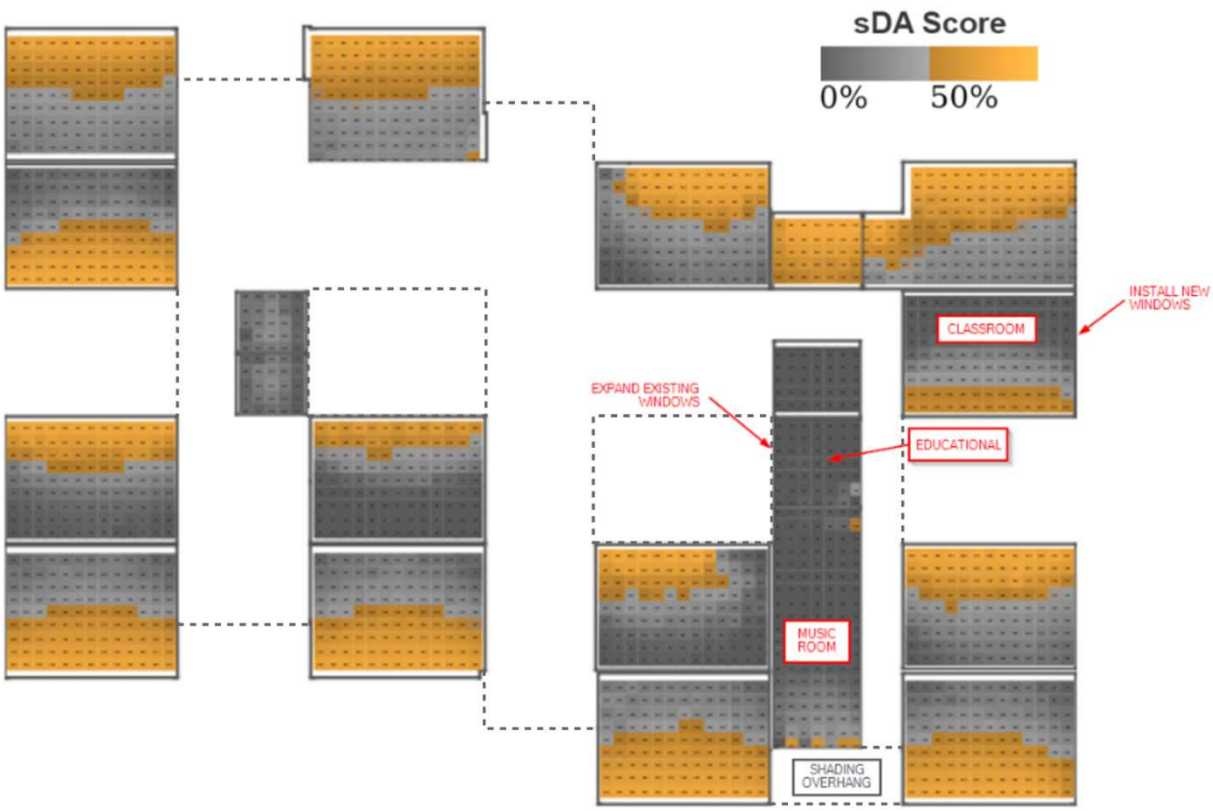


Figure 103 – Recs for Case Study Daylight Access, Level 1; Adapted from (LightStanza, n.d.-b)

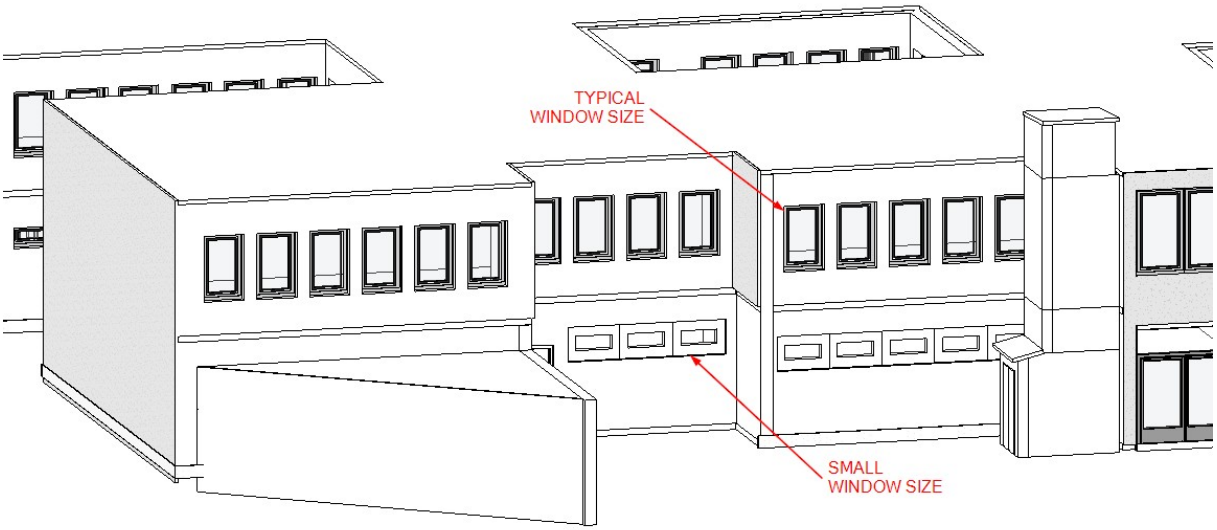


Figure 104 – Case Study Standard Window Sizes (Revit)

To quantify the impact of these recommendations, two alternative daylight simulations were conducted, one expanding existing windows only and the other expanding existing windows and installing new ones where indicated in Figure 102 and Figure 103. As shown in Table 45, both alternatives notably increase sDA while maintaining overall ASE below the maximum of 20%. As the additional improvement from installing new windows is relatively marginal, the "expand existing windows" approach will be used to determine the cumulative effect of recommendations at the end of this section. The assessment score of 51 resulting from this recommendation translates to an integrated measure score of 60 ("Acceptable") for IEQ1, subsequently raising the IEQ analysis block score to 65 ("Good") and the Project score to 65 ("Good"). The sDA results of each alternative are expressed graphically in the partial floor plans shown in Figure 105 and Figure 106.

Table 45 – Impact of Recommendations on Daylight Simulation Results

	Case Study Design	**Expand Existing Windows**	**Expand Existing & Install New Windows**
sDA	30.5%	46.4%	48.9%
ASE	7.0%	8.3%	9.7%
THRIVE Assessment Score	31 ("Low")	51 ("Acceptable")	55 ("Acceptable")

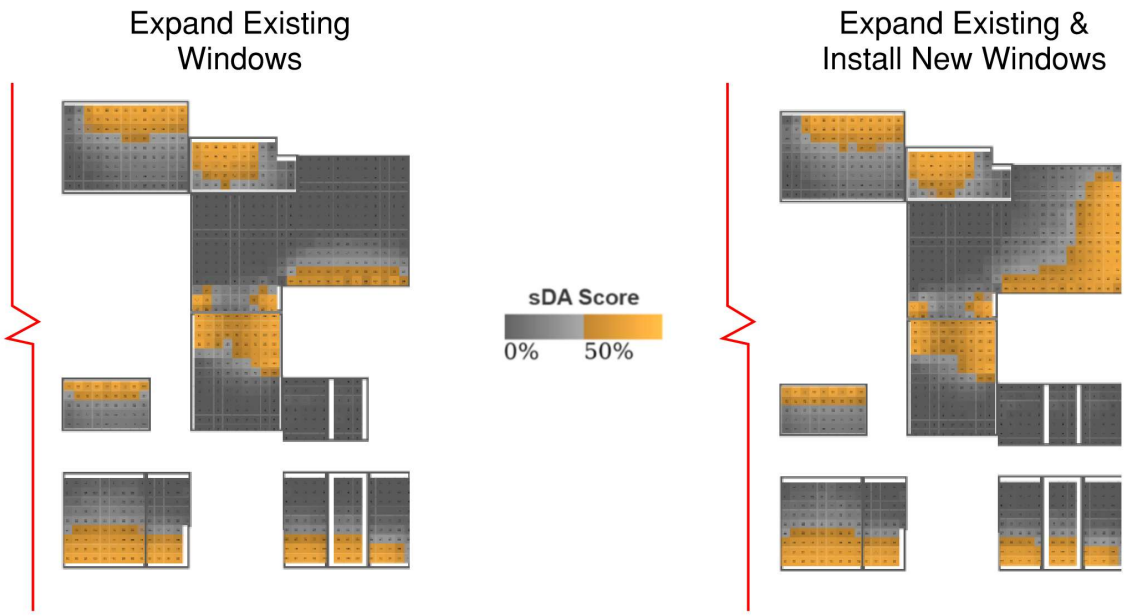


Figure 105 – Impact of Recs on sDA, Partial Floor Plans, Ground Level; Adapted from (LightStanza, n.d.-b)

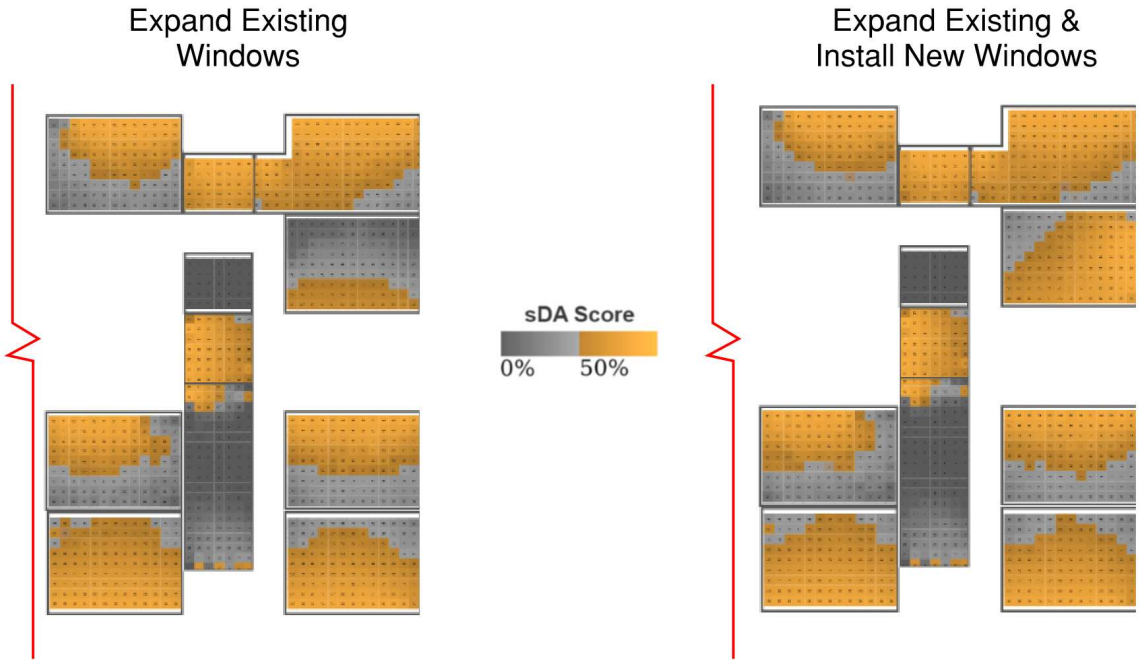


Figure 106 – Impact of Recs on sDA, Partial Floor Plans, Level 1; Adapted from (LightStanza, n.d.-b)

The main driver for poor performance in IEQ2 is failing the heating-mode compliance check for Seasonal Thermal Comfort. It should be noted that the use of the maximum design air speed of 0.25 m/s in the PMV calculations may be overly conservative considering the real average air speed could be significantly less. However, without the ability to take post-renovation measurements, the use of a lower figure at this stage in the project could not be justified. Further considering the relative humidity,

metabolic rate, and clothing level assumptions necessary for the calculation, the results cannot be considered exceptionally precise. Nevertheless, a sensitivity check using the CBE Tool default air speed of 0.10 m/s and a relative humidity of 50% as less conservative assumptions still did not yield heating-mode compliance at the 21°C setpoint. Thus, it is reasonable to conclude modifications to the system will be necessary for optimal performance.

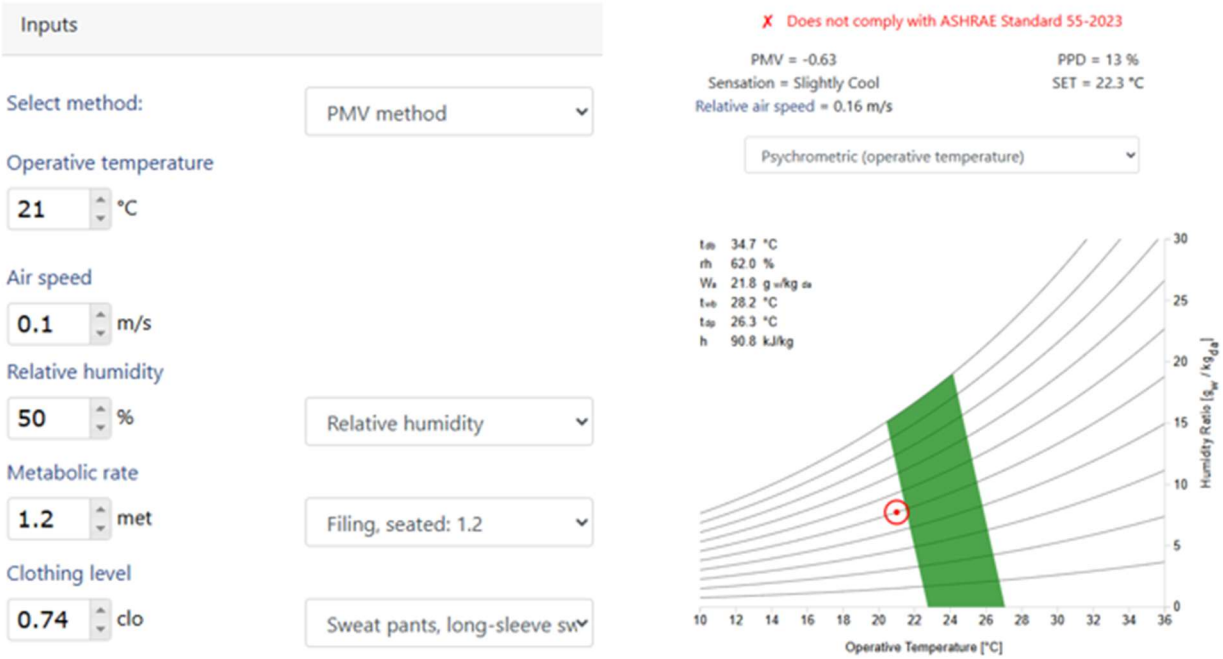


Figure 107 – Case Study PMV Heating-Mode Sensitivity Check (Tartarini et al., 2020)

The combination of the following strategies for heating mode is proposed to comply with the Seasonal Thermal Comfort assessment.

- Increase the heating mode setpoint to 22°C.
- Ensure the average air speed in mechanically conditioned spaces does not exceed 0.10 m/s and verify with post-renovation measurements. Potential strategies to manage air speed include the use of low velocity "displacement" diffusers, operable diffusers to avoid direct air jets onto occupants, and configuration of the system supply fan to operate at reduced speed in heating mode.

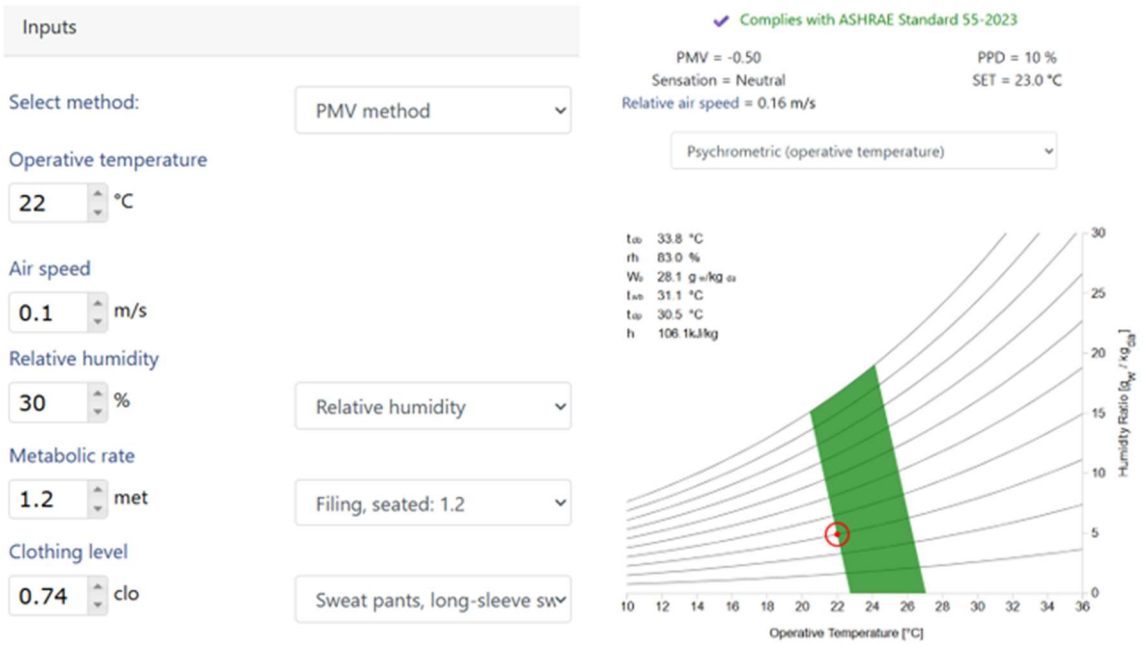


Figure 108 – Case Study PMV Heating-Mode Compliance with Proposed Recs (Tartarini et al., 2020)

Another sensitivity check was performed to confirm a 0.10 m/s air speed does not compromise the cooling-mode compliance results.

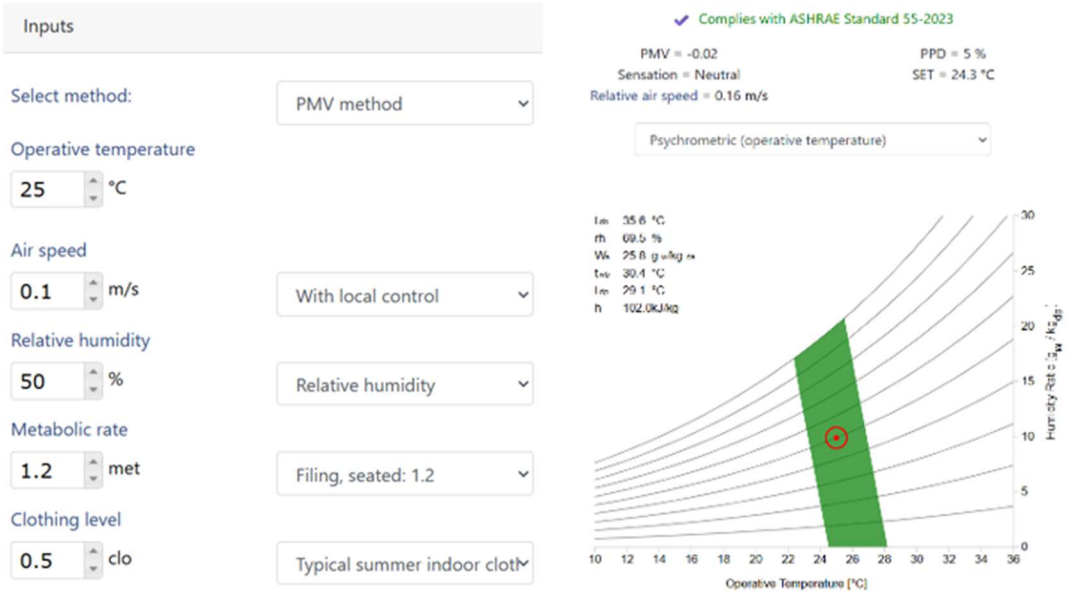


Figure 109 – Case Study PMV Cooling-Mode Air Speed Sensitivity Check (Tartarini et al., 2020)

The implementation of these recommendations to achieve heating-mode compliance raises the score for IEQ2 to 81 ("Good"), which subsequently raises the IEQ analysis block score to 70 ("Good") and the Project score to 66 ("Good").

The IEQ2 score also suffers from a lack of radiant heating or cooling as well as specified humidity control capabilities for the ventilation system. It is understood that a radiant ceiling system was originally

intended to be included in the project but had to be removed due to budgetary constraints. Post-reno humidity sensor measurements over the first full year after construction completion should be reviewed for compliance with 30%-60% relative humidity (RH) in all regularly occupied spaces. If achieved, the project may update its THRIVE score accordingly. Based on pre-reno sensor data depicted in Figure 110, exceeding 60% RH is a more likely issue than falling below 30%. Therefore, if certain spaces are found to be problematic post-reno, dedicated dehumidifiers are a possible solution. As these are a relatively costly option, if many spaces still fall outside the 30%-60% RH range, more holistic modifications to the HVAC system should be considered.

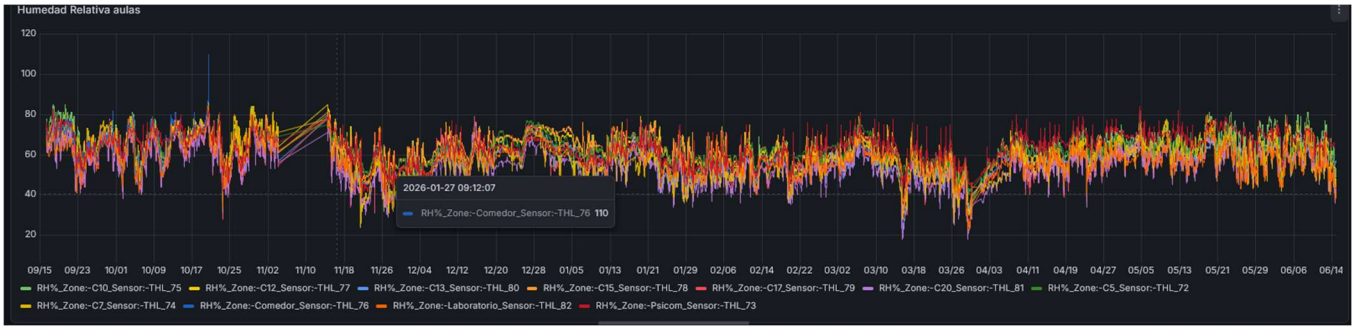


Figure 110 – Year-Round Relative Humidity in Case Study Classrooms, Pre-Renovation (TECNALIA)

Despite the strong analysis block-level results for RAI, poor performance in RAI3 – Equitable Accessibility brings to light certain considerations neglected by the case study project. Notably, the project fails to fully accommodate the multi-lingual local population as well as movement- or sensory-impaired individuals through accessible door operation options or multi-lingual/multi-sensory signage.

Of all proposed recommendations to improve THRIVE performance, those pertaining to RAI3 are anticipated to be the most simple, straightforward, and cost-effective. The following strategies are proposed in order from highest-to-lowest priority based on anticipated cost and accessibility return on investment (ROI). As there is no data to infer the number of potential occupants with movement, language, or sensory impairments, the accessibility benefit of each measure is assumed to be roughly equal. Therefore, lowest cost = highest ROI. Implementing all three recommendations brings the RAI3 score up to 100 ("Excellent"), consequently increasing the RAI analysis block score to 86 ("Excellent") and the project score to 67 ("Good").

- Ensure all signage on the project that communicates information is written in, at a minimum, Catalan, Spanish, and English. If the school registry or local census data indicates more than 5% of the respective population has a different mother tongue (e.g. Arabic), include these languages on the signage as well.
- Ensure all wayfinding signage on the project includes a tactile (e.g. braille) or audible means of communicating information.
- Install accessible means of operation at all main entrance doors (e.g. wave-to-open, vertical hand press, or foot press features).

Also of note, EC1 - Life Cycle Carbon carries a relatively modest "Acceptable" result, despite GWP being listed first among AEGIR's most relevant KPI (Zabek et al., 2023), thus warranting further exploration.

The standard PV panels and ETICS façade are the primary drivers of the project's embodied life cycle carbon, making up over 50% of the cradle-to-gate (A1-A3) impact. Covering the majority of the roof, the solar panels represent a significant financial as well as carbon investment for the project. This investment is justifiable considering the importance of solar power to project's renewable energy goals and the effectiveness of the panels reflected in the "Excellent" performance class result for OC4 - Renewable Energy. However, per performance benchmarks established by One Click LCA, the chosen

panels from Phono Solar rank 211 out of 254 energy production systems from renewable energy in terms of cradle-to-gate GWP / m^2 of panel (See Figure 111).

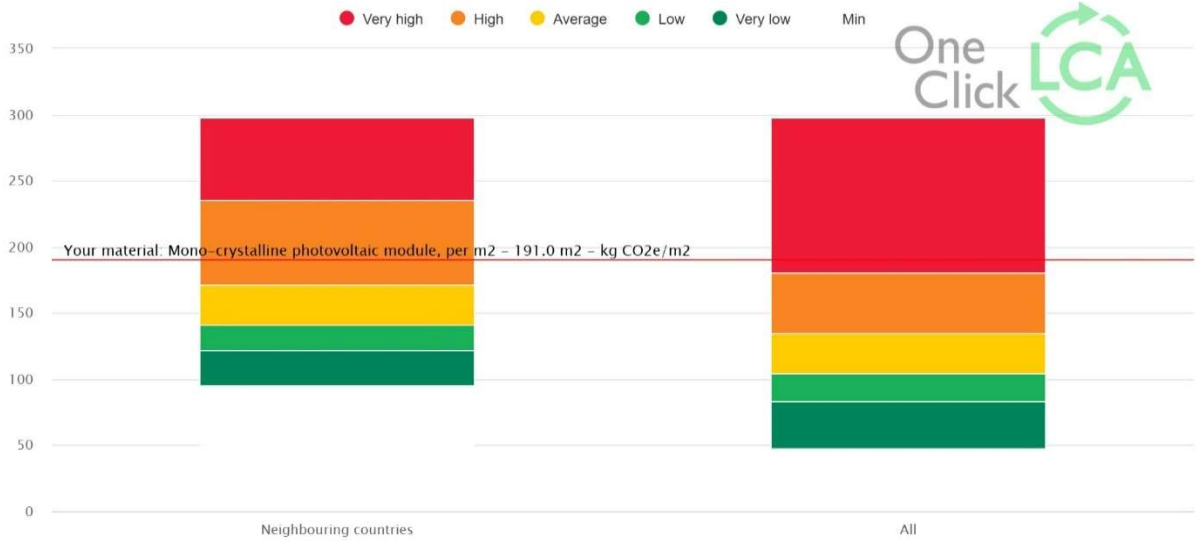


Figure 111 – Standard PV Panels GWP Benchmark (One Click LCA, 2015)

This figure suggests there is significant room for improvement exploring alternative panels with similar energy generation capacity at a lower upfront GWP. Normalized for Watt-peak (Wp), a measure of the maximum theoretical power output of a PV panel, the following options shown in

Table 46 carry a lower cradle-to-grave (A1-C4) GWP than the currently specified Phono Solar module.

Table 46 – Recommended Standard PV Panel Alternatives for the Case Study Building; Adapted from (Kumar, 2026; Kumar Singh, 2025; LV, 2023; Yang, 2023) with AI

PV Panel Manufacturer	PV Panel Product / EPD	Power Peak	Total GWP / Wp (A1-C4)
Phono Solar	Mono-crystalline photovoltaic module, per m2, 12.70 kg/m2 (Phono Solar Technology Co.,Ltd)	585 Wp	0.874 kg CO2e
LONGi	Mono-crystalline photovoltaic module, per m2, 1722 x1134 x 30 mm, 20.8 kg/panel, 1.95 m2/panel, 10.6 kg/m2, LR5-54HIH, LR5-54HPB, LR5-54HPH, LR5-54HTB, LR5-54HTH (LONGi)	560 Wp	0.848 kg CO2e
SAATVIK Green Energy Limited	Mono-crystalline photovoltaic module, LxWxT: 2382x1134x30 mm, 12.46 kg/m2, 33.63 kg/unit, N-TOPCON G12R (Saatvik Green Energy Limited)	625 Wp	0.436 kg CO2e
ReNew Energy Global	Monocrystalline bifacial solar module, 12.59 kg/m2, 236.14 Wp/m2, 32.5 kg/unit, Power=610 Wp, area=2.582 m2, M10, 144 Cells TOPCon Bifacial Solar Module (ReNew Energy Global PLC)	610 Wp	0.431 kg CO2e

From this comparison, the Saatvik and Renew panels have the potential to significantly contribute to lower GWP and an improved EC1 score for the case study project. The power class for each panel is within the range of 560-625 Wp, maintaining maximum power output per panel in the same order of magnitude. As this comparison does not incorporate site-specific irradiation or bifacial gain, these factors should be studied further to verify comparable GWP / kWh of energy output for the case study

site before final selection of an alternative. It should also be noted that supplementary elements such as mounting, inverters, and cabling are outside the system boundary for this comparison.

The impact of the ETICS façade can be attributed to the large surface area covers, its relatively high embodied carbon intensity compared to the AEGIR panels, and the use of a broad, generic EPD in the proposed life cycle carbon assessment model. The original intent of the case study project was to use the AEGIR panels for the entire façade; however budgetary constraints led to the partial replacement with ETICS. The limitations regarding ETICS noted in Section 4.3 dictated the use of a generic EPD, potentially overestimating the GWP of the final system. Although the full use of AEGIR panels would likely yield the best results, if chosen with care, an optimized ETICS could still significantly improve outcomes for EC1.

As choice of insulation is a key driver for the GWP of an ETICS system, the substitution of Owens Corning Thermafiber Mineral Wool in the assumed BOD system with the bio-based insulation used for the AEGIR panels has the potential to significantly lower life cycle carbon at a lower cost burden than installing the full AEGIR panel. Normalized for a thermal resistance of RSI = 4.1 m^2K/W and considering biogenic carbon storage, the GWP difference on a per-square meter basis can be seen in Table 47.

Table 47 – Case Study ETICS Insulation Comparison with Recommended Alternative; Adapted from (Gaillard, 2020; Owens Corning, 2021) with AI

Insulation Type	Manufacturer – Product	Total GWP / m2 (A1-C4)
Mineral Wool	Owens Corning - Thermafiber	6.6 kg CO2e
Wood Fiber	Soprema - Pavawall Smart	-11.7 kg CO2e
	Net Reduction	18.3 kg CO2e

It should be noted that when biogenic carbon storage is neglected, the fossil-based GWP of Pavawall is higher than that of Thermafiber at 16.5 kg CO2e / m2. Another critical consideration is fire resistance. As mineral wool has inherently superior fire resistance to combustible materials such as wood fiber, care must be taken to ensure appropriate fire resistance of the system is maintained when pursuing the proposed alternative. Potential measures to achieve this include fire breaks via strips of mineral wool embedded in the wood fiber, and the use of non-combustible render or cover layers.

These recommendations for PV and ETICS alternatives have been assessed in One Click LCA to quantify their combined potential impact. The ReNew Energy Global panels were input in place of Phono Solar, with the quantity adjusted to maintain energy performance according to the power peak ratio. To represent the wood-fiber alternative ETICS, a generic EPD for ETICS with wood-fiber insulation issued by the same program operator as the ETICS with stone wool insulation was selected. This EPD includes Pavawall Smart among its representative data set. The result of just these two substitutions nearly doubles the GWP reduction from the baseline from 19.9% to 38.6%, as detailed in Table 48 and Figure 112. This reduction translates to an EC1 score of 70 (“Good”), consequently raising the Embodied Carbon analysis block score to 71 (“Good”) and the Project score to 65 (“Good”).

Table 48 – GWP Impact of Embodied Carbon Case Study Recommendations

Baseline Result	Proposed Result	Further Recs	Reduction with Further Recs
318,012 kg CO2e	254,877 kg CO2e	195,129 kg CO2e	38.6%

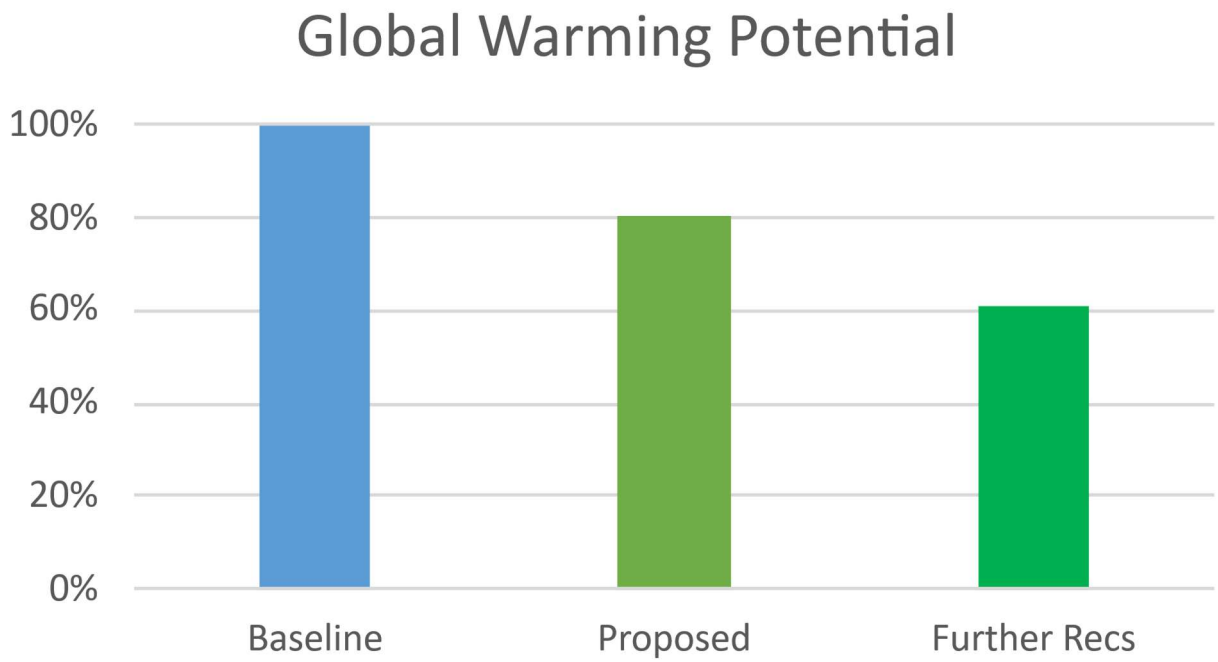


Figure 112 – Comparison of Baseline, Proposed, and Further Recommendation Case Study EC1 Results

At the analysis block level, the results are generally consistent with no glaring weaknesses. All scores fall within an 8-point range (60-68) spanning the high-end of "Acceptable" to the low-end of "Good" performance bands. The weakest block, Indoor Environmental Quality, is dragged down by relatively low scores in Daylight Access and Thermal Comfort despite strong performance in IAQ. While AEGIR's emphasis on improved ventilation is reflected in the IAQ score, the limitations and recommendations outlined in this section show where the case study project is lacking and how it can achieve a more holistically comfortable indoor environment for building occupants.

In summary, the implementation of all recommendations in this section with quantified score impact (PV and ETICS alternatives, expanding existing windows, temperature setpoint and air speed modifications, and equitable accessibility enhancements) in combination yield the analysis block and project level results shown in Table 45.

Table 49 – Cumulative Impact of Proposed Recommendations for Improvement

Analysis Block	Case Study Initial Results	Results with Cumulative Recommendations
Embodied Carbon	61 ("Good")	71 ("Good")
Operational Carbon	65 ("Good")	65 ("Good")
Indoor Environmental Quality	60 ("Acceptable")	75 ("Good")
Resilience, Aesthetics, & Inclusiveness	68 ("Good")	86 ("Excellent")
Project	**64 ("Good")**	**73 ("Good")**

Considering the holistic nature of THRIVE, it is also critical to note that implementation of the proposed recommendations in the section should be investigated iteratively, ensuring that improvement in one integrated measure or analysis block does not compromise the performance of another. For example, the expansion of existing windows and/or addition of new windows should be reflected in updated energy simulations to verify the impact on Operational Carbon outcomes.

5.8. DISCUSSION: REFLECTIONS ON THRIVE & GUIDING FRAMEWORKS

General Reflections

THIRVE benefits from the integration of two distinct guiding frameworks. The NEB-SAM anchors THRIVE in a flexible, holistic foundation that encourages project teams to iteratively reflect on decisions impacting decarbonization, occupant health, and well-being criteria. LEEDv5 contributes more structured, quantitative assessment methods with clear procedures and measurable outcomes, particularly concerning life cycle carbon, energy performance, and objective indoor environmental conditions. An example of this balance can be seen in the Responsible Sourcing assessment under EC3, where the robust multi-attribute scoring system for product documentation provided by LEEDv5 credit MRc4 gives concrete structure to the ideology and intent behind NEB-SAM indicator B.2.2. As explored in Section 5.7, AEGIR's Level(s)-based KPI have largely translated to success in aligned THRIVE integrated measures for the case study project. This supports the notion that Level(s) principles are inherently baked into THRIVE without serving directly as guiding framework and helps validate the choice of NEB and LEED to represent modern sustainability standards, at least in the context of the EU and US.

Regarding decarbonization, EC1 outlines a procedure for quantifying the cradle-to-grave life cycle carbon emissions for the new material constituting the renovation. The guidance for this assessment between NEB-SAM indicator S.3.2 and LEEDv5 credit MRc2 is largely similar. For EC1, the reference service life (RSL) of 50 years is drawn from NEB rather than the 60-year default stipulated by LEED. As both default RSL are considering new construction and renovation, opting for the lower of the two is intended to better represent the actual service life of a renovation, which is generally lower compared to new construction. LEEDv5 provides the stipulated equivalences that must be guaranteed between the baseline and proposed models (e.g. operating energy performance). The dual-scoring approach yields slightly higher results on the LEED-side, when adapting LEEDv5 thresholds to NEB performance classes, than the purely NEB-SAM derived NEB-side. This implies NEB could have more stringent demands regarding embodied carbon, although it should be noted that the LEED-side scoring adaptation involved qualitative deduction on the part of the author and is not based purely on empirical data.

On the operational side, OC1 quantifies emissions directly via the NEB-SAM indicator S.3.1-based Operational Emissions assessment, and indirectly through a dual-sided calculation approach to energy performance. S.3.1 defines its baseline as "an average of the annual operational GHG emissions per unit floor area of the building stock, at national or EU level, to which the building belongs", which facilitates applying the procedure to new buildings as well as renovations. As a streamlined, renovation-specific framework, THRIVE instead establishes the baseline as the building's pre-renovation condition, providing a simpler calculation procedure and incentivizing the improvement of worst-in-class buildings. A notable difference between the guiding frameworks pertaining to the Energy Performance assessment is their energy source timeline. While NEB-SAM indicator S.1.1 outlines a procedure based on current energy source performance, LEEDv5 credit EAc3 uses a future source approach that aims to anticipate continued grid decarbonization. THRIVE balances these present-day and future outlooks by weighting each procedure equally in the Energy Performance assessment, again using the pre-renovation condition as the baseline. The case study yielded a significantly lower score for the Future Source calculation (36) than Current Source (71), implying that LEEDv5 has more stringent scoring thresholds for EAc3 compared to S.1.1 that outweigh the consideration of a further decarbonized grid.

THRIVE builds on the guiding frameworks to tie the embodied and operational carbon analysis blocks together with the novel Carbon Payback integrated measure. This measure treats the project as a carbon investment, calculating the time it takes to transition from a net carbon cost to a net carbon benefit. Neither the NEB-SAM nor LEEDv5 have a procedure for this figure, which provides a straightforward indication of a renovation project's decarbonization potential.

Between daylight, thermal comfort, and indoor air quality (IAQ), THRIVE addresses three primary metrics for indoor environmental quality (IEQ). The Daylight Simulation assessment, developed through the largely similar procedures outlined in NEB-SAM indicator B.4.2 (via the WELLv2 Light Exposure feature) and LEEDv5 credit EQc2 (Option 5, PATH 4), represents the most detailed quantification of daylight access and thus caries the majority of the weight in this analysis block. A notable difference between the guiding frameworks is the stipulated illuminance thresholds. EQc2 requires $sDA_{300/50\%}$ for all regularly occupied spaces, while allowing for a softer $sDA_{150/50\%}$ requirement for areas without "visual tasks" and with design targets of 225 lux. B.4.2 allows the use of $sDA_{150/50}$ in all regularly occupied spaces. To simplify the simulation procedure while conservatively maintaining the highest standards, $sDA_{300/50\%}$ is required for all regularly occupied spaces in THRIVE.

Thermal Comfort performance is quantified primarily through the Seasonal Thermal Comfort assessment, which uses a unified procedure to meet the intent of NEB-SAM indicator B.4.3 (via the WELLv2 Thermal Performance feature) and LEEDv5 credit EQc2 (Option 3), with both referencing ASHRAE Standard 55. To build on the guiding frameworks, THRIVE quantifies the ambiguous LEEDv5 requirement to "explain how the design considers thermal conditions that align and adjust with changing seasons". This is achieved by requiring a compliance check in both heating and cooling mode for mechanically conditioned spaces, or for naturally conditioned spaces, in both summer and winter. The proportional split between modes based on percentage of operational time in each encourages proper prioritization of comfort strategies based on the project's climate.

IAQ is quantified via balanced assessments of the concentration of air pollution (measured or projected) and the presence of strategies to mitigate pollution. THRIVE brings together the results-driven procedure of NEB-SAM indicator S.5.1 with strategies to deliver improvement from LEEDv5 prerequisite/credits EQp2 and EQc1. Similar to OC1, the ability to establish a baseline for improvement based on worst-case pre-renovation conditions incentivizes the revitalization of buildings with the greatest need for improvement in IAQ. Although LEEDv5 awards 1 point for EQc1 for compliance with "Increased Ventilation" OR "Enhanced Indoor Air Quality Design", THRIVE adjusts this logic to require both for reaching a maximum score. This decision considers the fact that ventilation does not uniformly control all pollutants, while further promoting verification of pollutant control and multiple-strategy approaches to improved IAQ.

The Resilience, Aesthetics, and Inclusiveness (RAI) analysis block diverges from the previous logic of generally assigning equal weight to the NEB- and LEED-based assessments within its integrated measures. By nature, the NEB-SAM is much more robust in its handling of these more abstract criteria compared to LEEDv5. Therefore, it was deemed impractical to dilute the influence of NEB by forcing its criteria into 50/50 weighting.

The growing acknowledgement of resilience as a key aspect of holistic building sustainability is evidenced by the extensive hazard characterization and design procedures outlined in NEB-SAM KPI B.3 – Resilience to Extreme Events, as well as the inclusion of a resilience-specific credit in LEEDv5, EQc4 – Resilient Spaces, that did not exist in previous versions of the rating system. In THRIVE, the fire, water, and wind resilience assessments isolate among the wide range of metrics listed under NEB-SAM indicator B.3.2 those which can be most directly influenced by envelope-focused deep renovation. These essentially serve as redundancy check against local code requirements for design to resist these forces of nature, ensuring the highest levels of resilience regardless of project jurisdiction. For projects located in municipalities with modern, robust buildings codes, these assessments are likely to score well simply by meeting code compliance. The LEEDv5 credit EQc4 provides the basis for a manually operable window assessment to ensure adaptability in the face of events such as extreme heat waves or power outages, resulting in a more well-rounded THRIVE scoring methodology for Hazard Resilience.

Consideration of aesthetics via the Visual Experience integrated measure represents an area still largely untouched by LEEDv5 and thus a clear and unique contribution from the NEB-SAM to THRIVE. Certain principles outlined under indicator B.7.1 easily translate directly to envelope-focused deep renovation applications (e.g. axis composition, rhythm/repetition, materials), while others required adaptation for the THRIVE assessment. The openings principle is largely dependent on surrounding natural areas, inhibiting projects in dense urban environments. This principle is thus augmented by drawing on criteria from LEEDv5 credit EQc2 (Option 1, PATH 2) to offer a compliance through other view types. Light-shadow effects as defined in B.7.1. can be largely dependent on the design and transparency of partition walls and furnishings. Considering these elements are often not within the scope of deep energy retrofits, THRIVE seeks to maintain the intent this of principle while filtering its scope to best address the potential of a deep renovation project.

The Equitable Accessibly integrated measure is designed to be highly flexible based on the project's scope and local context. Criteria for door clear width and multi-sensory wayfinding are outlined in NEB-SAM indicators B.5.1 and B.5.2, as well as LEEDv5 credit EQc3, with THRIVE drawing from the more stringent requirements in NEB. EQc3 contributes the criteria for accessible door operation and multilingual signage. Considering the vastly more multi-lingual environment of the EU compared to the US, it is notable that the multilingual signage criteria comes from LEED rather than NEB. This provides a clear example of how the guiding frameworks can continue to grow and learn from one another, even in ways opposite to what one would expect.

The NEB-SAM provides the 0-100 scoring scale and translation to qualitative performance classes to facilitate clear communication of results. LEEDv5-based assessments are adapted to this scale for integration, guided by alignment with NEB-SAM dimension-level performance class thresholds for sustainability and beauty. Where necessary, certain NEB-SAM indicator-level performance class thresholds are adapted to align with the corresponding dimension-level thresholds, ensuring consistent significance of the 0-100 score throughout THRIVE (e.g. ~40-60 = Acceptable, ~60-80 = Good). For example, under the S.3 indicator-level performance class thresholds are much lower than those of the sustainability dimension. Thus, for EC1 and OC1, rather than delivering a score directly equivalent to the percentage improvement in emissions as stipulated in S.3.1 and S.3.2, the score is converted based on the corresponding dimension-level thresholds, exemplified in Figure 113.

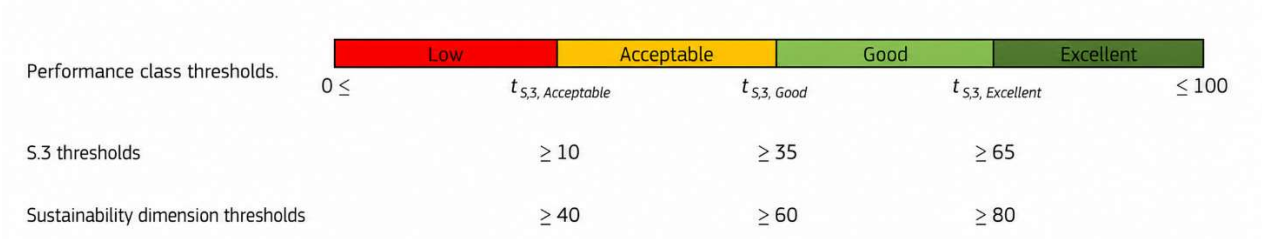


Figure 113 – NEB-SAM Performance Class Thresholds: Indicators vs Dimension Discrepancy Example; Adapted from (Lourenco et al., 2024) with AI

THRIVE Limitations

Throughout its development, THRIVE faced several limitations due to time, data, and software constraints. The hope is that the methodology detailed in this MBUILD final dissertation can serve as "version 1", a base upon which THRIVE can be improved and expanded through future iterations.

In general, thus far THRIVE has only been demonstrated and tested on a single case study building. This provides a limited sample size to identify potential issues that could arise between differing climates, building typologies, and local contexts. The sample size of one also does not allow for proper validation of established performance class thresholds. The ability to review the distribution of Low, Acceptable,

Good, and Excellent results at each level of granularity across a larger pool of THRIVE projects would help to either validate the thresholds as fair or identify where recalibration may be needed. To suit projects such as the case study educational building, THRIVE adapts thresholds and requirements for "Renovation - Non-residential" projects under the NEB-SAM, which is some cases differ from "Renovation - Residential". Thus, THRIVE in its current form is not fully optimized for application to residential deep renovation projects. Considering the growing global population and housing crises affecting much of the developed world, demand for residential construction is high and the need to optimize our use of existing building stock for residential purposes critical.

The construction timeline of the case study project also means THRIVE assessment results have yet to be validated with post-renovation data. (Jain et al., 2020) concluded from their building performance evaluation of a UK school building that optimal operations and maintenance (O&M) of building systems for better energy and IEQ has a significant impact on outcomes generally applicable across school projects. Thus, validation of design results with as-built BoQ, energy meter data, temperature, air speed, and air pollutant concertation measurements, and occupant satisfaction surveys post-renovation would provide great value to THRIVE. As THRIVE is intended to guide projects the design phase, this data cannot be explicitly required to engage with the framework. It could serve well to explore a dual-phase approach to THRIVE assessment, similar to split design and construction phase certification approach available through LEED. THRIVE currently does not take into consideration the economic pillar of sustainability, considering only environmental and social metrics. The inclusion of a life cycle cost analysis (LCCA) to pair with the carbon payback assessment could add a valuable dimension for project teams to assess the economic feasibility of different strategies.

Regarding the analysis whole-life carbon, EC1 is a life cycle carbon assessment tracking only GWP rather than a whole building life cycle assessment (WBLCA) considering further environmental impact categories. This limitation is primarily driven by software limitations under the educational license of One Click LCA available for this MBUILD final dissertation. While the life cycle carbon assessment achieves the goal of quantifying embodied carbon emissions through GWP, a WBLCA would provide a more complete representation of the environmental impact generated by the materials in a deep renovation project. In addition to GWP, LEEDv5 credit MRc2 requires the quantification of the following in its WBLCA approach.

- *Depletion of the stratospheric ozone layer*, in kg CFC-11e
- *Acidification of land and water sources*, in moles H+ or kg SO2e
- *Eutrophication*, in kg nitrogen equivalent or kg phosphate equivalent
- *Formation of tropospheric ozone*, in kg NOx, kg O3e, or kg ethene
- *Depletion of nonrenewable energy resources*, in megajoules (MJ) using CML/depletion of fossil fuels in TRACI

As a cradle-to-grave rather than cradle-to-cradle analysis, EC1 also lacks the ability to account for the circularity potential of materials through consideration of life cycle stage D. For the Responsible Sourcing assessment under EC3, responsible sourcing ratio (RSR) results are tied to performance classes qualitatively based the author's judgment rather than empirically. Considering the multi-attribute scoring (MAS) approach is new feature in LEEDv5 differing substantially from product sourcing credits in previous versions, there is not yet sufficient data to quantitatively benchmark THRIVE scoring for this procedure.

On the operational carbon side, the OC3 does not consider ventilation energy recovery and thermal bridging assessment procedures outlined in LEEDv5 credit EAc2 (Options 2 and 3) and thus has room for expansion into a more robust measure. The novel carbon payback measure is particularly volatile as it has no guiding framework procedures from which to draw inspiration. Considering the lack of research conducted on carbon payback periods, the Carbon Payback scoring thresholds are based on a single study reporting only the average payback period among a sample of "ecologically favorable" projects.

As more data for benchmarking this metric becomes available, the assigned thresholds for EC2/OC2 should be revisited and adjusted as necessary.

Concerning IEQ, and the primary pillars of which it is composed, the consideration acoustic comfort is notably missing in THRIVE. The findings of (Hamimi et al., 2017), that acoustic comfort showed no significant relationship with occupant satisfaction, support the decision to omit this pillar of IEQ in favor of dedicating more time to the development of other assessments. Nevertheless, expansion of the IEQ analysis block to factor in acoustics would result in a more robust and well-rounded assessment framework. Furthermore, deep renovation projects often include the installation of new, energy-efficient light fixtures. However, lighting comfort is assessed only via daylight access, without consideration of interior lighting quality. When assessing daylight access, uniform thresholds for sDA inherently favor projects in sunnier climates.

Temperature and humidity thresholds for thermal comfort, while based on established research to reflect what is generally considered "comfortable" for most people, fail to account for local and regional variance in what conditions populations have adapted to. For example, the definition of "hot and humid" is likely to differ substantially according to someone in Norway compared to Costa Rica.

Regarding indoor air quality, pollutant concentration assessments based on projections and systems specs carry limited accuracy compared to real post-renovation measurements. The ability to engage with THRIVE in the design phase, before post-reno measurements are available, is necessary. However, the development of construction-phase and use-phase validation requirements should be explored. The option to set the baseline for air pollutant concentration improvement as a single maximum pre-renovation concentration measurement has the potential to skew results due to an unrepresentatively bad incident. Sensitivity analyses comparing resulting assessment scores under different baseline requirements (e.g. an average of the 5 highest measurements over the course of a year) across multiple case study projects could better inform the extent of this limitation. By only explicitly requiring consideration of CO2, the Air Pollutant Concentration assessment potentially under-values the impact of non-CO2 pollutants such as VOC, particulate matter, and formaldehyde on occupant health and well-being.

Finally, in respect to RAI, Hazard Resilience fails to account for seismic resistance among its assessments. This omission is due to the relatively low potential of envelope-focused deep renovation to impact seismic resilience compared to the other studied forces (fire, water, wind). Furthermore, the complexity of structural analysis required to assess seismic resilience per NEB-SAM indicator B.3.2 criteria is beyond the scope of this MBUILD final dissertation. Nevertheless, envelope assemblies can play a key role in seismic resistance in certain structural systems. Furthermore, THRIVE currently does not consider additional hazards which are less globally prevalent yet highly relevant in certain locations (e.g. tsunami, volcanic ash). The fire and water resistance assessments are limited to the outermost layer of envelope assemblies for simplicity of analysis; however, this could lead to poor representation of the resilience of certain assemblies employing more complex fire and/or water resistance strategies.

The interior-exterior visual contact principle under the Transparency assessment for Visual Experience is not well suited for residential projects or those where privacy is a high priority. Due to a scope that extends well beyond building renovation design and construction strategies, THRIVE does not currently incorporate any NEB-SAM indicators from the Inclusiveness dimension. Rather, indicators from the Beauty dimension along with LEEDv5 credits are relied upon to assess project inclusiveness.

Foundation for Potential Industry Influence

With further development and promotion, THRIVE has the potential to positively influence the construction industry's approach to deep renovation in the EU, US, and beyond. The broad appeal of THRIVE lies in its user-friendly and streamlined approach to deep renovation, unique to the guiding

frameworks on which is was built. Within the NEB-SAM, a practitioner must sift through an extensive guidance document for criteria and procedures relevant to deep renovation. Under LEED, there is no rating system specific to deep renovation, with "major renovations" rather being addressed under the building design and construction (BD+C) rating system. By translating principles and procedures from both into a simplified framework tailored to deep renovation, THRIVE offers a lower barrier to entry for deep renovation project teams seeking to holistically optimize their work. The broad base of industry professionals with previous NEB or LEED experience can find elements of familiarity within THRIVE, further lowering the learning curve and encouraging adoption.

A distinctive feature of THRIVE is the use of linear interpolation for scoring across assessments, particularly when adapting threshold-based LEEDv5 credits. Conventional rating systems such as LEED often lead to point chasing near thresholds, encouraging project teams to do the bare minimum to reach their desired score. The approach to instead score performance along a continuous scale eliminates arbitrary incentives when near a point threshold with an immediate falloff once reached. Rather improvement is always and uniformly rewarded, subtly encouraging practitioners to view decarbonization and well-being as open-ended goals ripe for innovative solutions rather than simply prescriptive targets to be met.

Following the spirit of NEB, THRIVE is not designed to be a competitive rating system awarding certification, but rather a tool to support holistic assessment and interdisciplinary coordination which outputs clear results. However, a clear benefit of rating systems such as LEED is the ability for governments to tie permitting requirements or incentives (e.g. tax credits) to levels of certification. The layer of structure inspired by LEED gives THRIVE a scoring architecture that can facilitate these policies through a third party verification of the reported results. THRIVE's layered results output further gives municipalities the flexibility to tie requirements or incentives to the overall project performance or specific analysis blocks or integrated measures, based on local priorities. Thus, THRIVE has the potential to serve as a bridge between voluntary evaluation and structured regulation, all in the name of a better built environment.

6

CONCLUSIONS

6.1. GENERAL CONCLUSIONS

This MBUILD final dissertation sets out to determine the extent to which the deep renovation of existing buildings can achieve holistic, modern global standards for decarbonization and well-being. In response the **T**ransatlantic, **H**olistic **R**enovation assessment framework for decarbonization, **I**ndoor environmental quality, and **E**quity (THRIVE) has been developed and applied to a real building renovation project. THRIVE integrates two cutting edge frameworks for sustainability in the built environment, the EU-based New European Bauhaus Self-Assessment Method (NEB-SAM) and the US-based LEEDv5 BD+C rating system to create an assessment framework tailored for decarbonization and well-being in deep renovation. Throughout the proposal of THRIVE, the goal became not only to quantify the potential of deep renovation but also explore how THRIVE can improve projects and promote optimized deep renovation as a strategy to achieve global climate targets.

By delivering results in a quantitative (score) and qualitative (performance class) format across four levels of granularity (1. individual assessment, 2. integrated measure, 3. analysis block, and 4. project), THRIVE is able to clearly communicate a headline level of performance while identifying relative strengths and highlighting areas of relative weakness for targeted improvement. TRHIVE draws from the flexibility of NEB, the structure of LEED, and the widespread familiarity with at least one or the other throughout the global construction industry. These qualities, streamlined for deep renovation, create a low barrier to entry for project teams and government municipalities to engage with THRIVE, improve their projects, and promote buildings that are healthier for both planet and people.

Seeking to design energy renovation building envelope packages to support scaling of the EU Renovation Wave, the EU-Horizon AEGIR project was chosen to facilitate a case study. Specifically, the demonstration educational building in Malgrat de Mar, Spain was selected to test and showcase the THRIVE methodology. The case study project achieved an overall THRIVE project score of 64 ("Good"), with consistent analysis block scores ranging from 60 (“Acceptable”) for Indoor Environmental Quality (IEQ) to 68 (“Good”) for Resilience, Aesthetics, and Inclusiveness (RAI). These results demonstrate that, judged against modern criteria, deep renovation can meaningfully advance both decarbonization and occupant well-being simultaneously. However, performance at the integrated measure level contained of a wide range of scores, from 25 (“Low”) for Equitable Accessibility, to 87 (“Excellent”) for Indoor Air Quality (IAQ). This disparity suggests that widespread, simultaneous achievement at a more granular level requires early coordination between project stakeholders and deliberate attention to considerations that may fall outside traditional deep renovation scope.

With further development and promotion, THRIVE has the potential to positively influence the construction industry’s approach to deep renovation in the EU, US, and beyond.

6.2. SPECIFIC CONCLUSIONS

Key findings from the case study results along with gathered insights on the guiding frameworks and THRIVE are organized in response to the research objectives. Note that all proposed recommendations for the case study should be considered iteratively and holistically, ensuring improvement in one area does not compromise performance in others.

i. By extracting insights for cutting-edge sustainable building practice from the EU-based NEB-SAM and US-based LEEDv5 specific to deep renovation projects, THRIVE establishes itself as transatlantic framework streamlined to address the core research question, *To what extent can the deep renovation of existing buildings achieve holistic, modern global standards for both decarbonization and human health & well-being criteria?*".

ii. Via the Embodied Carbon (EC) and Operational Carbon (OC) analysis blocks and the integrated measures therein, THRIVE presents a range of metrics to quantify whole life carbon emissions for deep renovation solutions, most directly through EC1, OC1, and EC/OC2 – Carbon Payback.

EC Case Study Results & Recommendations
Analysis Block Results: 61 ("Good")

As measured in EC1 – Life Cycle Carbon, the proposed project design achieves nearly a 20% reduction in global warming potential (GWP) compared to the baseline, with the proposed model yielding 254,877 kg CO2e. The primary GWP contributors identified in the proposed model are the standard photovoltaic (PV) panels and ETICS with stone wool insulation, together accounting for over half of the A1–A3 emissions.

Targeted recommendations to reduce the impact of these components include:

- Substituting the proposed Phono Solar panels (0.874 kg CO2e/Wp) for a lower-GWP alternative with comparable power output. Modules from Saatvik Green Energy (0.436 kg CO2e/Wp) or ReNew Energy Global (0.431 kg CO2e/Wp) were identified as potentially strong options.
- Replacing the stone wool insulation within the ETICS to match the Soprema Pavawall Smart bio-based wood fiber insulation used in the AEGIR panels. Note that care must be taken to ensure consistent fire-resistance properties when exploring this substitution.

Modeling both recommendations together, using the ReNew Energy Global panels and a generic ETICS EPD including Pavawall Smart among its representative data set, nearly doubled the achieved GWP reduction from 19.9% to 38.6%.

A strong score of 78 ("Good") for EC3 – Circularity & Sourcing reflects the AEGIR project's commitment to the use of secondary material and future recycling or reuse strategies.

EC Lessons Learned
The guidance and outlined procedures for conducting a life cycle carbon assessment were found to be quite similar between NEB-SAM and LEEDv5. One notable difference between the two is the stipulated default reference service life (RSL), with NEB setting it at 50 years and LEED at 60. THRIVE methodology chooses to follow NEB with the lower option expected to better represent the real service life of a renovation project compared to new construction. The dual-scoring approach to EC1 yields slightly higher results on the LEED-side, implying NEB could have more stringent demands regarding embodied carbon. The high embodied carbon impact of the PV panels illustrates that investment in renewable energy is not automatically the lowest whole-life carbon choice. The significant GWP reduction potential through alternative panels underscores the importance of jointly evaluating embodied and operational carbon rather than optimizing for one in isolation.

OC Case Study Results & Recommendations
Analysis Block Results: 65 ("Good")

OC1 quantified a strong 64.3% reduction in operational emissions between the post- and pre-renovation condition of the project, representing a savings of 45,443 kg CO2e / year. OC2 delivers a carbon payback period of 5.6 years by comparing these savings to the embodied carbon investment established by EC1. Energy performance scored markedly better under the NEB-based current source assessment procedure (71) than the LEED-based future source procedure (36). A score of 0 for electrification stems from the retained biomass boiler, which kicks on to supplement the heat pump at a relatively high temperature threshold of 15°C. The boiler also serves domestic hot water and an unrenovated, combustion-based kitchen. OC4 was the standout measure, yielding a score of 85 ("Excellent") for renewable energy. PV panels cover 44% of the project's electricity consumption, and storage capacity of the second-life battery comfortably exceeds the determined flexibility requirements. This strong performance reflects the AEGIR project's prioritization of the use of renewable energy.

No specific recommendations were raised regarding this analysis block, as the overall "Good" performance at block-level and relatively high performance across its integrated measures suggest the best opportunities for targeted investment to improve the project lie in other areas. In general, phasing out the biomass boiler entirely, transitioning the building to be 100% electric, and further improvements to energy efficiency and renewables to approach net zero carbon could push this block to "Excellent".

OC Lessons Learned
Through the novel Carbon Payback measure, THRIVE ties together the embodied carbon of the retrofit materials and the operational carbon impact in single metric, in a way neither guiding framework does independently. While this metric is highly valuable as means to communicate the whole-life carbon performance of a renovation, previous research on which to establish a scoring scale and corresponding performance classification is limited. As future research provides more data for benchmarking, the scale established in the EC2/OC2 methodology should be revisited and refined. The gap between the current- and future-source Energy Performance scores suggests that LEEDv5 credit EAc3, which anticipates continued grid decarbonization, applies notably more stringent thresholds than the NEB-SAM indicator S.1.1. THRIVE aims to balance the approach and demands of each procedure via equal weighting in OC1. The "0" Electrification score, despite otherwise strong outcomes among OC1 assessments, highlights the difficulty of achieving electrification demands established by LEEDv5 credit EAc1.

iii. The indoor environmental quality (IEQ) analysis block provides layered, comprehensive results across daylight, thermal comfort, and indoor air quality (IAQ) indicators.

IEQ Case Study Results & Recommendations
Analysis Block Results: 60 ("Acceptable")

IEQ was the weakest analysis block overall and at the integrated measure-level contains a wide range of outcomes between "Low" performance in thermal comfort and "Excellent" performance in indoor air quality (IAQ).

Despite the use of coated, high-VLT glazing at all new windows and glazed doors, daylight simulations yielded an overall spatial daylight autonomy (sDA) of just 30.5% for the project, driving down the score for IEQ1 – Daylight Access. Considering the often limited scope of a deep energy retrofit regarding daylight optimization, recommendations include first expanding existing window openings, followed by adding new openings to increase daylight access in the lowest-sDA rooms.

IEQ2 – Thermal Comfort underperformed primarily due to failing heating-mode compliance under ASHRAE Standard 55 via predicted mean vote (PMV) calculations. Recalculation considering the following recommendations was found to achieve heating-mode compliance while maintaining cooling-mode compliance:

- Increasing the heating setpoint to 22°C.
- Limiting average air speed to 1.0 m/s, using strategies such as displacement diffusers, manually operable diffusers, and reduced fan speed in heating mode as necessary.

Excellent performance in IEQ3 – Indoor Air Quality reflects the AEGIR project's emphasis on improved ventilation, though a general lack of consideration for pollutants beyond CO2 represents a potential gap that should be assessed through post-renovation air measurements.

IEQ Lessons Learned

The multi-level delivery of results produces a well-differentiated quantification of IEQ performance for the case study. At the analysis block level, daylight access, thermal comfort, and IAQ together yield acceptable overall performance. At the integrated measure level, the identification of strong IAQ outcomes alongside relatively poor daylight and thermal comfort results clearly communicates strengths and limitations that a single aggregate IEQ score would have obscured. The daylight simulation results suggest that deep renovations which do not alter interior programming may be subject to a ceiling on improving daylight access to regularly occupied spaces. The daylight simulation procedure for LEEDv5 was found to be more stringent than the WELLv2 procedure referenced by the NEB-SAM, requiring $sDA_{300/50\%}$ for typical spaces rather than $sDA_{150/50\%}$, with THRIVE opting to conservatively follow the LEED threshold. The use of uniform sDA thresholds was noted to inherently favor projects in sunnier climates.

THRIVE again builds on the guiding frameworks by dividing the ASHRAE Standard 55-based thermal comfort assessment procedures found in NEB-SAM and LEEDv5 into winter and summer compliance checks. Weighting the contribution of each check based on the percentage of time the project building spends operation in each promotes prioritization of comfort strategies based on the project's climate. However, there remains room for improvement in the adaptability of THRIVE to best define "comfort" depending on local context.

Potential limitations were identified regarding the Air Pollutant Concentration assessment warranting further exploration:

- Skewed results due to a baseline set by a single, unrepresentatively bad pre-renovation measurement.
- Optional consideration of non-CO2 pollutants (e.g. VOC, formaldehyde) underestimating the potential of these pollutants to aggregate independent of CO2 concentration and ventilation rates.

iv. The resilience, aesthetics, and inclusiveness (RAI) analysis block reaches beyond standard metrics for sustainability assessment, quantifying the value a project provides in more abstract yet still fundamental aspects of well-being.

RAI Case Study Results & Recommendations

Analysis Block Results: 68 ("Good")

This analysis block is driven by strong performance in Hazard Resilience and Visual Experience. Per THRIVE assessment criteria, the envelope achieves 91% fire-resistant and 54% water-resistant coverage, with all new windows meeting wind-resistance criteria and all new and existing windows confirmed to be manually operable. These results validate safety and resilience as key performance indicators of the AEGIR system. High scores across the Visual Experience assessments may be largely attributed to the visual integration of the project's physical, energy,

and ventilation systems, a vision established early in the design phase through multi-disciplinary collaboration.

While the main entry doors were determined to meet THRIVE clear width criteria, the project fails to achieve any of the remaining Equitable Accessibility criteria for accommodating the multi-lingual local population and those with disabilities. The following recommendations are anticipated to be the easiest and most cost-effective way for the project to improve THRIVE performance.

- Ensure all informational signage is provided in Catalan, Spanish, and English at minimum, adding further languages if a given non-official-language population is confirmed to exceed 5% locally (e.g., Arabic according to the immigrant population in the area).
- Incorporate tactile (e.g., braille) or audible wayfinding communication.
- Install accessible entrance door operators (e.g., wave-to-open, hand press, or foot press mechanisms).

RAI Lessons Learned

Even the most healthy, attractive, and climate positive structures are not truly sustainable if they cannot adequately provide shelter and safety for occupants against a range of natural threats, making resilience a key aspect of holistic assessment. Modern frameworks are catching up with this idea, evidenced by the extensive resilience practices outlined in the NEB-SAM, and the inclusion of a resilience-specific credit in LEEDv5 not present in previous versions.

THRIVE provides value in its isolation of practices between both frameworks most relevant to envelope-focused deep renovation. This leads to a streamlined assessment process encouraging the selection of envelope components that are highly resilient against key natural forces regardless of a project's local code requirements. However, the constraints of economic feasibility should be considered, as uniform resilience criteria could lead to impractical over-design against certain hazards in certain local contexts. Furthermore, current assessment limitations to the outermost envelope layers for fire and water resistance are acknowledged to potentially over-simplify the procedures, failing to capture resilience performance in more complex assemblies.

Aesthetic considerations via Visual Experience are largely governed by the NEB-SAM though supplemented by LEEDv5 "quality views" criteria to create more flexibility for different project environments. While many NEB-SAM principles were directly applicable to THRIVE, some such as "light-shadow effects" required adaptation to better fit the scope of a deep renovation. Case study results support the notion that proper coordination and forethought can produce an architectural vision that successfully masks the typically fragmented, modular appearance of prefabricated panels to create more aesthetically pleasing spaces with these systems. Equitable Accessibility captures the most stringent criteria between shared considerations in the NEB-SAM and LEEDv5 while having the flexibility to adapt to different renovation project scopes.

The contribution of the multilingual signage assessment coming from LEED despite the vastly more multilingual populations in the EU highlights how the guiding frameworks can contribute to both THRIVE and each other in unexpected ways. The poor case study performance in this measure indicates holistic consideration of accessibility and inclusiveness may still be overlooked even in cutting edge sustainable renovation initiatives such as AEGIR.

v. Through the delivery of normalized scores across levels of granularity tied to qualitative performance classes, THRIVE presents a thorough, user-friendly representation of a project's performance regarding whole-life decarbonization and holistic occupant well-being.

6.3. FUTURE RESEARCH

The methodology outlined in this MBUILD final dissertation and demonstrated on the case study project constitutes "version 1" of THRIVE. Considering the limitations of this proposed methodology (identified in Section 5.8), the following lines of future research would well serve the further development of the framework, leading to more robust future iterations.

- **Expanding the validation base:** THRIVE has so far been tested on a single case study, which limits confidence in its performance class thresholds and applicability across differing climates and building typologies. Applying THRIVE to a larger, more diverse pool of deep renovation projects would allow the distribution of Low/Acceptable/Good/Excellent outcomes to be properly validated or recalibrated at each level of granularity. Consequently, application to the additional 3 demonstration buildings making up the AEGIR project serves as a logical next step. Among these buildings there is a multi-family residential building in Denmark, and a single-family home in Romania. Application to these projects therefore presents the opportunity to further optimize THRIVE for residential applications through assessment pathways drawing from residential rather than non-residential NEB-SAM criteria. Given the scale of global housing need, developing and validating residential-specific thresholds is a priority extension.
- **Incorporating post-occupancy validation:** Throughout the development of this MBUILD final dissertation, construction of the AEGIR Spain demo building was ongoing. Thus, the design-phase results for THRIVE could not be verified against as-built performance. Future research should explore more intentional procedures for post-renovation validation through as-built bill of quantities (BoQ), energy meter data, temperature, humidity, and air speed measurements, pollutant concentration monitoring, and occupant satisfaction surveys. A dual-phase THRIVE assessment structure, mirroring LEED's separate design and construction certification stages, offers a potential path to formalize post-renovation validation while preserving THRIVE's usability as a design-phase decision support tool.
- **Adding an economic dimension:** In its current form, THRIVE evaluates only environmental and social sustainability pillars. An integrated measure on life cycle cost analysis (LCCA) quantifying the economic payback period of deep renovation strategies would add a valuable dimension for assessing feasibility, return on investment, and balancing environmental and social benefits vs economic constraints. Similar to Carbon Payback this measure could be shared between the embodied and operational analysis blocks, presenting a natural extension of the framework's investment-based logic.
- **Building on the Embodied Carbon methodology:** EC1 – Life Cycle Carbon has the potential for expansion from a purely GWP-based life cycle carbon assessment to a multi-impact category life cycle analysis (LCA). Future work to consider further impact categories for the EC1 score, starting with those stipulated by LEEDv5 for a whole-building LCA, would offer a more well-rounded picture of a project's embodied environmental impact. Furthermore, exploration of adapting the assessment methodology to reflect cradle-to-cradle impact would allow for the capture of material circularity potential unaddressed under the current measure. The multi-attribute scoring (MAS) assessment procedure under EC3 – Circularity & Sourcing, drawn from a new feature of LEEDv5, would also benefit from empirical benchmarking across a larger sample of projects to calibrate its performance thresholds beyond qualitative judgment.
- **Refining and expanding Operational Carbon scope:** The Carbon Payback measure (EC2/OC2), being a novel THRIVE contribution without precedent in either guiding framework, should have its scoring thresholds revisited as more research on carbon payback periods for deep renovation becomes available to establish more reliable benchmarks. Expanding the validation base also serves to generate more data regarding carbon payback, enabling iterative development of the integrated measure as more projects undertake THRIVE assessment. Expansion of OC3 – Peak Demand to incorporate ventilation energy recovery and thermal bridging assessment

procedures, consistent with LEEDv5 credit EAc2, would offer more complete consideration of system-level strategies to minimize demand on grid resources.

- **Broadening IEQ coverage:** Acoustic comfort and interior lighting quality represent natural areas for expansion within the IEQ analysis block, especially considering lighting system upgrades are a common strategy to enhance energy efficiency as part of deep renovation. Making daylight simulation and thermal comfort thresholds adaptable to better address varying local climates and contexts should be explored. Within IEQ3 – Indoor Air Quality, future research should test alternative baseline-setting methodologies (e.g., averaging the highest measurements over a year rather than using a single maximum pre-renovation reading) across multiple case studies to assess sensitivity of results to unrepresentative outlier conditions.
- **Strengthening Resilience, Aesthetics & Inclusiveness**: Future work should address additional hazards (e.g. seismic) in RAI1 – Hazard Resilience, while also incorporating measures to avoid costly over-design against those not relevant to the project's local context. The interior–exterior visual contact assessment under RAI2 – Visual Experience should be reconsidered or adapted for residential and privacy-sensitive project types for which it is currently poorly suited. The exploration of incorporating indicators from the NEB-SAM Inclusiveness dimension could expand THRIVE's treatment of inclusiveness beyond physical design elements. Given the abstract nature of these indicators, they may serve better as opening guidelines within THRIVE rather than direct scoring mechanisms.

REFERENCES

3A Composites. (2026). *ALUCOBOND A2*. 3A Composites. https://www.alucobond.com/en/products/by-brand/alucobond-a2/

A Renovation Wave for Europe | European Hydrogen Observatory. (2025, June 20). https://observatory.clean-hydrogen.europa.eu/eu-policy/renovation-wave-europe

ASHRAE. (2003). *Addendum n to ANSI/ASHRAE Standard 62-2001, Ventilation for Acceptable Indoor Air Quality*. http://www.ashrae.org,

ASHRAE. (2022). *ANSI/ASHRAE Standard 62.1-2022: Ventilation for Acceptable Indoor Air Quality*.

ASHRAE. (2023). *ASHRAE Standard 241-2023: Control of Infectious Aerosols*.

ASHRAE 55 and 61: Guidelines. (n.d.). *Guidelines for creating comfortable and accessible indoor environments*.

ASHRAE, & IES. (2022). *ANSI/ASHRAE/IES Standard 90.1-2022: Energy Standard for Buildings Except Low-Rise Residential Buildings*.

Baggio, M., Tinterri, C., Mora, T. D., Righi, A., Peron, F., & Romagnoni, P. (2017). Sustainability of a Historical Building Renovation Design through the Application of LEED® Rating System. *Energy Procedia*, *113*, 382–389. https://doi.org/10.1016/j.egypro.2017.04.017

Bektasiadou, E. (2024). Transforming a European Commission's Building into Beautiful, Sustainable and Inclusive Spaces: Renovation and adaptation aligned to the New European Bauhaus principles. *PLEA 2024 Re Thinking Resilience Proceedings of 37th PLEA Conference Sustainable Architecture and Urban Design the Book of Proceedings*, 1491–1496.

Bienert, S., Kuhlwein, H., Schmidt, Y., Gloria, B., & Agbayir, B. (2023). *Embodied Carbon of Retrofits Ensuring the ecological payback of energetic retrofits*.

British Standards Institution (BSI). (2025). *Flood resilient construction. Improving the flood performance of buildings. Guide*.

Building Research Institute (ITB). (2015). *Declaration No. 031/2015: Verification of 360optimi and One Click LCA software*.

Carrol, A. (2025, July 9). *Embodied carbon vs. operational carbon | One Click LCA*. https://oneclicklca.com/en-us/resources/articles/embodied-carbon-vs-operational-carbon

Chen, Q., Huang, B., Wu, Y., Zhang, H., Habib, U., & Che, Z. (2025). Research on Carbon Reduction Path for Whole-Process Design of Prefabricated Envelope System Based on SEM. *Buildings*, *15*(5). https://doi.org/10.3390/buildings15050751

Christiansen, K. (2026, January 16). *WHAT'S THE PROBLEM WITH PRE-1980 BUILDINGS?* Facility Condition Insights. https://www.linkedin.com/pulse/whats-problem-pre-1980-buildings-kyle-christiansen-ra-eepoe/

CORTIZO. (n.d.). *FICHA TÉCNICA COR 70 INDUSTRIAL*.

Curiel Martín, R. (2025). *ANEXO I-CÁLCULO ESTRUCTURAL DE FACHADA*.

DECARBONIZATION IN LEED v5. (n.d.).

DiLaura, D., Houser, K., Mistrick, R., & Steffy, G. (Eds.). (2011). *The Lighting Handbook* (10th ed.). Illuminating Engineering Society of North America.

Directorate-General for Environment. (2025, May 12). LEED certification to deepen alignment with Level(s) and EU Taxonomy in the European market. *European Commission Green Forum*. https://green-forum.ec.europa.eu/news/leed-certification-deepen-alignment-levels-and-eu-taxonomy-european-market-2025-05-12_en

Embodied Carbon - World Green Building Council. (n.d.). Retrieved March 14, 2026, from https://worldgbc.org/climate-action/embodied-carbon/

EPA Center for Corporate Climate Leadership. (2025). *Emission Factors for Greenhouse Gas Inventories*.

European Commission. (2026). *COMMISSION STAFF WORKING DOCUMENT Supporting life-cycle approaches to decarbonise European buildings*.

Eurostat. (2026, May 13). *Share of energy from renewable sources*. https://ec.europa.eu/eurostat/databrowser/view/nrg_ind_ren/default/table?lang=en

Fokaides, P. (2025). Recent Developments in Life Cycle Assessment Implementation in the EU: Advancing Sustainability Through Level(s) and the New European Bauhaus. *2025 10th International Conference on Smart and Sustainable Technologies Splitech 2025*. https://doi.org/10.23919/SpliTech65624.2025.11091693

Gaillard, Y. (2020). *EPD: PAVAWALL SMART*.

Gao, S., Yang, L., Li, Y., Liu, S., Zhang, H., Arens, E., & Zhai, Y. (2023). Metabolic rate in children and adolescents: Tabulate values for common activities and comparisons with standards and adult values. *Building and Environment*, *244*. https://doi.org/10.1016/j.buildenv.2023.110804

Ghorbany, S., Hu, M., & Nouri, A. (2025). Commercial buildings decarbonization: Benchmarks and strategies for the United States sustainable commercial construction. *Sustainable Cities and Society*, *124*. https://doi.org/10.1016/j.scs.2025.106324

Guardian Glass. (n.d.). *Guardian Glass Performance Calculator* (4.1.0.9855).

Hamimi, A., Tharim1, A., Hanim, I., Samad2, A., & Ismail2, M. (2017). SOCIAL SCIENCES & HUMANITIES Relationship between Indoor Environmental Quality (IEQ), Occupant's Satisfaction and Productivity in GBI Rated Office Building using SEM-PLS. In *Pertanika J. Soc. Sci. & Hum* (Vol. 25).

Heather Benjamin. (2025a, August 20). *Look into LEED v5: Gianni Giorgi–Alberti*. USGCB. https://www.usgbc.org/articles/look-leed-v5-gianni-giorgi-alberti

Heather Benjamin. (2025b, September 10). *Look into LEED v5: Ascent MKE*. USGBC. https://www.usgbc.org/articles/look-leed-v5-ascent-mke

Herrero, N., Uriarte, A., & Sánchez, V. (2025). *D6.6 Metamodel for building operation Digital and physical incremental renovation packages enhancing environmental and energetic behaviour and use of resources version 1.0*.

HM Government. (2019). *Fire Safety APPROVED DOCUMENT B*.

Home - AEGIR. (2022). https://aegirproject.eu/

Illuminating Engineering Society. (2023). *ANSI/IES LM-83-23: Approved Method – IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*.

Int-Hout; Dan. (2014). *Compliance to Standard 55*. www.krueger-hvac.com.

Ismaeel, W. S. E. (2022). Reviewing Sustainable building renovation considering indoor environmental quality. *2022 Engineering and Technology for Sustainable Architectural and Interior Design Environments Etsaide 2022*. https://doi.org/10.1109/ETSAIDE53569.2022.9906366

IWBI. (2025). *WELL Building Standard version 2*. https://v2.wellcertified.com/en/wellv2/overview

Jain, N., Burman, E., Robertson, C., Stamp, S., Shrubsole, C., Aletta, F., Barrett, E., Oberman, T., Kang, J., Raynham, P., Mumovic, D., & Davies, M. (2020). Building performance evaluation: Balancing energy and indoor environmental quality in a UK school building. *Building Services Engineering Research and Technology*, *41*(3), 343–360. https://doi.org/10.1177/0143624419897397

Jay Arnaud, & Astudillo Larraz, J. (2023). *Digital and physical incremental renovation packages enhancing environmental and energetic behavior and use of resources*.

Karmann, C., Schiavon, S., Graham, L. T., Raftery, P., & Bauman, F. (2017). Comparing temperature and acoustic satisfaction in 60 radiant and all-air buildings. *Building and Environment*, *126*, 431–441. https://doi.org/10.1016/j.buildenv.2017.10.024

Katsigiannis, E., Gerogiannis, P. A., Atsonios, I., Bonou, A., Mandilaras, I., Georgi, A., Papadopoulou, S., Tsoutis, C., & Founti, M. (2022). Energy assessment of a residential building renovated with a novel prefabricated envelope integrating HVAC components. *Iop Conference Series Earth and Environmental Science*, *1078*(1). https://doi.org/10.1088/1755-1315/1078/1/012130

Katsigiannis, E., Gerogiannis, P. A., Atsonios, I., Founti, M., Mandalaki, M., & Vazakas, A. (2025). The environmental and energetic impact of prefabricated envelope components with bio-based materials for deep renovation. *E3s Web of Conferences*, *654*. https://doi.org/10.1051/e3sconf/202565401009

Koolen, D., De Felice, M., & Busch, S. (2023). *FLEXIBILITY REQUIREMENTS AND THE ROLE OF STORAGE IN FUTURE EUROPEAN POWER SYSTEMS*.

Kumar, S. (2026). *EPD: NTOPCON Bifacial G12R*.

Kumar Singh, R. (2025). *EPD: M10, 144Cell TOPCon, Bi-Facial Solar Module*.

Leichter, M., Dodoo, A., & Piccardo, C. (2025). Life cycle assessment of energy renovation versus demolition and new construction in the context of a social housing project. *Clean Technologies and Environmental Policy*, *27*(4), 1845–1861. https://doi.org/10.1007/s10098-024-03054-z

LightStanza. (n.d.-a). *General Help Guides*. Retrieved April 23, 2026, from https://lightstanza.com/general-workflow-help-guides/

LightStanza. (n.d.-b). *LightStanza* (5.58.27).

Lourenco, P. B., Maloutas, T., Santamouris, M., Widera, B., Ansaloni, F., Balaras, C., Katuric, I., Kolokotsa, D., Rossetto, T., Senatore, G., Tomaszewicz, A., Medeiros, E., Gkatzogias, K., Pohoryles, D., & Romano, E. (2024). *A practical guide to the New European Bauhaus self-*

assessment method and tool (K. Gkatzogias, E. Romano, & P. Negro, Eds.). European Union. https://doi.org/10.2760/3134833

LV, H. (2023). *EPD: Solar photovoltaic module*.

Madson, K., Franz, B., Leicht, R., & Nelson, J. (2022). Evaluating the Sustainability of New Construction Projects over Time by Examining the Evolution of the LEED Rating System. *Sustainability Switzerland*, *14*(22). https://doi.org/10.3390/su142215422

New European Bauhaus Compass. (n.d.).

New European Bauhaus-inspired future JRC site in Seville. (n.d.). European Union. Retrieved March 28, 2026, from https://new-european-bauhaus.europa.eu/new-european-bauhaus-inspired-future-jrc-site-seville_en

Oficina Catalana del Canvi Climátic. (2025). *Guia de càlcul d'emissions de gasos amb efecte d'hivernacle (GEH)*.

One Click LCA. (n.d.-a). *Average Material Quantities*. Retrieved April 24, 2026, from https://help.oneclicklca.com/en/articles/275887-average-material-quantities

One Click LCA. (n.d.-b). *Average Quantities of Reinforcement in Concrete*. Retrieved April 24, 2026, from https://help.oneclicklca.com/en/articles/275888-average-quantities-of-reinforcement-in-concrete

One Click LCA. (2015). *One Click LCA*. One Click LCA, Ltd.

Owens Corning. (2021). *EPD: Thermafiber ® Mineral Wool*.

Plebankiewicz, E., & Grącki, J. (2025). Long-Term Building Renovation Strategies—F-TOPSIS Analysis of Solutions Applied in the Chosen European Union Countries. *Buildings*, *15*(4). https://doi.org/10.3390/buildings15040607

Pops Facades. (n.d.). *How Long Does Cladding Last? Lifespan Expectations by Material Type*. Pops Facades. Retrieved April 30, 2026, from https://popsfacades.co.uk/how-long-does-cladding-last-lifespan-expectations-by-material-type/

QUALITY OF LIFE IN LEED v5. (n.d.).

Rosado-García, M. J., Kubus, R., Argüelles-Bustillo, R., & García-García, M. J. (2021). A new european bauhaus for a culture of transversality and sustainability. *Sustainability Switzerland*, *13*(21). https://doi.org/10.3390/su132111844

Saadoon Abdulaali, H., S Usman, I. M., Hanafiah, M. M., Jamal Abdulhasan, M., Talib Hamzah, M., & akar nazal, A. (2020). Impact of poor Indoor Environmental Quality (IEQ) to Inhabitants' Health, Wellbeing and Satisfaction. *International Journal of Advanced Science and Technology*, *29*(3s), xx–xx.

Salvalai, G., & Zhao, F. (2025). Active prefabricated façade with building-integrated photovoltaic (APF-BIPV) technologies for high energy efficient building renovation: a systematic review of recent research advancements. *Energy and Buildings*, *348*. https://doi.org/10.1016/j.enbuild.2025.116440

Sameh, R., Ismaeel, W. S. E., & Othman, F. (2021). Sustainable building renovation and indoor environmental quality. *Proceedings of the 37th Annual Arcom Conference Arcom 2021*, 574–583.

Secondo-Maglia, J. G., Alapont-Ramón, J. L., De-Rossi-Estrada, M., & Sánchez Gómez, S. (2024). Measuring the Influence of Industrialization in Deep Energy Renovations: A Three-Case Study Utilizing Key Performance Indicators (KPIs). *Buildings*, *14*(11). https://doi.org/10.3390/buildings14113448

Sesana, M. M., Salvalai, G., Brutti, D., Mandin, C., & Wei, W. (2021). ALDREN: A methodological framework to support decision-making and investments in deep energy renovation of non-residential buildings. *Buildings*, *11*(1), 1–20. https://doi.org/10.3390/buildings11010003

Sto. (2020). *StoTherm® ci Mineral System Components*.

Sto. (2026). *StoTherm Mineral*. Sto. https://www.sto.es/s/c/a0KSe000000fdYuMAI/stotherm-mineral?language=es

Tartarini, F., Schiavon, S., Cheung, T., & Hoyt, T. (2020). *CBE Thermal Comfort Tool: online tool for thermal comfort calculations and visualizations* (2.5.7).

TESCOR Enginyeria. (2025). *PROYECTO EJECUTIVO PARA LA REHABILITACIÓN DEL CEIP MARIÀ CUBÍ I SOLER SITUADO EN MALGRAT DE MAR*.

Tran, D. B., Tran, V. T., Pham, X. A., & Nguyen, V. T. (2023). A General Framework for Sustainability Assessment of Buildings: A Life-Cycle Thinking Approach. *Sustainability Switzerland*, *15*(14). https://doi.org/10.3390/su151410770

TRESPA METEON MATERIAL PROPERTY DATASHEET. (2022). www.trespa.info

Udisi, B., Osman, F., Gorgolewski, M., Saunders, K., Devraj-Kizuk, R., & Kemp, S. (2024). Embodied Carbon Impacts of Building Envelope Systems. *Iop Conference Series Earth and Environmental Science*, *1363*(1). https://doi.org/10.1088/1755-1315/1363/1/012070

United Network Studio. (2026). *AEGIR Smart renovation solution for retrofitting*.

USA Country Summary. (2025, September 22). Climate Action Tracker. https://climateactiontracker.org/countries/usa/

USGBC. (2025). *LEED Credit Library*. https://www.usgbc.org/credits

USGBC. (2026). *CRITERIA AREAS & ACHIEVEMENT IN LEED v5*.

USGBC Announces First Projects Certified Under LEED v5. (2025, August 25). CleanLink. https://www.usgbc.org/articles/us-green-building-council-announces-first-projects-certified-under-leed-v5

Vaczi, M. (2022, March 1). *Fire Safety And BROOF(t4): Updates Explained*. SOPREMA UK Blog. https://www.soprema.co.uk/blog/fire-safety-and-broof-t4-updates-explained

Vahidi, E., Kirchain, R., Burek, J., & Gregory, J. (2021). Regional variation of greenhouse gas mitigation strategies for the United States building sector. *Applied Energy*, *302*. https://doi.org/10.1016/j.apenergy.2021.117527

Villalba Mendez, G., Curcoll, R., & Monteiro, V. (2025). *Greenhouse gas observations from the metropolitan area of Barcelona by ICTA-UAB*. https://webs.uab.cat/atmosphere/greenhouse-gas-monitoring/

Võsa, K.-V., Kurnitski, J., Felsmann, C., Meinsenbach, A., Carli, M. D., Tonon, M., & Iivonen, M. (2023). National methods fail to calculate standardized deep renovation concepts for dwellings:

Benchmarking in three EU climates. *E3s Web of Conferences*, *396*. https://doi.org/10.1051/e3sconf/202339604014

Walker, L., Hischier, I., & Schlueter, A. (2022). Does context matter? Robust building retrofit decision-making for decarbonization across Europe. *Building and Environment*, *226*. https://doi.org/10.1016/j.buildenv.2022.109666

Yang, W. (2023). *EPD: Mono-crystalline Double glass, N-Type, solar photovoltaic modules*.

Zabek, M., Delft, T. U., Konstantinou, T., & Klein, T. (2023). *D2.3: Sustainable requirements PROJECT REFERENCE*.

Zabek, M., Konstantinou, T., & Galvez-Martos, J.-L. (2024). Circularity potential of building products: Material Flow Analysis of façade building components. In B. Widera, M. Rudnicka-Bogusz, J. Onyszkiewicz, & A. Woźniczka (Eds.), *PLEA 2024: (Re)thinking Resilience. The book of proceedings*. Politechnika Wrocławska, Oficyna Wydawnicza. https://doi.org/10.37190/plea_2024

Zahrmann, A. (2024, December 16). *What is an LCA? 3 life-cycle assessment examples*. One Click LCA. https://oneclicklca.com/en-be/resources/articles/life-cycle-assessment-examples-and-lca-defined/

Zhao, N. (2025, April 8). *Almost Half of the Owner-Occupied Homes Built Before 1980*. National Association of Home Builders. https://eyeonhousing.org/2025/04/almost-half-of-the-owner-occupied-homes-built-before-1980/

Zhivov, A., & Lohse, R. (2021). What is Deep Energy Retrofit? In *SpringerBriefs in Applied Sciences and Technology* (pp. 7–8). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/978-3-030-66211-0_3

ANNEXES

Annex A.1 – Input Quantities for Whole-Life Carbon Assessment

Classification	Component	Quantity	Unit
AEGIR	Rockwool Insulation	185.5[a]	m2
AEGIR	OSB	370.9	m2
AEGIR	Steel Structural Framing	2279.7	kg
AEGIR	Aluminum Structural Framing	1.3	kg
AEGIR	Wood Fiber Insulation	29.7[b]	m3
AEGIR	Waterproofing	185.5	m2
AEGIR	Window Glazing	4430.0	kg
AEGIR	Window Framing	1388.6	kg
AEGIR	HPL Cladding	186.9	m2
AEGIR	Aluminum Composite Cladding	16.9	m2
ETICS	ETICS	291.6[c]	m2
ETICS	Window Glazing	6863.7	kg
ETICS	Window Framing	2093.3	kg
ETICS	Glass Door Glazing	1453.4	kg
ETICS	Glass Door Framing	329.6	kg
ETICS	Steel Door	2	units
ETICS+C	ETICS	402.0	m2
ETICS+C	HPL Cladding	241.9	m2
ETICS+C	Reclaimed Wood Cladding	118.7	m2
ETICS+C	Aluminum Composite Cladding	72.5	m2
Structure	AEGIR Panel Footings - Concrete	17.94	m3
Structure	AEGIR Panel Footings - Rebar	0.46	m3
Structure	AHU / Battery Support Slabs - Concrete	20.83	m3
Structure	AHU / Battery Support Slabs - Rebar	0.27	m3
Roof PV	Standard PV Panels	332.3[d]	m2
Roof PV	Flexible PV Module	26.7[e]	m2

a) In the Baseline model, thickness is adjusted from 120mm to 109mm to maintain equivalent thermal performance

b) In the Baseline model, this quantity is adjusted to 32.7 m3 to maintain equivalent thermal performance.

c) In the Baseline and Proposed models, this quantity has been adjusted from the 422m2 calculated from take-offs to reflect accurate thermal performance. EPD Reference R = 1.65 m2K/W, Real R = 1.14 m2K/W.

d) In the Baseline model, this quantity is adjusted to 368.9 m2 to maintain equivalent energy performance.

e) In the Baseline and Proposed model, this quantity has been adjusted by a factor of 1/3 from the actual project area to account for the Watt-peak (Wp) capacity difference between the utilized EPD and actual specified Wp (EPD Wp =150, Project Wp = 50).

Annex A.2.1 – EPD Assignments for Whole-Life Carbon Assessment – Baseline

Component	Material	Environmental Data Source
Rockwool Insulation	Stone wool (mineral wool) insulation, unfaced, L = 0.031 W/mK, R = 1 m2K/W, 31mm, 1.86 kg/m2, 60 kg/m3, (Range: 51-65kg/m3), 22% slag content	One Click LCA
OSB	Oriented strand board (OSB), 613 kg/m3, 3% moisture content	One Click LCA
Steel Structural Framing	Steel hot dip galvanised Europe 2022, blast furnace route, production mix, at plant, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm	Worldsteel 2023 LCA Methodology Report
Aluminum Structural Framing	Extruded aluminium profiles for window and door frames, generic, 60% recycled content, average world aluminium manufacturing technology	One Click LCA
Wood Fiber Insulation	Wood fibre weather resistant insulation for walls and roof, L = 0.043 W/mK, 180 kg/m3, average World wood pulp manufacturing technology, Lambda=0.043 W/(m.K)	One Click LCA
Waterproofing	PP underlay sheet, 0.15 kg/m2, EN15804+A2, ref. year 2022	ÖKOBAUDAT 2022
Window Glazing	Float glass, single pane, 4 mm, 10 kg/m2, 2500 kg/m3	One Click LCA
Window Framing	Extruded aluminium profiles for window and door frames, generic, 60% recycled content, average world aluminium manufacturing technology	One Click LCA
HPL Cladding	HPL laminate cladding, 8.1 mm, 11.6 kg/m2	KBOB
Aluminum Composite Cladding	Aluminium sandwich panel with thermoplastic core, 4 mm, 7.04 kg/m2	EPD Aluminiumverbundplatten Aluminium Deutschland
ETICS	ETICS with stone wool insulation, R=1.65-5.25 m2K/W, 38.9 kg/m2	FDES

Component	Material	Environmental Data Source
Glass Door Glazing	Float glass, single pane, 4 mm, 10 kg/m2, 2500 kg/m3	One Click LCA
Glass Door Framing	Steel hot dip galvanised Europe 2022, blast furnace route, production mix, at plant, typical thickness between 0.3 - 3 mm. typical width between 600 - 2100 mm	Worldsteel 2023 LCA Methodology Report
Steel Door	Steel door with mineral wool core, fire rated, 900x2000 mm, 74 kg/unit	One Click LCA
Reclaimed Wood Cladding	Timber cladding for walls and ceilings, 31.699 kg/m2, 700 kg/m3	EPD Timber cladding for walls and ceilings
AEGIR Panel Footings - Concrete	Ready-mix concrete, normal strength, generic, C25/30 (3600/4400 PSI) with CEM II/A-S, 10% GGBS content (280 kg/m3; 17.5 lbs/ft3 total cement)	One Click LCA
AEGIR Panel Footings - Rebar	Reinforcement steel (rebar), generic, 97% recycled content (typical), A615	One Click LCA
AHU / Battery Support Slabs - Concrete	Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), S1 XC0/XC1, 10% (typical) recycled binders in cement (min cem. content: 280 kg/m3 / 18.72 lbs/ft3), Portland-fly ash cement CEM II/A-V 42.5, (version 2024)	One Click LCA
AHU / Battery Support Slabs - Rebar	Reinforcement steel (rebar), generic, 97% recycled content (typical), A615	One Click LCA
Standard PV Panels	Photovoltaic systems, calculated average for Spain, 14.5 kg/m2, P=500 Wp	One Click LCA
Flexible PV Module	Monocrystaline photovoltaic module, per m2, 2.4 kg/m2, 150 Wp, 138.5 Wp/m2, Green Energy CIGS	EPD MD-24125-EN | Green Energy Group ApS

Annex A.2.2 – EPD Assignments for Whole-Life Carbon Assessment – Proposed

Component	Material	Environmental Data Source
Rockwool Insulation	Stone wool insulation, unfaced, L= 0.034 W/mK, R= 1 m2K/W, 34 mm, 1.73 kg/m2, 51 kg/m3, Ventirock Duo (ROCKWOOL Peninsular S.A.U.)	EPD ROCKWOOL® Stone Wool Thermal Insulation for buildings
OSB	Oriented strand board (OSB), 613 kg/m3, 3% moisture content	One Click LCA
Steel Structural Framing	Hot-dip galvanized steel profiles and accessories for plasterboard, 7850 kg/m3 (Gyproc Saint Gobain (2022))	EPD Gyproc Steel Profiles and Accessories, ver. 2
Aluminum Structural Framing	Aluminium profiles, 2700 kg/m3 (Gesamtverband der Aluminiumindustrie e.V.)	EPD Aluminiumprofil pressblank
Wood Fiber Insulation	Wood fiber insulation panel, biogenic CO2 not subtracted (for CML), L=0.039 W/mK, R=4.1 m2K/W, 160 mm, 18.4 kg/m2, 115 kg/m3, Lambda=0.039 W/(m.K), PAVAWALL® SMART 160 mm (SOPREMA SAS)	FDES
Waterproofing	Waterproof membrane from nonwoven HDPE for roof and wall underlay, 0.175 mm, 145 g/m2, DuPont™ Tyvek® 2507B (DuPont)	EPD DuPont™ Tyvek® 2507B - DuPont de Nemours (Luxembourg) s.à r.l.
Window Glazing	Uncoated flat glass, 2500 kg/m3, Guardian ExtraClear™, Guardian UltraClear™ (Guardian Europe)	EPD Uncoated flat glass, laminated safety glass and coated flat glass Guardian Europe S.à.r.l.
Window Framing	Aluminium profiles, 2700 kg/m3 (Gesamtverband der Aluminiumindustrie e.V.)	EPD Aluminiumprofil pressblank
HPL Cladding	High pressure laminate (HPL) panels, 8 mm, 11.2 kg/m2, Trespa® Meteon EDF (Nemho)	EPD S-P-07213 Trespa® Meteon® EDF grade 8mm
Aluminum Composite Cladding	Composite panel with double sided aluminium sheet and mineral filled polymer core, 4 mm, 7.6 kg/m2, ALUCOBOND A2 (3A Composites GmbH)	EPD ALUCOBOND A2

Component	Material	Environmental Data Source
ETICS	ETICS with stone wool insulation, R=1.65-5.25 m2K/W, 38.9 kg/m2	FDES
Glass Door Glazing	Uncoated flat glass, 2500 kg/m3, Guardian ExtraClear™, Guardian UltraClear™ (Guardian Europe)	EPD Uncoated flat glass, laminated safety glass and coated flat glass Guardian Europe S.à.r.l.
Glass Door Framing	Hot-dip galvanized steel profiles and accessories for plasterboard, 7850 kg/m3 (Gyproc Saint Gobain (2022))	EPD Gyproc Steel Profiles and Accessories, ver. 2
Steel Door	Steel door with mineral wool core, fire rated, 900x2000 mm, 74 kg/unit	One Click LCA
Reclaimed Wood Cladding	Timber cladding for walls and ceilings, 31.699 kg/m2, 700 kg/m3 (FRAPONT S.A.)	EPD Timber cladding for walls and ceilings
AEGIR Panel Footings - Concrete	Ready-mix concrete, normal strength, generic, C25/30 (3600/4400 PSI) with CEM II/A-S, 10% GGBS content (280 kg/m3; 17.5 lbs/ft3 total cement)	One Click LCA
AEGIR Panel Footings - Rebar	Reinforcement steel (rebar), generic, 97% recycled content (typical), A615	One Click LCA
AHU / Battery Support Slabs - Concrete	Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), S1 XC0/XC1, 10% (typical) recycled binders in cement (min cem. content: 280 kg/m3 / 18.72 lbs/ft3), Portland-fly ash cement CEM II/A-V 42.5, (version 2024)	One Click LCA
AHU / Battery Support Slabs - Rebar	Reinforcement steel (rebar), generic, 97% recycled content (typical), A615	One Click LCA
Standard PV Panels	Mono-crystalline photovoltaic module, per m2, 12.70 kg/m2 (Phono Solar Technology Co.,Ltd)	EPD Mono-crystalline Double glass, N-Type, solar photovoltaic modules
Flexible PV Module	Monocrystaline photovoltaic module, per m2, 2.4 kg/m2, 150 Wp, 138.5 Wp/m2, Green Energy CIGS (Green Energy Group ApS)	EPD MD-24125-EN | Green Energy Group ApS

Annex A.3 – Responsible Sourcing Multi-Attribute Scoring

Eligible Product Documentation	Criteria Areas					LEED Multi-Attribute Score (max = 5)
	Human Health	Climate Health	Ecosystem Health	Social Health & Equity	Circular Economy	
Biobased Content, Non-Wood (½ x verified biobased content %)	-	-	-	-	%	up to 1
BIFMA Level (2024) Tier 1 or Tier 2	-	*	-	-	%	0+
BIFMA Level (2024) Tier 3	1	*	-	1	%	2+
BIFMA Level (2024) Tier 4	2	*	1	1	1	5
Cradle to Cradle: Bronze (Version 3.1)	1	-	-	-	%	1+
Cradle to Cradle: Bronze (Version 4.0/4.1)	1	-	-	1	%	2+
Cradle to Cradle: Silver (Version 3.1)	2	-	-	1	%	3+
Cradle to Cradle: Silver (Version 4.0/4.1)	2	1	1	1	1	5
Cradle to Cradle: Gold (Version 3.1)	3	1	1	1	1	5
Cradle to Cradle: Gold (Version 4.0/4.1)	3	2	1	2	2	5
Cradle to Cradle: Platinum (Version 3.1)	3	2	2	2	2	5
Cradle to Cradle: Platinum (Version 4.0/4.1)	3	3	2	3	3	5
Cradle to Cradle: Certified Circularity, Bronze (v4.1)	1	-	-	-	%	1+
Cradle to Cradle: Certified Circularity, Silver (v4.1)	1	-	-	-	1	2
Cradle to Cradle: Certified Circularity, Gold (v4.1)	1	-	-	-	2	3
Cradle to Cradle: Certified Circularity, Platinum (v4.1)	1	-	-	-	3	4
Cradle to Cradle: Material Health Certificate, Bronze (v3.1/v4.0/v4.1)	1	-	-	-	-	1
Cradle to Cradle: Material Health Certificate, Silver (v3.1/v4.0/v4.1)	2	-	-	-	-	2
Cradle to Cradle: Material Health Certificate, Gold (v3.1/v4.0/v4.1)	3	-	-	-		3
Cradle to Cradle: Material Health Certificate, Platinum (v3.1/v4.0/v4.1)	3	-	-	-		3

Eligible Product Documentation	Criteria Areas: Human Health	Climate Health	Ecosystem Health	Social Health & Equity	Circular Economy	LEED Multi-Attribute Score (max = 5)
Declare (v2.0)	1	-	-	-	-	1
Declare: Third-party Verified and Red List Free or Red List Approved (v2.0)	2	-	-	-	-	2
EPD: Product-Specific Type III	-	1	-	-	-	1
EPD: Optimized (>20% reduction in GWP)	-	2	1	-	-	3
EPD: Optimized (>40% reduction in GWP and >10% reduction in three additional impact categories)	-	3	2	-	-	5
Global Green TAG: Product Health Declaration	2	-	-	-	-	2
Green Seal GS-11 Certified	2	-	-	-	-	2
HPD: Pre-Checked for LEED, min 1000ppm	1	-	-	-	-	1
HPD: Third-Party Verified, 100ppm, Avoidance of Chemicals of High Concern	2	-	-	-	-	2
Materials Reuse (100% reused product)	-	2	1	-	2	5
Recycled Content (½ x pre-consumer % + 1x post-consumer %)	-	-	-	-	%	up to 1
Wood Products: Legal Sourcing with Disclosure	-	-	1	-	-	1
Wood Products: SFI "100% recycled content" label	-	-	1	-	1	2
Wood Products: PEFC "Recycled" label	-	-	1	-	1	2
Wood Products: FSC "Recycled" label	-	-	1	-	1	2
Wood Products: SFI CoC "Promoting Sustainable Forestry and Recycled Content" label	-	-	1	-	1	2
Wood Products: PEFC "Certified" label	-	-	2	1	-	3
Wood Products: SFI CoC "Promoting Sustainable Forestry" label	-	-	2	1	-	3
Wood Products: FSC "Mixed" label	-	-	2	2	-	4
Wood Products: FSC "100%" label	-	-	3	2	-	5
USGBC-Approved Extended Producer Responsibility Program	-	-	-	-	1	1
Other USGBC-Approved Programs	TBD					
Note: Products with more than one eligible document can combine scores across different criteria areas (horizontally) to get a total multi-attribute score for the product. However, scores from within a single criteria area (vertically) are not additive and the product will be assigned the hightest achieved value in the criteria area only.						

(USGBC, 2026)

Annex A.4 – IEQ Analysis Room List

Level	Room #	Room Name	Area (m2)	Reg Occ Space?	Temp Control Device?
Ground Level	1	CLASSROOM	21	Yes	Yes
Ground Level	2	WC	9	No	N/A
Ground Level	3	SECRETARY	32	Yes	Yes
Ground Level	4	OFFICE	17	Yes	Yes
Ground Level	5	OFFICE	17	Yes	Yes
Ground Level	6	OFFICE	16	Yes	Yes
Ground Level	7	MEETING	16	Yes	Yes
Ground Level	8	TUTORING	11	Yes	Yes
Ground Level	9	TUTORING	10	Yes	No
Ground Level	10	COPY ROOM	10	No	N/A
Ground Level	11	FOOD STORAGE	29	No	N/A
Ground Level	12	KITCHEN	23	Yes	No
Ground Level	13	KITCHEN	48	Yes	No
Ground Level	14	CLASSROOM	33	Yes	Yes
Ground Level	15	MEP	11	No	N/A
Ground Level	16	WC	3	No	N/A
Ground Level	17	CLASSROOM	54	Yes	Yes
Ground Level	18	CLASSROOM	54	Yes	Yes
Ground Level	19	CLASSROOM	54	Yes	Yes
Ground Level	20	CLASSROOM	51	Yes	Yes
Ground Level	21	CLASSROOM	54	Yes	Yes
Ground Level	22	CLASSROOM	52	Yes	Yes
Ground Level	23	STORAGE	6	No	N/A
Ground Level	24	TUTORIAL	9	Yes	Yes
Ground Level	25	TUTORIAL	9	Yes	Yes
Ground Level	26	STORAGE	6	No	N/A
Ground Level	27	WC	4	No	N/A
Ground Level	28	WC	2	No	N/A
Ground Level	29	WC	12	No	N/A
Ground Level	30	WC	10	No	N/A
Ground Level	31	EATING ROOM	19	Yes	Yes
Ground Level	32	WC	8	No	N/A
Ground Level	33	FACULTY ROOM	44	Yes	Yes
Ground Level	34	CAFETERIA	111	Yes	Yes
Ground Level	35	HALLWAY	18	No	N/A
Ground Level	36	WAITING ROOM	36	No	N/A
Ground Level	37	HALLWAY	14	No	N/A
Ground Level	38	HALLWAY	132	No	N/A
Ground Level	40	MEP	24	No	N/A
Ground Level	41	HALLWAY	95	No	N/A
Ground Level	66	WC	2	No	N/A
Ground Level	67	WC	2	No	N/A
Ground Level	68	WC	2	No	N/A
Ground Level	69	WC	2	No	N/A
Ground Level	70	WC	2	No	N/A

Level	Room #	Room Name	Area (m2)	Reg Occ Space?	Temp Control Device?
Ground Level	71	WC	2	No	N/A
Ground Level	72	HALLWAY	20	No	N/A
Ground Level	80	VESTIBULE	13	No	N/A
Level 1	42	CLASSROOM	50	Yes	Yes
Level 1	43	CLASSROOM	47	Yes	Yes
Level 1	44	CLASSROOM	48	Yes	Yes
Level 1	45	CLASSROOM	50	Yes	Yes
Level 1	46	CLASSROOM	51	Yes	Yes
Level 1	47	CLASSROOM	49	Yes	Yes
Level 1	48	CLASSROOM	52	Yes	Yes
Level 1	49	CLASSROOM	48	Yes	Yes
Level 1	50	CLASSROOM	15	Yes	Yes
Level 1	52	CLASSROOM	55	Yes	Yes
Level 1	53	CLASSROOM	48	Yes	Yes
Level 1	54	IT	48	Yes	Yes
Level 1	55	LIBRARY	50	Yes	Yes
Level 1	56	CLASSROOM	50	Yes	Yes
Level 1	57	CLASSROOM	48	Yes	Yes
Level 1	58	MUSIC ROOM	45	Yes	Yes
Level 1	59	EDUCATIONAL	16	Yes	Yes
Level 1	60	CLASSROOM	15	Yes	Yes
Level 1	61	WC	29	No	N/A
Level 1	62	HALLWAY	38	No	N/A
Level 1	63	HALLWAY	26	No	N/A
Level 1	64	TUTORING	9	Yes	Yes
Level 1	65	TUTORING	9	Yes	Yes
Level 1	73	CIRCULATION	43	No	N/A
Level 1	74	HALLWAY	55	No	N/A
Level 1	75	CIRCULATION	38	No	N/A
Level 1	76	HALLWAY	145	No	N/A
Level 1	77	WC	11	No	N/A
Level 1	78	STORAGE	20	No	N/A
Level 1	79	COPY ROOM	9	No	N/A

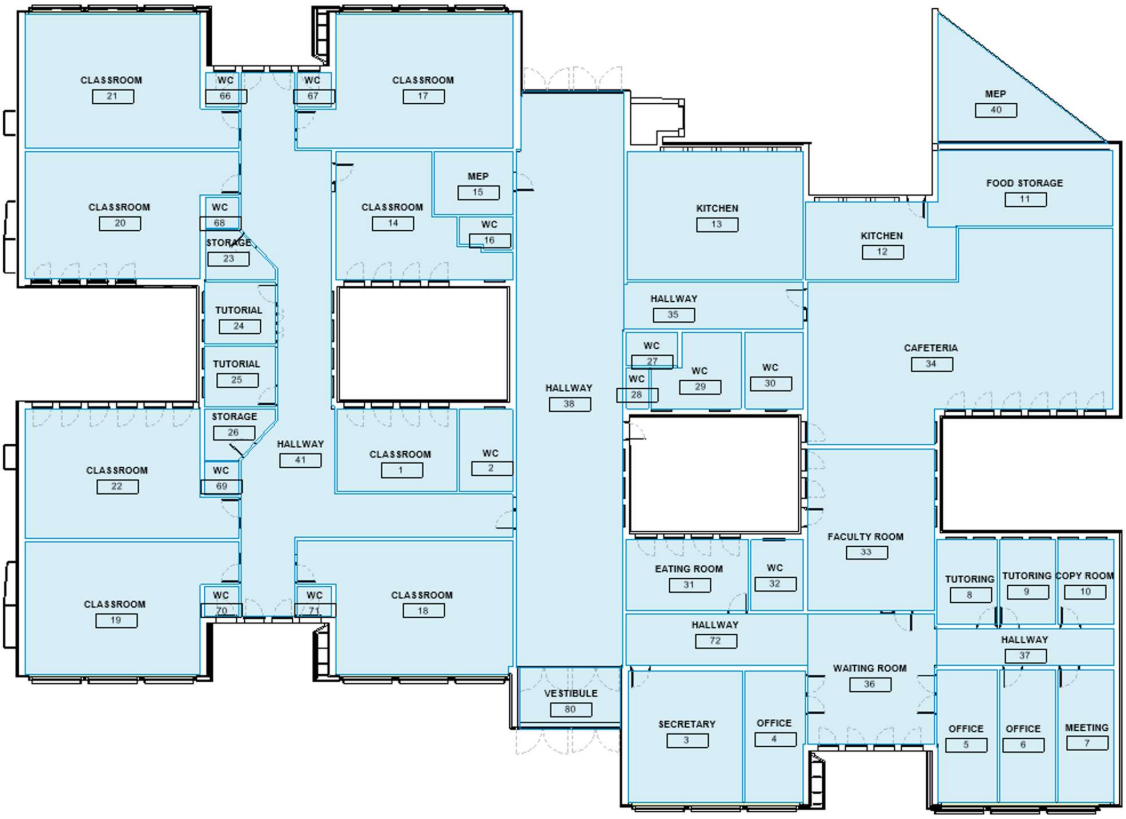


Figure 114 – Room Numbers; Ground Level

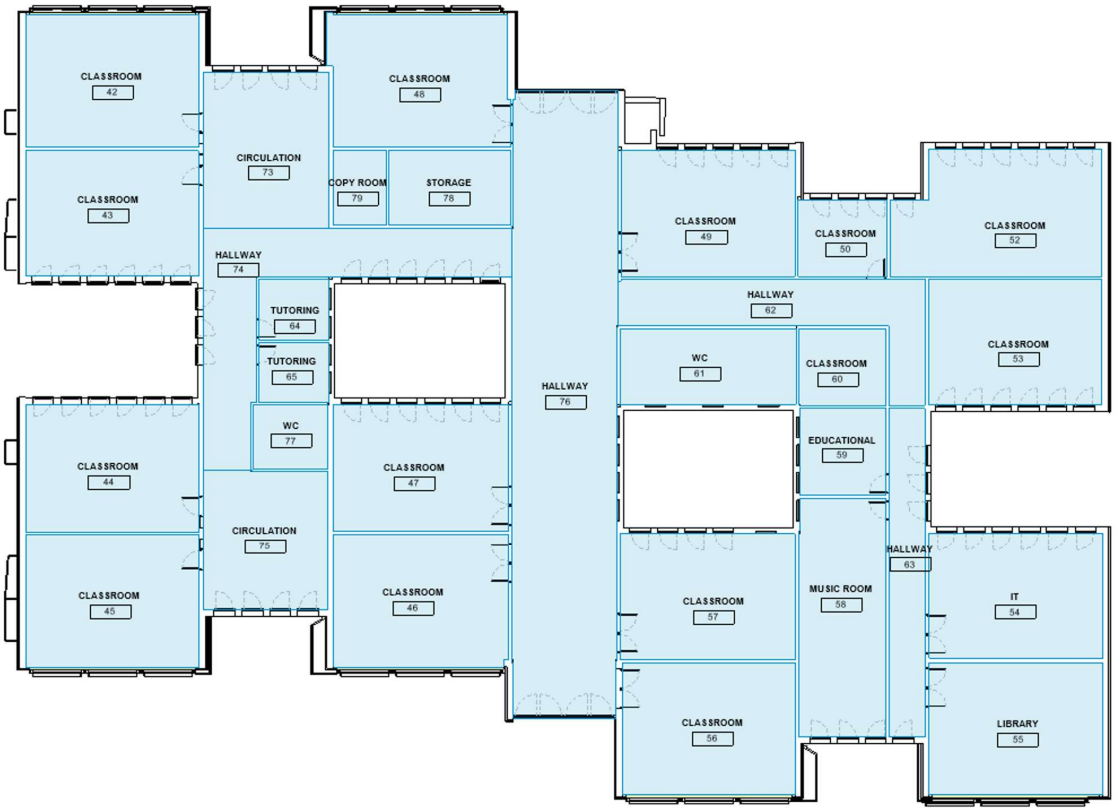
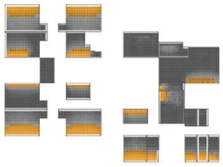
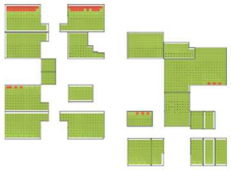
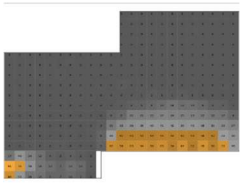
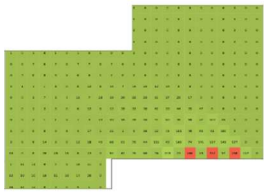
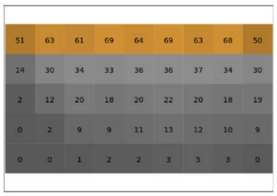
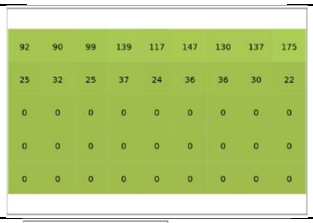
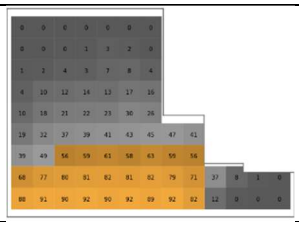
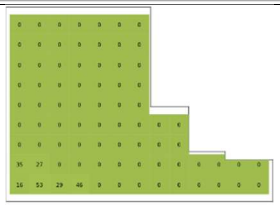
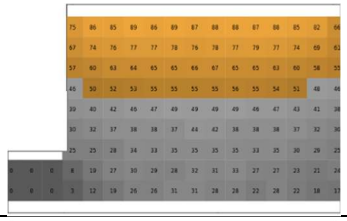
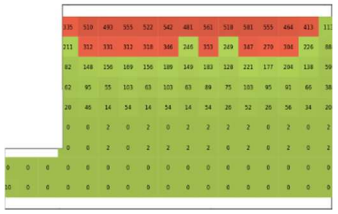
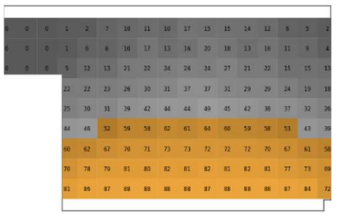
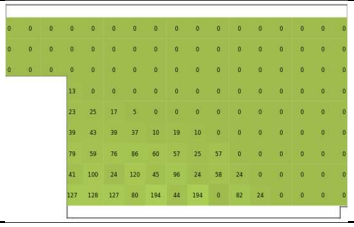
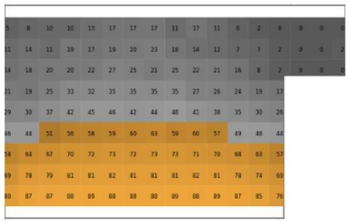
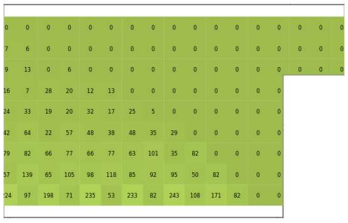
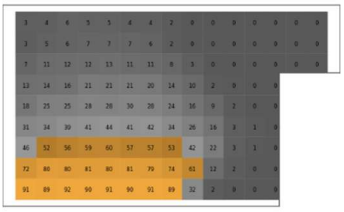
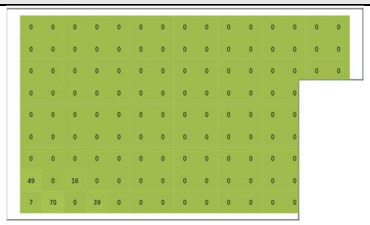
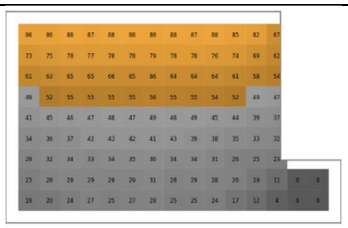
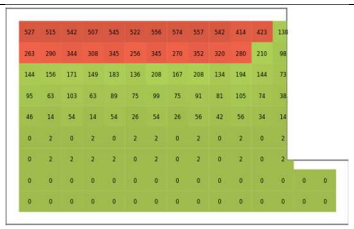
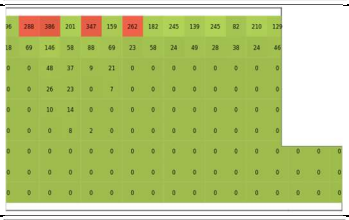
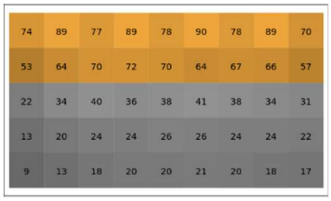
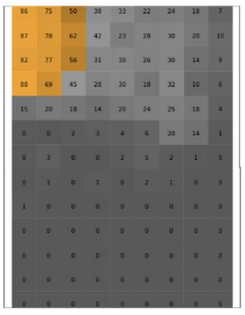
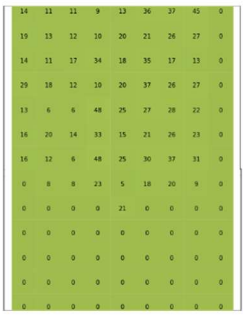
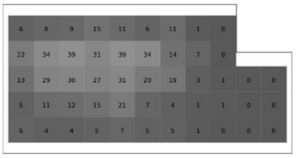
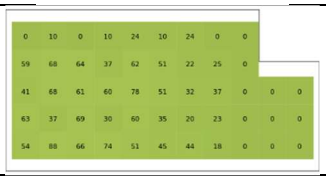
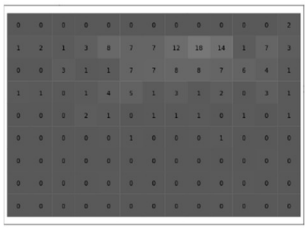
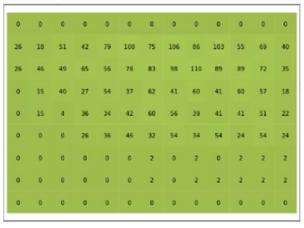
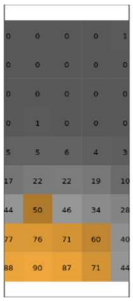
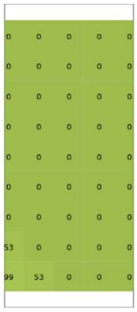
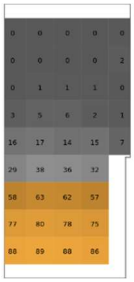
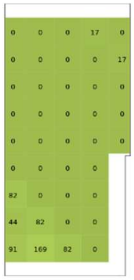
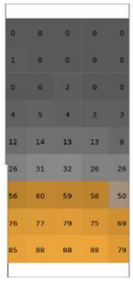
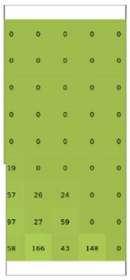
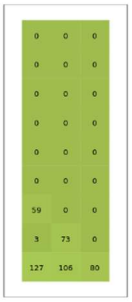
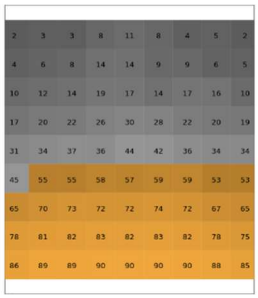
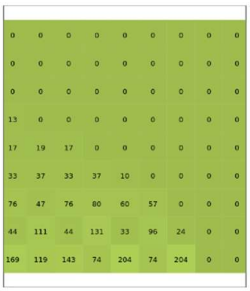


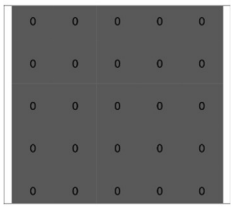
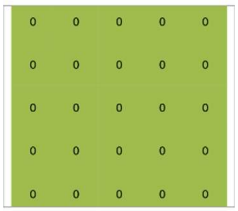
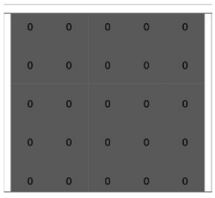
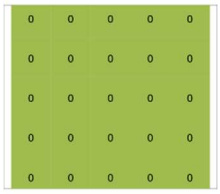
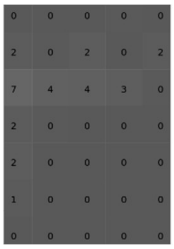
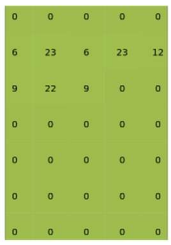
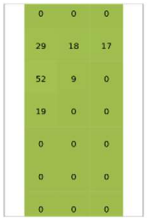
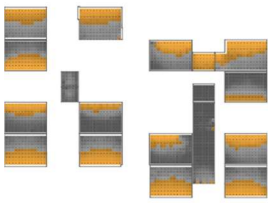
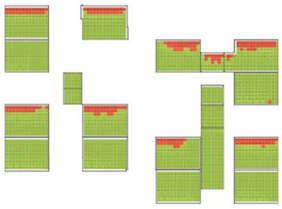
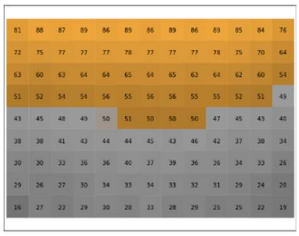
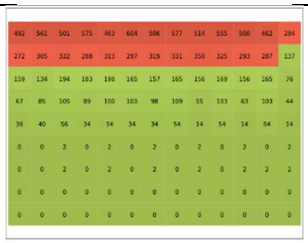
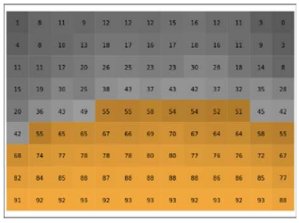
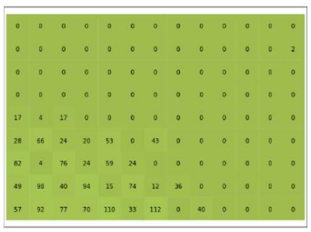
Figure 115 – Room Numbers; Level One

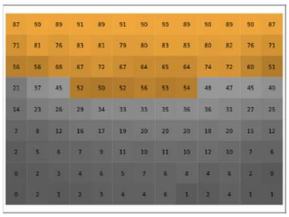
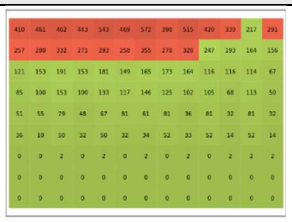
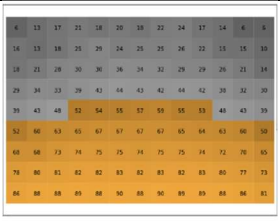
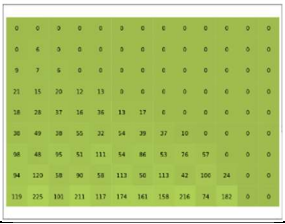
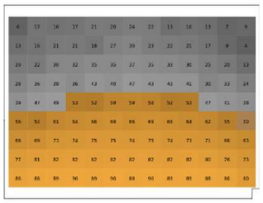
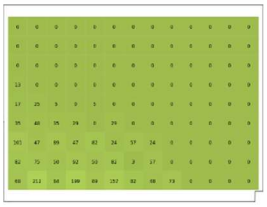
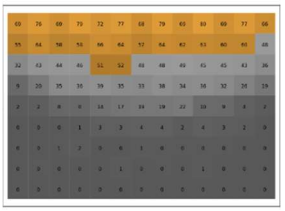
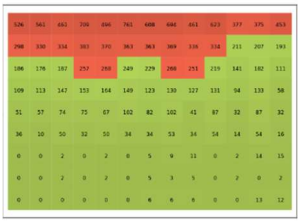
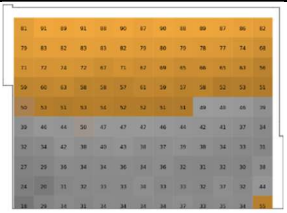
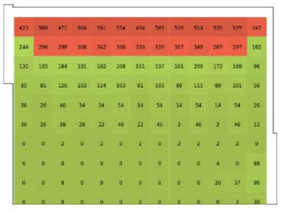
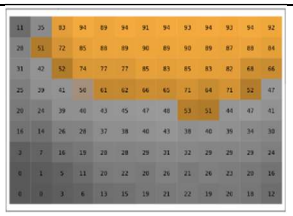
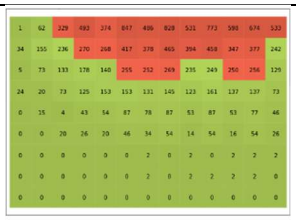
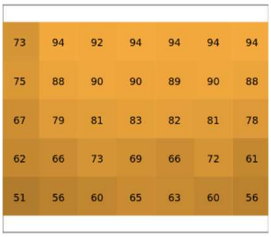
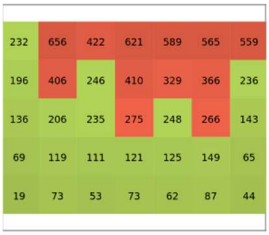
Annex A.5 – Room-by-Room Daylight Simulation Results

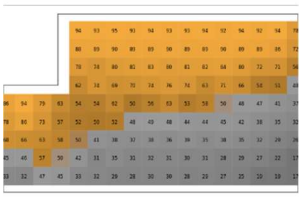
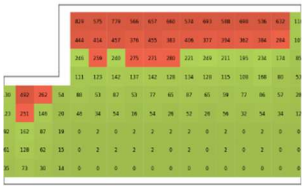
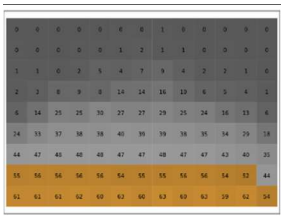
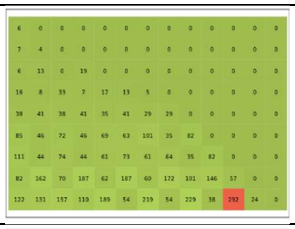
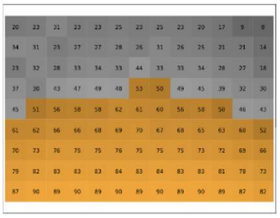
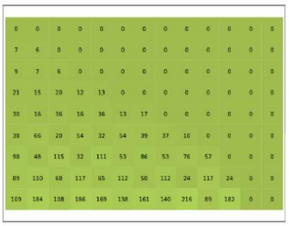
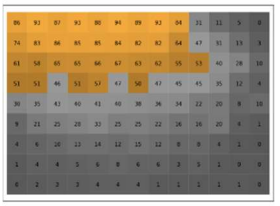
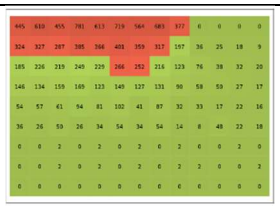
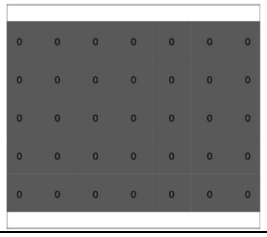
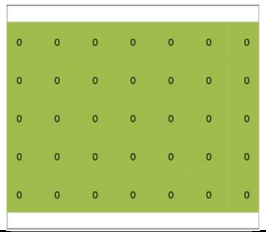
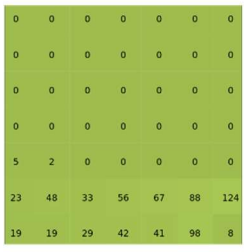
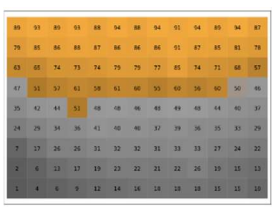
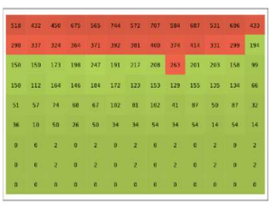
Name (#)	Area (m^2)	sDA Results	sDA Score	ASE Results	ASE Score
Ground Level	757.1		21.9%		3.0%
CAFETERIA (34)	110.9		8.5%		1.0%
CLASSROOM (1)	21.1		20.0%		0%
CLASSROOM (14)	33.3		31.6%		0%
CLASSROOM (17)	54.1		40.9%		17.4%
CLASSROOM (18)	54.5		39.3%		0%
CLASSROOM (19)	54.0		37.8%		0%

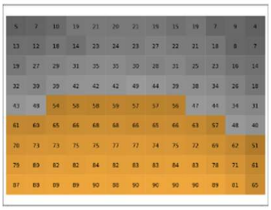
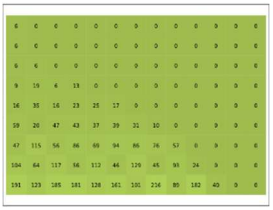
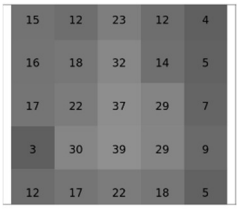
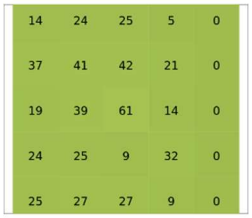
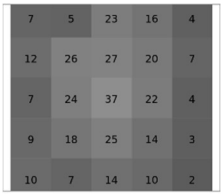
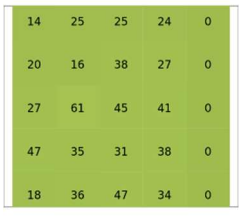
Name (#)	Area (m^2)	sDA Results	sDA Score	ASE Results	ASE Score
CLASSROOM (20)	51.1		19.5%		0%
CLASSROOM (21)	53.7		41.3%		19.0%
CLASSROOM (22)	51.8		8.9%		3.0%
EATING ROOM (31)	18.9		40.0%		6.7%
FACULTY ROOM (33)	44.3		9.4%		0%
KITCHEN (12)	23.5		0%		0%
KITCHEN (13)	48.1		0%		0%

Name (#)	Area (m^2)	sDA Results	sDA Score	ASE Results	ASE Score
MEETING (7)	16.1		20.0%		0%
OFFICE (4)	16.9		29.3%		0%
OFFICE (5)	16.9		33.3%		0%
OFFICE (6)	15.9		33.3%		
SECRETARY (3)	32.3		43.2%		0%

Name (#)	Area (m^2)	sDA Results	sDA Score	ASE Results	ASE Score
TUTORIAL (24)	9.3		0%		0%
TUTORIAL (25)	9.3		0%		0%
TUTORING (8)	11.0		0%		0%
TUTORING (9)	10.3		0%		0%
Level 1	805.3		38.8%		10.9%
CLASSROOM (42)	50.2		48.7%		21.4%
CLASSROOM (43)	47.4		50.4%		0%

Name (#)	Area (m^2)	sDA Results	sDA Score	ASE Results	ASE Score
CLASSROOM (44)	48.3		38.5%		17.9%
CLASSROOM (45)	50.4		50.4%		0%
CLASSROOM (46)	51.2		50.4%		0%
CLASSROOM (47)	48.9		23.1%		23.9%
CLASSROOM (48)	51.8		49.2%		18.5%
CLASSROOM (49)	48.3		38.5%		22.2%
CLASSROOM (50)	15.0		100%		34.3%

Name (#)	Area (m^2)	sDA Results	sDA Score	ASE Results	ASE Score
CLASSROOM (52)	54.9		56.9%		23.4%
CLASSROOM (53)	47.8		21.4%		0.9%
CLASSROOM (56)	49.9		55.6%		0%
CLASSROOM (57)	48.3		28.2%		17.1%
CLASSROOM (60)	14.5		0%		0%
EDUCATIONAL (59)	16.5		0%		0%
IT (54)	47.8		44.4%		22.2%

Name (#)	Area (m^2)	sDA Results	sDA Score	ASE Results	ASE Score
LIBRARY (55)	50.2		48.7%		0%
MUSIC ROOM (58)	45.4		3.8%		0%
TUTORING (64)	9.3		0%		0%
TUTORING (65)	9.3		0%		0%

Annex A.6 – Inputs for VRP Calculations

Zone	Space Type	Area (m2)	Max. Occupants	Design Outdoor Airflow (m3/h)	Min. Outdoor Airflow (m3/h)
PB.1	Classrooms (ages 5-8)	51.5	28	1260	186
PB.2	Daycare (through age 4)	51.5	28	1260	186
PB.3	Classrooms (ages 5-8)	51.5	28	1260	186
PB.4	Daycare (through age 4)	51.5	28	1260	186
PB.5	Daycare (through age 4)	51.5	28	1260	186
PB.6	Daycare (through age 4)	51.5	28	1260	186
PB.7	Classrooms (ages 5-8)	31	7	315	55
PB.8	Classrooms (ages 5-8)	21	10	450	450
PB.9	Cafeteria / fast food dining	19	16	460.8	87
PB.10	Conference / meeting	47	30	1350	186
PB.11	Office space	9.5	4	180	180
PB.12	Office space	16	6	270	270
PB.13	Booking/waiting	38	4	180	180
PB.14	Office space	16	6	270	270
PB.15	Office space	15	4	180	180
PB.16	Office space	11.5	6	270	270
PB.17	Office space	10	2	90	90
PB.18	Office space	11.5	1	45	45
PB.19	Conference / meeting	16	12	540	87
PB.20	Cafeteria / fast food dining	110	94	2658	420
PB.21	Conference / meeting	9.5	3	135	135
PB.22	Conference / meeting	9.5	3	135	135
P1.1	Classrooms (age 9 plus)	47.5	28	1260	186
P1.2	Classrooms (age 9 plus)	47	28	1260	186
P1.3	Classrooms (age 9 plus)	47	28	1260	186
P1.4	Classrooms (age 9 plus)	47	28	1260	186
P1.5	Classrooms (age 9 plus)	47	28	1260	186
P1.6	Classrooms (age 9 plus)	47	28	1260	186
P1.7	Classrooms (age 9 plus)	47	28	1260	186
P1.8	Classrooms (age 9 plus)	47	28	1260	186
P1.9	Art classroom	54	28	1260	186
P1.10	Classrooms (age 9 plus)	45	28	1260	186
P1.11	Classrooms (age 9 plus)	47	28	1260	186
P1.12	Classrooms (age 9 plus)	47	28	1260	186
P1.13	Computer Lab.	47	28	1260	186
P1.14	Lobbies/prefunction	44	28	1260	186
P1.15a	Conference / meeting	9.9	3	135	135
P1.15b	Conference / meeting	9.3	3	135	135
P1.16	Lobbies/prefunction	43	28	1260	1260
P1.17	Classrooms (age 9 plus)	14.6	14	630	93
P1.18	Classrooms (age 9 plus)	17.5	14	630	93
P1.19	Music/theater/dance	29	28	1260	186
P1.20	Libraries	47.5	28	1260	186

Zone	Space Type	Area (m2)	Max. Occupants	Design Outdoor Airflow (m3/h)	Min. Outdoor Airflow (m3/h)
P1.21	Classrooms (age 9 plus)	15	6	270	55
System Population (maximum simultaneous # of occupants served by system)			528		

a) Min. Outdoor Airflow = Design Outdoor Airflow indicates a constant air volume zone.

b) Zone air distribution effectiveness of Ez = 1.0 assumed for all zones.

Annex A.7 – Definitions for Aesthetic / Visual Experience Metrics

Metric	Definition
Axis Composition	The arrangement of forms on either side of a line (visible or imaginary), which can symbolize structure, movement, direction, line of rotation, etc. In a composition, forms and masses can be arranged either asymmetrically or symmetrically. Axes are used for the balanced organization of elements in architectural and urban design projects. There can be multiple axes and compositional orders in a design.
Hierarchy	In architecture, hierarchy refers to the arrangement of forms, masses and spaces in a fixed order - from the most to the least important. Hierarchy is used to emphasize/expose a particular element(s) in a composition and is most often established by means of size, shapes, colors or placement.
Transformation	A kind of repetition of form, a modification in response to certain conditions without changing the coherence of the whole concept. Shapes can be stretched, enlarged, reduced, rotated, etc.
Rhythm/Repetition	Rhythm is determined by the use of repeated forms. In architecture, repetition usually refers to a pattern in which the same shape, size, and color is used repeatedly throughout a project. In the case of repetition, the shapes remain constant; in the case of rhythm, they change, but are still recognizable
Massing	Massing refers to the spatial forms of a building, contained in three dimensions. Masses are not two-dimensional surfaces, but volumes. The term can be applied to the building as a whole or to its elements, which are characterized by a certain distinctiveness (achieved, for example, by the use of a different color, shape or translucency of the mass). "Visually light" masses are usually characterized by the use of light colors, transparency (of glass), reduced size in relation to neighboring volumes or other building elements. "Heavy" masses are recognized by dark colors (often the use of materials such as stone or concrete), low transparency, and dominant volume.
Lines & Spaces	Contrast of vertical and horizontal lines/planes or curved and straight lines/planes.
Surface	The external (visible) surface of elements that frame an architecture or space, (i.e. walls, ceilings, floors, other structural elements and furnishings).
Aperture	A window, door, other opening that provides a controlled connection between the interior and the exterior of a building.
Materials	Visually contrasting materials, such as light and dark color materials, transparent and solid materials, smooth and rough texture materials.

Source: (Lourenco et al., 2024)