Co-funded by the European Union

ERASMUS MUNDUS JOINT MASTER DEGREE

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

MBUILD

CARBON-INTELLIGENT MATERIAL PLANNING IN EARLY DESIGN: A DIGITAL WORKFLOW AND CASE STUDY USING RIB ITWO FOR SUSTAINABLE BUILDING PLANNING

ANIES SALOMIE NIVETHA GNANARAJ

Supervision: Prof. Christian Baier (University), Basil Oser (Company)

Gießen, September 2025

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

CARBON-INTELLIGENT MATERIAL PLANNING IN EARLY DESIGN: A DIGITAL WORKFLOW AND CASE STUDY USING RIB ITWO FOR SUSTAINABLE BUILDING PLANNING

ANIES SALOMIE NIVETHA GNANARAJ

Supervision: Prof. Christian Baier (University), Basil Oser (Company)

Gießen, September 2025

U.PORTO THM TECHNISCHE HOCHSCHULE MITTELHESSEN U.PORTO

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, 2024.

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.

ACKNOWLEDGEMENTS

I am deeply grateful to the MBUILD program and its dedicated team for providing the foundation and opportunity to pursue this research. I also extend my sincere appreciation to the entire team at the 5D Institute for their collaboration, support, and for offering such a dynamic environment in which to conduct my work

I sincerely thank **Prof. Christian Baier** for his invaluable guidance as both my university advisor and head of the 5D Institute, helping me bridge academic research with industry insights. My deep thanks also go to **Basil Oser** for his supportive supervision and enriching input throughout this journey.

To my **friends,** for making this journey not only easier but also enjoyable

To my **partner**, your love and patience have been a constant source of strength.

To my **family**, thank you for your unwavering belief in me. A special thanks to my **sister**, your support has truly been my foundation.

This thesis would not have been possible without all of you. Thank you.

ABSTRACT

Keywords: . Embodied Carbon, Early-Stage Design, Decarbonization, Building Information Modelling (BIM), RIB ITWO

The building sector is a primary contributor to global CO_2 emissions, with embodied carbon from materials and construction accounting for a growing share of its climate impact. These emissions are largely locked in during the early design phase, where the potential for mitigation is greatest. However, current digital workflows rarely provide designers with actionable carbon data at this stage.

This thesis develops and evaluates a digital workflow for carbon-intelligent material planning using the RIB iTWO Sustainability Module. Through a case study of a conceptual office building, the research demonstrates how Building Information Modelling (LOD 100–200) can be integrated with environmental datasets such as ÖKOBAUDAT to support early-stage decision-making. The workflow enables scenario simulation and comparative analysis of material alternatives based on embodied carbon ($kgCO_2e/m^2$), lifecycle cost, and CO_2 shadow pricing.

The results show that early-stage optimisation can reduce embodied carbon by up to 52% compared to the base case, depending on the material substitution strategy. At the building component level, walls and structural systems demonstrated the highest potential for carbon savings, while trade-off analysis revealed cost increases of 3–36% depending on the decarbonisation pathway. These findings underline the importance of coupling carbon reduction with financial evaluation, making sustainability decisions more transparent and robust.

By embedding carbon analytics directly into digital planning workflows, this research provides a replicable methodology to operationalise abstract sustainability goals into quantifiable outcomes. The study concludes that integrating cost, carbon, and lifecycle performance data through RIB iTWO empowers architects and planners to decarbonise the built environment from its earliest stages supporting compliance with EU climate policies and enabling more resilient, data-driven design practices.

GENERAL INDEX

ACKNOWLEDGEMENTS i

ABSTRACT iii

RESUMO v

1. INTRODUCTION 1

1.1. MOTIVATION OF THE THESIS 1

1.2. BACKGROUND AND RELEVANCE 2

1.3. PROBLEM STATEMENT 4

1.4. AIM 5

1.5. RESEARCH OBJECTIVES AND QUESTIONS 5

RESEARCH QUESTIONS 6

2. CONTEXT AND LITERATURE REVIEW 8

2.1. OVERVIEW 8

2.2. ROLE OF CARBON IN BUILDING SUSTAINABILITY 9

2.2.1. DEFINITION AND IMPORTANCE OF CARBON IN BUILT ENVIRONMENT 9

2.2.2. EMBODIED VS. OPERATIONAL CARBON: A LIFE CYCLE PERSPECTIVE 9

2.2.3. MEASURING AND UNDERSTANDING CARBON EMISSIONS IN THE BUILT ENVIRONMENT 10

2.3. EARLY-STAGE DESIGN AS THE PRIMARY LEVERAGE POINT FOR SUSTAINABILITY AND EMBODIED CARBON MITIGATION 11

2.3.1. STRATEGIC INFLUENCE OF EARLY DESIGN STAGES 11

2.3.2. DECISION INFLUENCE CURVE: THE CASE FOR EARLY COMMITMENT 12

2.3.3. THE STRATEGIC ADVANTAGE OF EARLY DESIGN FOR MAXIMIZING SUSTAINABILITY OUTCOMES 13

2.3.4. CHALLENGES IN ADDRESSING EMBODIED CARBON AT EARLY DESIGN STAGES 13

2.4. DIGITAL TOOLS FOR EARLY-STAGE SUSTAINABILITY INTEGRATION 14

2.4.1. BIM AND SUSTAINABILITY INTEGRATION IN EARLY-STAGE DESIGN 14

2.4.2. INTRODUCTION TO RIB ITWO AS A DIGITAL PLANNING TOOL 15

2.5. RESEARCH JUSTIFICATION 16

2.6. STATE OF THE ART 17

3. MATERIAL SELECTION AND DECARBONISATION IN THE BUILT ENVIRONMENT 19

3.1. Introduction: The Climate Imperative of Material Choice 19

3.1.1. Strategic Framework for Material Decarbonisation 19

3.1.2. Avoid-Shift-Improve (ASI) Model 20

3.1.3. Strategic Relevance of the ASI Model in Material Planning 20

3.2. Decarbonisation Strategies Across the Lifecycle 21

3.2.1. Design efficiency: structural rationalization and spatial optimization 21

3.2.2. High-impact material hotspots: reduction strategies 21

3.2.3. Material Selection: Low-Carbon Substitution and Product Transparency 23

3.3. Contextual Determinants of Material Decarbonisation Strategies 24

3.3.1. Multi- Dimensional enabling conditions 24

3.3.2. Stakeholder Roles and Collaborative Enablers 24

4. RIB iTWO AS A DIGITAL CATALYST FOR CARBON-AWARE PLANNING 26

4.1. RIB iTWO as a Digital Catalyst 26

4.1.1. Introduction to RIB iTWO in the Sustainability Context 26

4.1.2. Core planning infrastructure: catalogs and interoperability 27

4.1.3. Catalog 27

4.2. RIB iTWO as a Digital Catalyst 28

4.3. Integration with ÖKOBAUDAT and Environmental EPDs 30

4.3.1. Core Data Provided by ÖKOBAUDAT Datasets 30

4.3.2. Integration of ÖKOBAUDAT via Sustainability Labels in RIB iTWO 31

4.3.3. Functional Capabilities in RIB iTWO 32

4.4. Multi-level presentation of sustainability results 32

4.5. Systemic Integration of Catalogs within RIB iTWO 34

4.5.1. Digital Workflows for Early-Stage Carbon Planning 34

4.5.2. Implementation Considerations 36

5. METHODOLOGY 37

5.1. Research Rational 37

5.2. Performance Evaluation Metrics: Carbon, Cost, and CO_2 Pricing 39

5.2.1. Selection Criteria for Building Materials 39

5.2.2. Primary Evaluation Metrics 40
5.2.3. Building-Level Carbon Emissions Calculation 40
5.2.4. Material-Level Carbon Emissions Calculation 41
5.3. Performance Benchmarking and Classification 42
5.4. Material Quantity Extraction and BIM Inputs 43
6. CASE STUDY 44
6.1. Case study and parameters 44
6.1.1. Overview of the case study 44
6.1.2. Purpose and Relevance to This Study 45
6.1.3. Scenario Modelling and Variant Definition 45
6.2. Workflow Overview: System Architecture and Project Implementation .. 47
6.2.1. Part I: Model Transfer – Revit to RIB iTWO 48
6.2.2. Part II: Early Setup in RIB iTWO 49
6.2.2.1. BIM Qualifier :Data Validation, Quality Assurance and Model Transfer 49
6.2.2.2. Element Planning: Hierarchical Work Item Structuring 50
6.2.3. Part III: Data Input and Evaluation 57
6.2.3.1. Parametric Label Configuration and Life Cycle Allocation 58
6.2.3.2. Understanding the input modules 59
I. Commodity Catalog 60
II. Cost Code Catalog 63
III. Assemblies 63
IV. Estimate 64
7. RESULT AND DISCUUSION 67
7.1. Base Case 67
7.1.1. Base Case Definition: Establishing the Reference Performance Level 67
7.1.2. Performance Classification of Base Case Embodied Carbon 70
7.1.3. Interpretation: Case 1 – Carbon Reduction Insights from Baseline Assessment 70
7.2. Case 1 - Optimized design of base 71
7.3. Case 2 – Medium level 73
7.4. Case 3 – Ambitious level 75

7.5. RESULTS COMPARISON 77
7.5.1. OVERVIEW OF FINDINGS 77
7.5.2. BENCHMARKING AND POLICY ALIGNMENT 83
7.6. DISCUSSION 84
8. CONCLUDING REMARKS: TOWARDS A NEW PARADIGM OF CARBON-INTELLIGENT DESIGN 88
9. REFERENCES 92
10. ANNEXES 95

INDEX OF FIGURES

Fig.1 – Left: Global CO_2 emissions by sector. Source : Adapted from the World Green Building Council, Global Status Report, 2019, Right: projected emissions from new construction in case a no-intervention scenario(2022-2040), Source : Adapted from the UN Environment Global Status Report 2017 2

Fig. 2 – Buildings Sector Remains Off-Track for Decarbonisation. Source: Adapted from the GlobalABC (2022). Global Status Report for Buildings and Construction 3

Fig. 3 – Hierarchy of carbon reduction strategies across the building lifecycle, Source: Adapted from the Embodied carbon regulation in the European construction sector : An analysis of the economic impact 4

Fig. 4 - Thematic overview of study structure 8

Fig. 5- Projected change in embodied and operational carbon shares in buildings under business-as-usual scenarios. Source: Adapted from Life-Cycle Thinking from Building Materials and Climate (GlobalABC) 9

Fig. 6 - Lifecycle Assessment Phase & Carbon Emissions Across the Building Life Cycle. Source : Adapted from LETI embodied carbon Primer 10

Fig. 7 - Lifecycle Assessment Phase & Carbon Emissions Across the Building Life Cycle. Source : Architecture 2030 "Why The Built Environment" 11

Fig. 8 -Influence of Early Design Stages and long-term sustainability outcomes 12

Fig. 9 - Decision Influence Curve with Sustainability Annotations 13

Fig. 10 - RIB iTWO enables multi-criteria sustainability screening. Source: New in RIB iTWO 2025 – Sustainability (User manual) 15

Fig. 11 - Circular ASI Strategy Wheel illustrating the interconnection between avoid, shift, and improve measures. Source : United Nations Environment Programme. (2023). Building materials and the climate: Constructing a new future 19

Fig. 12 - Passive design strategies. Source: Adapted from Passive House Accelerator 21

Fig. 13 - High impact materials in office building typologies. Adapted from LETI embodied carbon Primer 22

Fig. 14 - The categories in which a project's embodied carbon can be reduced for little to no cost. Source: RMI Reducing Embodied Carbon in Buildings 23

Fig. 15 - Strategies to reduce embodied carbon throughout the design and development process. Source: RMI Reducing Embodied Carbon in Buildings 24

1. Fig. 16 - Project Structure in RIB iTWO. 27

Fig. 17 - Full range of functions, from the label catalogs and data catalogs to the various modules, such as Bill of Quantities, Estimate & Elemental costing. Source: New in RIB iTWO 2025 – Sustainability (User manual). 29
Fig. 18 - RIB iTWO Sustainability Label configuration panel, linking CO_2e values to lifecycle phases (A1–C4). 29
Fig. 19 - A schematic flow of ÖKOBAUDAT integration 30
Fig. 20 - Sustainability Label Tree showing project-level linkage of ÖKOBAUDAT datasets (offline and online) 31
Fig. 21 - BoQ Sustainability Tab with graph 33
Fig. 22 - Sustainability dashboard view in RIB iTWO visualizing emissions 34
Fig. 23 - Integrated Planning Workflow in RIB, illustrates the centralized data architecture of RIB iTWO, connecting BIM models, catalogs, configuration templates, and documents to support alternative-based project planning. 35
Fig. 24 - Methodology Framework 38
Fig. 25 - Conceptual 3-Storey Office Building Used as Reference Model 44
Fig. 26 - Reference Model detail 45
Fig. 27 - Overview of Integrated Workflow for Model-Based Cost and Sustainability Planning in RIB iTWO 47
Fig. 28 - Structured Data Exchange via IFC/CPI Interface: Exporting from Revit to RIB iTWO 48
Fig. 29 - Process of Creating a project 49
Fig. 30 - Model Validation and CPI Data Qualification Workflow in RIB iTWO BIM Qualifier. 50
Fig. 31 - Hierarchical structuring of work items in Element Planning, showing linkage between BIM components, cost assemblies, and sustainability datasets. 51
Fig. 32 – Workflow of generating elemental planning 51
Fig. 33 - Element Planning interface -creating a work item 52
Fig. 34 - Selection Set interface 53
Fig. 35 - Examples of rule-based Quantity Take-Off (QTO) syntax 54
Fig. 36 - Sample QTO Syntax in RIB iTWO for Different Construction Elements 54
Fig. 37 – Quantities Calculation to BoQ assignment 55
Fig. 38 - Integrated Cost and Sustainability Planning Workflow in RIB iTWO 57
Fig. 39 - Sustainability Label 58
Fig. 40 - Example case 60
Fig. 41 - Understanding the commodities 60
Fig. 42 – Creating A Commodites list 61

Fig. 43 – Creating A Commodities list....62
Fig. 44 – Conversion factor calculation....62
Fig. 45 – Cost Code Catalog....63
Fig. 46 – Assemblies catalog....63
Fig. 47 – Material Decomposition of the wall....64
Fig. 48 – Material Decomposition of the wall....65
Fig. 49 – Output Calculation....66
Fig. 50 - Embodied Carbon Contributions Component- Base Case....68
Fig. 51 - Comparative Embodied Carbon Contributions of Wall and Slab Elements....68
Fig. 52 – Co2 vs. Unit Cost and CO_2 Shadow Price per Item....68
Fig. 53 - Material Quantities & Associated Embodied Carbon Values....68
Fig. 54 - Sustainability dashboard base case....69
Fig. 55 - Embodied Carbon Contributions Component - Case 1....71
Fig. 56 – Co2 vs. Unit Cost and CO_2 Shadow Price per Item - Case1....71
Fig. 57 - Sustainability dashboard - Case1....72
Fig. 58 - Sustainability Reporting LCA by Phase – Case1....72
Fig. 59 - Embodied Carbon Contributions Component – Case 2....73
Fig. 61 - Sustainability dashboard - Case 2....74
Fig. 62 - Sustainability Reporting LCA by Phase – Case 2....74
Fig. 63 - Embodied Carbon Contributions Component – Case 3....75
Fig. 64 – Co2 vs. Unit Cost and CO_2 Shadow Price per Item – Case 3....75
Fig. 65 - Sustainability Reporting LCA by Phase – Case 3....76
Fig. 67 - Comparative visual showing embodied carbon (tCO_2e) versus total cost (€) for each design case and shadow pricing....81
Fig. 68 - Visualisation of embodied carbon across the cycles for each case....82
Fig. 69 - Sustainability dashboard (Case3)....84
Fig. 70 - Overall performance comparison of Base, Case 1, Case 2, and Case 3 across key sustainability & cost indicators....87

INDEX OF TABLES

Table 1 - BIM supports sustainability assessment from LOD 100 to LOD 500. 14
Table 2- Strategic Reduction Measures by Element 22
Table 3 - Overview of Catalog Types in RIB iTWO 28
Table 4 - Core data fields provided by ÖKOBAUDAT datasets 31
Table 5 - Material selection Criteria 39
Table 6 - Carbon Performance Benchmarks for Office Buildings 42
Table 7 - Overview of Selected Circularity Scenarios and Rationale 46
Table 8 - Quantified Model Components and Visualization by Building Element 56
Table 9 - Profile of Base Case Construction Components 67
Table 10 - Profile of Base with Benckmark 70
Table 11 - Embodied Carbon emission across the cases 77
Table 12 – Performance of wall systems 78
Table 13 – Performance of Concrete works 78
Table 14 – Performance of Structural systems 79
Table 15 – Performance of fenestration systems 80
Table 16 – Performance of cost-carbon trade-offs 80
Table 17 – Embodied carbon across cycles 82
Table 18 – Benchmark across cases 83
Table 19 – Benchmark Thresholds for Embodied CO_2e (A1–A3) – Reference 83
Table 20 – Summary of the performance 86

SYMBOLS, ACRONYMS AND ABBREVIATIONS

Institutional and Organizational Acronyms

CBECS – Commercial Buildings Energy Consumption Survey

CEN – European Committee for Standardization

COP21 – UN Climate Change Conference

EGD – European Green Deal

ETF – Enhanced Transparency Framework

EU – European Union

EN – European Standard

IPCC – Intergovernmental Panel on Climate Change

ISO – International Organization for Standardization

NDCs – Nationally Determined Contributions

NGOs – Non-Governmental Organizations

RIBA – The Royal Institute of British Architects

SDGs – Sustainable Development Goals

UNEP – United Nations Environment Programme

UNFCCC – United Nations Framework Convention on Climate Change

WGBC – World Green Building Council

Digital Tools and Construction Terminology

ACC – Autodesk Construction Cloud

BEP – BIM Execution Plan

BIM – Building Information Modelling

CDE – Common Data Environment

LOD – Level of Development

MEP – Mechanical, Electrical and Plumbing

Carbon and Environmental Metrics

EC3 – Embodied Carbon in Construction Calculator Tool

EPD – Environmental Product Declaration

LCA – Life Cycle Assessment

LCC – Life Cycle Cost

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

PCR – Product Category Rules

WBLCA – Whole Building Life Cycle Assessment

Sustainability Certifications

BREEAM – Building Research Establishment Environmental Assessment Method

DGNB – German Sustainable Building Council

LEED – Leadership in Energy and Environmental Design

Units and Symbols

cm – Centimetres

kg – Kilograms

Gt – Gigatons

m – Meters

m^2 – Square Meters

MJ – Megajoule

un – Unit

Environmental Impact Indicators

ACI / AP – Acidification Potential

ADPE / ADPe – Abiotic Depletion Potential (Elements)

ADPF / ADPf – Abiotic Depletion Potential (Fossil Fuels)

BCS – Biogenic Carbon Storage

CFC – Chlorofluorocarbon

CO_2 – Carbon Dioxide

C_2H_4 – Ethene

EUT / EP – Eutrophication Potential

FOLA – Formation of Ozone in Lower Atmosphere

GWP – Global Warming Potential

GHG – Greenhouse Gas

POCP – Photochemical Ozone Creation Potential

ODP – Ozone Depletion Potential

SO_2 – Sulphur Dioxide

1

INTRODUCTION

1.1. MOTIVATION OF THE THESIS

Achieving global decarbonization targets is impossible without transforming the built environment, a key contributor to climate change and responsible for around 37% of global CO_2 emissions [1]. A growing share of these emissions stems from embodied carbon, linked to construction processes and material production [1]. Unlike operational emissions, which can be reduced after occupancy, embodied carbon is locked in at the time of construction, making the early design phase a critical window for climate action [2].

At the same time, the construction sector is undergoing a digital shift, particularly in Europe, with Building Information Modelling (BIM) becoming central to design coordination and planning. While BIM holds promise for integrating sustainability into design, its practical use often remains limited to documentation, clash detection, or data management, rarely extending to guiding sustainability decisions [3, 4]. This is especially true during early planning stages, when sustainability outcomes could be most influenced.

Currently, early BIM models are often too schematic or disconnected from environmental data to offer actionable insights. Without embedding key metrics such as embodied carbon, lifecycle cost, or material circularity, BIM risks being a passive platform rather than an agent of low-carbon design [5].

To address this gap, RIB iTWO introduces a next generation planning environment that links BIM with sustainability analytics. Its 6D sustainability module integrates real-time CO_2 tracking, Environmental Product Declarations (EPD) based material libraries, cost scheduling, and scenario simulations. These features offer a unified interface where designers and planners can compare environmental impacts and costs early in the design process [6].

However, RIB iTWO remains underutilized in early-stage design workflows, largely perceived as a tool tailored for cost engineers rather than architects. This perception reflects a broader challenge in the digital construction landscape, where tools often emphasize technical precision at the expense of usability and interdisciplinary collaboration thereby hindering wider adoption among design professionals.

This thesis is motivated by two core objectives. First, it aims to evaluate how RIB iTWO's sustainability features can support material selection and embodied carbon optimization during the early design phase. Second, it seeks to explore how embedding CO_2 intelligence into planning tools can drive low-carbon design strategies and enable more sustainable decision-making throughout the design process. By leveraging RIB iTWO's capabilities, this research aims to demonstrate how digital decision-making, if applied early, can become a powerful lever for decarbonizing the built environment.

1.2. BACKGROUND AND RELEVANCE

The building and construction sector remains central to the global climate crisis, accounting for nearly 40% of annual CO_2 emissions worldwide. Of this, approximately 28% arises from operational energy use and 11% from materials shown in Figure 1and construction activities [8]. This makes the sector the largest single contributor to global greenhouse gas emissions. Importantly, these emissions are not only a function of building use but are increasingly driven by what is known as embodied carbon.

As of 2023, the sector was responsible for roughly 34% of global energy-related CO_2 emissions and over 32% of final energy consumption, with embodied carbon alone contributing nearly 2.9 gigatonnes annually [7]. These "upfront" emissions, which occur before a building becomes operational, are projected to comprise over 50% of total carbon emissions from new buildings constructed between now and 2050 [8]. Unlike operational emissions which can be reduced post-occupancy through efficiency upgrades or renewable energy, the embodied emissions are irreversible once construction is complete.

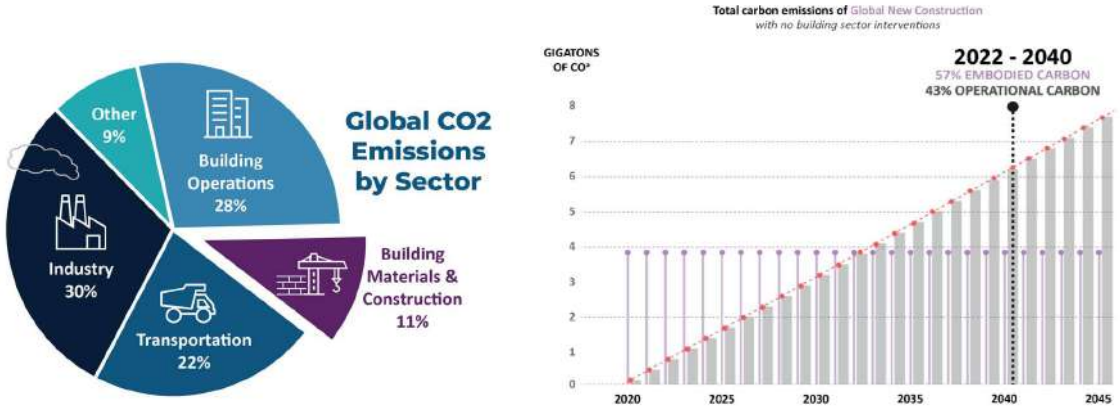


Fig.1 – Left: Global CO_2 emissions by sector. Source : Adapted from the World Green Building Council, Global Status Report, 2019, Right: projected emissions from new construction in case a no-intervention scenario(2022-2040), Source : Adapted from the UN Environment Global Status Report 2017

Despite progress in green building certifications and the adoption of renewable energy systems, the building sector remains significantly off course in meeting the climate targets set by the Paris Agreement. If current practices continue without intervention, cumulative CO_2 emissions from new construction worldwide between 2020 and 2045 are projected to rise sharply. By 2040 alone, emissions from new construction could exceed 7 gigatonnes ($GtCO_2$) annually, with embodied carbon contributing approximately 57% and operational carbon the remaining 43%, as shown in Figure 1.

From 2015 to 2023, emissions from buildings rose by 5.4%, directly contradicting the 28.1% reduction required by 2030 to stay within the 1.5°C global warming threshold [7]. The Global Buildings Climate Tracker (GBCT) underscores this misalignment, reporting a 6.8% rebound in building energy intensity following the COVID-19 pandemic and a persistent upward trend in emissions. As of 2021, operational CO_2 emissions from buildings had reached an estimated 10 $GtCO_2$, surpassing both 2020 and pre-pandemic levels.

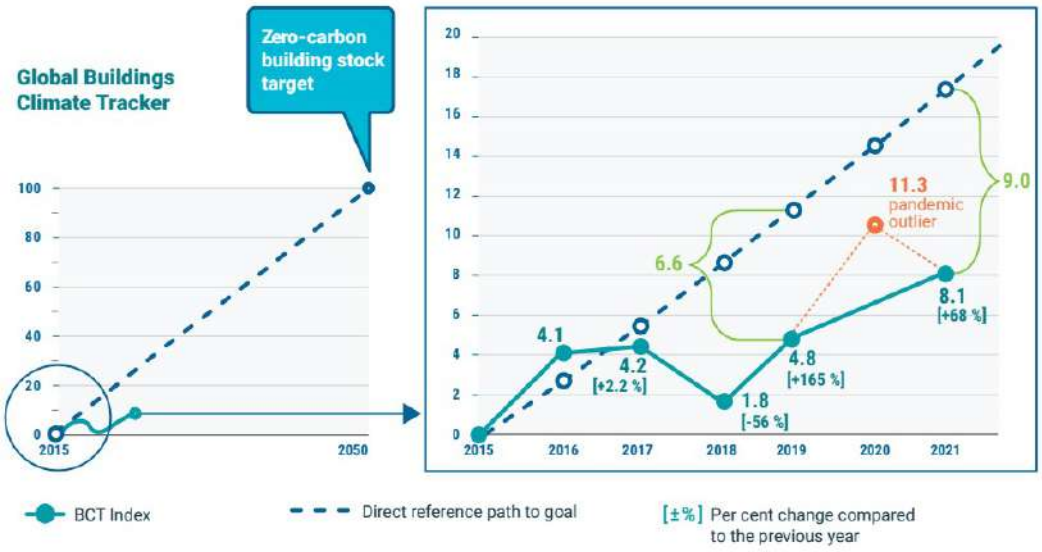


Fig. 2 – Buildings Sector Remains Off-Track for Decarbonisation. Source: Adapted from the GlobalABC (2022). Global Status Report for Buildings and Construction

The Figure 3 shows that the buildings sector remains off track for 2050 decarbonisation, with emissions rebounding sharply in 2021 after a brief decline. The performance gap emphasized by both the Global Buildings Climate Tracker (GBCT) and global emissions inventories underscores the urgent need for systemic decarbonisation measures, particularly in material-related emissions. As the global building floor area is projected to double by 2060, with urbanisation accelerating in Africa and Asia, early-stage interventions become not just relevant but essential [9].

Currently, approximately 60% of building sector emissions originate from the production and delivery of construction materials [10]. This highlights a major opportunity to adopt renewable, low-carbon, and locally sourced alternatives**.** Yet, their implementation remains limited, with few comparative studies quantifying embodied carbon savings and limited accessibility of such insights during early design even when they are most impactful [8].

Compounding this issue, conventional planning and procurement often exclude carbon metrics during the conceptual and schematic stages**,** missing key opportunities for emission reductions.

In response, BIM has evolved into a platform for integrating EPDs**,** enabling early-stage simulation of lifecycle emissions**.** As of 2023, around 40% of major firms were using BIM for energy and carbon analysis, indicating a shift toward digital carbon intelligence [7].

The World Green Building Council's 2030 vision calls for a 40% reduction in embodied carbon and net-zero operational emissions, emphasizing digital tools**,** transparent carbon data, and interdisciplinary collaboration as critical enablers [8].

However, technology alone is not enough. A true transition requires changes in procurement strategies**,** design culture**,** and organizational workflows. Tools-like RIB iTWO**,** with sustainability reporting**,** CO_2 labelling**,** and scenario simulation, help integrate carbon metrics into planning and empower practitioners to make proactive, carbon-conscious decisions**.**

1.3. PROBLEM STATEMENT

The greatest potential to mitigate embodied carbon lies in the early planning and design phases, where foundational decisions shape a building's entire lifecycle [11, 12, 13]. Adopting a whole-life carbon perspective at this stage enables the projection of low-carbon development pathways and the strategic application of circular design principles such as material reuse, adaptability, and end-of-life recyclability. By aligning early design intent with downstream environmental outcomes, upstream interventions can significantly reduce the cumulative carbon footprint [12] of the built environment as shown in the Figure 3.



Fig. 3 – Hierarchy of carbon reduction strategies across the building lifecycle, Source: Adapted from the Embodied carbon regulation in the European construction sector : An analysis of the economic impact

Research indicates that over 80% of a building's lifecycle carbon impacts are determined during the concept and schematic design phases [12]. Paradoxically, this is also the stage where carbon data is least accessible and least integrated into decision-making. In current practice, embodied carbon is frequently treated as a compliance requirement rather than a core design consideration, often addressed late in the project lifecycle or delegated to external consultants. This delayed and fragmented approach significantly undermines its potential to inform critical decisions related to material selection, construction techniques, and procurement strategies.

This disconnect arises from fragmented digital workflows, low interoperability, and the limited analytical capacities of conventional design tools. Although BIM has improved data coordination, its potential for early-stage carbon optimization remains underutilized, especially within cost-driven design contexts [14]. Architects and planners often lack accessible, actionable benchmarks to evaluate low-carbon options when their impact would be most significant.

To address this critical gap, the RIB iTWO Sustainability Module offers new capabilities for assigning CO_2-equivalent values to modelled components, simulating alternative scenarios, and embedding carbon data into cost estimation and tendering workflows. This represents a potential shift in practice which can bring sustainability criteria upstream in the design process.

This thesis investigates whether carbon-integrated digital tools specifically the RIB iTWO Sustainability Module can support low-carbon decision-making during the earliest phases of building design. Through scenario testing, workflow analysis, and professional case study evaluation, the research assesses both the technical performance and strategic value of the tool in real-world planning environments.

By situating this inquiry at the intersection of climate urgency, early design decisions, and digital transformation, this thesis contributes to a growing body of research on embedded sustainability. Beyond addressing a technical shortfall, it explores a strategic opportunity, repositioning Architecture, Engineering, and Construction (AEC) professionals as proactive agents of decarbonisation, which can deliver carbon intelligence where it has the greatest leverage.

1.4. AIM

This research aims to develop and evaluate a carbon-intelligent material planning workflow using the RIB iTWO's Sustainability Module during the early design phase of building projects. It investigates how the digital integration of environmental data, specifically embodied carbon metrics can support informed material selection, optimize lifecycle performance, and align early-stage decisions with long-term sustainability goals.

Specifically, the study seeks to:

- Identify key barriers to adoption of carbon-integrated planning tools and assess the practical usability of the RIB iTWO module across interdisciplinary teams, particularly among architects, planners, and cost managers.
- Develop a structured framework that links early-stage design processes with quantifiable environmental metrics, including embodied carbon, circularity potential, and lifecycle cost.
- Advance data-driven, value-oriented planning practices within the European construction sector by demonstrating how digital tools can meet emerging regulatory, climate, and procurement expectations.

1.5. RESEARCH OBJECTIVES AND QUESTIONS

To achieve its aim, this research sets out the following key objectives:

1. Assess the technical capabilities and real-world applicability of the RIB iTWO's Sustainability Module within a professional design and planning context.
2. Investigate the integration potential of embodied carbon and sustainability metrics into early-stage design workflows using RIB iTWO.
3. Identify key challenges and enabling conditions that influence the adoption of 6D sustainability features in interdisciplinary project environments.
4. Examine the role of RIB iTWO in supporting planners, designers, and consultants in delivering sustainability-focused advisory services.
5. 5: Develop a practical framework for embedding carbon intelligence into BIM-enabled planning workflows from the outset of project development.

The research objectives are designed to directly support the central aim of developing and evaluating a carbon-intelligent material planning workflow using RIB iTWO. They address both the technical functionality of the tool and its integration into early-stage design processes. By investigating usability, adoption challenges, and the potential for embedding carbon metrics into planning workflows, the objectives establish a foundation for proposing a practical framework that aligns digital design practices with sustainability goals.

RESEARCH QUESTIONS

To address the above objectives, the following research questions are formulated:

- **RQ1 corresponds to Objective 1**:
  How can RIB iTWO's sustainability module support early-stage material selection and embodied carbon reduction strategies during the conceptual design phase?
- **RQ2 addresses Objectives 2 and 3**:
  What are the key challenges and opportunities in embedding CO_2 intelligence into early-stage design workflows using RIB iTWO, and how do practitioners and clients perceive its value?
- **RQ3 aligns with Objectives 4 and 5**:
  How can the integration of cost, carbon, and performance data in RIB iTWO enhance sustainable decision-making and position design professionals as sustainability advisors within the European construction sector?

1.6. SCOPE, SIGNIFICANCE AND LIMITATIONS

Scope

This study focuses on the early design and planning stages of building projects, with particular emphasis on the operational use of the RIB iTWO Sustainability Module. It investigates how the tool can support sustainability-driven material planning and decision-making during conceptual and schematic design.

The scope includes:

- Evaluating the integration of the RIB iTWO Sustainability Module in a real-world project, with attention to its usability across multidisciplinary teams (architects, planners, project managers).
- Exploring early-phase material selection strategies and their potential to reduce embodied carbon.
- Assessing how environmental data outputs such as CO_2-equivalent metrics and lifecycle indicators can inform early design decisions prior to detailed specification and documentation.

Significance

This research is highly relevant to the AEC industry, academia, and society, addressing the construction sector's role in meeting climate goals and advancing sustainable practices.

Academic Contribution: The study enhances scholarly understanding of how digital tools influence early-stage decisions in BIM-enabled environments, particularly regarding sustainability integration.

Industry Application: It provides a practical framework for embedding sustainability metrics into design and cost planning, offering actionable insights for firms aligning with environmental, social, and governance (ESG) goals.

Societal Relevance: In the context of the global climate crisis and increasing regulatory pressure, the research highlights the potential of digital planning tools to improve both environmental and economic performance.

Policy and Compliance Alignment: Findings show that early integration of CO_2 tracking and lifecycle analysis supports compliance with EU policies such as the Taxonomy Regulation and European Green Deal.

Quantified Impact: Initial simulation tests indicate that early-stage optimization through RIB iTWO can reduce embodied carbon by up to 30% and projected operational energy use by up to 20%.

Educational Advancement: The case-based approach supports academic programs in BIM, sustainability, and construction management, contributing to curriculum development and professional training.

In essence, the study positions digital integration in early design as a strategic driver for climate-responsible construction practices.

Limitations

Despite its contributions, the research acknowledges several limitations:

Design Phase Focus: The study is limited to conceptual and schematic design phases, excluding post-construction performance evaluation and long-term sustainability monitoring.

Regulatory Scope: It does not address how RIB iTWO outputs integrate with regulatory processes such as Environmental Impact Assessments (EIA) or planning approvals.

Context-Specific Evaluation: The empirical work is based on a single firm, limiting the generalizability of the findings across diverse project types or organizational structures.

Tool-Specific Focus: The study concentrates solely on RIB iTWO and its BIM interoperability. It does not compare other digital tools that may offer alternative functionalities.

While these limitations frame the study's boundaries, they also provide a strong foundation for future research into carbon-intelligent planning and the broader adoption of sustainability-focused digital workflows.

2

CONTEXT AND LITERATURE REVIEW

2.1. OVERVIEW

The literature review is systematically structured to establish a robust theoretical foundation for the investigation of carbon-intelligent material planning in early-stage design through the integration of digital workflows. As depicted in Figure 4, the review follows a logical progression of thematic areas, organized into four interrelated pillars: (I) contextual understanding of the built environment's carbon impact, (II) identification of leverage points during early design phases, (III) material-level carbon performance and assessment, and (IV) the enabling role of digital tools in sustainability integration. These pillars collectively converge to substantiate the selection of the RIB iTWO platform as a focal point for exploring digitalized, carbon-informed decision-making in ABC practice.

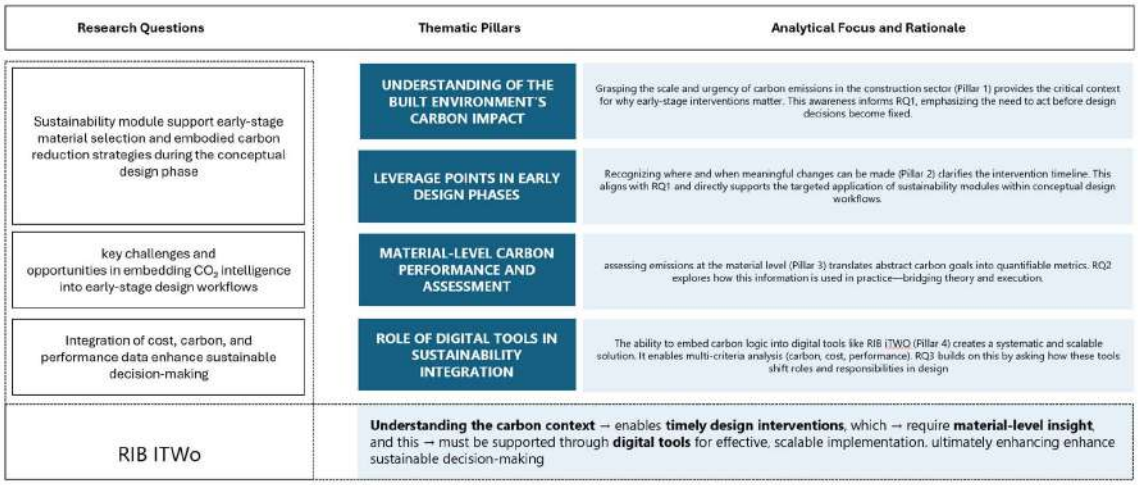


Fig. 4 - Thematic overview of study structure

This framework anchors the inquiry into carbon-intelligent material planning, guiding the analytical direction of the chapters that follow. Each pillar shapes the structure and progression of the research.

2.2. ROLE OF CARBON IN BUILDING SUSTAINABILITY

2.2.1. DEFINITION AND IMPORTANCE OF CARBON IN BUILT ENVIRONMENT

The built environment is a major contributor to global greenhouse gas (GHG) emissions, accounting for approximately 39% of energy-related CO_2 emissions, of which 28% are attributed to operational energy use and 11% to embodied carbon [2][15]. Understanding this division is critical to advancing sustainable practices in AEC. In 2021, operational carbon accounted for approximately 75% of total building-related emissions, with embodied carbon comprising 25% shown in Figure 5. By 2050, due to improvements in building energy performance and increased grid decarbonization, embodied carbon is projected to rise to 49%, nearly equalling operational emissions. This illustrates the growing significance of upfront emissions and the need for early-stage carbon-informed planning.

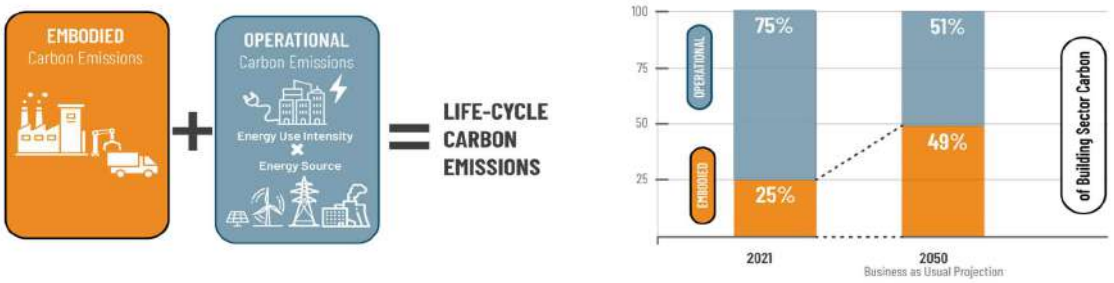


Fig. 5- Projected change in embodied and operational carbon shares in buildings under business-as-usual scenarios. Source: Adapted from Life-Cycle Thinking from Building Materials and Climate (GlobalABC)

A building's total carbon footprint comprises both operational and embodied carbon. Operational carbon refers to emissions resulting from the use of a building over its lifespan, specifically heating, cooling, lighting, and ventilation. These emissions can be reduced through improvements in energy efficiency and the integration of renewable energy systems [17][18].

In contrast, embodied carbon includes emissions generated during the extraction, manufacturing, transportation, installation, maintenance, and eventual disposal of building materials. Unlike operational carbon, these emissions occur mostly in the early phases of the project and are locked in once construction begins, rendering them irreversible [2][19]. This temporal distinction underscores the strategic significance of early design interventions in reducing life-cycle environmental impacts.

2.2.2. EMBODIED VS. OPERATIONAL CARBON: A LIFE CYCLE PERSPECTIVE

To evaluate the environmental impacts of buildings comprehensively, Life Cycle Assessment (LCA) provides a systematic framework that spans all project phases—from raw material extraction (A1) to end-of-life treatment (C4).Embodied carbon is highest during the product phase (A1–A3), which accounts for 65–85% of total embodied emissions, followed by the construction (A4–A5), use (B1–B7), and end-of-life phases (C1–C4) shown in Figure 6. These up-front emissions dominate early in the process and must be addressed during the design stage.

In LCA terminology, embodied carbon is predominantly concentrated in the "cradle-to-gate" stages (A1–A3), but may also extend through transportation (A4), construction (A5), use (B stages), and end-of-life processing (C1–C4) in "cradle-to-grave" assessments [17][19]. Historically, operational carbon has dominated the carbon profile of buildings. However, this trend is rapidly shifting. In high-performance

and net-zero energy buildings, embodied carbon can constitute up to 50% of total life-cycle emissions [17]. As energy systems become more efficient and electricity grids are progressively decarbonized, the relative share of embodied emissions is projected to surpass operational emissions by 2050 [16][19].

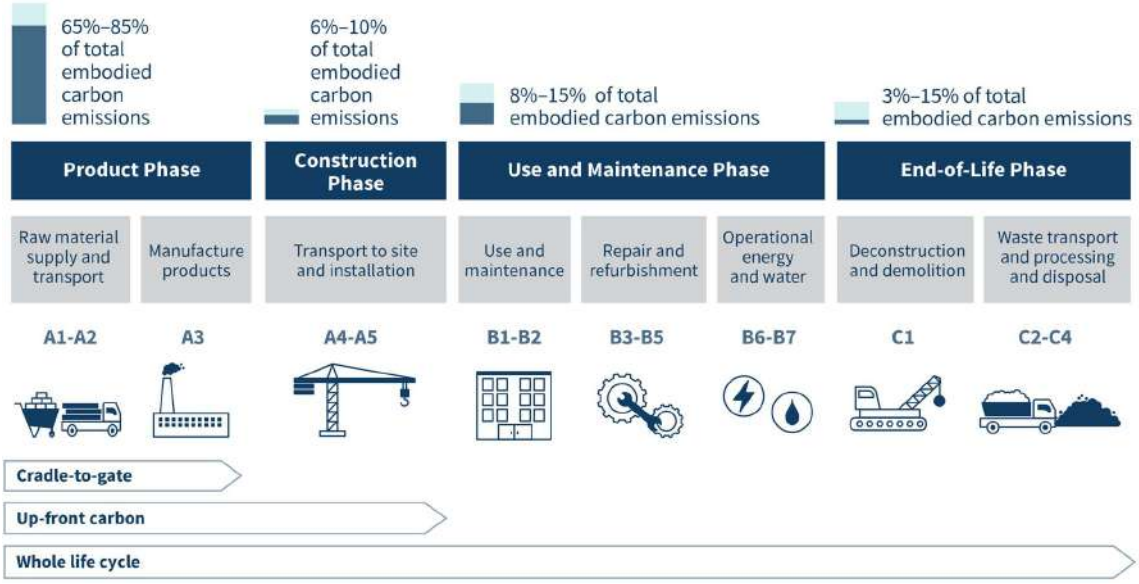


Fig. 6 - Lifecycle Assessment Phase & Carbon Emissions Across the Building Life Cycle. Source : Adapted from LETI embodied carbon Primer

This trajectory calls for a paradigm shift in sustainability strategy—one that prioritizes carbon reduction measures at the material and design stages, before operational strategies are even implemented.

2.2.3. Measuring and Understanding Carbon Emissions in the Built Environment

Recognizing the critical role of both embodied and operational carbon requires robust, scalable tools for quantification and comparison. This is essential for evidence-based decision-making in sustainable building practices.

At the Building Level, the macro-scale carbon performance is assessed through Whole Building Life Cycle Assessment (WBLCA), aligned with the EN 15978 standard. WBLCA captures emissions from cradle to grave, enabling designers and planners to compare alternative design options using metrics such as kg CO_2e/m^2/year [17]. There are tools that can support scenario modelling and optimization based on both embodied and operational carbon metrics.

At the Material Level, material-specific carbon data is commonly derived from EPDs, developed in accordance with Product Category Rules (PCRs). Most EPDs report cradle-to-gate emissions (A1–A3), while extended declarations may also cover stages A4 through C4 [16][19]. Despite increasing adoption, EPDs often suffer from data inconsistency, variable scope, and non-standardized formats, which can complicate direct comparisons [18][20].

Carbon Hotspots in Building Materials, Certain materials like concrete, steel, and aluminium are collectively responsible for approximately 23% of total global CO_2 emissions, with concrete alone contributing 11%, steel 10%, and aluminium 2% [21] shown in Figure 7 . Most of these emissions stem from applications within the built environment, particularly in structural systems, façades, and enclosures. This concentration of emissions in a small set of materials highlights the urgent need for targeted carbon reduction strategies through low-carbon alternatives, design efficiency, and material reuse initiatives.

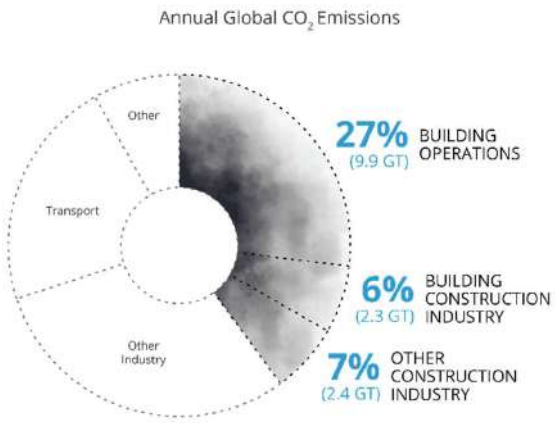


Fig. 7 - Lifecycle Assessment Phase & Carbon Emissions Across the Building Life Cycle. Source : Architecture 2030 "Why The Built Environment"

While tools such as WBLCA and EPDs have advanced the capacity to quantify embodied and operational carbon, their impact is contingent upon the timing of their application within the design process. When deployed retrospectively during technical design development or after construction, their potential to inform substantial carbon reductions is significantly diminished. This limitation underscores a critical insight emerging from current literature: the mitigation of lifecycle emissions is most effective when carbon intelligence is embedded at the earliest project stages. The strategic alignment of quantification tools with conceptual and schematic design phases enables proactive material specification, spatial optimization, and scenario evaluation.

Accordingly, early-stage planning constitutes a decisive leverage point for carbon mitigation, where foundational design decisions have the greatest influence on long-term environmental outcomes. The following section critically examines this temporal window and its significance in shaping low-carbon building strategies.

2.3. EARLY-STAGE DESIGN AS THE PRIMARY LEVERAGE POINT FOR SUSTAINABILITY AND EMBODIED CARBON MITIGATION

2.3.1. Strategic Influence of Early Design Stages

The architectural design process typically progresses through six defined phases: Strategic Definition, Concept Design, Developed Design, Technical Design, Construction, and Handover. Among these, the Concept Design and Developed Design stages collectively referred to as the early design stages, exert the greatest influence on a building's long-term performance, cost structure, and environmental impact [22][23]. According to the Royal Institute of British Architects (RIBA), decisions made during these phases can determine up to 80% of a building's overall environmental footprint [23].

Key attributes such as spatial organization, orientation, materiality, and system integration are typically established in this early window, effectively locking in a significant portion of the project's lifecycle carbon emissions. Early-stage choices shape both embodied and operational carbon trajectories, and their downstream implications are difficult to reverse once the project enters technical development or construction. As noted by Andrade and Liu, embedding sustainability considerations during this early phase enables broader intervention opportunities, minimal disruption to design logic, and lower implementation costs [24][25].

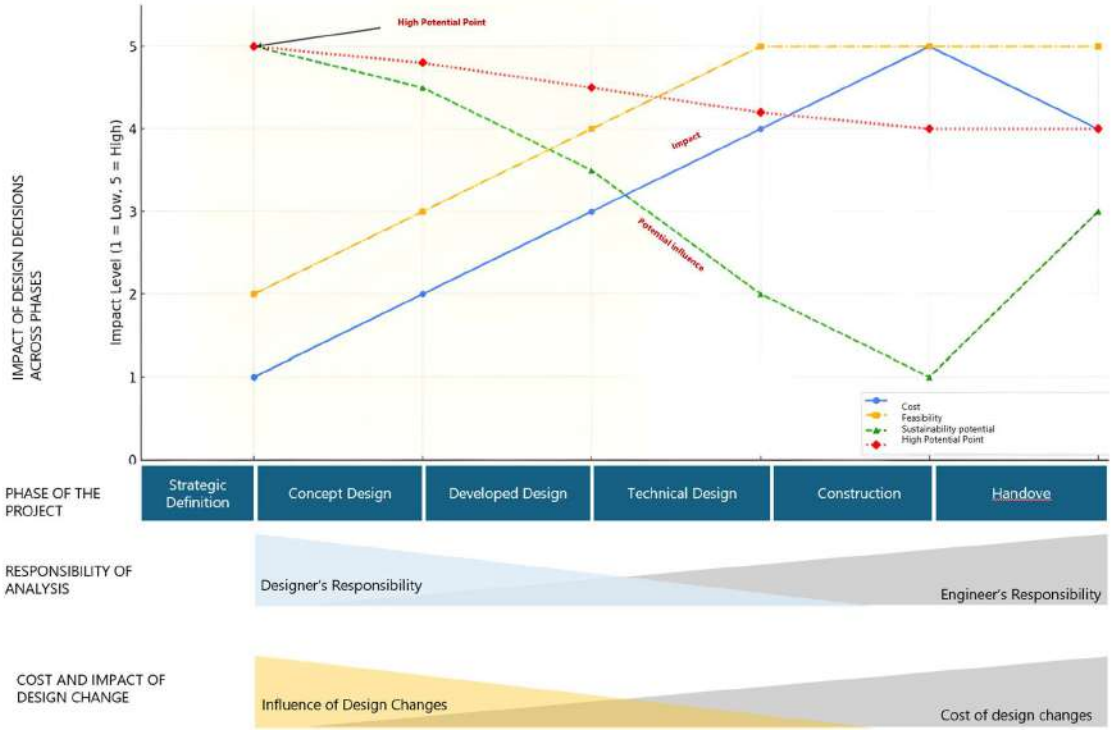


Fig. 8 -Influence of Early Design Stages and long-term sustainability outcomes

2.3.2. Decision Influence Curve: The Case for Early Commitment

The Decision Influence Curve, a conceptual model rooted in systems engineering and architectural planning, illustrates how design flexibility and influence diminish exponentially as the project advances, while change costs and locked-in environmental impacts escalate [26][27]. This nonlinear relationship underscores the imperative of committing to sustainability objectives during the earliest stages.

Bragança et al. emphasize that the earlier sustainability strategies are integrated, the wider the range of viable solutions and the fewer trade-offs required [28]. Critical early decisions concerning building form, massing, passive systems, window-to-wall ratios, and material choices establish the baseline for embodied emissions and operational energy use [29]. Wang et al. further argue that such early-phase parameters are key drivers of lifecycle performance and occupant well-being [29].

Beyond environmental benefits, this curve also highlights the shifting professional responsibility within the AEC industry: architects and engineers who engage sustainability early position themselves not only as designers but also as strategic partners in long-term carbon management and value creation. This expands their role from delivering design outputs to shaping broader sustainability outcomes across the project lifecycle [30].

Moreover, aligning sustainability commitments with the Decision Influence Curve is increasingly critical for regulatory compliance and certification pathways. Frameworks such as the EU Taxonomy, Level(s), and DGNB require early documentation of lifecycle performance, while green financing mechanisms link funding eligibility to demonstrable in early-stage carbon targets [31]. This external pressure reinforces the need to front load sustainability, ensuring that design decisions satisfy both project goals and broader policy obligations.

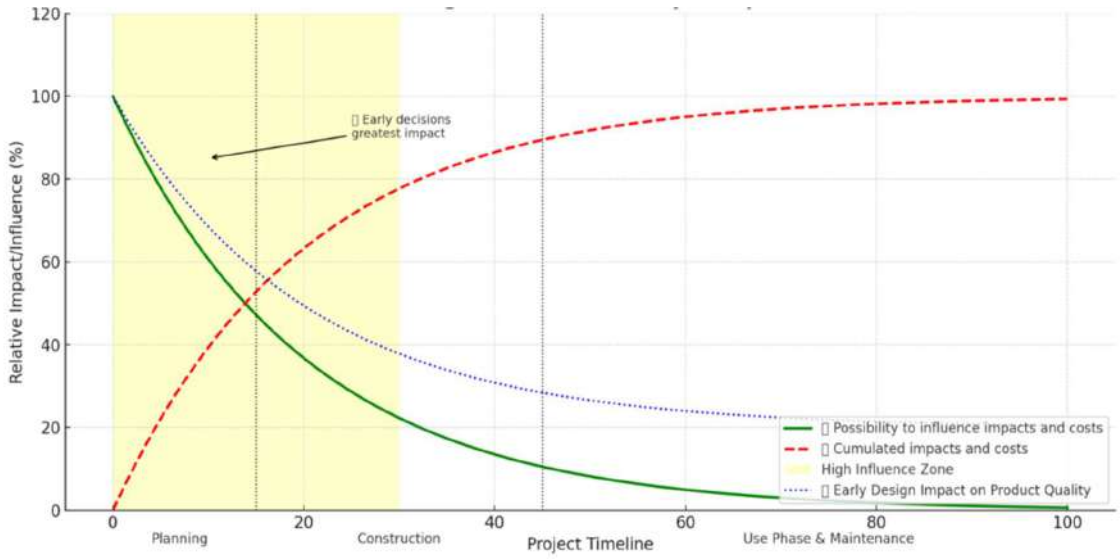


Fig. 9 - Decision Influence Curve with Sustainability Annotations

This model clarifies that early design is not merely preparatory, it is strategically decisive. Deferring sustainability considerations to later phases risks diminished efficacy, higher costs, and reduced alignment with lifecycle carbon goals. As such, front loading sustainability into early planning is both environmentally and economically prudent.

2.3.3. The Strategic Advantage of Early Design for Maximizing Sustainability Outcomes

Building on the principles outlined in Sections 2.3.1 and 2.3.2, the strategic advantage of early-stage design rests on three interlinked rationales:

1. **Maximum impact at minimum cost**: Low-carbon strategies such as passive ventilation, thermal massing, or biogenic materials are most effective and cost-feasible when applied in the conceptual stage, compared to retrofits later in the process [30].
2. **Design flexibility and integration**: With fewer structural or contractual constraints, early design enables holistic solutions that align aesthetic, functional, and environmental performance objectives [30][31].
3. **Lifecycle lock-in**: Key decisions on façade assemblies, window placement, or daylighting have long-term implications for operational energy, embodied emissions, and user comfort [31].

To leverage these opportunities, digital tools are increasingly employed in schematic workflows ranging from Life Cycle Assessment integrations to Building Performance Simulation, that allow iterative optimization. Empirical studies demonstrate that proactive early use of such tools can achieve 20–40% reductions in lifecycle carbon and energy impacts [32][33].

2.3.4. Challenges in Addressing Embodied Carbon at Early Design Stages

Although early design is critical for reducing embodied carbon, it is constrained by two key challenges.

1. **Lack of Data and Certainty:** Accurate carbon assessment in early stages is hindered by limited access to Environmental Product Declarations (EPDs), especially for non-standard or innovative materials. Existing LCA databases often differ in geographic relevance and methodological scope [34][35]. Moreover, early designs are based on provisional material choices, leading to estimates

with high uncertainty. This discourages commitment to low-carbon strategies at a stage when they could be most impactful.

2. **Material Lock-In Effects:** Once structural systems and façade elements are selected, typically concrete, steel, and glazing. They are rarely revised, despite accounting for up to 80% of upfront embodied carbon [31][32][35]. These early decisions effectively fix a large share of emissions. As integrating sustainability early expands available options and reduces trade-offs [36], yet traditional workflows often delay these considerations.

To address this, carbon intelligence must be embedded in early design tools and workflows, ensuring sustainability is a core design driver, not a late-stage adjustment.

2.4. DIGITAL TOOLS FOR EARLY-STAGE SUSTAINABILITY INTEGRATION

2.4.1. BIM AND SUSTAINABILITY INTEGRATION IN EARLY-STAGE DESIGN

BIM has emerged as a foundational digital infrastructure within the AEC industry, enabling parametric, data-rich modelling environments that support lifecycle assessment, integrated design, and cross-disciplinary collaboration. As defined by ISO 19650, BIM represents the "organization and digitization of information about buildings and civil engineering works," signifying a major departure from conventional 2D drafting toward multidimensional design management across geometry (3D), scheduling (4D), cost (5D), and increasingly, sustainability (6D) domains [38]. BIM's integration of performance metrics is particularly impactful during early design phases (LOD 100–200), when design flexibility is highest and decisions most consequential to environmental outcomes. Through simulations for daylight access, thermal comfort, ventilation, and embodied carbon analysis, BIM enables data-informed planning before construction begins [39].

Table 1 - BIM supports sustainability assessment from LOD 100 to LOD 500.

LOD Level	Description	Benefit
LOD 100 - Conceptual Planning for Budget Control	Establish project feasibility and control early costs using conceptual massing models for strategic budget planning.	Early cost visibility and feasibility assessment.
LOD 200- Efficient Schematic Design for Faster Approvals	Accelerate approvals with clear schematic designs that define building components, reducing revisions and delays.	Faster approvals and fewer design revisions.
LOD 300- Detailed Modeling for Seamless Construction	Enable accurate coordination and avoid clashes with detailed models for smooth pre-construction planning.	Fewer on-site errors and better construction coordination.
LOD 400- Streamlined Fabrication for Reduced On-Site Delays	Deliver fabrication-ready models for precise prefabrication and efficient on-site assembly.	Minimized site delays and improved prefabrication.
LOD 500- As-Built Documentation for Efficient Facility Management	Provide complete as-built documentation to support long-term facility management and maintenance.	Better facility management and increased building longevity.

2.4.2. INTRODUCTION TO RIB ITWO AS A DIGITAL PLANNING TOOL

RIB iTWO, developed by RIB Software GmbH, exemplifies the convergence of design, cost, and sustainability assessment within a single digital environment. Originating as a 5D BIM platform incorporating geometry (3D), time (4D), and cost (5D). It has expanded to support 6D planning by embedding carbon analytics and lifecycle intelligence directly into project workflows [42].

This evolution mirrors broader industry shifts toward data-driven, lifecycle-based decision-making. Conventional workflows often rely on fragmented data and late-stage sustainability assessments, which limit opportunities for early optimisation. RIB iTWO addresses these challenges through a modular architecture that supports financial forecasting, procurement transparency, and scenario-based CO_2 simulations [43]. It allows users to visualise emissions, assign carbon values to components, and make comparative assessments between material strategies, capabilities that are increasingly necessary to meet climate policy requirements and investor expectations [44].

RIB iTWO and Early-Stage Sustainability

RIB iTWO's most strategic contribution lies in enabling carbon-aware decisions during the conceptual and schematic design phases (LOD 100–200), where the trajectory of environmental performance can be most effectively shaped. The platform aligns with established international and national standards, including EN 15804 for EPDs, ISO 14040/44 for LCA, and integrates directly with national LCA databases such as ÖKOBAUDAT [42][45].

By embedding CO_2 performance indicators into digital catalogs and quantity take-offs, RIB iTWO empowers stakeholders to evaluate material options not only in terms of cost but also embodied carbon and overall environmental impact [46] shown in Figure 10. This real-time integration supports compliance with the EU Taxonomy for Sustainable Activities and facilitates alignment with certification schemes such as DGNB and BREEAM, which reward early-phase carbon optimisation [47].

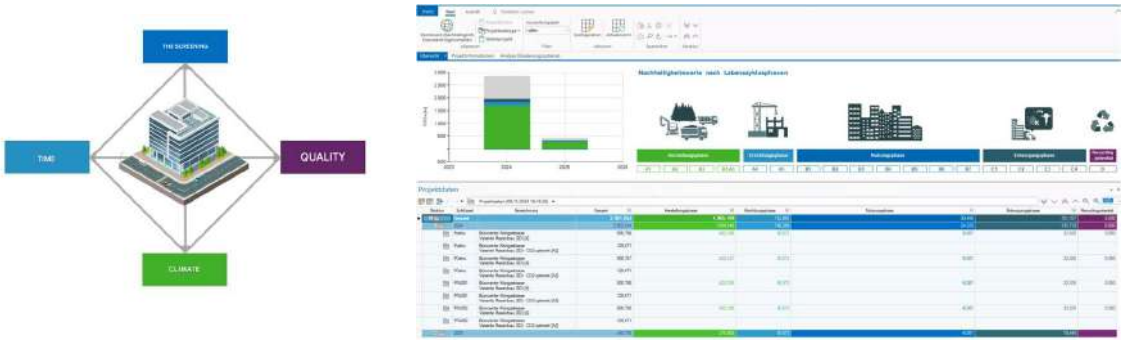


Fig. 10 - RIB iTWO enables multi-criteria sustainability screening. Source: New in RIB iTWO 2025 – Sustainability (User manual).

Recent technical guidance from organisations such as UNEP (2023) and GIZ (2021) has further underscored the importance of digital tools that enable whole-life carbon tracking and procurement transparency during early design stages. RIB iTWO's catalog-driven architecture and scenario simulation interface directly address this need, supporting low-carbon decision-making before detailed specifications are locked in [48].

While RIB iTWO demonstrates clear alignment with sustainability frameworks and offers significant technical capabilities for integrated lifecycle planning, its evaluation in academic literature, particularly regarding early-phase workflows remains limited. This gap is most critical at the point where sustainability potential is highest: the early design stages.

Accordingly, this thesis investigates the operationalisation of RIB iTWO's sustainability functions in a real-world case study. Chapter 4 explores how the tool facilitates carbon-informed planning, catalog-based material selection, and scenario simulation within a live project context, providing a critical evaluation of its role in enabling early-stage decarbonisation.

2.5. RESEARCH JUSTIFICATION

Despite its technical sophistication and commercial adoption, RIB iTWO remains underexplored in academic discourse, particularly about its ability to support early-stage sustainability integration. While the tool's functionalities are well-documented in manuals and industry case studies, there is limited empirical research evaluating its usability in interdisciplinary workflows, its impact on material decision-making, or its effectiveness in carbon-conscious planning during low-resolution design stages.

This research aims to address that gap by positioning RIB iTWO not merely as a project management tool, but as a strategic enabler for carbon-intelligent decision-making. As the construction sector moves toward holistic lifecycle planning and performance-based procurement, there is a pressing need for digital tools that deliver both consistency in data and actionable sustainability insights. Accordingly, this study will assess the operational potential of RIB iTWO through a real-world case study in Chapter 6, analysing its effectiveness in transforming traditional, cost-driven planning into environmentally responsive decision-making from the earliest phases of design development.

2.6. STATE OF THE ART

The importance of reducing embodied carbon in buildings is now a global priority. Embodied emissions, which arise from material extraction, processing, transport, and construction, are increasingly significant as operational energy use declines due to improved efficiency and renewable energy adoption [1] [2]. Research confirms that early-stage design decisions particularly those involving structure and material selection exert the highest influence on a building's long-term carbon footprint [15] [23][24]. Despite this, many tools and workflows fail to address embodied carbon effectively at this critical phase.

Findings presented in Annex A2 highlight several persistent gaps in sustainability practice within the building sector. The NBS Sustainability Survey (2025) shows that while 72% of professionals report integrating sustainability during the design phase, 84% believe it should begin at the strategy and briefing stages, revealing a 12% gap between belief and practice due to client demands, data limitations, and inadequate tools. At the organizational level, the Ramboll Sustainable Buildings Market Study (2023) demonstrates growing strategic momentum, with 50% of companies embedding net-zero into corporate strategies (a 19% increase from previous cycles) and 92% of these setting measurable carbon-reduction targets,marking a shift from aspirational pledges to quantifiable pathways. Yet, as the World Green Building Trends Report (2021) indicates, only 37–47% of professionals rank embodied carbon among their top three design priorities, despite evidence that it contributes 50–70% of life-cycle emissions in many new buildings. Collectively, these findings emphasize the critical leverage of early design, where up to 70% of sustainability outcomes are determined, but also expose an adoption gap that can only be bridged through structured frameworks such as early-stage LCA, digital scenario analysis, and integrated platforms like RIB iTWO, which enable material selection, circularity, and carbon-informed decision-making at the point of maximum design freedom.

Digital frameworks such as Building Information Modelling (BIM) have gained widespread use across the Architecture, Engineering, and Construction (AEC) industry, offering opportunities to integrate sustainability considerations directly into design models [3][14][39]. Several tools now support early-stage environmental assessments [12][41]. These tools utilize Environmental Product Declarations (EPDs) and standardized life cycle assessment protocols ISO 14040 to quantify embodied impacts [18][45]. In theory, this ecosystem of tools and data could allow for carbon-informed decision-making from the earliest stages of design.

In practice, however, this integration remains limited. Studies highlight that although designers have access to EPDs and LCA tools, these are often introduced late in the process during detailed design or regulatory compliance by which time material decisions have already been locked in [2][16][19][20]. Even when BIM is used, sustainability features are frequently overlooked, underutilized, or misaligned with early-phase workflows [3][5][22]. The gap between available data and design-phase application continues to limit the impact of digital tools on embodied carbon mitigation.

Within this context, the RIB iTWO platform represents a notable advancement. Originally developed as a 5D BIM tool integrating geometry, cost, and time, it now includes a Sustainability Module that embeds CO_2 performance data directly into the planning model [6][42]. Drawing from national LCA databases such as ÖKOBAUDAT [46], the platform enables designers and planners to assign carbon coefficients to individual components and simulate material scenarios based on both environmental and financial metrics [42][43][44]. This dual layer functionality allows for real time decision making that reflects lifecycle carbon outcomes during early design stages (LOD 100–200) [6][42][47].

Despite its technical capabilities, RIB iTWO remains underutilized for early-stage carbon planning. Historically adopted by contractors and cost engineers, the platform's integration into architectural workflows has been limited [6][42]. Its academic evaluation is also sparse, particularly regarding its role in supporting early-phase material optioneering and real-time embodied carbon feedback. Barriers

include the steep learning curve, lack of interoperability with concept design tools, and limited exposure among architects [5][44].

This disconnects between potential, and practice reveals a persistent challenge in the state of the art: while digital tools for embodied carbon assessment have matured, their deployment at the point of maximum design freedom remains insufficient. As UNEP (2025) and DGNB (2023) emphasize, lifecycle carbon intelligence must be embedded into upstream planning to meet global decarbonization targets [7][47]. To achieve this, digital workflows must evolve from retrospective analysis to strategic design decision support.

This thesis responds to that need. By deploying RIB iTWO's Sustainability Module within a real-world case study, it aims to demonstrate how carbon metrics can inform material selection decisions in real-time. The research reframes BIM not just as a modelling tool, but as an environmental decision-making interface, enabling project teams to align functional, cost, and carbon goals from the earliest stages of design. In doing so, the study advances the state of the art by operationalizing existing technical capabilities within a structured, design-responsive, and workflow-integrated sustainability planning process.

3

MATERIAL SELECTION AND DECARBONISATION IN THE BUILT ENVIRONMENT

3.1. INTRODUCTION: THE CLIMATE IMPERATIVE OF MATERIAL CHOICE

Material selection plays a pivotal role in decarbonising the built environment, particularly when decisions are made during the early design phases. These choices influence not only embodied carbon but also the building's long-term lifecycle performance, economic viability, and environmental resilience [10][15]. The regulatory frameworks and climate objectives that are aligned with the Paris Agreement and the EU Green Deal have intensified decarbonisation of construction materials has become a strategic imperative [1][2]. This chapter explores key strategies, planning frameworks, and digital tools that support carbon - intelligent material decision making, aiming to enable reductions in greenhouse gas (GHG) emissions at the point of highest design leverage.

3.1.1. STRATEGIC FRAMEWORK FOR MATERIAL DECARBONISATION

A central pillar in the strategic decarbonisation of construction materials is the Avoid–Shift–Improve (ASI) model, which provides a structured and holistic approach to reducing carbon emissions across the building material life cycle. The model addresses three interrelated levers of intervention:



Fig. 11 - Circular ASI Strategy Wheel illustrating the interconnection between avoid, shift, and improve measures. Source : United Nations Environment Programme. (2023). Building materials and the climate: Constructing a new future

A central pillar in the strategic decarbonisation of construction materials is the Avoid–Shift–Improve (ASI) model, which provides a structured and holistic approach to reducing carbon emissions across the building material life cycle. The model addresses three interrelated levers of intervention.

3.1.2. AVOID-SHIFT-IMPROVE (ASI) MODEL

Avoid: Minimise Demand and Waste through Circular Economy Principles

Avoiding emissions is the most effective step and involves reducing the need for new materials via circular economy principles. This includes Material-efficient design using digital tools and life cycle thinking to optimise quantity early on. Adaptive reuse and renovation, which can reduce emissions by 50–75% compared to new builds. The use of secondary materials, salvaged from demolition or industrial offcuts, to displace virgin inputs.in parallel, Design for disassembly (DfD), enabling materials to be recovered and reused, positioning buildings as future material banks. Collectively, these measures shift the construction sector from a linear to a circular resource model, minimising waste and embodied carbon. [49][50].

Shift: Transition to Renewable, Regenerative, and Low-Carbon Materials

The second lever focuses on replacing high-carbon materials with low-impact alternatives: Timber, bamboo, and agricultural residues offer scalable, low-carbon options when sustainably sourced. Vernacular construction methods such as straw bale and rammed earth demonstrate high durability and minimal environmental impact. And Regenerative land management, integrated with material production, supports biodiversity and carbon sequestration [49][50].

Improve: Decarbonise the Production of Conventional Materials

Where conventional materials remain necessary, emissions must be reduced through technological and process innovation: Electrification of production, shifting to renewable energy in cement kilns and metal smelting. Carbon capture and storage (CCUS) for energy- and process-related emissions, especially in cement. Substitution and optimisation, including clinker reduction, recycled steel, and low-carbon binders (e.g., fly ash, calcined clay). Additionally Modular and prefabricated construction, enhancing material efficiency and reducing on-site waste [49][50].

3.1.3. STRATEGIC RELEVANCE OF THE ASI MODEL IN MATERIAL PLANNING

The ASI model aligns strongly with the whole life-cycle approach and supports integrated decision-making across all project phases from early design to end-of-use [49]. It emphasises:

- **Early intervention**: The ability to avoid emissions is greatest at the design stage, reinforcing the strategic value of upfront planning.
- **Multiscale application:** ASI can be applied at material, building, district, and national policy levels.
- **Equity and just transition**: The model supports inclusive strategies that consider the needs of the informal sector, marginalised communities, and future generations.

According to UNEP (2023), full implementation of ASI strategies could enable net-zero emissions from building materials by 2060, provided they are supported by cross-sector collaboration, public investment, and strong regulatory frameworks [49] [50].

3.2. DECARBONISATION STRATEGIES ACROSS THE LIFECYCLE

Mitigating embodied carbon in the built environment is essential for aligning architectural and engineering practices with global climate targets. Unlike operational emissions, which diminish with grid decarbonization and high-performance systems, embodied carbon is emitted upfront often before building occupation thus having a more immediate climate impact [2]. The following strategies provide a multi-dimensional, evidence-based framework for embodied carbon reduction at both component and system levels.

3.2.1. DESIGN EFFICIENCY: STRUCTURAL RATIONALIZATION AND SPATIAL OPTIMIZATION

Design efficiency targets the reduction of material quantity and structural mass through optimized architectural and engineering layouts [51]. The "less is more" philosophy translates into specific design actions:

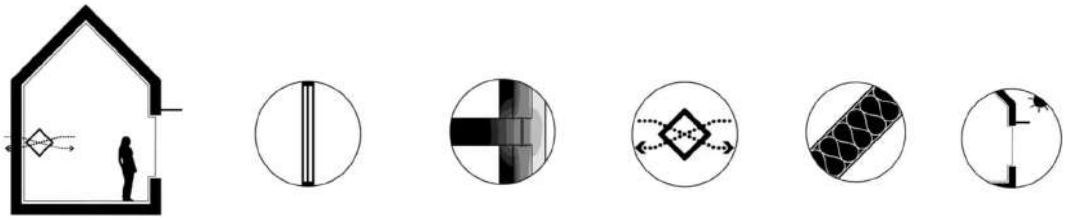


Fig. 12 - Passive design strategies. Source: Adapted from Passive House Accelerator

- **Grid Optimization**: Rational structural spans and efficient load transfer mechanisms reduce the need for excessive reinforcement and thick concrete slabs.
- **Volume Minimization** Curtailing floor-to-ceiling heights, wall thicknesses, and circulation spaces can lower the gross floor area (GFA) without compromising function.
- **Passive Massing Strategies:** Efficient building geometry that leverages solar orientation, wind flow, and daylight access can reduce energy loads, minimizing the need for additional structural or service components.
- **Redundancy Elimination**: Avoiding overdesign can result in 10–25% embodied carbon savings, particularly in concrete-intensive systems such as columns and foundations.
- **Computational Tools**: Parametric modelling and finite element optimization allow real-time iteration and material quantity benchmarking early in the design process [51][52].

3.2.2. HIGH-IMPACT MATERIAL HOTSPOTS: REDUCTION STRATEGIES

Targeting high-impact material hotspots is one of the most effective strategies for reducing embodied carbon in buildings. These typically include reinforced concrete, aluminium, facade systems, and virgin steel components which account for most a building's upfront carbon emissions (A1–A3 stages).

The bar chart in Figure 13 illustrates the percentage contribution of various building components to total embodied carbon emissions in a typical mixed-use development, both before and after reduction measures. The longer pink bars represent the baseline emissions, while the darker segments indicate emissions after applying mitigation strategies such as material substitution, structural optimization, or reuse. Among the components, upper floors emerge as the highest contributor, accounting for up to 23% of total embodied carbon even after reductions. Foundations, envelopes, frames, and piling also represent significant emission sources, each contributing approximately 10–15%. In contrast, internal walls, ceiling finishes, floor finishes, and external works have smaller shares, typically under 5%. The difference between the baseline and reduced emissions visually demonstrates the impact of targeted reduction strategies, underscoring the importance of focusing early-stage design efforts on high-impact components like the superstructure and foundation to achieve meaningful carbon savings.

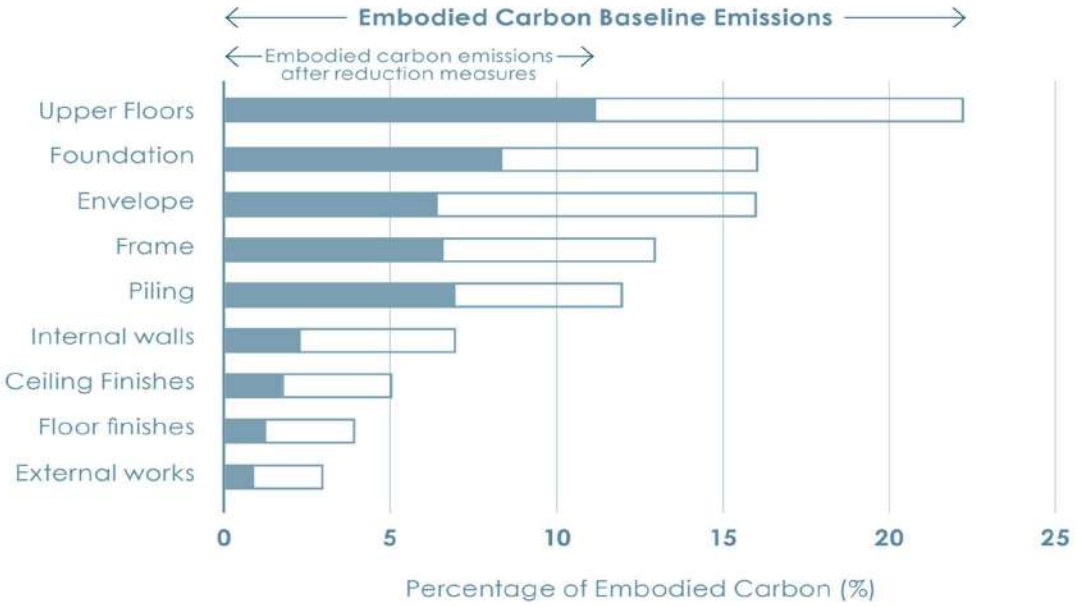


Fig. 13 - High impact materials in office building typologies. Adapted from LETI embodied carbon Primer

These typology-based patterns highlight the need to align carbon reduction strategies with specific functional and usage profiles [52]. They demonstrate that high-impact components vary by building type and performance demands. Targeted interventions should focus on elements with the greatest reduction potential. Components relevant to early-stage planning (LOD 200) are summarized in Table 2.

Table 2- Strategic Reduction Measures by Element

Building Element	Embodied Carbon Reduction Strategies
Structure (Substructure and Superstructure)	-Optimize sub/superstructure options early in design. - Conduct framing grid studies and structural rationalization. - Reduce weight via voids and material substitution (e.g., GGBS, recycled steel). - Design frames with dual functions (e.g., structural + shading).
Envelope (Facade and Roof)	- Compare embodied carbon across facade types using benchmark data. - Focus on concealed components with high carbon - Enable reuse and design for disassembly at end-of-life.
Design for Manufacture and Assembly	- Compare embodied carbon across facade types using benchmark data. - Focus on concealed components with high carbon intensity - Enable reuse and design for disassembly at end-of-life.

3.2.3. Material Selection: Low-Carbon Substitution and Product Transparency

Material selection remains one of the most decisive levers in embodied carbon reduction. High-impact substitutions can significantly cut emissions, especially when interventions occur during early design[53] [54].

Key Substitution Strategies:

The Evidence-based procurement and transparent material comparisons across product categories and states the strategies [47][55].

- **Cement Substitution**: Replacing traditional CEM I with CEM III/A (containing ≥30% GGBS) can reduce concrete emissions by 30–60% without compromising structural performance.
- **Metal Recovery and Reuse:** Recycled steel or reclaimed aluminium can reduce emissions by up to 90% compared to virgin materials.
- **Element-Level LCA:** Early detection of carbon-intensive components through digital LCA tools enables informed substitutions aligned with design and structural performance

Likewise, Substituting reinforced concrete with CLT (Cross-Laminated Timber) can achieve a 60–70% reduction in embodied carbon. Replacing fired brick with rammed earth can result in a 75–80% emissions reduction. And using cellulose insulation instead of EPS (Expanded Polystyrene) can reduce CO_2 emissions by 60–85% [19].

Three detailed case studies conducted by RMI in collaboration with Skanska, a global construction and development firm, identified the key categories in which a project's embodied carbon can be significantly reduced at little to no additional cost. By analysing real-world building, a mid-rise concrete and steel office, a timber-framed multifamily structure, and a tilt-up warehouse. The study demonstrated that targeted interventions in materials such as concrete, rebar, insulation, glazing, and finish materials can achieve 19–46% reductions in upfront embodied carbon, with cost premiums un These findings are showing in Figure 14 [19].



Fig. 14 - The categories in which a project's embodied carbon can be reduced for little to no cost. Source: RMI Reducing Embodied Carbon in Buildings

The study demonstrates the feasibility of embodied carbon reduction using currently available materials and evaluate economic impact, ensuring any changes cost less than or equal to 1% of the total construction budget.

3.3. CONTEXTUAL DETERMINANTS OF MATERIAL DECARBONISATION STRATEGIES

3.3.1. MULTI- DIMENSIONAL ENABLING CONDITIONS

While embodied carbon metrics provide a quantitative foundation, the feasibility and effectiveness of material decarbonisation strategies are mediated by broader contextual factors. This section identifies four key enabling conditions that shape the practical application and systemic impact of low-carbon material strategies [56].

1. **Climatic Suitability and Regional Context** : Climate zones influence the technical suitability of materials like insulation types must align with thermal demands, frost protection, and moisture performance across regions [49] [50][56].
2. **Raw Material Availability** : The environmental advantage of low-carbon materials can be eroded by transport and processing emissions. Selection must therefore be tailored to locally available resources such as fly ash, recycled steel, or timber [56].
3. **Social and Employment Effects**: Preference is given to materials that enable local employment, support low-skilled labour, and promote decent working conditions especially in prefabrication and circular economy sectors advancing the goals of SDGs 8 and 12 [50] [56].
4. **Circularity Readiness and Market Maturity**: Materials are assessed for alignment with circular principles (e.g., modularity, reusability, design for disassembly) and the presence of supportive infrastructure such as EPD registries, reclamation networks, and take-back schemes [49] [50][56].

3.3.2. STAKEHOLDER ROLES AND COLLABORATIVE ENABLERS

Enabling conditions are co-produced environments shaped by stakeholders across the construction value chain. Architects and structural engineers influence early-stage decisions such as span layout and material intensity. Suppliers and manufacturers affect the availability of carbon-optimized alternatives and EPD transparency. Contractors manage implementation logistics that impact modularity and reuse potential. Clients and public developers define sustainability ambitions, budget tolerances, and procurement criteria, often setting the baseline for innovation [56].

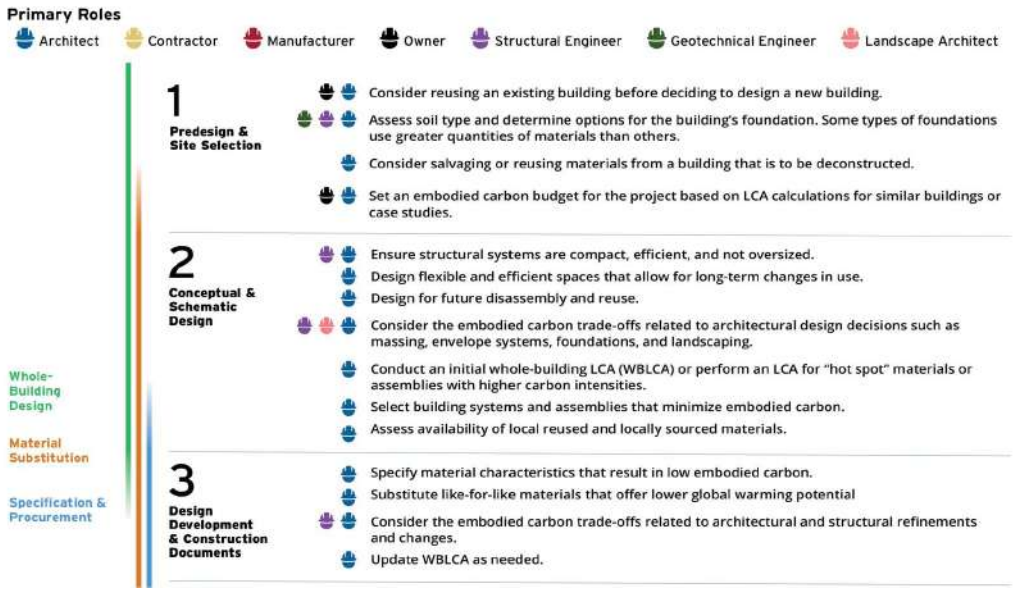


Fig. 15 - Strategies to reduce embodied carbon throughout the design and development process. Source: RMI Reducing Embodied Carbon in Buildings

This Figure 15 underscores the importance of early stakeholder involvement and clearly assigned responsibilities across project phases [19]. It highlights that collaboration not only in design but also in specification and procurement is essential to minimizing embodied carbon and it is inherently a multidisciplinary endeavour. Key enablers include,

- **Early Stakeholder Involvement**: Integrated design teams, including structural, MEP, architectural, and cost consultants must collaboratively define carbon budgets during conceptual design stages [44][50][56].
- **Carbon Literacy Training**: Stakeholders must understand carbon metrics to enable informed trade-offs during design and procurement [49] [50].
- **Collaborative Procurement**: Tenders should include embodied carbon criteria, supplier EPDs, and transparent material declarations [56].

Evidence from industry case studies suggests that early and integrated design can reduce total life-cycle carbon emissions by up to 30%, especially when embodied and operational carbon are treated with equal priority [52].

Toward an Integrated Enabling Ecosystem

Together, these enabling conditions define the systemic landscape within which material decarbonisation strategies must be embedded. By aligning technical suitability with regional resource availability, socioeconomic equity, and circular infrastructure readiness, stakeholders can translate carbon-conscious design intent into actionable practice. These conditions are not static; they evolve through innovation, policy shifts, and market maturation. Regulatory frameworks such as EU GPP, EN 15978, and national building codes are accelerating this evolution by embedding lifecycle carbon criteria into procurement and compliance structures [47][50]. Within this evolving ecosystem, stakeholder alignment, carbon literacy, and cross-disciplinary collaboration are not peripheral considerations; they are essential levers for mainstreaming decarbonisation and operationalising systemic change in the construction industry.

4

RIB ITWO AS A DIGITAL CATALYST FOR CARBON-AWARE PLANNING

4.1. RIB iTWO AS A DIGITAL CATALYST

This chapter explores the capabilities of RIB iTWO as a digital planning environment designed to support carbon-informed decision-making during the early stages of building design. It examines the platform's integration within the digital construction ecosystem, its catalogue driven infrastructure, and the sustainability modules that enable lifecycle carbon evaluation, scenario analysis, and regulatory alignment.

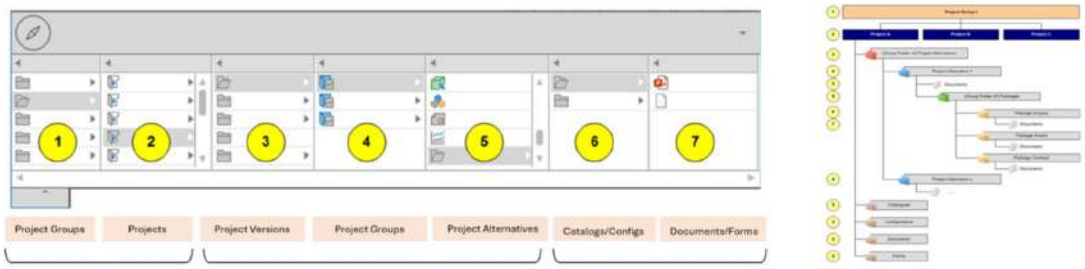
4.1.1. INTRODUCTION TO RIB iTWO IN THE SUSTAINABILITY CONTEXT

RIB iTWO, developed by RIB Software GmbH, integrates design, cost, time, and sustainability assessment within a unified digital environment. Evolving from a 5D BIM platform combining 3D geometry, 4D scheduling, and 5D cost estimation it now supports 6D planning by embedding lifecycle carbon analytics into early-stage workflows [42]. This shift reflects a broader industry trend toward data-driven, lifecycle-based planning, where sustainability becomes a proactive design driver rather than a post-design constraint. It embeds environmental metrics such as CO_2 intensity and lifecycle emissions directly into project catalogs and quantity take-offs[57]. This enables early-stage, multi-criteria evaluation of material choices based on both environmental and financial performance.

RIB iTWO also supports sustainability certifications (e.g., DGNB, LEED, BREEAM) and aligns with the EU Taxonomy, enabling early compliance tracking and transparent procurement. By integrating sustainability intelligence during conceptual and schematic design phases (LOD 100–200), it maximizes the potential for embodied carbon reduction when design freedom is highest and impact most significant. As such, RIB iTWO functions not just as a planning tool, but as a strategic enabler of decarbonised construction.

4.1.2. CORE PLANNING INFRASTRUCTURE: CATALOGS AND INTEROPERABILITY

The project structure in RIB iTWO 2025 mirrors real-world planning and execution phases illustrated in Figure 15. Each project is organized hierarchically and may contain multiple versions, alternatives, catalogs, configurations, and documents. This structure supports alignment with the FSAE (Fee Structure for Architects and Engineers) work phases [58].



1. *Fig. 16 - Project Structure in RIB iTWO*. RIB Software GmbH. (2024). Source : *RIB iTWO – Basics* (User manual).

The RIB iTWO project navigator is structured to organize data hierarchically across several interrelated components. Project Groups act as top-level containers to cluster similar projects, with each Project representing the central hub for planning and execution data. Within a project, multiple Project Versions capture iterative snapshots for traceability, although only the latest version remains editable.

Each version may be divided into Project Phases (e.g., Tender, Contract, Execution), aligning with real-world construction workflows. To support design flexibility, Project Alternatives (PAs) allow parallel technical or design options, all referencing common Catalogs, standardized libraries of BoQ items, units, and settings. Packages (SPs) structure procurement tasks into discrete units, each progressing through Inquiry, Award, and Contract stages. Supporting layers include Configurations, which define estimation logic and comparison settings (typically managed by administrators), and Documents, which house editable project files like contracts and quantity take-offs. This architecture supports clear data governance, version control, and streamlined project planning[58][60].

4.1.3. CATALOG

In the RIB iTWO digital environment, catalogs constitute the core planning infrastructure. Functioning as structured, parametric repositories, they enable standardized, interoperable, and model-driven workflows across the entire project lifecycle [59]. These catalogs ensure data consistency, semantic integrity, and reusability from early design stages through to procurement and execution. In construction informatics, they are often termed parametric libraries, reflecting their role in driving automation and harmonization within digital planning processes.

Each catalog entry incorporates standardized units, classification systems (e.g., DIN 276, Uniformat), and configurable metadata. More than just data repositories, catalogs actively drive consistency, automation, and cross-disciplinary coordination throughout the planning process.

The catalog system comprises several interlinked types, each tailored to specific domains of planning and execution shown in table 3 [59].

Table 3 - Overview of Catalog Types in RIB iTWO

Catalog Type	Description
Commodity Catalons	Define fundamental building materials and components, specifying parameters such as density, unit pricing, and embodied carbon coefficients).
Assembly Catalog	Represent integrated construction systems (e.g., façade or wall types) by grouping commodities and processes into reusable planning units.
Cost Code Catalog	Provide a hierarchical classification system for labour, materials, and equipment to support automated cost modelling and structured quantity take-off.
Sustainability Label Catalog	Embed environmental metrics such as CO_2e values, lifecycle stages (A1–C4), and circularity indicators into the digital planning environment
Resource and Crew Mix Catalog	Define labour crew compositions and productivity rates, supporting precise scheduling and resource management

Functional Roles of Catalogs Across the Project Lifecycle

In RIB iTWO, catalogs serve as the digital backbone throughout all phases of a construction project, ensuring continuity, semantic consistency, and lifecycle transparency from initial modelling to execution and post-handover operations.

Their role extends well beyond static data storage, enabling core planning functions such as automated classification of BIM elements, structured quantity extraction using parametric assemblies, and cost estimation through commodity and cost code hierarchies[60]. Sustainability planning is facilitated through the integration of carbon data and lifecycle metrics via Sustainability Label Catalogs, while scheduling processes are supported through resource modelling based on crew compositions and standard productivity benchmarks [57]. For procurement, catalogs enable the generation of BoQs and tender packages aligned with catalog-driven components. This modular system not only enhances coordination and regulatory compliance but also enables scenario analysis, variant comparisons, and cross-disciplinary optimization of both cost and carbon performance. As such, catalogs in RIB iTWO function as active instruments of integrated planning, driving informed decision-making across the entire project lifecycle.

4.2. RIB iTWO as a Digital Catalyst

The Sustainability Label Catalog in RIB iTWO 2025 represents a foundational component in the software's transition from cost-centric planning to sustainability-integrated project management [59][60]. These labels serve as metadata forms that encapsulate environmental performance indicators, enabling standardized tracking of sustainability metrics at object level across the project hierarchy, from cost codes and commodity items to BoQ components and assemblies.



Fig. 17 - Full range of functions, from the label catalogs and data catalogs to the various modules, such as Bill of Quantities, Estimate & Elemental costing. Source: New in RIB iTWO 2025 – Sustainability (User manual).

Environmental data within labels is structured according to lifecycle phases (A–D), following DIN EN 15804. This is achieved through a specialized 'Eco phase' data type, which ensures that all values, CO_2e, particulate emissions, and recyclability [57] and can be recorded phase-specifically shown in Figure 17 . It illustrates the process of linking the phases and as Input fields record unit-based emissions (e.g., kg CO_2e/m^2), while output fields compute project-level totals across all life cycle stages.

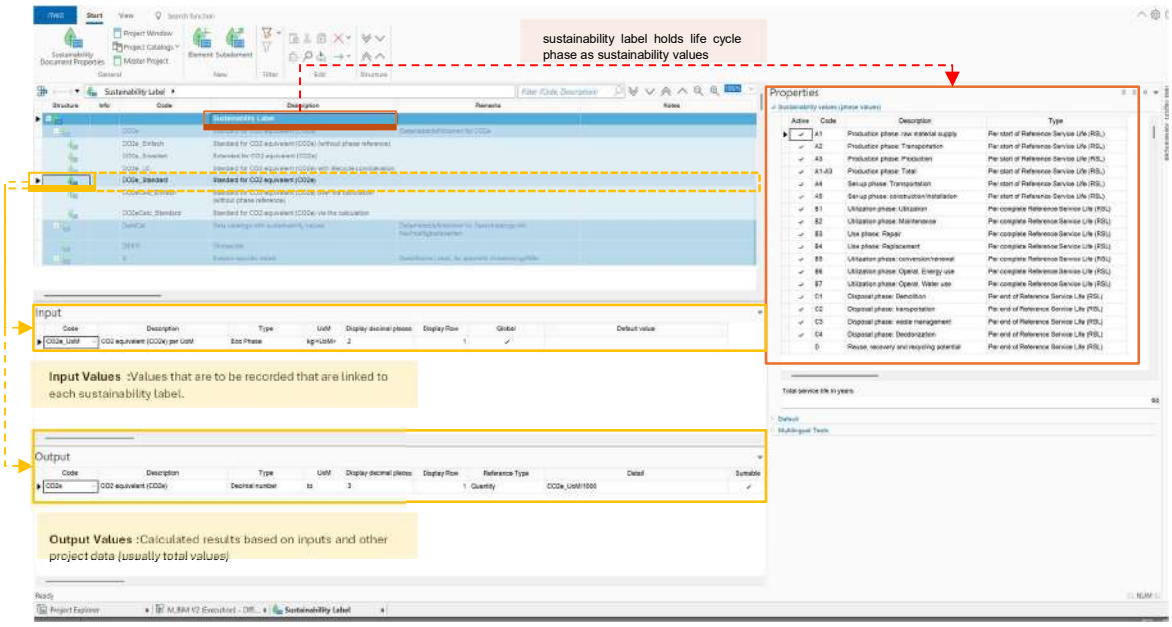


Fig. 18 - RIB iTWO Sustainability Label configuration panel, linking CO_2e values to lifecycle phases (A1–C4).

Each label includes two core value types:

Input Values: Raw sustainability data, e.g., embodied CO_2e (kg/m^2), resource usage, or recyclability rates, mapped to lifecycle phases (A1–A5, B1–B7, C1–C4, D).

Output Values: Calculated totals based on material quantities, fuel use, or area metrics. These values enable automated aggregation for variant analysis and cross-phase evaluation.

The labelling system is modular and hierarchical, allowing flexible assignment at different levels (item, resource, assembly) [59]. This supports lifecycle transparency, ensuring that environmental metrics remain traceable throughout design, costing, and procurement processes.

4.3. INTEGRATION WITH ÖKOBAUDAT AND ENVIRONMENTAL EPDS

A major advancement introduced in RIB iTWO 2025 is the direct integration with ÖKOBAUDAT, the official German LCA (Life Cycle Assessment) database for construction products, maintained by the Federal Ministry for Housing, Urban Development and Building. This integration enables the automatic import and updating of third-party verified environmental datasets, including XML-based EPDs into the RIB iTWO catalog system [57]. These datasets can be directly assigned to project elements using sustainability labels, allowing for precise, verifiable, and lifecycle-specific carbon accounting embedded into cost planning and procurement workflows.

Figure 18 illustrates the schematic showing the data flow between XML-based EPD imports, catalog item mapping, integration of ÖKOBAUDAT and ecoinvent datasets, and their application in BIM-LCA workflows.

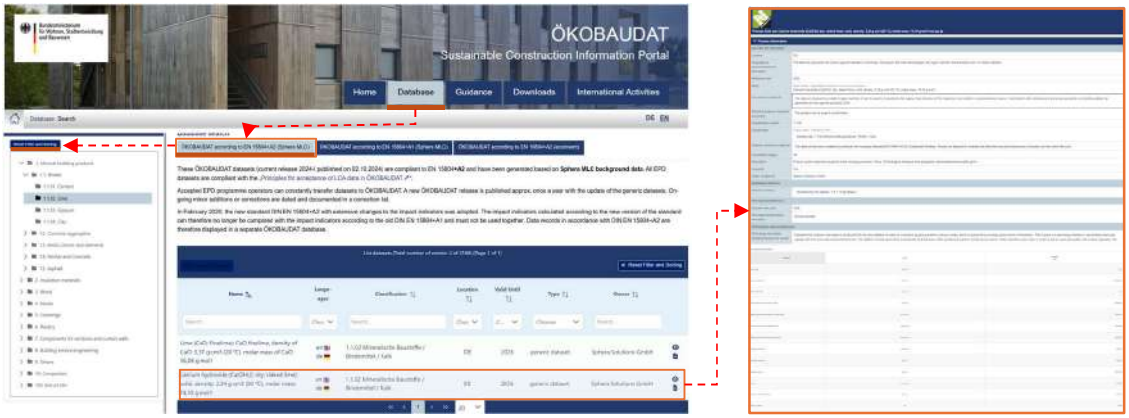


Fig. 19 - A schematic flow of ÖKOBAUDAT integration

4.3.1. CORE DATA PROVIDED BY ÖKOBAUDAT DATASETS

ÖKOBAUDAT provides standardized environmental data for construction materials, covering lifecycle phases A1 to D in line with EN 15804. The datasets include CO_2 and other impact indicators, resource usage, and waste flows per functional unit [46][57]. This data supports LCA-based decision-making in early planning stages.

Table 4 - Core data fields provided by ÖKOBAUDAT datasets

CATEGORY	DATA PROVIDED
General Information	Product name, material group, application area, data owner, manufacturer (if applicable), dataset UUID
Dataset Versioning	Version number, publication date, validity period, background database (e.g., Sphera MLC, ecoinvent)
Standards Compliance	EN 15804 (A1 or A2), ISO 14025, ISO 14040/44
Life Cycle Modules Covered	A1–A3 (product stage), A4–A5 (construction), B1–B7 (use phase), C1–C4 (end of life), D (recovery benefits)
Environmental Indicators	-GWP ,Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Ozone Depletion Potential (ODP) , Abiotic resource depletion (fossil and minerals)
Resource Use	Primary energy demand (renewable, non-renewable), use of secondary fuels, freshwater consumption
Waste & Output Flows	Hazardous/non-hazardous waste, radioactive waste, components for reuse, recovery, or disposal
Unit of Measurement	Functional unit (e.g., per m^2, per m^3, per kg)
Additional Notes	Modelling assumptions, data sources, comments on representativeness

4.3.2. Integration of ÖKOBAUDAT via Sustainability Labels in RIB iTWO

RIB iTWO enables direct linking of environmental data to project elements using a sustainability label structure [57]. Users can assign ÖKOBAUDAT datasets—either: Offline data (OEKO - Ökobaudat (offline data)) or Online data via connector (OEKO_ON - Ökobaudat (Onlinedaten über Connector))

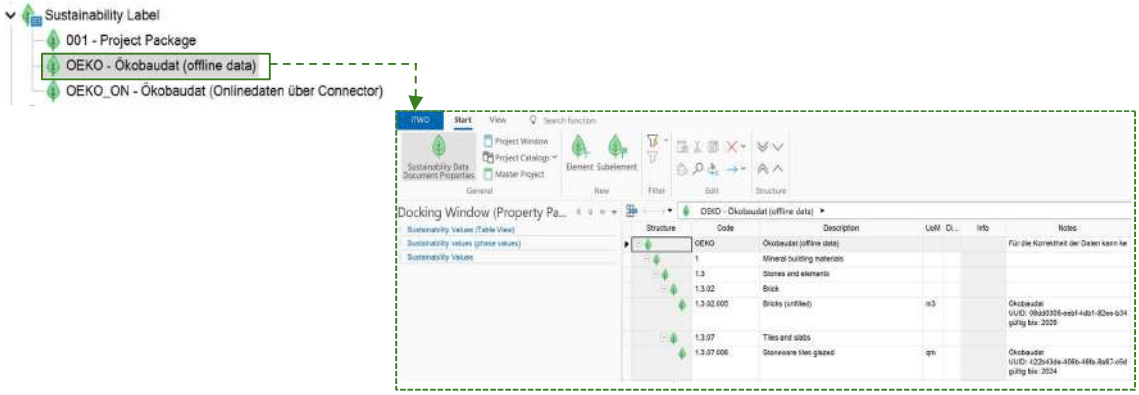


Fig. 20 - Sustainability Label Tree showing project-level linkage of ÖKOBAUDAT datasets (offline and online)

These datasets can be:

- Assigned to a project package, ensuring consistency across environmental assessments.
- Used in both offline and real-time modes, depending on availability or project requirements.
- Cross-linked with other catalog features, such as: Estimates, Bo, Assemblies and materials

This integration allows carbon data from EPDs to inform quantity take-off, cost planning, and sustainability reporting [46][57]. Ensuring traceability and alignment with DGNB, BNB, and EU GPP requirements.

4.3.3. FUNCTIONAL CAPABILITIES IN RIB ITWO

RIB iTWO's integration with ÖKOBAUDAT and EPDs enables the following capabilities:

- Direct parsing of XML-based EPDs, in both ÖKOBAUDAT and IBU (Institute Baune und Umwelt) formats
- Mapping of environmental indicators—including CO_2-equivalent values, Global Warming Potential, resource consumption, and end-of-life recyclability—to catalog items, assemblies, and Bill of Quantities (BoQ) components
- Custom EPD support, enabling the use of region-specific or manufacturer-specific declarations, provided they comply with EN 15804
- Regular update cycles, ensuring access to the most recent certified environmental data across all projects

By embedding ÖKOBAUDAT-linked data directly into the planning and cost catalog logic, RIB iTWO transforms environmental data into actionable carbon intelligence,integrated across design, estimation, procurement, and regulatory compliance processes [46][57] [58][60]. For this study, datasets compliant with EN 15804+A2 and based on the Sphera MLC background database were prioritized to ensure conformity with current EU regulatory frameworks. Where necessary, cross-validation using ecoinvent-based A2 datasets was conducted to ensure international comparability.

4.4. MULTI-LEVEL PRESENTATION OF SUSTAINABILITY RESULTS

As sustainability becomes a design and procurement imperative, the effective communication of environmental data is as critical as its quantification. RIB iTWO addresses this need by offering three core formats for presenting sustainability results: BoQ Sustainability Views, Reports, and Dashboards [57]. Each format supports specific decision-making levels,ranging from granular data entry to strategic benchmarking and thereby enhancing stakeholder engagement throughout the project lifecycle.

1. BoQ– Sustainability Tab View

Functionally, BoQ Sustainability Tab delivers an itemized, tabular view of environmental performance metrics, including CO_2e per unit of measurement (UoM), total CO_2e, and lifecycle stage attribution. Data is dynamically linked to sustainability labels (e.g., ÖKOBAUDAT), ensuring traceability and live updates [57]. Also gives feasibility to compare various options through graphs shown in figure 20.

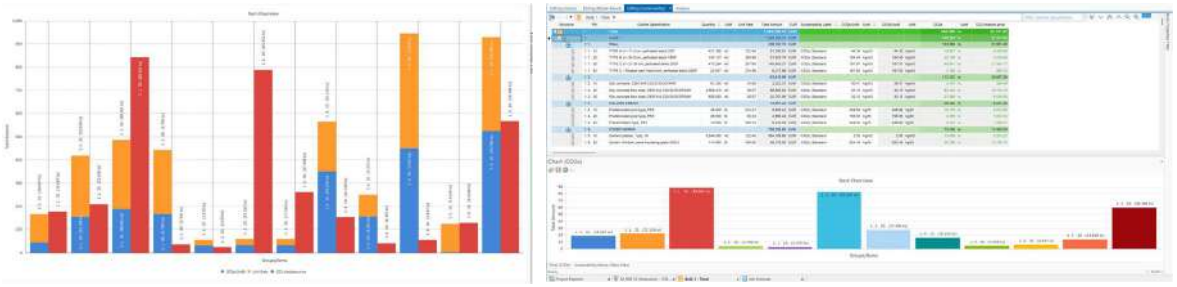


Fig. 21 - BoQ Sustainability Tab with graph

BoQ's micro-level transparency is ideal for tracking material-specific emissions and phase-by-phase distribution (A1–D). Its interactive workflows functions such as Update, allow real-time recalculations and hierarchical roll-ups and the traceability of BoQ's is helpful [57]. The EPD data can be directly sourced using F3 navigation, ensuring full alignment with certified databases like ÖKOBAUDAT and IBU.

In a municipal school project, planners used the BoQ tab to compare two slab variants. A switch to low-carbon concrete (EN 15804+A2 compliant) yielded a 12% CO_2e reduction in modules A1–A3,instantly reflected in the BoQ totals.

2. Sustainability Reports – Sorted Evaluations and Print Lists

RIB iTWO's reporting module generates structured outputs through configurable sorting schemes, suitable for regulatory audits and tender submissions.

Available formats include:

- Sorted BoQ Reports with Emission Breakdowns
- Lifecycle Phase-Based Evaluations
- Award Procedure Reports featuring CO_2-based surcharges or shadow pricing

Used highly in, Regulatory Compliance for reports support documentation for DGNB, BNB, and EU GPP requirements [57]. Custom Sorting data_that can be grouped by lifecycle phase, material group, BoQ level, or cost code. And Tender Integration data can be directly embedded into award procedures, enabling CO_2-based bidder evaluation.

3. Dashboards – Project and Cross-Project Monitoring

Dashboards in RIB iTWO 2025 offer visual aggregation of sustainability KPIs. Views are customizable at both project and portfolio levels [57], with modules for:

- Total Emissions vs. Budget/Area (e.g., CO_2e/m² GFA)
- Lifecycle Phase Distribution
- Low-Carbon Variant Comparisons
- Cross-Project Aggregation by DIN 276 or building type



Fig. 22 - Sustainability dashboard view in RIB iTWO visualizing emissions

Mostly integrated in Strategic Oversight for KPIs and graphics support high-level monitoring of CO_2e performance across multiple projects. Lifecycle Integration in projects like simulate 50–60 years operational impacts, aligning with EN 15804 modules B and C. And Stakeholder Engagement to Intuitive visuals (e.g., CO_2 trees or shadow prices) improve accessibility for non-technical users like investors or city planners.

They are intended for executive decision-makers, ESG managers, and portfolio planners seeking to monitor and compare outcomes across multiple projects.

4.5. SYSTEMIC INTEGRATION OF CATALOGS WITHIN RIB iTWO

4.5.1. DIGITAL WORKFLOWS FOR EARLY-STAGE CARBON PLANNING

The catalog system in RIB iTWO is deeply embedded across all core modules, supporting systemic integration that enables real-time data propagation across design, costing, scheduling, procurement, and sustainability domains [57][59], illustrated in Figure 22. Each catalog item is parameterized and version-controlled, ensuring that updates in one module automatically reflect in others, thereby eliminating redundancy and improving decision-making agility.

This integration supports a range of advanced capabilities:

- Live synchronization between BIM objects and cost/environmental datasets.
- Automated mapping of imported IFC components to corresponding catalog entries.
- Standardized structure for BoQs, enabling consistent and scalable cost estimation.
- Cross-project catalog reusability, allowing benchmarking, quality assurance, and corporate-level planning standardization.

Additionally, the catalog system supports interoperability with external reference databases and regulatory frameworks, such as ÖKOBAUDAT for EPDs [57], eBKP for Swiss cost classification, and DIN 276 for German construction cost structuring. This compliance-ready integration enables users to align digital planning with national and EU-level regulatory standards, including lifecycle-based sustainability assessment protocols.

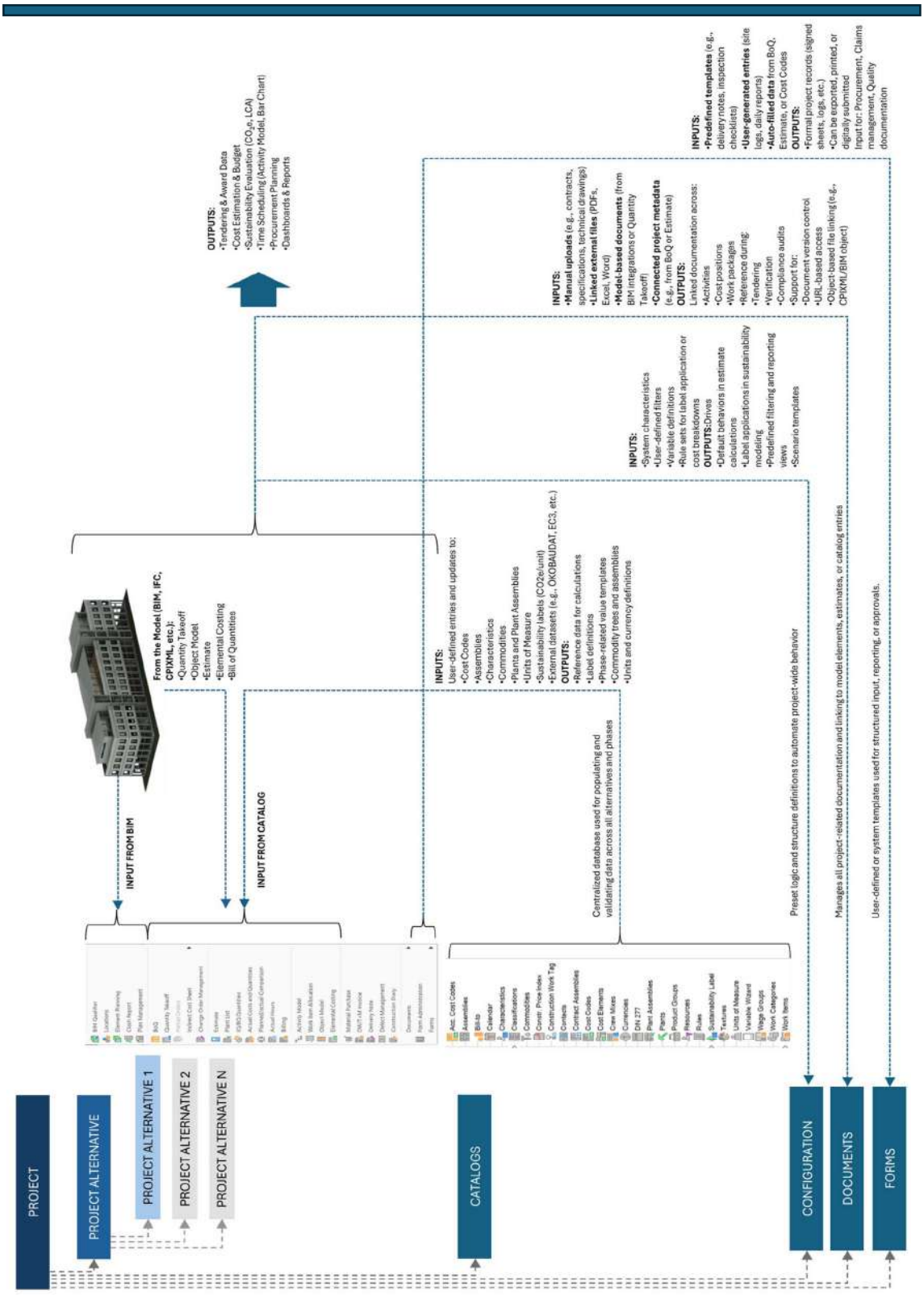


Fig. 23 - Integrated Planning Workflow in RIB, illustrates the centralized data architecture of RIB iTWO, connecting BIM models, catalogs, configuration templates, and documents to support alternative-based project planning.

4.5.2. Implementation Considerations

The successful adoption of RIB iTWO for carbon-informed planning depends on both its technical capabilities and the organizational context within which it is deployed. This section outlines the platform's strategic strengths as well as the key challenges that may influence implementation outcomes.

Strategic Strengths

RIB iTWO brings many benefits that make it a great fit for sustainable project delivery. One key feature is its ability to provide real-time carbon dashboards. This means you can dynamically track carbon dioxide equivalent (CO_2e) emissions throughout all stages of a project, across different components, and even for various design options. This continuous monitoring allows for transparent decision-making, helping project teams understand and reduce their environmental impact effectively.

Furthermore, RIB iTWO offers catalog-driven transparency when it comes to environmental data. The platform links environmental information directly to digital catalogs. This ensures that sustainability metrics for materials are fully traceable, aligning with recognized environmental product declarations (EPDs) and official life cycle assessment (LCA) datasets such as ÖKOBAUDAT. This detailed, material-level insight helps in selecting more sustainable options with clear environmental footprints.

Finally, the platform excels by integrating LCA, costing, and scheduling. It unifies carbon analysis with traditional cost estimation and project timelines within a single, cohesive environment. This comprehensive approach allows for multi-criteria optimization, enabling project managers to make informed decisions that consider not only financial implications and deadlines but also the environmental impact of their choices.

Potential Barriers

Even with all its strengths, there are still some hurdles that could prevent carbon-integrated workflows from reaching their full potential. One significant challenge lies in BIM interoperability limitations. Different Building Information Modelling (BIM) environments often use varying data structures and modelling practices. This can make it difficult to seamlessly exchange data and automatically generate sustainability indicators, slowing down the process of integrating carbon analysis.

Another barrier is the availability of EPD data by region. Environmental Product Declarations (EPDs) are crucial for accurate environmental calculations, but their coverage and the quality of their datasets can vary significantly depending on the region. This is especially true outside of the EU, where a lack of consistent EPD data can impact the reliability and comparability of environmental assessments, making it harder to get a clear picture of a project's environmental impact.

Finally, training and organizational readiness play a big role in successful implementation. For these workflows to be truly effective, teams across different disciplines need to build their capacity. A lack of familiarity with life cycle assessment (LCA) principles, how to manage digital catalogs, or even how to use RIB iTWO's sustainability module can significantly delay the adoption of these important carbon-integrated processes.

5

METHODOLOGY

5.1. RESEARCH RATIONAL

This study adopts a Design Science Research (DSR) methodology within a practice-based case study, aimed at reducing embodied carbon intelligence into the earliest stages of architectural planning. The rationale stems from the need to reposition carbon assessment at the conceptual design phase, where decisions have the highest leverage on whole-life emissions.

The research utilizes the RIB iTWO,'s integrated 6D functionalities including LCA, CO_2 tracking, and shadow pricing. These capabilities are tested in a real-world office building project, reflective of standard workflows in the European AEC context and aligned with EU sustainability policy frameworks, such as the EU Green Deal.

A quantitative, simulation-driven approach is applied to test the platform's ability to optimize carbon and cost outcomes. The rationale comprises three core dimensions:

Strategic: Early-stage decisions account for most embodied emissions, yet carbon intelligence is rarely embedded at this point.

Technical: The new sustainability features in RIB iTWO provide a unique environment to test integrated carbon-cost workflows.

Empirical: There is a research gap in tool-based approaches that unite material selection, carbon metrics, and economic planning in a single platform.

Justification for Approach and Alignment with Thesis Objectives

The use of DSR within an embedded case study provides a rigorous framework for developing and validating a digital planning workflow that incorporates sustainability metrics into early design. This methodology aligns directly with the thesis objective by directly impacting the operationalized carbon and cost intelligence at the point of maximum design flexibility and environmental impact.

The digital workflow in cantered on RIB iTWO, links Revit -based geometric modelling (LOD 100–200) with EPD -integrated material catalogs, cost estimation, and scenario -based sustainability analysis. By quantifying outcomes such as kg CO_2e/m^2 and applying shadow pricing, the study enables data-driven decisions that address both environmental and financial performance.

Each phase,from input criteria definition and IFC-compatible modelling to simulation of material variants and carbon-cost trade-offs and contributes to a replicable framework that supports climate-aligned architectural planning.

FRAMEWORK DEVELOPMENT METHODOLOGY

The central objective of this study is to develop a replicable and integrative digital framework for supporting material selection and sustainability evaluation during the early stages of design.

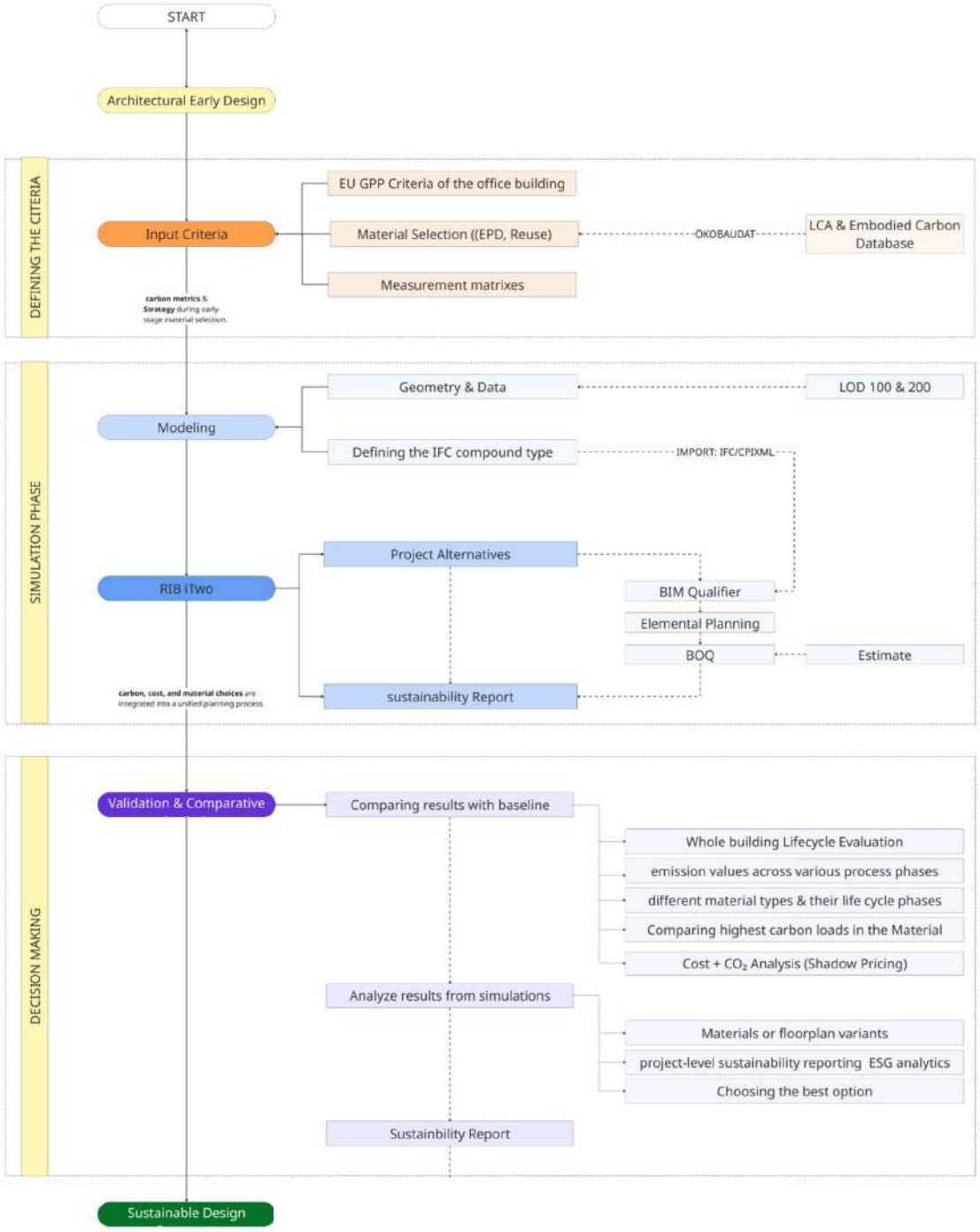


Fig. 24 - Methodology Framework

The framework is structured around a digital workflow linking early design inputs to measurable sustainability outcomes.

A mid-level office building serves as the case study to demonstrate the application of this framework. A Revit model (LOD 100–200) defines the initial geometry and facilitates the extraction of quantities for key assemblies. Subsequently, the model is transferred into RIB iTWO, where materials are systematically mapped to catalog incorporating cost codes, EPD data, and sustainability labels.

This integration supports variant simulations and comparative evaluations based on carbon and cost metrics. By connecting architectural modelling, material quantification, and lifecycle assessments, the workflow creates a cohesive, performance-driven process for making carbon-informed decisions at early design stages.

5.2. Performance Evaluation Metrics: Carbon, Cost, and CO_2 Pricing

5.2.1. Selection Criteria for Building Materials

To ensure methodological rigor in assessing embodied carbon during early design phases, this study employs a strategic material selection framework that targets components with the highest leverage on whole-life environmental performance. The approach prioritizes carbon-intensive, decision-critical materials that not only contribute disproportionately to life-cycle emissions but also shape the spatial, structural, and economic trajectory of the project. Five interdependent criteria rooted in environmental science, life cycle thinking, and digital construction planning shown in table 4.

Table 5 - Material selection Criteria

Criterion	Description
Embodied Carbon Impact	Materials with high cradle-to-gate emissions particularly reinforced concrete, structural steel, and mineral-based insulation are prioritized for carbon reduction due to their dominance in stages A1–A3 of the product lifecycle [52][53].
Design Influence	Structural and envelope elements specified early in the design process, such as slabs, external walls, and columns, are emphasized due to their low substitutability and long-term lock-in effects.
EPD Availability	Preference is given to materials with verified EPDs, compliant with EN 15804 and accessible through platforms like ÖKOBAUDAT, to ensure transparency and regulatory alignment [46][55].
Cost and Procurement Sensitivity	Materials that carry high capital costs or are frequently value-engineered such as façades, glazing systems, and insulation. And are examined for their dual influence on carbon and economic trade-offs.
Digital Compatibility	The material selection process is filtered through compatibility with digital tools such as RIB iTWO, ensuring integration with structured catalogs, cost codes, and sustainability attributes for effective scenario modelling [42][48].

This framework ensures the prioritization of high-leverage material systems those with significant carbon intensity and early design dependency and maximizing decarbonisation opportunities while preserving relevance within real-world project delivery.

5.2.2. Primary Evaluation Metrics

To support evidence-based decision-making in early-stage design, this study employs a tri-metric performance framework encompassing embodied carbon**,** lifecycle cost, and CO_2 shadow pricing**.** This multidimensional evaluation enables a balanced assessment of environmental impact and financial feasibility, fostering informed trade-offs in material selection and design strategy.

- **Embodied Carbon (kg CO_2e/m^2)**: Embodied carbon is the primary sustainability metric, calculated per material component and normalized per gross floor area. Life cycle emissions are modelled using RIB iTWO's LCA module, covering stages A1–A3 and, where relevant, extending to C4. Data is sourced from EPDs compliant with ÖKOBAUDAT and aligned with EN 15804, allowing cross-comparison across material variants [61][63][64].
- **Lifecycle Cost (€/m^2)**: Lifecycle cost estimates are derived through RIB iTWO's cost planning tools, supplemented with benchmarked unit rates from public tenders. This enables the assessment of the cost implications of low-carbon substitutions, supporting procurement-relevant decision-making, both in terms of initial investment and total lifecycle expenditure [62].
- **CO_2 Shadow Price (€/tonne CO_2e)**: A shadow price is applied to material-related emissions, internalizing environmental externalities within financial analyses. This reflects emerging regulatory trends such as the EU Emissions Trading System (EU ETS) and the Carbon Border Adjustment Mechanism (CBAM), aligning project-level assessments with policy-driven carbon pricing signals [61][62].

Together, these metrics provide a robust decision framework for evaluating design alternatives in terms of both climate performance and economic viability.

5.2.3. Building-Level Carbon Emissions Calculation

A Whole Building Life Cycle Assessment (WBLCA) approach is used to quantify emissions at the project scale, following international best practices (DOE, 2024; RMI, 2021) [63].

Key methodological steps include:

- **System Boundary Definition:** Emissions are modelled from cradle-to-gate (A1–A3) and optionally up to end-of-life stages (C1–C4) [61][63].
- **Quantity Extraction:** Quantities are derived from LOD 100–200 BIM models, exported via IFC format to ensure structured data input.
- **Life Cycle Inventory (LCI) Data:** Emission factors are sourced from verified databases such as ÖKOBAUDAT [64].
- **Normalization and Reporting:**
    - kg CO_2e/m^2 (gross floor area) – for benchmarking and variant comparisons
    - kg CO_2e/m^2/year – for payback calculations and intensity assessments (when operational energy is considered).Operational stages B6–B7 are excluded unless explicitly assessing whole-life carbon, in accordance with EN 15978.

5.2.4. Material-Level Carbon Emissions Calculation

At the product level, carbon values are derived from PCR-compliant EPDs, focusing on A1–A3 stages: raw material extraction, transport, and manufacturing. Optional A4–C4 stages are included where data availability permits, and project relevance is confirmed [61][64].

Impact intensities are expressed as:

- kg CO_2e/kg – for bulk materials (e.g., concrete, steel)
- kg CO_2e/m^2 – for assemblies and surface finishes (e.g., façade systems, insulation)
- kg CO_2e/t – for precast components

Digital verification tools are used to cross-check emissions values and benchmark results against broader industry datasets [63][64].

While the primary analysis is grounded in cradle-to-gate (A1–A3) data, selective cradle-to-grave (A1–C4) modelling was performed using standardized assumptions to explore downstream implications. This provides a strategic approximation of whole-life carbon impacts, illustrating how early-stage material decisions may cascade through the building's lifecycle. Such forward-looking assessments reinforce the importance of early intervention in achieving long-term carbon reductions [63].

LCA Formula and Carbon Calculation Approach

The embodied carbon was calculated using a standard quantity × emission factor method, normalized per gross floor area. The core formula is as follows:

$$\text{Embodied Carbon (kg CO}_2\text{e)} = \sum_{i=1}^{n} Q_i \times EF_i$$

Where:

- Qi: Quantity of material i (in kg, m^2, or m^3)
- EFi: Emission factor of material i (in kg CO_2e/unit)
- n: Total number of assessed materials

This absolute value was then normalized per gross floor area (GFA) to facilitate comparison across project scales:

$$\text{Embodied Carbon Intensity} = \frac{\sum Q_i \times EF_i}{\text{GFA}} \quad (\text{kg CO}_2\text{e/m}^2)$$

This normalized metric enables benchmarking against leading international standards, including RICS, LETI, and the World GBC. All calculations were conducted in RIB iTWO, which automates quantity extraction from BIM models and maps materials to EPDs compliant with EN 15804 [61][63][64]. Where EPDs were not available, emission factors were conservatively estimated using default ÖKOBAUDAT datasets, ensuring methodological consistency and avoiding underreporting.

CO_2 Shadow Pricing and Cost–Carbon Integration

To bridge environmental performance with financial assessment, this study integrates CO_2 shadow pricing—a method of assigning monetary value to embodied emissions based on their externalized climate cost. Shadow pricing does not reflect a direct expenditure but acts as a proxy for future regulatory liabilities, fostering forward-looking financial planning.

A base shadow price of €100 per tonne CO_2e was applied, aligned with projected 2030 benchmarks from the EU Emissions Trading System (EU ETS) and guidance issued by the European Investment Bank (EIB) [61][62]. To capture market and policy uncertainty, a ±25% sensitivity range was tested.

$$\text{Shadow Cost}_{CO_2} = \text{Embodied Carbon (kg } CO_2e) \times \frac{CO_2 \text{ Price (€)}}{1000}$$

This shadow cost was combined with conventional lifecycle cost (LCC) values to produce hybrid carbon–cost indicators like Early design alternatives, public procurement evaluations, ESG-aligned investment metrics and Climate conscious design strategies.

By embedding shadow pricing into early-phase decision-making, the study anticipates carbon pricing regulations, aligns with the Carbon Border Adjustment Mechanism (CBAM), and enables stakeholders to internalize climate-related financial risk [62][63].

5.3. PERFORMANCE BENCHMARKING AND CLASSIFICATION

Performance Benchmarking and Classification provides a structured approach to evaluating and contextualizing the environmental performance of office buildings, specifically concerning embodied and operational carbon emissions. Benchmarking enables the quantification and assessment of a building's carbon footprint relative to established industry standards and best practices, thereby facilitating transparent performance tracking and targeted improvement measures [65][66]. By integrating validated datasets, including DGNB-certified building performance data and EU-level comparative benchmarks, this section establishes clear thresholds and performance classifications ranging from typical to high-performing against which project-specific outcomes can be measured.

This comparative methodology aids stakeholders in identifying performance gaps, prioritizing interventions, and achieving compliance with sustainability certifications or regulatory frameworks.

The following benchmarking table integrates values primarily from the DGNB Study (2021) for embodied carbon emissions and typical operational carbon intensities, while also aligning with overarching performance benchmarks from the European Commission's JRC Level(s) framework [65][66].

Table 6 - Carbon Performance Benchmarks for Office Buildings

Performance Metric	**Top Performing**	**Average / Typical**	**Higher-End (Less Sustainable)**
Embodied Carbon (A1–A3)	≤ 6.6 kg $CO_2e/m^2/yr$ (~265 kg CO_2e/m^2 total)	~9.1 kg $CO_2e/m^2/yr$ (~365 kg CO_2e/m^2 total)	≥ 12 kg $CO_2e/m^2/yr$ (≥ 500 kg CO_2e/m^2 total)
Operational Carbon (Energy Use)	≤ 9 kg $CO_2e/m^2/yr$	~10 kg $CO_2e/m^2/yr$	≥ 15 kg $CO_2e/m^2/yr$
Whole-Life Carbon (50-year)	≤ 16 kg $CO_2e/m^2/yr$	~19 kg $CO_2e/m^2/yr$	≥ 25 kg $CO_2e/m^2/yr$
Recommended Source	DGNB, Level(s)	DGNB, Level(s), IPCC	DGNB, JRC European averages

5.4. MATERIAL QUANTITY EXTRACTION AND BIM INPUTS

Material quantity extraction was based on a simplified building model developed in Autodesk Revit, configured at LOD100–200 to represent the conceptual and schematic design stages. This level of detail captured essential massing, envelope systems, and primary structural elements, which is adequate for evaluating the influence of early design choices on embodied carbon outcomes.

A structured preparation process was implemented to ensure semantic integrity and interoperability across platforms:

Object classification and parameterization were applied to key components, including walls, slabs, façade systems, and insulation to ensure consistency in naming, spatial hierarchy (levels, zones), and embedded metadata such as material specifications and geometric attributes.

IFC type mapping was explicitly defined through Revit's *IFC Export Mapping* settings, aligning Revit categories with standardized classes (e.g., IfcWallStandardCase, IfcSlab, IfcColumn) in accordance with ISO 16739. This step ensured that elements were machine-readable and correctly interpreted by external systems, avoiding generic proxies such as IfcBuildingElementProxy, which can undermine downstream automation.

The finalized model was exported in IFC or CPIXML format, both of which support open, structured data exchange and maintain the semantic richness required for lifecycle-based analysis. By aligning Revit-based modelling inputs with downstream tools through IFC/CPIXML interoperability, the workflow ensured a continuous, transparent data flow across platforms, facilitating accurate quantity take-off, BoQ generation, and early-stage lifecycle assessment.

6

CASE STUDY

6.1. CASE STUDY AND PARAMETERS

6.1.1. OVERVIEW OF THE CASE STUDY

The reference project employed in this study is a conceptual three-storey office building, originally developed by the institute using Autodesk Revit as part of its training program in digital planning and sustainability assessment. Architecturally, the model is defined by a rectangular footprint, a repetitive structural grid, masonry wall infill, and glazed façade elements, characteristics typical of mid-scale institutional office buildings. It includes essential spatial configurations such as vertical circulation cores, open-plan interiors, and modular curtain wall systems.

Developed to Level of Development (LOD) 200, the model functions as a pedagogical prototype that offers both geometric precision and semantic richness. Its intermediate detail level supports meaningful parametric analysis, quantity take-off, and lifecycle assessment, while preserving the flexibility required for scenario-based testing and early-stage design evaluation.



Fig. 25 - Conceptual 3-Storey Office Building Used as Reference Model

Key Building Parameters

- Building Type: Mid-scale Office Building (3 storeys)
- Gross Floor Area: 2,776 m^2
- Assumed Service Life: 60 years
- Development Level: LOD 100 and LOD 200 (Revit)

This typology was selected due to its relevance in urban development and its material-intensive components specifically the structural system, envelope, and interior partitions, which represent major contributors to embodied carbon. The model's standardized nature allows for robust comparative

assessment of material strategies, system boundaries, and digital workflows within a controlled environment.

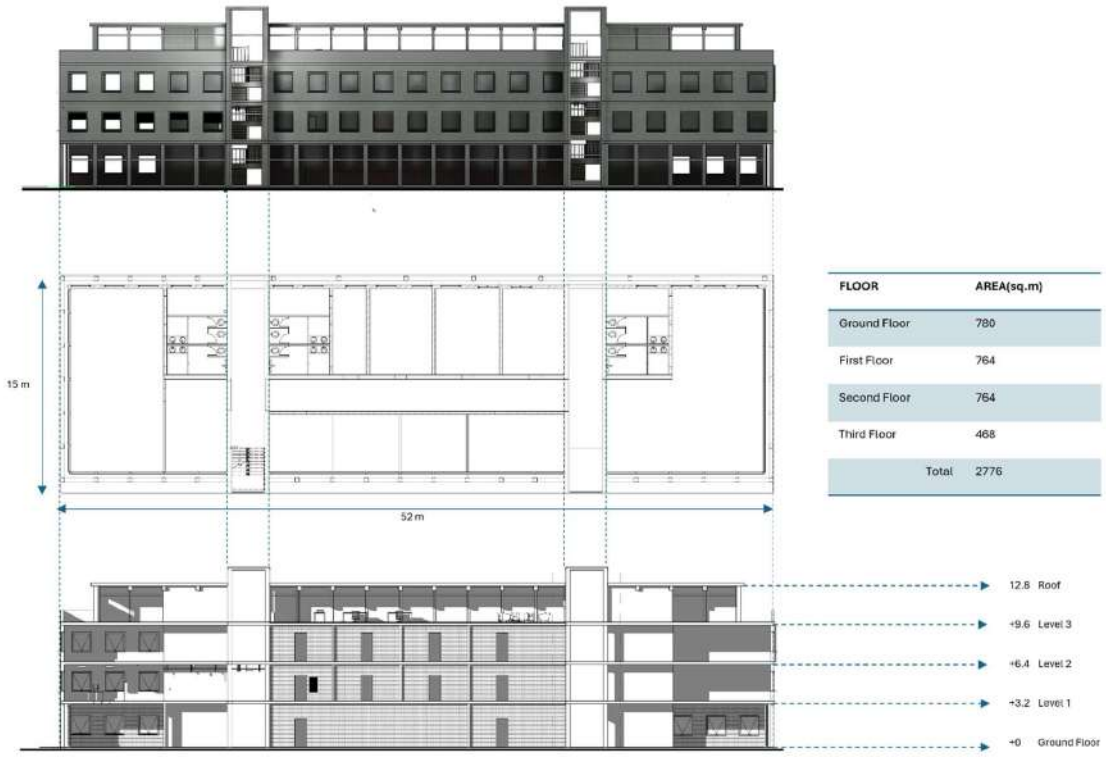


Fig. 26 - Reference Model detail

6.1.2. Purpose and Relevance to This Study

The use of a conceptual, non-realized "ghost" model offers a unique advantage for sustainability-focused research: it eliminates uncertainties commonly found in live projects such as incomplete data, evolving client briefs, or irregular modelling standards and instead enables structured experimentation across design variants. By serving as a controlled and replicable testbed, the model facilitates consistent application of parametric analyses, quantity take-offs, and lifecycle carbon estimations.

This aligns with the core objective of the study: to investigate how BIM enabled digital workflows can support early-stage sustainability planning through integrated material selection and carbon evaluation. The model is available at both LOD 100 and LOD 200, enabling direct comparison of different levels of planning detail and their influence on data quality, simulation accuracy, and decision-making effectiveness.

6.1.3. Scenario Modelling and Variant Definition

To properly understand how different material and spatial choices affect both carbon emissions and costs, a specific set of design variations was created and put into action using the RIB iTWO platform. Our strategy for scenario modelling focused on three main areas.

One key area was material substitution. This involved replacing common materials like fired brick or standard concrete with options that produce fewer emissions. Think of things like recycled aggregate concrete, prefabricated polyethylene (PE) elements, and engineered timber assemblies.

We also looked at structural and envelope configurations. This meant adjusting things like wall types, slab systems, and insulation to see how they influenced the embodied carbon (specifically Modules A1-A3, which cover manufacturing and construction) and the overall cost.

Finally, we defined lifecycle system boundaries. We evaluated two different emission scopes. The first was "cradle-to-gate" (A1-A3), which focuses on the short-term impact from production to the factory gate. The second was "cradle-to-grave" (A1-C4), giving us a broader view of long-term sustainability implications, including end-of-life phases.

Each of these variations was set up using data from catalogs and material definitions linked to Environmental Product Declarations (EPDs) within RIB iTWO. This allowed for automated quantity take-offs, lifecycle assessments, and cost simulations. The digital environment made it easy to compare these scenarios side-by-side, which helped us transparently weigh the trade-offs between saving carbon, procurement costs, and how constructible something was. These variants directly address common requirements in public tenders, especially those that ask for lifecycle-based justifications for sustainable material strategies.

Selection of Scenarios: Rationale and Scope

To explore the potential of construction strategies within a standard office building typology, three design scenarios, Case 1 (Base Level), Case 2 (Medium Level), and Case 3 (Ambitious level) were developed and tested. These cases represent a stepwise progression in material circularity and embodied carbon reduction, aligned with EU GPP criteria and ÖKOBAUDAT datasets. Case 1 serves as the regulatory baseline using conventional materials and methods. Case 2 introduces intermediate-level strategies such as modular detailing and bio-based substitutions to achieve moderate gains. Case 3, the most ambitious, adopts DfD, cradle-to-cradle logic, and digital LCA integration to maximize carbon savings and reuse potential. This tiered structure enables both benchmarking and performance evaluation across practical implementation levels.

Table 7 - Overview of Selected Circularity Scenarios and Rationale

CASE	SCENARIO TITLE	CIRCULARITY LEVEL	PURPOSE OF SELECTION
1	Compliance-Oriented Design	Low (≥30%)	Serves as a baseline scenario using conventional methods; aligns with EU GPP core compliance requirements.
2	Medium Circularity Framework	Medium (≥50%)	Introduces reversible detailing and sustainable material substitutions to test practical improvements.
3	High Sustainability Oriented	High (≥75%)	Tests the upper limits of carbon reduction through full DfD, biogenic materials, and digital LCA tools.

6.2. WORKFLOW OVERVIEW: SYSTEM ARCHITECTURE AND PROJECT IMPLEMENTATION

The evaluation of circularity scenarios was conducted within a structured digital environment enabled by RIB iTWO, a model-based cost and sustainability planning platform. The workflow diagram presented below integrates two critical layers:

(1) The internal structure of RIB iTWO, which governs data flow between building components, cost items, and sustainability modules.

(2) The project-specific sequence of actions outlined detailly within each respective section, detailing actions such as importing the Revit model, performing quantity take-off, applying material substitutions, estimating CO_2e using ÖKOBAUDAT data, and generating scenario-based reports.

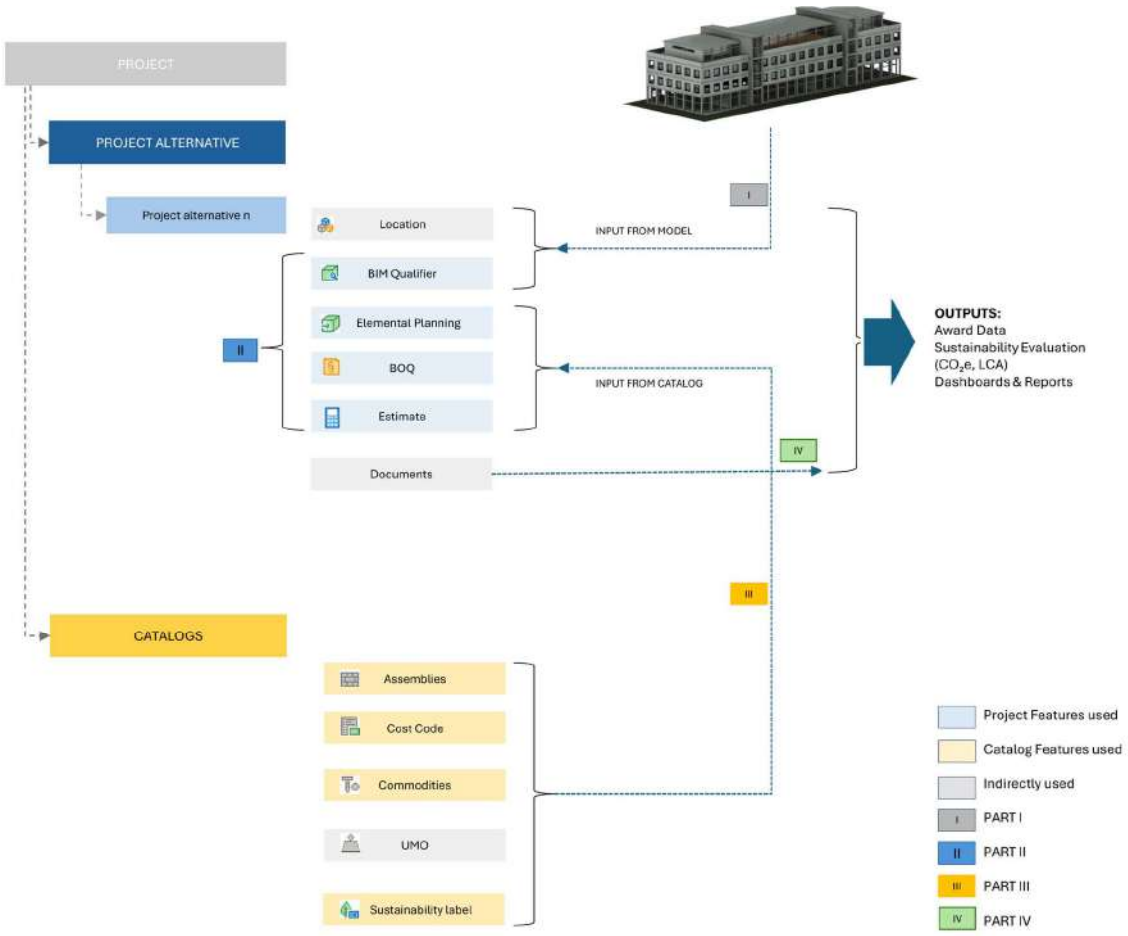


Fig. 27 - Overview of Integrated Workflow for Model-Based Cost and Sustainability Planning in RIB iTWO

The diagram illustrates the complete digital workflow for scenario assessment using RIB iTWO(1), and structured into project specific sequence(2) of four phases: (I) Model import from Revit via CPI XML; (II) Initial setup including BIM qualification, element planning, BoQ structuring, and cost estimation; (III)

Catalog integration with assemblies, cost codes, and sustainability labels; and (IV) Output generation for award data, embodied carbon analysis (CO_2e), and sustainability dashboards.

This dual-layer workflow ensures alignment between system capabilities and research objectives, enabling consistent, transparent, and reproducible sustainability assessments across all three design cases.

PROJECT WORKFLOW OVERVIEW: STRUCTURED PHASES FOR SCENARIO ASSESSMENT

To ensure a transparent and repeatable process for developing and accessing circularity scenarios, the project-specific workflow is organized into four distinct phases:

i. **Model Transfer – Revit to RIB iTWO** , this stage involves preparing the architectural model in Autodesk Revit at LOD 100–200 and exporting it using CPI (Cost Planning Interface) for structured import into RIB iTWO. Model geometry and classification elements are aligned with the RIB catalog to support quantity mapping.

ii. **Early Setup in RIB iTWO**, upon import, initial configuration includes defining element types, linking work items to model components, setting up QTO formulas for rule-based quantity extraction, and establishing BoQ structure. This foundation ensures compatibility with both cost and carbon calculations.

iii. **Data Input and Evaluation**, Material-specific data such as unit prices, embodied carbon factors (from ÖKOBAUDAT), and recycled content percentages are manually or semi-automatically integrated. Design scenarios are then created through material substitutions and reversible detailing, followed by benchmarking of CO_2e and cost outputs across all cases.

iv. **Reporting and Decision Support**, the final stage involves generating detailed sustainability and cost reports within RIB iTWO. Customized dashboards and tabular outputs visualize embodied carbon, cost variations, and material lifecycle impacts across design scenarios

6.2.1. PART I: MODEL TRANSFER – REVIT TO RIB ITWO

Structured Data Exchange via CPI Interface

This section outlines the digital workflow for integrating a Revit-based Building Information Model (BIM) into the RIB iTWO environment using the CPI XML format. The process begins in Autodesk Revit, where the model is exported via the IFC/ CPI plug-in, a format specifically optimized for interoperability with RIB iTWO. Unlike the generic IFC format, CPI XML preserves object hierarchies and semantic structures, ensuring high-fidelity data exchange. Users can export either specific floors or the complete model as a .cpi.xml file.

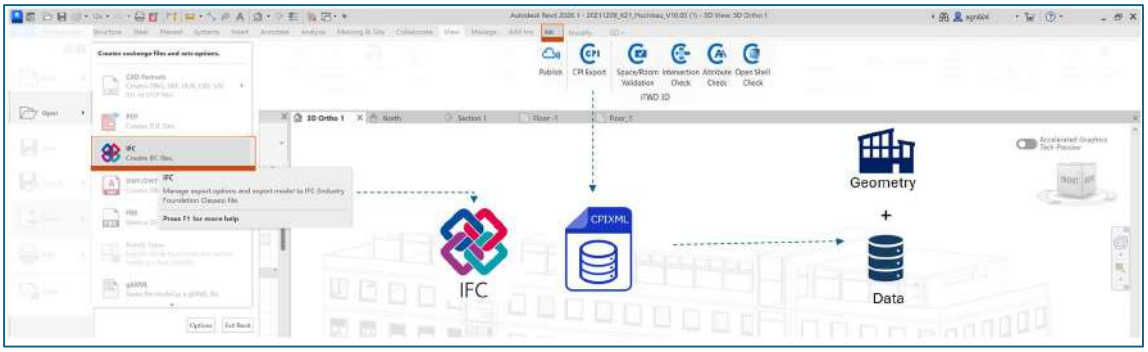


Fig. 28 - Structured Data Exchange via IFC/CPI Interface: Exporting from Revit to RIB iTWO

This diagram illustrates two standardized methods for transferring building model data from Autodesk Revit to RIB iTWO: CPI XML (Cost Planning Interface) and IFC (Industry Foundation Classes). The CPI XML format enables structured, quantity-linked export for cost and material mapping, while IFC supports geometry-based import with broader interoperability. Both formats facilitate the integration of model elements into RIB's element planning and quantity take-off modules for downstream sustainability analysis.

Once imported into RIB iTWO, the model is reviewed through the BIM Qualifier module and then linked with RIB iTWO for further processing.

6.2.2. PART II: EARLY SETUP IN RIB ITWO

The workflow begins with the creation of a new project environment in RIB iTWO, which serves as the central container for all subsequent planning activities, data inputs, and design evaluations. Within this environment, users define one or more Project Alternatives, each representing a distinct design or construction scenario to be developed and analysed. This structure enables parallel assessment of varying strategies such as different material configurations, construction methods, or sustainability targets within a unified project framework. By maintaining separate yet comparable alternatives under a single project, planners can streamline comparative analysis, ensure data consistency, and generate decision-support outputs for each scenario.

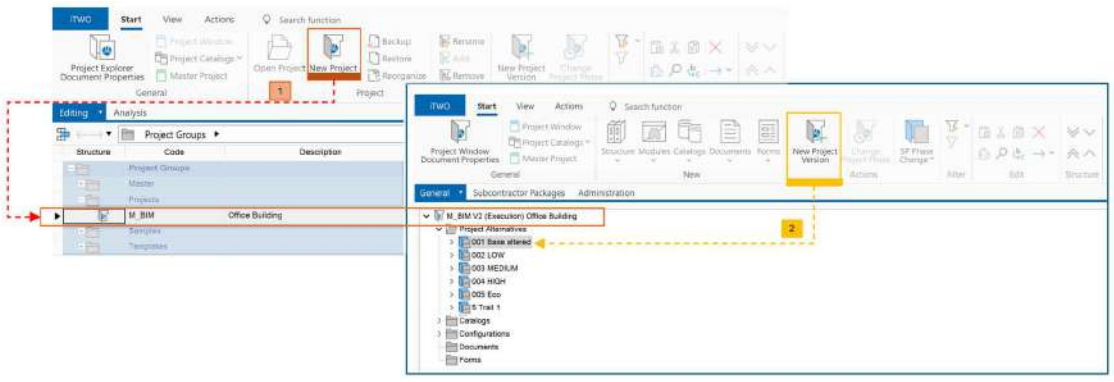


Fig. 29 - Process of Creating a project

6.2.2.1. BIM QUALIFIER :DATA VALIDATION, QUALITY ASSURANCE AND MODEL TRANSFER

Once a Project Alternative has been created and the CPI model successfully imported, the next step involves opening the BIM Qualifier module in RIB iTWO. This initiates a structured inspection and validation workflow to ensure the accuracy, completeness, and consistency of the imported building model prior to its integration into planning and evaluation processes.

The imported model is displayed in a hierarchical Model Overview, allowing users to navigate spatial units, component categories, and varying levels of detail with precision.

- **Model Loading & Visualization**: After import, the model is displayed in the *Model Overview*, where all geometric and component objects are listed hierarchically, allowing structured navigation across building parts and detail levels.
- **Quality Check Activation**: The *Quality Check* tool performs automated data integrity assessments, detecting issues such as missing families, overlapping geometry, or spatial inconsistencies. It also verifies the correctness of resource assignments.

- **Common Issue Categories**: Typical errors flagged include component conflicts, special geometry issues, missing object families, and collection structure problems all of which are categorized for systematic correction.
- **Model Transfer**: Once validated, the *Transfer CPI Data* function commits the qualified model, including geometry, metadata, and classifications into the project database, enabling cost planning and sustainability analysis.

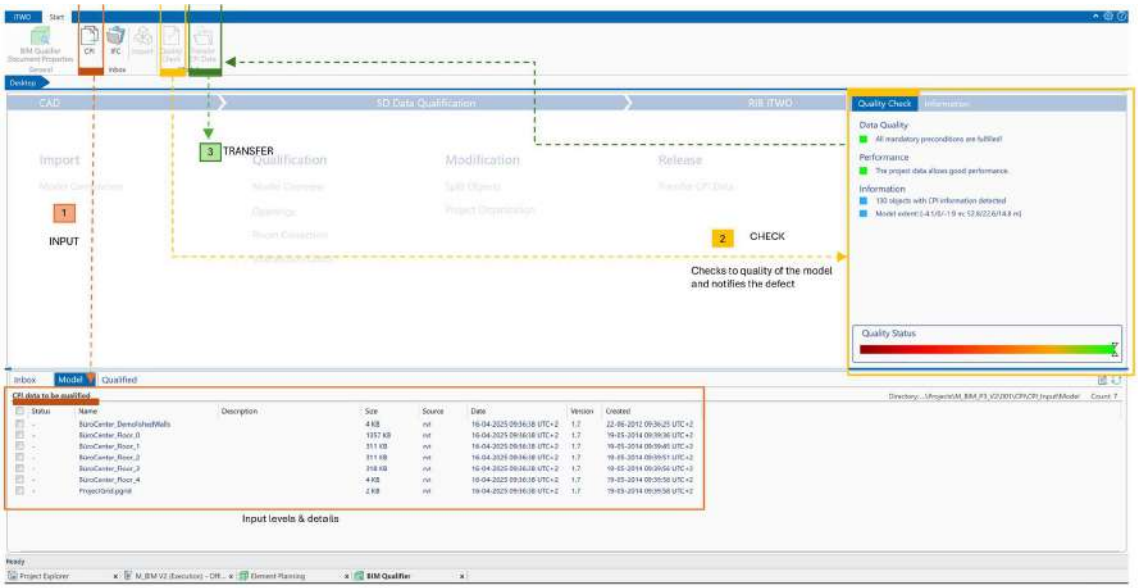


Fig. 30 - Model Validation and CPI Data Qualification Workflow in RIB iTWO BIM Qualifier.

The diagram outlines the stepwise process for validating and qualifying imported CPI data within the BIM Qualifier module. Key stages include: (1) model loading and visualization via the Model Overview pane; (2) execution of automated data integrity checks using the Quality Check system to detect spatial conflicts, missing families, and malformed elements; and (3) final model transfer into the RIB iTWO project database using the Transfer CPI Data function

6.2.2.2. ELEMENT PLANNING: HIERARCHICAL WORK ITEM STRUCTURING

The *Element Planning* module in RIB iTWO serves as a critical interface between the digital building model and the project's cost planning structure. It enables model-based quantity take-off and facilitates the systematic creation of project-specific work items, forming the foundation for structured cost estimation. This process involves three key steps: (1) defining work items, (2) assigning model components, and (3) configuring quantity derivation formulas.

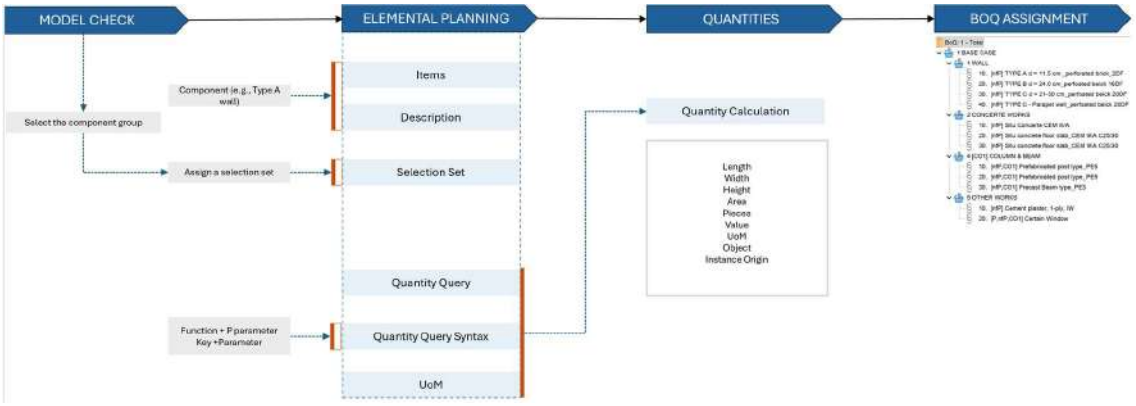


Fig. 31 - Hierarchical structuring of work items in Element Planning, showing linkage between BIM components, cost assemblies, and sustainability datasets.

Key advantages of this integrated approach include:

- Elimination of manual quantity errors through rule-based automation
- Accelerated and transparent BoQ generation, traceable to individual model components
- Direct integration with sustainability modules, including embodied CO_2 tracking using ÖKOBAUDAT datasets
- Reusability of work structures, templates, and cost assemblies across multiple projects

By aligning design intent with financial and environmental criteria early in the lifecycle, this method strengthens decision-making, promotes data integrity, and supports best practices in digital construction. It also reflects current EU policy directions, particularly those embedded in Level(s), the Digital Building Logbook, and broader sustainability assessment frameworks.

STEP 1: WORK ITEM

From the Project Alternative, the Elemental Planning module is generated. Within the BIM Qualifier module, the integrated model connects Revit-based BIM data to RIB iTWO through a coordinated, multi-stage workflow encompassing model transfer, validation, and rule-based quantity derivation. This structured process enables direct linking of model geometry to cost and planning elements, ensuring a traceable and automated approach to construction planning.

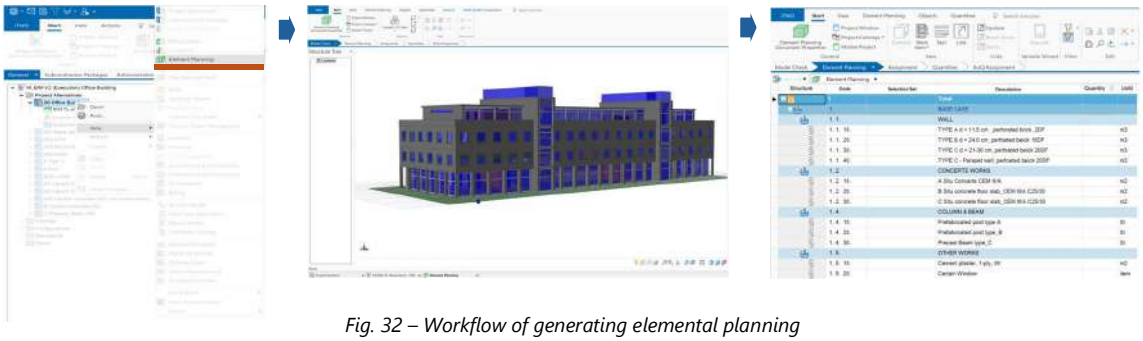


Fig. 32 – Workflow of generating elemental planning

The first stage within the Element Planning module involves the development of a hierarchical structure of internal work items, which operates independently of the external BoQ. This internal structure forms

the backbone of model-based cost planning by allowing precise assignments between BIM components and construction tasks. The hierarchy includes the following levels:

- **Elements/Sub-elements**: Organizational units that group related construction tasks, not directly associated with cost.
- **Work Items**: Cost-relevant units of construction activity used in estimation and planning.
- **Work Item Including Item**: Combined entries that generate both a work item and a BoQ line, streamlining model-to-cost linkage.

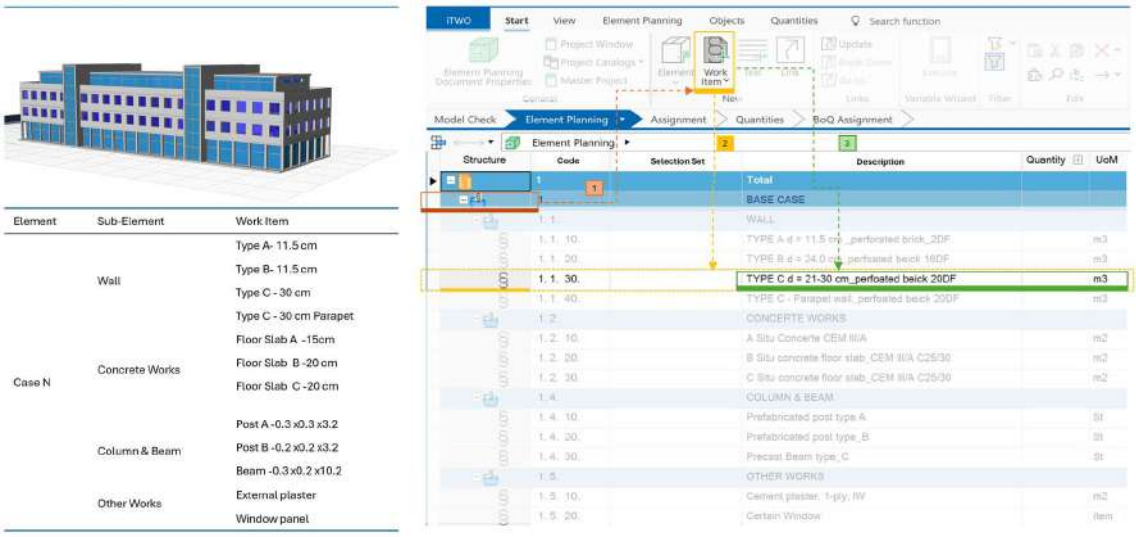


Fig. 33 - Element Planning interface -*creating a work item*

The Figure shows the *in the hierarchical structuring of work items and assignment of Revit BIM components to specific construction tasks using model-driven quantity extraction.* This structured approach ensures that each geometric element in the BIM model can be systematically associated with a specific construction activity and its associated cost implications. The module also supports template-based planning, allowing predefined structures and assemblies from previous projects to be reused. This feature enhances efficiency and standardization, particularly in multi-project or large-scale environments.

Ultimately, the Element Planning module bridges the digital model with structured cost data, aligning with industry norms and supporting scalable, standards-based workflows for quantity and cost planning.

STEP 2: SELECTION SET-ASSIGNING MODEL COMPONENTS

In RIB iTWO, the assignment of BIM components to work items is facilitated through Selection Sets—a dynamic grouping mechanism based on shared object attributes. These sets enable efficient and scalable linkage between model geometry and project tasks, forming the basis for accurate quantity take-off.

This is done through selecting an element through the component type/description/ on filter

Selection Sets are typically defined using filters within the Model Check phase, allowing users to isolate components according to parameters such as: Component category (e.g., walls, slabs) , Material type (e.g., concrete, masonry) & Geometric constraints (e.g., thickness ≥ 20 cm, surface area)

Once filtered, the selected elements are saved as dynamic sets and assigned to the relevant work items via drag-and-drop functionality. This establishes a live, traceable connection between model elements and cost planning structures.

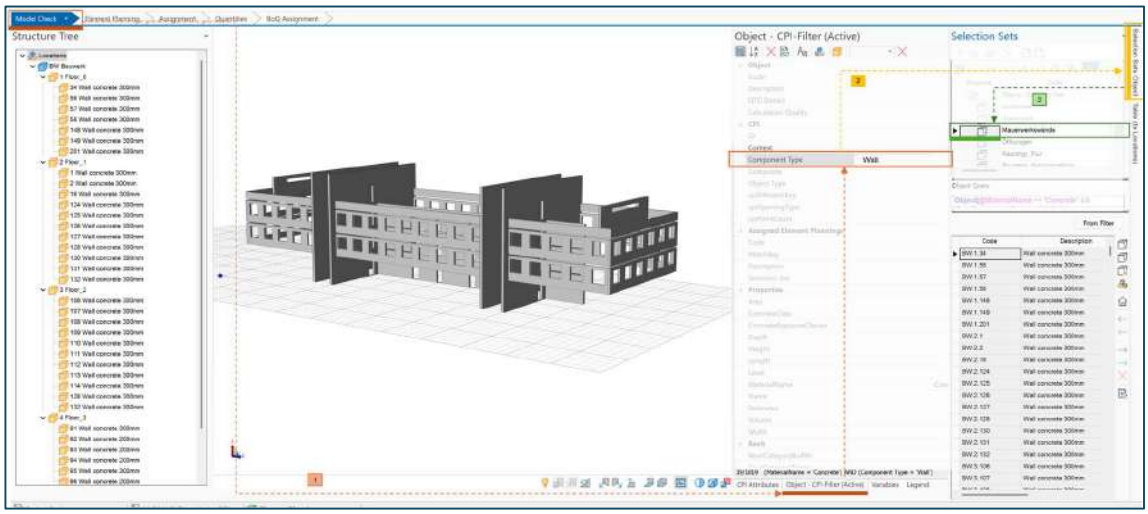


Fig. 34 - Selection Set interface

The above picture illustrates the Selection Set interface demonstrating the use of filter-based logic to group and assign. Example: BIM elements—such as 300 mm concrete walls—to corresponding construction work items. The use of Selection Sets offers several advantages:

- They are automatically adaptive to model changes, ensuring consistent data updates.
- They support reusability across similar projects or planning phases.
- They can be color-coded within the visualization interface for intuitive verification and error checking.

This method ensures that quantity derivation remains transparent, auditable, and synchronized with the evolving BIM model—critical for robust, model-driven cost estimation and lifecycle planning.

STEP 3: QUANTITY TAKE-OFF RULE DEFINITION IN RIB ITWO

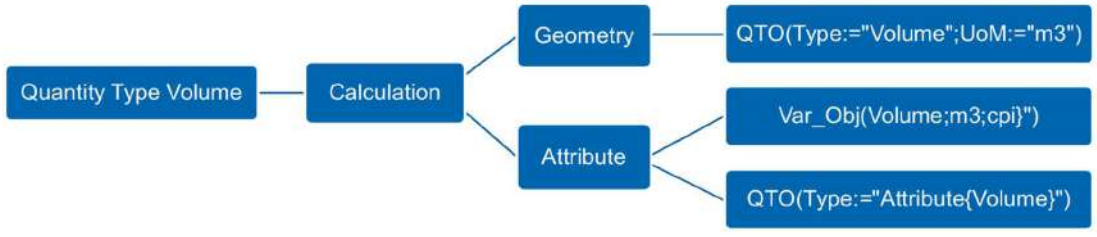
The final stage in model-based cost planning within RIB iTWO involves the definition of Quantity Take-Off (QTO) rules, which translate geometric and attribute data from the BIM model into quantifiable outputs for cost, scheduling, and sustainability analysis.

After BIM components have been assigned to relevant work items, QTO rules are applied to extract quantities in an automated, consistent, and traceable manner. These rules can leverage two principal data sources:

- **Attribute-Based Extraction:** Directly reads values from embedded CAD metadata (e.g., surface area, volume, or custom attributes defined in Revit).
- **Geometry-Based Calculation:** Uses the internal 3D model representation in RIB iTWO to compute values, offering higher transparency and independence from upstream modelling quality.

QTO rules in RIB iTWO follow a structured logic syntax, allowing users to define conditions and calculation types based on geometric or semantic criteria.

Below are typical examples using metadata-driven rules in figure 32 showing various construction components, enabling automated extraction of surface area, volume, and item counts from the BIM model. It is essential that all relevant components contain the necessary attribute fields (e.g., "Area"). If attributes are missing or incorrectly mapped, the resulting BoQ values may be null or erroneous. Therefore, model integrity and attribute completeness must be validated prior to QTO deployment.



Component	QTO Rule Syntax
Area of masonry walls (11.5 cm thick)	QTO(Type:="AreaMax";ConstrElement:="DepthOptOBBxy == (11,5 [cm])")
Count of prefabricated beams	QTO(Type:="AreaMax"; ConstrElement:="DepthOptOBBxy == (20 [cm])")
Surface area	QTO(Type:="BaseArea")



Fig. 35 - Examples of rule-based Quantity Take-Off (QTO) syntax

Quantity Take-Off (QTO) rule definition interface in RIB iTWO. The following figure 33 illustrates the structured assignment of QTO expressions to work items (1), the syntax-based Quantity Query column (2), and the rule editor pane (3), where a logic-based expression defines the extraction of volume for concrete walls thicker than 20 cm using the model's geometric parameter.

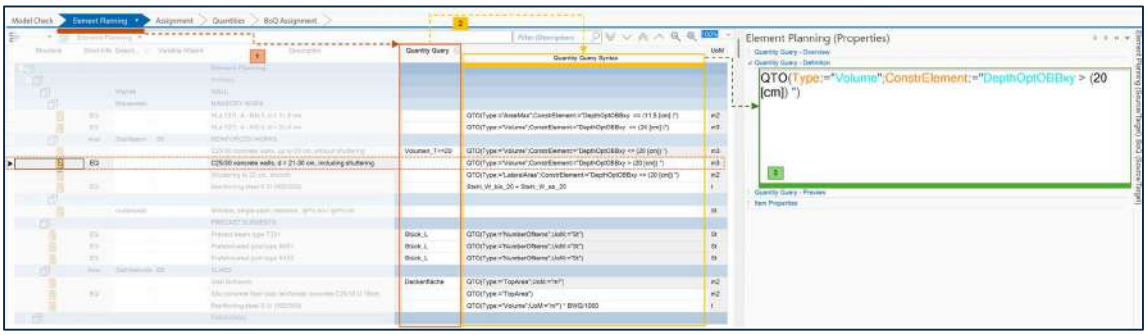


Fig. 36 - Sample QTO Syntax in RIB iTWO for Different Construction Elements

When using metadata-driven rules, it is essential that all relevant components contain the necessary attribute fields (e.g., "Area"). If attributes are missing or incorrectly mapped, the resulting BoQ values may be null or erroneous. Therefore, model integrity and attribute completeness must be validated prior to QTO deployment. By combining rule-driven logic with model-level data, RIB iTWO facilitates accurate, repeatable, and scalable quantity derivation—forming the analytical backbone for carbon tracking, cost estimation, and tender preparation.

STEP 4: FROM QTO TO BOQ ASSIGNMENT: LINKING QUANTITIES TO STRUCTURED OUTPUTS

After defining the QTO rules for relevant model components, users proceed to the Quantities module within RIB iTWO to verify and validate the calculated outputs. The system automatically computes key dimensional attributes such as length, width, area, and volume, based on the applied QTO logic and the BIM geometry or metadata.

These calculated quantities form the foundation for downstream integration into cost planning structures. Once verified, the derived quantities can be systematically linked to the external BoQ using the BoQ Assignment interface.

There are two primary workflows for BoQ integration:

- **Manual Import and Linking:** An external BoQ can be imported (e.g., from Excel or GAEB format) and linked to the internal work item structure using reference codes or mapping strategies.
- **Direct Assignment:** The BoQ line items can also be generated directly from the internal Element Planning structure if "Work Item Including Item" entries were created during the setup phase.

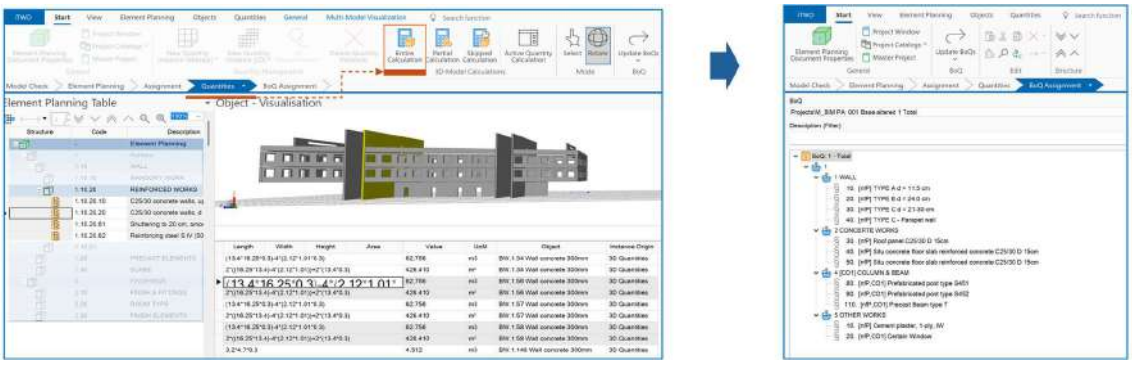


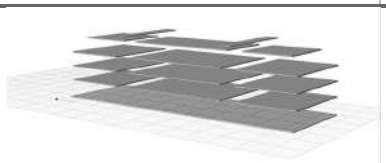
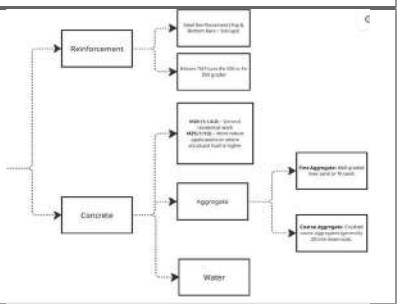
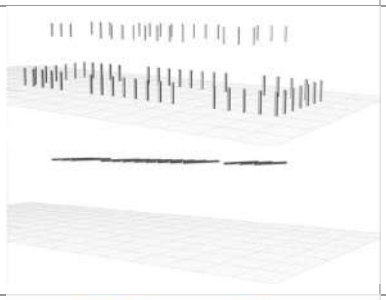
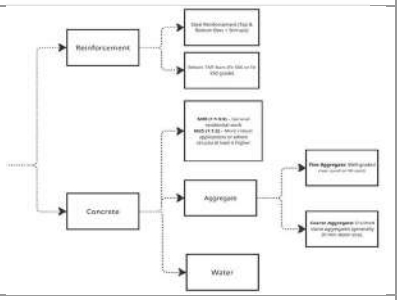
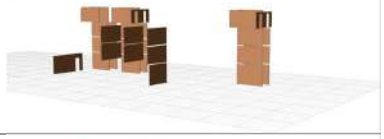
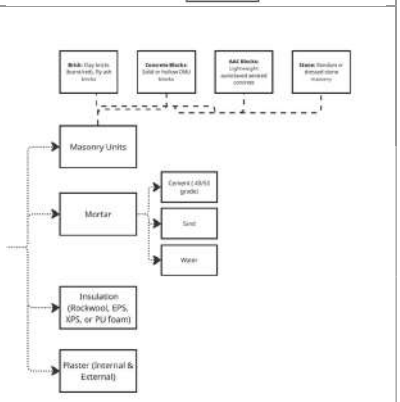
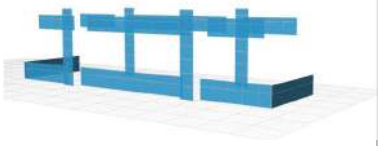
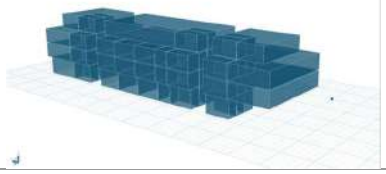
Fig. 37 – Quantities Calculation to BoQ assignment

The image illustrates the final stages of model-based cost planning in RIB iTWO—Quantity Calculation and BoQ Assignment. The left panel shows the "Quantities" module, where calculated attributes such as length, width, height, and area are derived automatically from the BIM model using predefined QTO rules. The "Entire Calculation" function aggregates these values across all assigned components. The right panel illustrates the BoQ Assignment interface, where verified quantities are linked to structured BoQ line items, enabling further processes.

BoQ Assignment of Model Components

Following the validation of quantity take-off (QTO) results within the "Quantities" module of RIB iTWO, the model components were systematically assigned to their corresponding BoQ, line items through the BoQ Assignment interface. Each building element ranging from floor slabs and structural frames to internal partitions, external walls, windows, and finishes. It was linked using either attribute-based or geometry-based quantity parameters. This structured assignment ensured that the model-derived quantities were accurately integrated into the cost planning system. By establishing a clear connection between quantified model components and BoQ positions, the process enabled traceable, data-driven workflows for cost estimation, tendering, and sustainability evaluation, enhancing consistency and transparency across the project lifecycle

Table 8 - Quantified Model Components and Visualization by Building Element

Building Component	Model Visualization	Material Decomposition
Floor Slabs **Volume (Attribute-based)**		
Columns & Beams **Number / Volume Combined**		
Type A – Internal Walls **Area (Attribute-based)**		
Type B – Internal Walls **Area (Attribute-based)**		
Type C – External Walls **Volume (Geometry-based)**		
Windows **Number of Items (Pieces)**		Number of Items
External Plaster **Area (Attribute-based)**		Readymade mix

6.2.3. PART III: DATA INPUT AND EVALUATION

The third phase of the sustainability planning workflow focuses on the definition of inputs and evaluation logic within RIB iTWO's integrated environment. At this stage, the system transitions from geometric-model-based planning (as established in Part II) to catalog-driven parameterisation, enabling structured evaluation of environmental impacts and material performance.

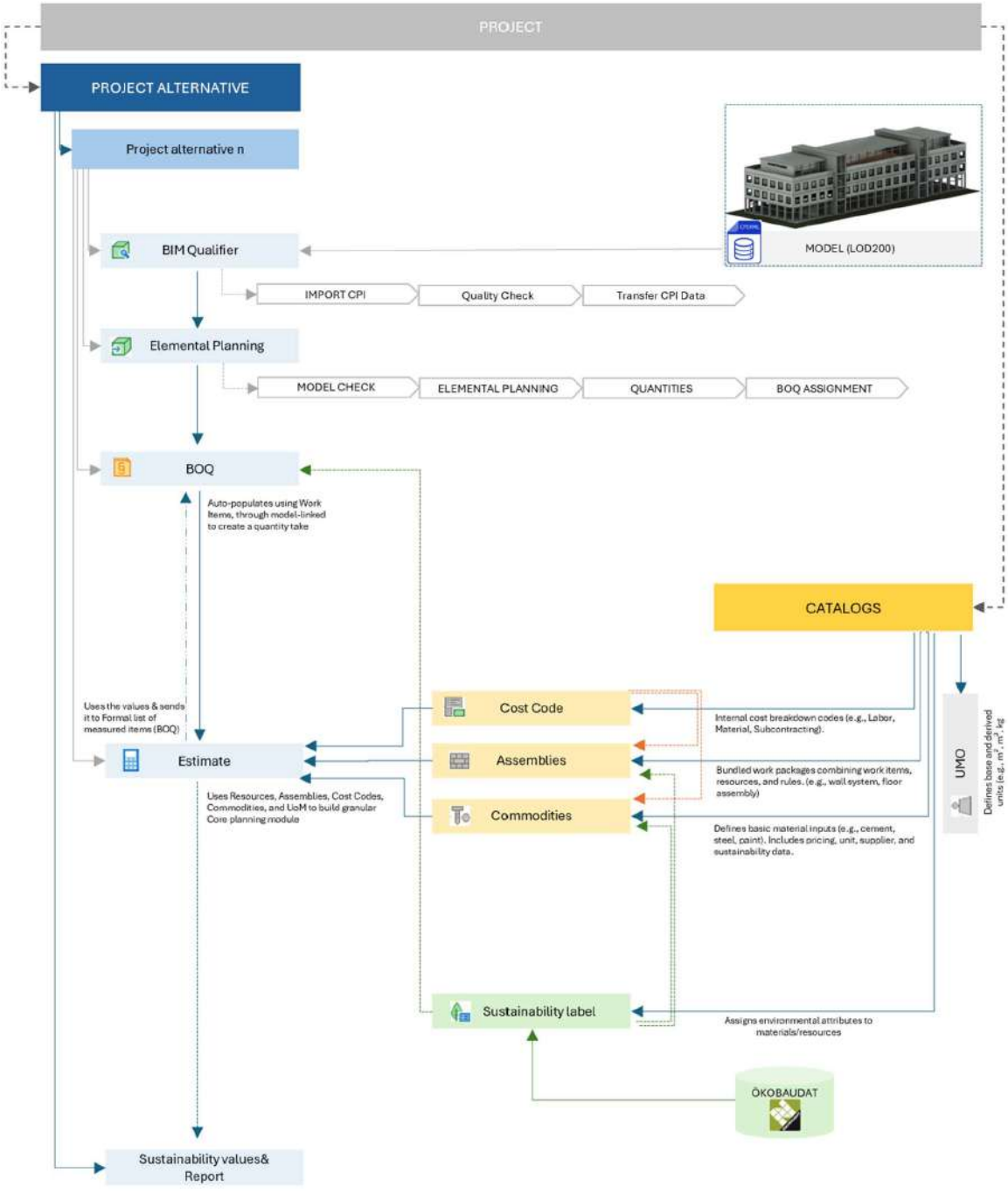


Fig. 38 - Integrated Cost and Sustainability Planning Workflow in RIB iTWO

This diagram illustrates the interconnected data flow between cost estimation components (BOQ, Cost Codes, Assemblies, Commodities) and sustainability evaluation modules in RIB iTWO. Catalog-based elements including resources, pricing, and environmental data are structured into granular planning modules using standardized units (UoM). The system enables automated quantity take-off linked to model-based work items, feeding into a formal BoQ and estimate. Sustainability labels sourced from ÖKOBAUDAT are assigned to materials to support environmental reporting and decision-making.

6.2.3.1. Parametric Label Configuration and Life Cycle Allocation

Label Catalog

The central configuration of sustainability values is managed through the Sustainability Label Catalog. This catalog-enables the definition and aggregation of sustainability indicators (e.g., CO_2e) on dedicated forms known as sustainability labels. These labels can be assigned to various objects, including BoQ items, estimate details, commodities, and more. Once assigned, specific values can be recorded within each label instance.

The definition area allows you to control which objects a sustainability label can be assigned to. Only labels that have been explicitly authorized for specific object types such as BoQ items that can be used in those contexts.

Sustainability Label Configuration and Phase-Based Allocation in RIB iTWO

RIB iTWO's Sustainability Label Catalog functions as a parametric library, comprising modular datasets that link building components to sustainability-related metadata. Each catalog entry acts as a rule-based template, storing both quantitative values (e.g., CO_2e/kg) and temporal characteristics (e.g., Reference Service Life), which can be dynamically assigned to items in the model or BoQ.

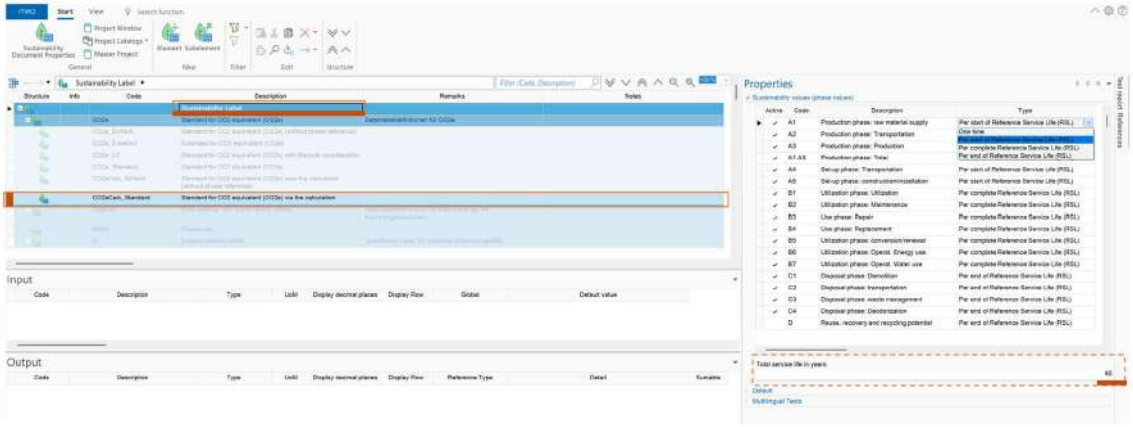


Fig. 39 - Sustainability Label

RIB iTWO's *Sustainability Label Catalog* functions as a parametric metadata library that enables the assignment of environmental indicators such as embodied CO_2 equivalents (CO_2e) to building materials and components. As shown in the interface, each label (e.g., CO2eCalc_Standard) defines the method for calculating or referencing carbon values and links them to specific life cycle phases, following the modular structure of DIN EN 15804. The configuration panel on the right display's active life cycle modules (e.g., A1–A5, B1–B7, C1–C4), each associated with a distribution type that determines when CO_2e impacts are accounted for within the building's *Reference Service Life (RSL)* or *Total Service Life (TSL)*.

Allocation types include "once," "per start," "over," or "per end" of RSL, ensuring accurate time-based modelling of impacts such as replacement, maintenance, and disposal. In this example, the TSL is set to 60 years, aligning with standard European assessment horizons. This configuration forms the basis for lifecycle-based sustainability calculations and reporting in iTWO's digital planning environment

Definitions for Lifecycle-Based Emission Allocation

Reference Service Life (RSL): The standard renewal interval for a building component or material, indicating how frequently it is expected to be replaced within the building's lifecycle. *Example: Carpet tiles = 10 years.*

Total Service Life (TSL): The overall duration used for sustainability assessments, typically defined at the project level. *Example: TSL = 60 years in accordance with European assessment frameworks.*

Per Start of Reference Service Life (RSL) Value is applied at the start of each RSL interval

Over the Entire RSL: Value is evenly distributed across the total service life:

Per End of Reference Service Life (RSL): Value is allocated at the end of each RSL cycle, similar to the *Per Start* method but temporally deferred.

Generating Sustainability Input Values from Estimate Output Values

Sustainability indicators in RIB iTWO are typically derived from cost estimation modules, including Cost Codes, Commodities and Assemblies.

Each of these modules forms part of the Estimate Detail Line, which captures both cost and environmental impact metrics. Sustainability inputs can be defined at multiple levels:

- Estimate Detail Level: Material or assembly-specific values (e.g., CO_2e per m^2 of insulation)
- BoQ Item Level: Aggregated values linked to quantities and work items

Sustainability values are typically calculated based on Estimate Details such as commodities, cost codes, assemblies, and P-assemblies. The system supports recording sustainability input values at multiple levels (e.g., estimate detail and item level), and it aggregates these inputs to compute total output values.

This multi-level approach enables comprehensive sustainability tracking across various components of a project.

Estimate: The estimation of sustainability values follows the same principles as traditional cost estimation and is based on concrete estimate detail lines. These lines refer to elements such as commodities, cost codes, and assemblies. All related catalogs are essential for this process.

6.2.3.2. UNDERSTANDING THE INPUT MODULES

EXPLAINING INPUT MODULES USING A 30 CM MASONRY WALL

To clarify the concept of sustainability input modules, it is helpful to examine how a typical building component such as a 30 cm thick masonry wall is modelled, assigned, and evaluated across different catalog structures. This component-oriented approach facilitates a clearer understanding of how sustainability values are recorded and calculated within the system.

Wall Element	Material	Comment
Structural Layer	Adobe (unfired clay) blocks (240 mm)	Sun-dried, low-energy, regional; biodegradable and reusable
Mortar	Clay-straw or lime mortar	Natural binder; reversible and compostable
Insulation	Blown-in cellulose (60 mm)	Recycled paper product; carbon-storing and compostable
Finish	Clay plaster	Earth-based, non-toxic, easy to reapply or recycle
Width of the wall :	300 mm , Brick size - 240 × 115 × 65 mm	

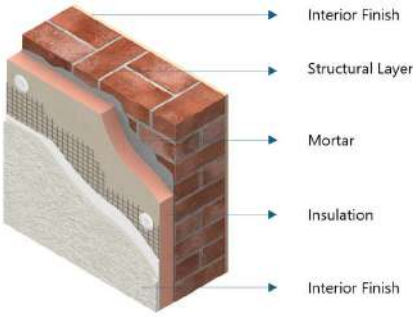


Fig. 40 - Example case

I. COMMODITY CATALOG

In RIB iTWO, a Commodity represents a standardized construction material or resource entry within the Sustainability Label Catalog. It serves as the basic unit for assigning environmental data to physical elements in the model or BoQ. Commodities bridge the gap between generic model geometry and specific, quantified material selections.

It defines a specific building material (e.g., fired clay brick, mineral wool insulation) and links it to key sustainability attributes such as embodied CO_2e per unit, reference service life (RSL), recyclability, and phase allocation type. Each commodity includes a reference unit (e.g., kg, m^2, m^3, piece) to ensure accurate quantity take-off and environmental calculation shown in . Commodities are organized within parametric catalog modules, allowing fast and consistent assignment to BoQ items or model elements during sustainability planning.

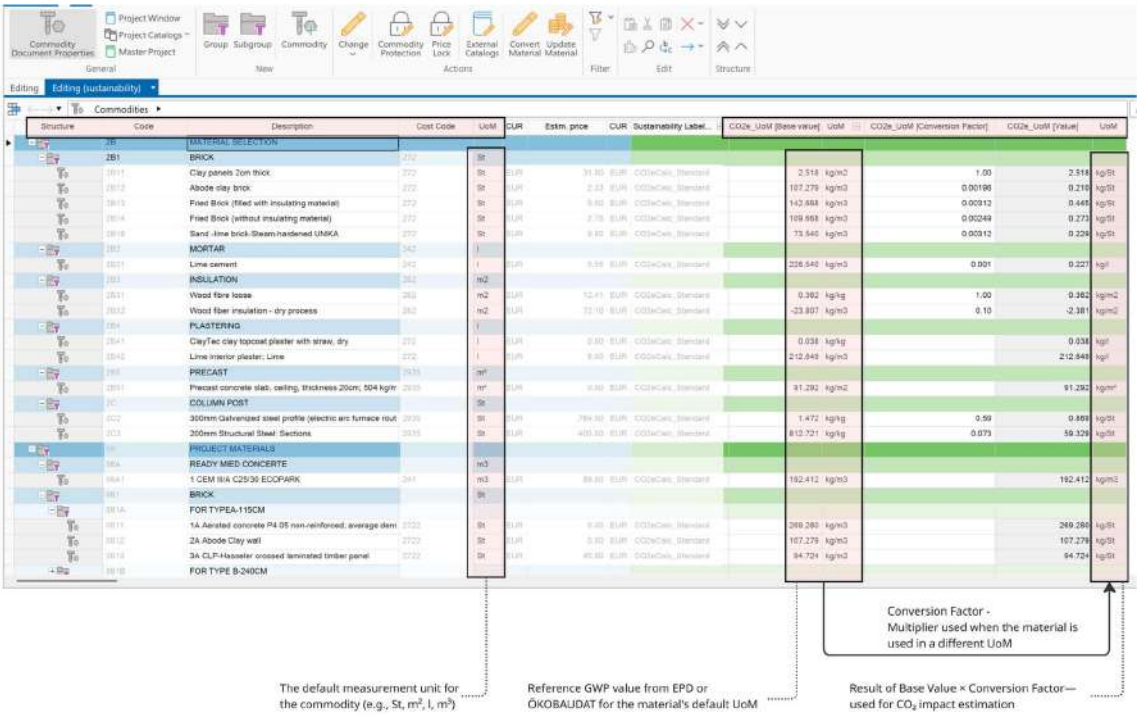


Fig. 41 - Understanding the commodities

RECORDING SUSTAINABILITY VALUES IN THE COMMODITY CATALOGUE

Sustainability values in RIB iTWO can be systematically documented within the Commodity Catalog through the assignment of corresponding sustainability labels. Each commodity entry defined by its structural classification, cost code, and unit of measurement (UoM) can be enriched with Global Warming Potential (GWP) data, typically sourced from Environmental Product Declarations (EPDs) or the ÖKOBAUDAT database.

As illustrated in the image, the process involves three key elements:

- **Base Value**: The reference CO_2e emission factor (e.g., in $kgCO_2e$ per kg or m^3) is entered for the default UoM of the material.
- **Conversion Factor**: When a material is used in a unit different from its default, a multiplier is applied to adapt the GWP data accordingly (e.g., converting from kg/m^3 to kg/St).
- **Final Value:** The CO_2e impact per actual UoM is calculated as the product of the base value and conversion factor, enabling accurate estimation across diverse material usages.

This structured approach enables the consistent integration of environmental data into material specification workflows, facilitating carbon-aware decision-making during cost planning, procurement, and lifecycle assessment processes. By aligning economic and ecological parameters at the commodity level, the system supports early-stage sustainability evaluation and compliance with European performance benchmarks. Sustainability values can be recorded directly in the commodity catalog by assigning the appropriate sustainability labels.

THE PROCESS OF CREATING AND LINKING A COMMODITY TO SUSTAINABILITY DATA

1. **Define the Commodity in the Catalog**: The material *Adobe clay brick (B31)* is added under the "BRICK general" group in the Commodities Catalog, with unit of measurement set to *St* (pieces) and a cost estimate of €5.60 per unit(market price .
2. **Cost code** is added from the cost code catalog illustrated in figure 38.

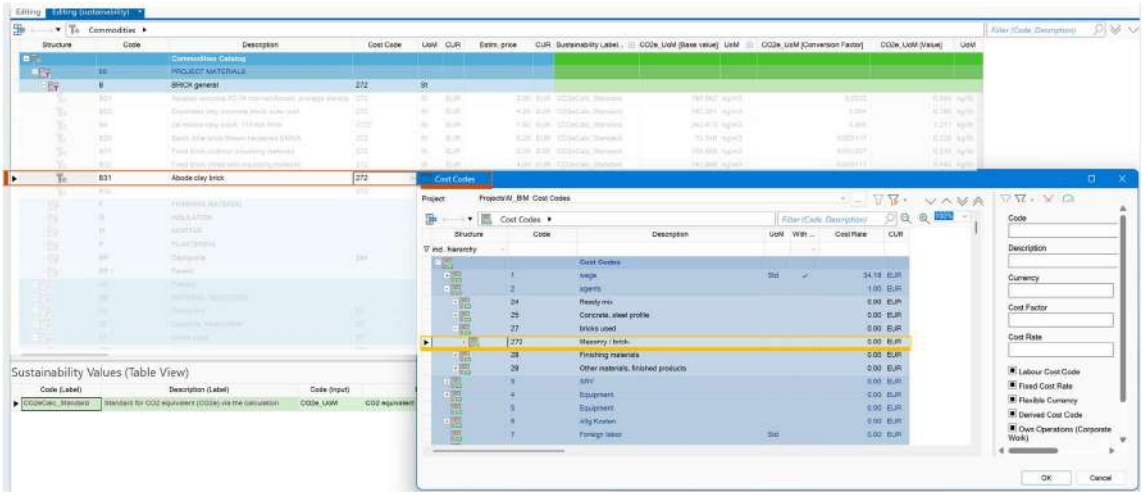


Fig. 42 – Creating A Commodites list

3. **Assign the Sustainability Label and Input Base Value**: A predefined sustainability label (*CO2eCalc_Standard*)

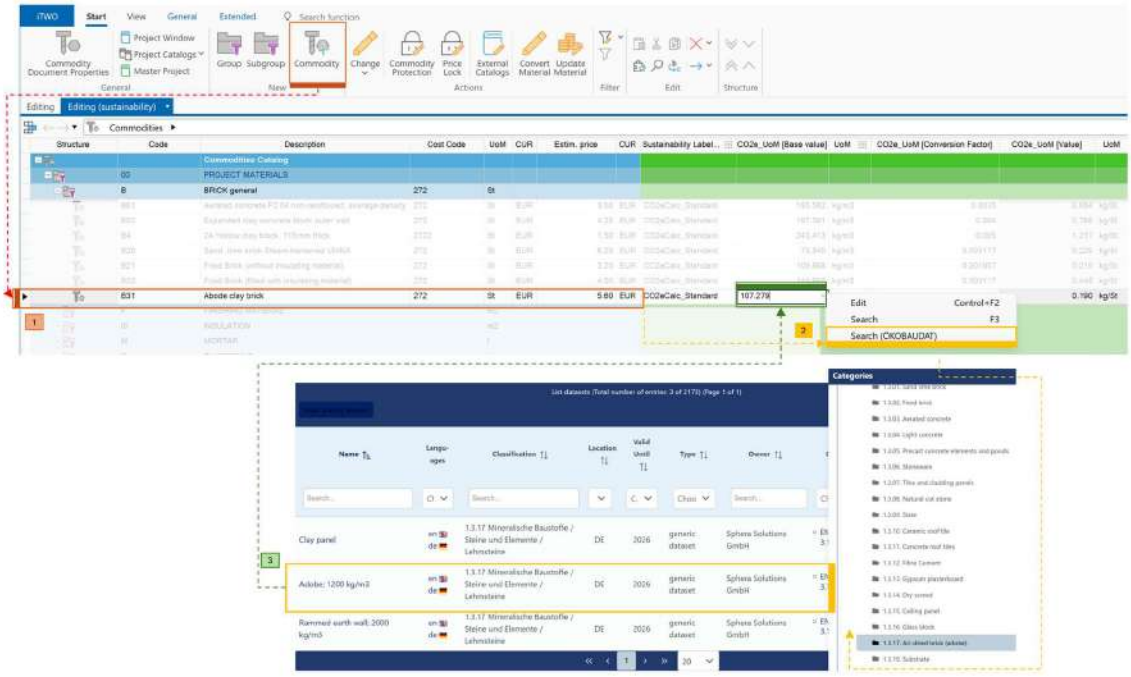


Fig. 43 – Creating A Commodities list

3**. Retrieve Verified CO_2e Data via ÖKOBAUDAT Search:** By initiating a database search through the label cell, verified environmental product declarations (EPDs) from ÖKOBAUDAT are accessed, specifically under 13.1.17 Air-dried brick (adobe) and The EPD titled Adobe; 1200 kg/m³, published by Sphera Solutions GmbH, is selected for its compatibility with the adobe brick specification and valid classification under mineral building materials shown in figure 38.

5. **CO. Manually Enter the Volume-Based Conversion Factor:** The conversion factor 0.001771 m³/St is manually input to reflect the volume of one brick, allowing the system to compute the CO_2e value per piece as 0.190 kg/St.

To calculate the conversion factor from kg/m³ to kg/St (i.e. per piece), we have to input the conversion factor, and the system will calculate the co2-UoM (value) .we need to compute the volume of one brick using the standard dimensions provided shown in figure 39.

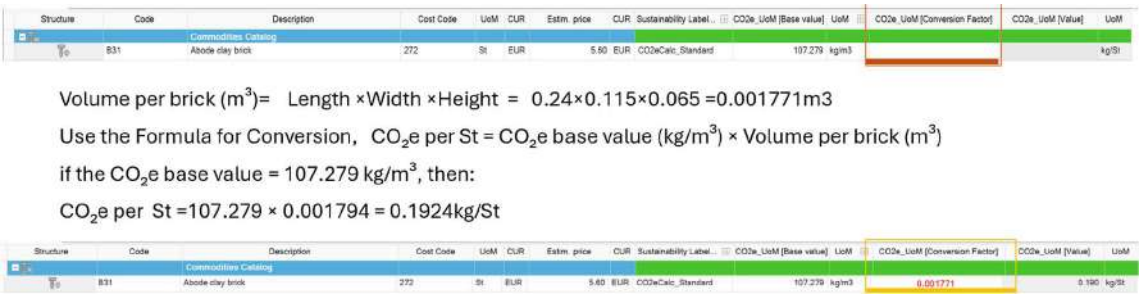


Fig. 44 – Conversion factor calculation

II. COST CODE CATALOG

The Cost Code Catalog in RIB iTWO helps organize both cost and sustainability data for different types of work or materials. Each cost code acts like an identity number for a specific task or product (e.g., diesel transport, mansory).

- **Fixed Cost Rate:** For cost codes with fixed rates (like diesel fuel), both the cost and the CO_2e value are saved directly in the catalog. When used in a project, these values are automatically filled in and shown as read-only. This saves time and ensures consistency across projects.
- **No Fixed Cost Rate:** For cost codes without fixed rates (like on-site work that changes from project to project), it's better to enter the CO_2e values manually at the estimate detail level. This allows for more flexibility based on the actual conditions of each project.

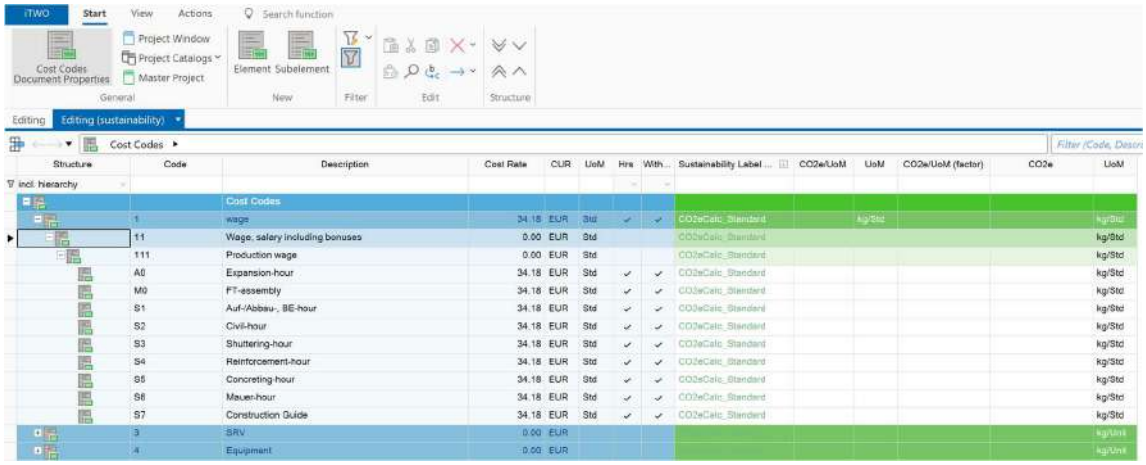


Fig. 45 – Cost Code Catalog

III. ASSEMBLIES

In RIB iTWO, assemblies serve as structured groupings of interrelated components—such as materials, labour, and equipment—that together represent a specific construction task or building element. Their primary function is to streamline cost estimation and sustainability assessment by encapsulating commonly recurring construction processes into reusable templates

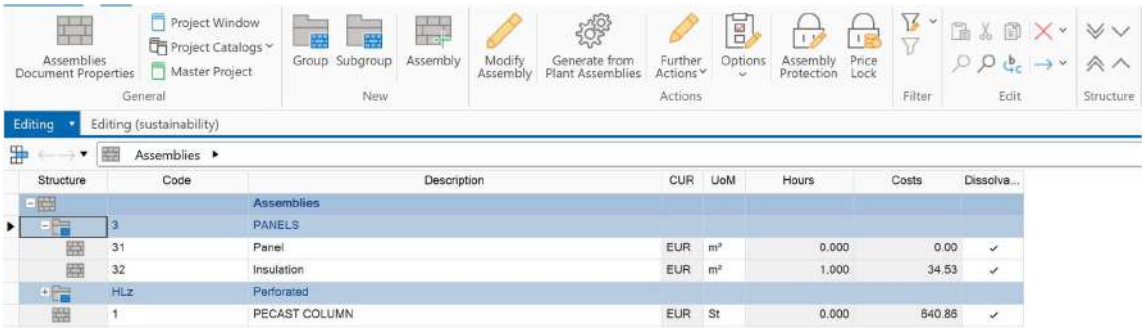


Fig. 46 – Assemblies catalog

While our planning approach places primary emphasis on material-level inputs and their associated environmental impacts, it is important to understand the roles of assemblies and cost codes within the broader RIB iTWO framework. Although these elements are not used extensively in our current workflow, they form the structural backbone of many conventional cost estimation and sustainability tracking processes. Familiarity with their function supports better system integration, especially when scaling up to more complex or model-driven workflows where assemblies and cost codes are more heavily utilized.

Once all relevant elements such as insulation, plaster, mortar, and other building materials have been systematically defined and assigned with sustainability labels in the Commodity Catalog, the dataset can be considered complete. At this point, we transition to the Estimate module, where these catalog entries are applied in detail lines for each construction item.

In this phase, the sustainability values recorded at the commodity level are either automatically inherited (for fixed-rate items) or manually entered (for variable-rate inputs) within the estimate detail lines. This step forms the foundation for calculating total CO_2e emissions and cost outputs for each building element. Ultimately, this structured data flows into the final BoQ, enabling traceable and transparent reporting across the project.

IV. ESTIMATE

The Estimate module in RIB iTWO serves as the central workspace where all detailed input values such as materials, quantities, unit rates, and sustainability metrics are defined, calculated, and managed. It is the most granular level of data entry, linking together the cost code catalog, commodity catalog, and sustainability labels for project-specific evaluation.

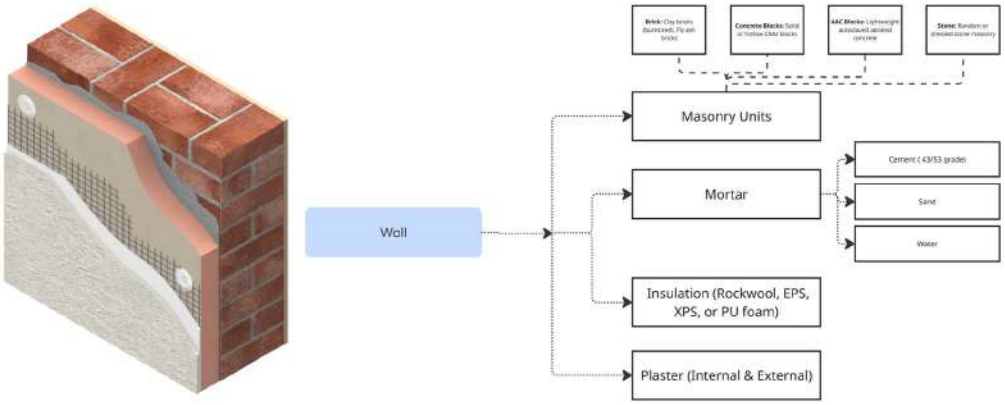


Fig. 47 – Material Decomposition of the wall

Each BoQ item (e.g., *External Wall*) is broken down into multiple estimate detail lines, which represent its constituent components. These lines capture all relevant data, including Material types, Labour and equipment inputs, Quantities and unit rates and CO_2e values (either from catalog or entered manually).

The following process demonstrates how sustainability values, such as CO_2e, are integrated into construction items within RIB iTWO by linking material data from the Commodity Catalog to the Estimate Module, and subsequently calculating totals in the BoQ.

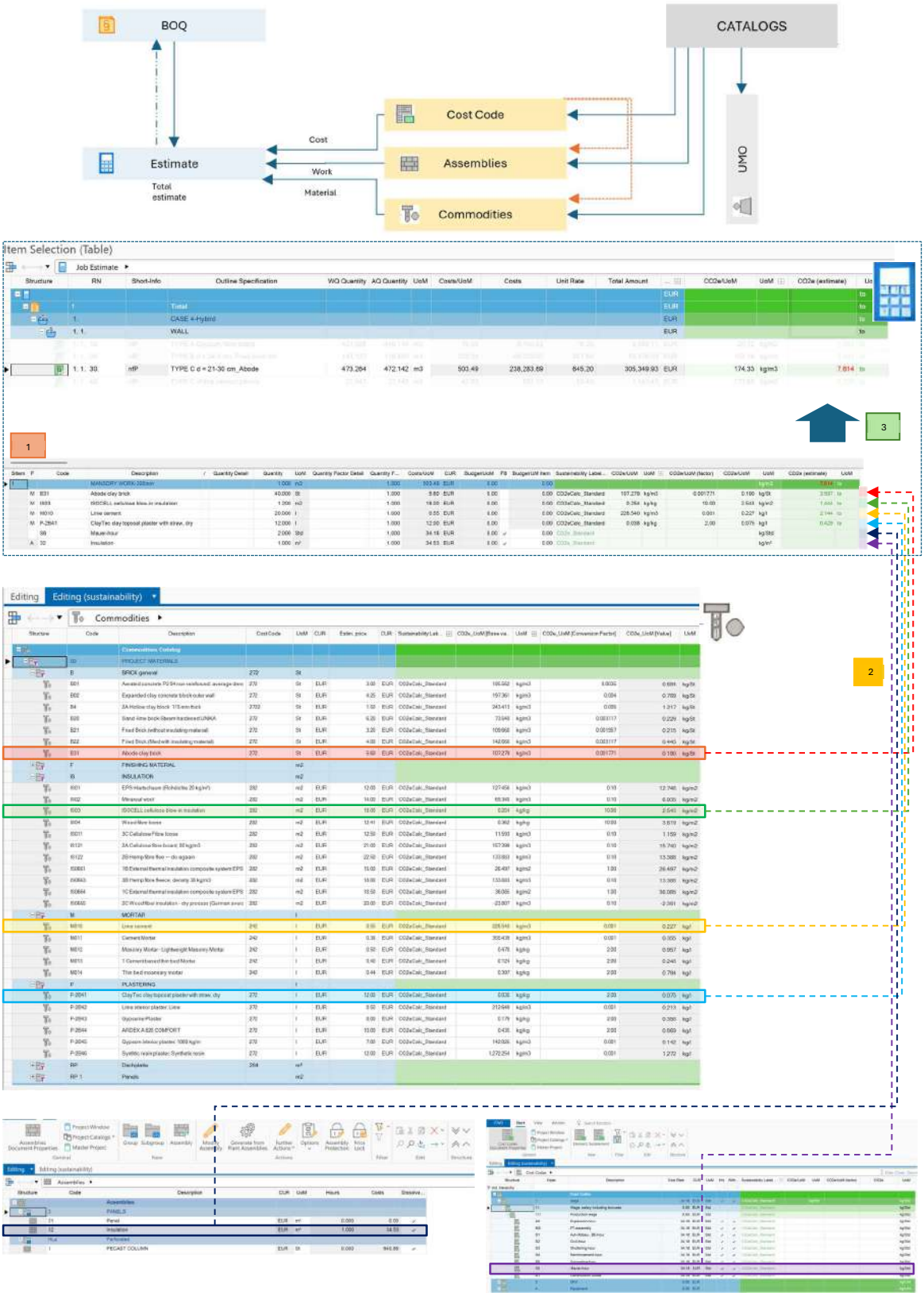


Fig. 48 – Material Decomposition of the wall

First, a construction item such as an external wall is defined at the BoQ level (Label 1). Next, the item is broken down into its detailed components, including bricks, mortar, insulation, and plaster (Label 2). These components are selected from the Commodity Catalog, where CO_2e values are already assigned. Depending on whether the cost codes have fixed or variable rates, these values are either automatically inherited or manually entered. Finally, RIB iTWO multiplies the CO_2e per unit by the respective quantities and sums the results (Label 3), providing the total environmental impact for the entire item. For example, 7.614 kg CO_2e/m^2 for the wall.

Transfer to Structured BoQ: Once all detail lines are completed, the estimate module aggregates the data including total quantities, costs, and sustainability outputs and transfers it to the final structured BoQ. This BoQ acts as the foundation for procurement, reporting, and sustainability evaluations. The hierarchical BoQ structure reflects all line items with their associated cost and CO_2e performance, making the data both transparent and traceable

Understanding the output : Unit-Level to Project-Level Carbon Emission Calculation in iTWO

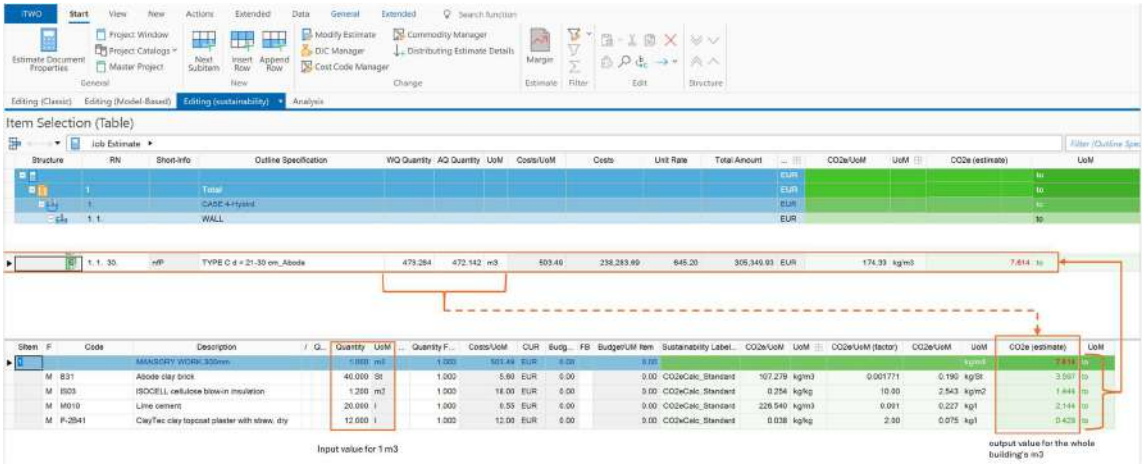


Fig. 49 – Output Calculation

In the sustainability view of RIB iTWO, the CO_2e value displayed in the lower table represents the calculated emissions per unit volume. 40 adobe clay bricks, 1.2 m^2 of cellulose insulation, 20 litres of lime cement, and 12 litres of clay topcoat plaster. These quantities form the basis for calculating the embodied CO_2 emissions per m^3 of wall, resulting in a total of 7.614 kg CO_2e/m^3.

In this case, per 1 m^3 of a specific building component such as a masonry wall. This value (e.g., 7.614 kg CO_2e/m^3) is derived by summing the individual contributions of all materials assigned to the component, based on their quantities and emission factors. The resulting figure is then multiplied by the total AQ quantity of that component (e.g., 472.142 m^3) to determine the total estimated CO_2 emissions for the item. This total is shown in the upper table and expressed in tons of CO_2e, reflecting the full environmental impact of that building element within the project scope.

Now that the CO_2e calculation for a single building component (e.g., 1 m^3 of masonry wall) is clearly understood, this methodology can be scaled and applied across the entire building, allowing for a complete assessment of the project's embodied carbon based on all material quantities and components defined in the BoQ.

7

RESULT AND DISCUUSION

7.1. BASE CASE

7.1.1. BASE CASE DEFINITION: ESTABLISHING THE REFERENCE PERFORMANCE LEVEL

To enable comparative evaluation of alternative material strategies, a Base Case is first defined. This case reflects a typical construction configuration that aligns with conventional practices in Central European office buildings, emphasizing regulatory compliance, structural reliability, and availability rather than sustainability optimization.

Table 9 - Profile of Base Case Construction Components

Component	Material	Justification
Wall Type A	Perforated Brick 2DF	Standard clay brick locally sourced; meets basic load-bearing and fire resistance criteria. Serves as a conventional performance baseline.
Wall Type B	Perforated Brick 16DF	Thicker unit enhances acoustic insulation and thermal inertia; represents baseline for internal structural partitioning.
Wall Type C & Parapet	Perforated Brick 20DF	High-mass unit used in external walls and parapets for structural integrity and environmental resistance; reflects traditional heavy-load application.
Slabs A–C	C20/25, C25/30 ECOPARK	Standard ready-mix concrete for general-purpose floor slabs; widely used with minimal eco-optimization.
Columns & Beams	Prefabricated PE5, PE3	Prefab concrete elements selected for speed of installation and cost efficiency; widely accepted structural solution.
Plaster	Cement Plaster 1-Ply	Conventional single-layer cement-based plaster used for wall finishing across building types.
Windows	MIG 3 Triple Glazing	Triple-pane insulated glazing unit selected to meet typical energy performance and acoustic comfort levels. No advanced sustainability features included.

The base case serves as the reference level against which various low-carbon material substitutions and system upgrades are assessed. Embodied carbon values are calculated based on standard datasets and average transport assumptions, using tCO_2e as the primary indicator for material-level performance.

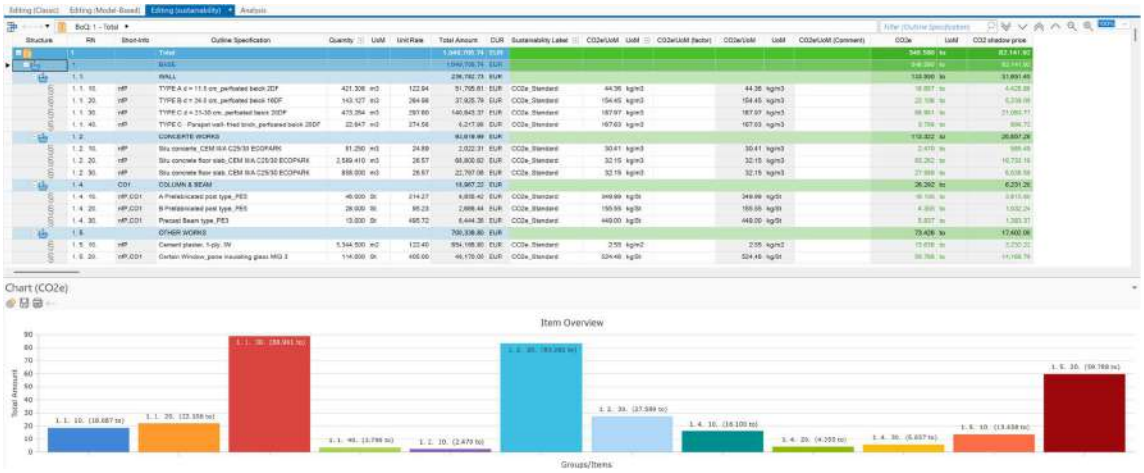


Fig. 50 - Embodied Carbon Contributions Component- Base Case

This chart visualizes the total embodied carbon (tCO_2e) per building component in the base case scenario. The highest contributors are Wall Type C (92.76 tCO_2e) and Slabs A–C (113.32 tCO_2e), followed by Windows (59.79 tCO_2e). These elements collectively dominate the carbon footprint, indicating key



Fig. 51 - Comparative Embodied Carbon Contributions of Wall and Slab Elements

The left chart illustrates the embodied carbon of wall types—Wall A (18.69 tCO_2e), Wall B (22.11 tCO_2e), and Wall C & Parapet (92.76 tCO_2e)—with Wall C emerging as the dominant contributor due to its larger volume and higher density units. The right chart shows that concrete slabs (Slabs A–C) contribute 113.32 tCO_2e, significantly exceeding any individual wall type. Together, walls and slabs represent over 60% of the total base case emissions, highlighting their critical role in any decarbonization strategy.

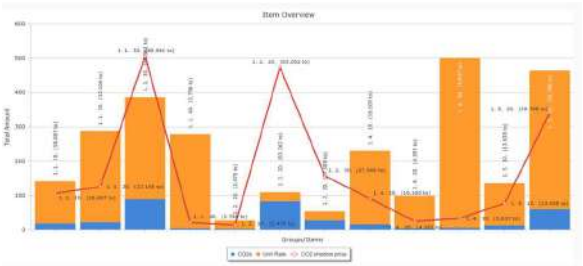


Fig. 52 – Co2 vs. Unit Cost and CO_2 Shadow Price per Item

This multi-axis chart compares the embodied carbon (blue bars), monetary unit rate (orange bars), and CO_2 shadow price (red line) across construction items. It reveals a non-linear relationship between environmental and economic costs, where some high-emission components, such as Wall Type C and slabs, show disproportionately low CO_2 shadow pricing, underscoring the need for carbon-informed procurement.



Fig. 53 - Material Quantities & Associated Embodied Carbon Values

This chart displays a direct comparison between material quantities (blue bars) and their associated embodied carbon values (orange bars). Despite similar quantities, certain components such as external walls and slabs exhibit significantly higher carbon impacts, confirming that material intensity alone does not predict carbon burden, material type and carbon factor are decisive.

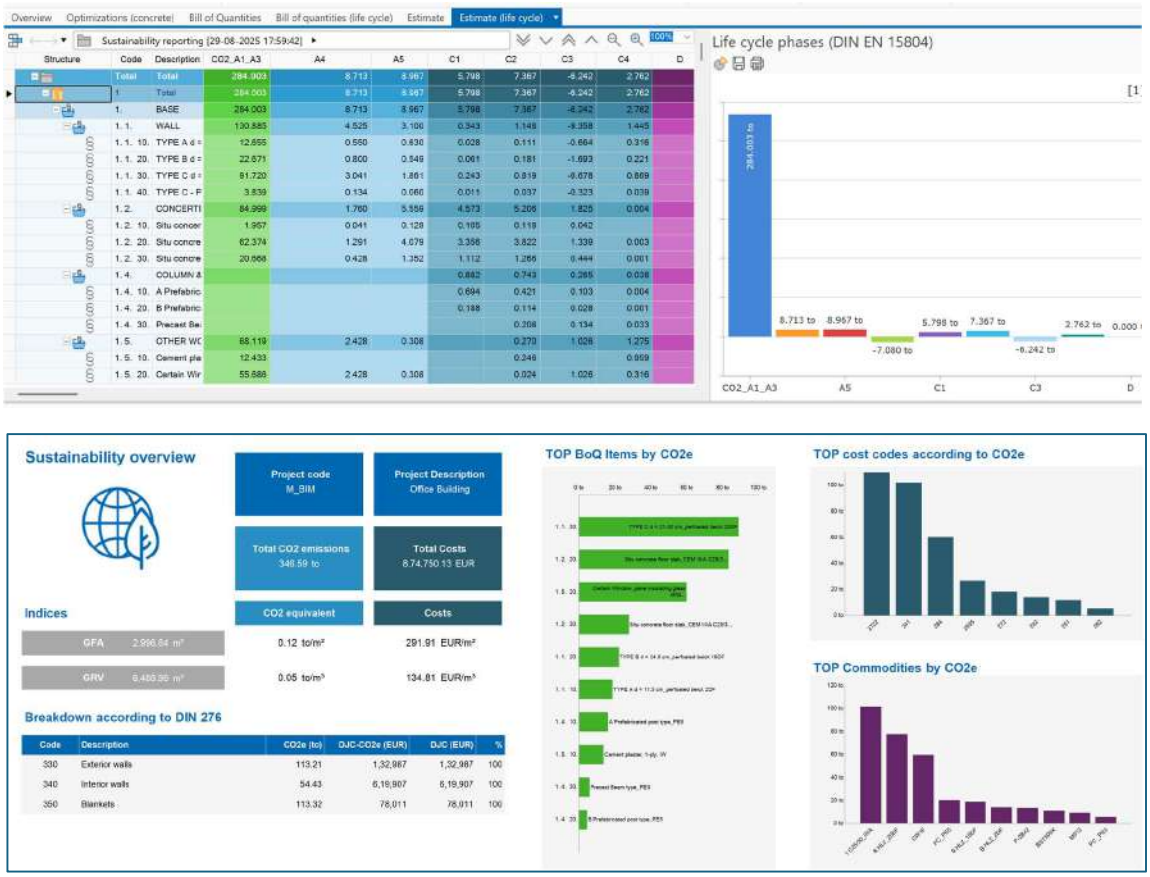


Fig. 54 - Sustainability dashboard base case

Key Observations

1. Fluctuating CO_2e and Unit Rates

- The WALL components (e.g., Type G d 24 cm, shown at 1.1.30) and FLOOR elements (e.g., insulation and plaster layers, shown at 1.4.30) exhibit very high total amounts, reflecting a combination of high embodied carbon and substantial cost inputs.
- In contrast, the FEN (Window Glazing) item at 1.2.10 shows minimal values, suggesting either limited material scope, indicating relatively efficient design or material selection.

2. Shadow Price Spikes

- The CO_2 shadow price line (red) peaks at 1.1.30 (WALL) and 1.2.20 (CONCRETE WORKS), highlighting items with either high total emissions or a significant cost burden from CO_2 pricing.
- Notable drops around 1.2.10 (FEN) and 1.2.30 (COLUMN & BEAM) may reflect lower-emission materials, carbon reduction strategies, or smaller scope.

3. Stacked Insight

- The visual ratio between CO_2e (blue bar) and Unit Rate (orange bar) offers insight into the environmental cost versus financial cost for each item: For instance, FEN has a low unit rate but a high CO_2e factor per m^2, suggesting low cost but high environmental impact.Conversely, CONCRETE WORKS show a balanced profile, indicating cost-effective and relatively lower-carbon material selection due to eco-optimized cement types.

7.1.2. Performance Classification of Base Case Embodied Carbon

To contextualize the environmental performance of the base case scenario, its embodied carbon is compared against European benchmarking values. The total embodied carbon of the base case amounts to 346.59 tCO_2e, which, distributed across the net floor area of 1,040 m^2, yields Embodide Carbon Intensity of 333.26kg CO_2e/m^2.This result places the base case within the "Average / Typical" performance band based on the DGNB benchmark scale for A1–A3 emissions.

Table 10 - Profile of Base with Benckmark

PERFORMANCE TIER	EMBODIED CARBON (A1–A3)	BASE CASE POSITION
Top Performing	≤ 6.6 kg $CO_2e/m^2/yr$ (~265 kg total)	Does not meet
Average / Typical	~9.1 kg $CO_2e/m^2/yr$ (~365 kg total)	Matches base case range
Higher-End (Less Sustainable)	≥ 12 kg $CO_2e/m^2/yr$ (≥ 500 kg total)	Below threshold

7.1.3. Interpretation: Case 1 – Carbon Reduction Insights from Baseline Assessment

The embodied carbon intensity of the base case estimated at approximately 333 kg CO_2e/m^2 places the design within the typical performance band for European office buildings. While it avoids the highest emission thresholds, it falls short of benchmark levels associated with high-performance, low-carbon construction, revealing critical opportunities for improvement. Key takeaways include:

1. **Wall Assemblies as Primary Emission Hotspots:** The WALL category particularly Type G d 24 cm perforated blocks emerged as the most carbon-intensive building element, exhibiting both high embodied CO_2e and elevated shadow prices. This signals an overreliance on high-emission masonry.

Design Implication: Transition to low-carbon masonry solutions such as recycled brick, hollow concrete blocks, or timber-based systems (e.g., CLT). Where structural constraints permit, hybrid wall systems may further reduce material volumes and associated emissions.

2. Effective Use of Eco-Cement in Structural Element: Within the CONCRETE WORKS, the use of CEM III/A (ECO_2PAK) demonstrated a notably reduced CO_2 profile per m^3, without impacting cost metrics.

Design Implication: Institutionalize eco-cement blends as the structural baseline. Prioritize mix optimization and structural rationalization (e.g.,span-to-depth ratios) to reduce concrete volume.

3. Hidden Carbon in Finishes and Fenestration: Despite smaller quantities, Recorded a high CO_2e/unit value, especially from PU insulation and insulated glazing (e.g., 524.46 kg CO_2e/m^2).

Design Implication: Increase scrutiny on finishing materials and glazing systems during specification. Integrate LCA data early and consider bio-based insulations (e.g., cellulose, hemp) and low-carbon glazing options with reduced embodied impact.

4. Shadow Pricing as a Diagnostic Tool: The application of CO_2 shadow pricing surfaced critical emission hotspots. such as specific wall and fenestration items that would be overlooked under cost-based decision-making alone.

Design Implication: Implement shadow pricing methodologies during early project budgeting and variant analysis. This supports informed trade-offs between cost and carbon equivalent alternatives.

The baseline performance underscores the importance of early-stage material selection, the potential of prefabrication, and the value of integrating environmental costing tools. These strategies collectively enable a shift toward carbon-optimized design, laying the foundation.

7.2. CASE 1 - OPTIMIZED DESIGN OF BASE

Case 1 introduces targeted material substitutions and optimized structural choices to reduce embodied carbon without altering the overall design logic. The strategy focuses on replacing high-emission elements such as perforated masonry blocks and conventional Portland cement with lower-carbon alternatives, including recycled bricks and CEM III/A eco-cement blends.

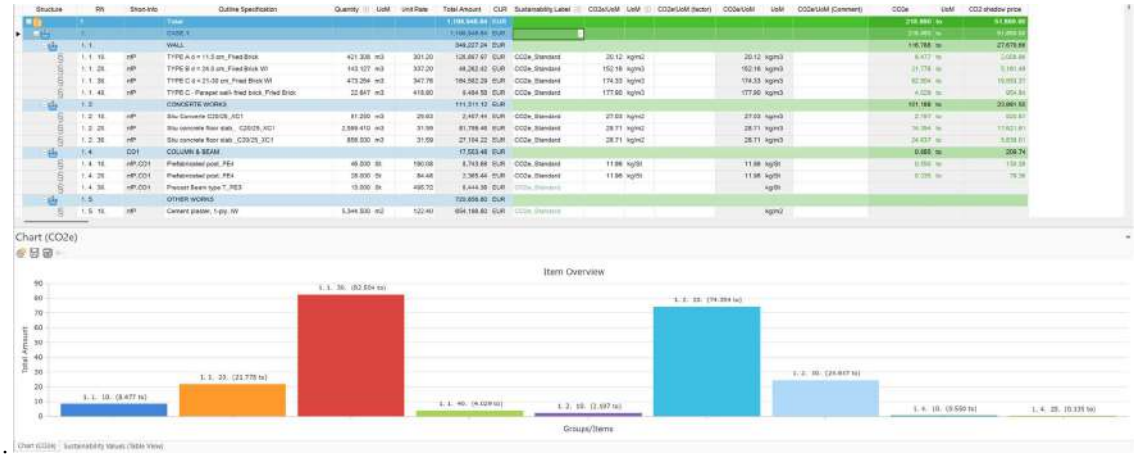


Fig. 55 - Embodied Carbon Contributions Component - Case 1

These changes aim to maintain performance and cost stability while achieving measurable sustainability improvements. Case 1 serves as the first step toward decarbonization, demonstrating how early specification changes can yield tangible environmental benefits with minimal disruption to the baseline design.

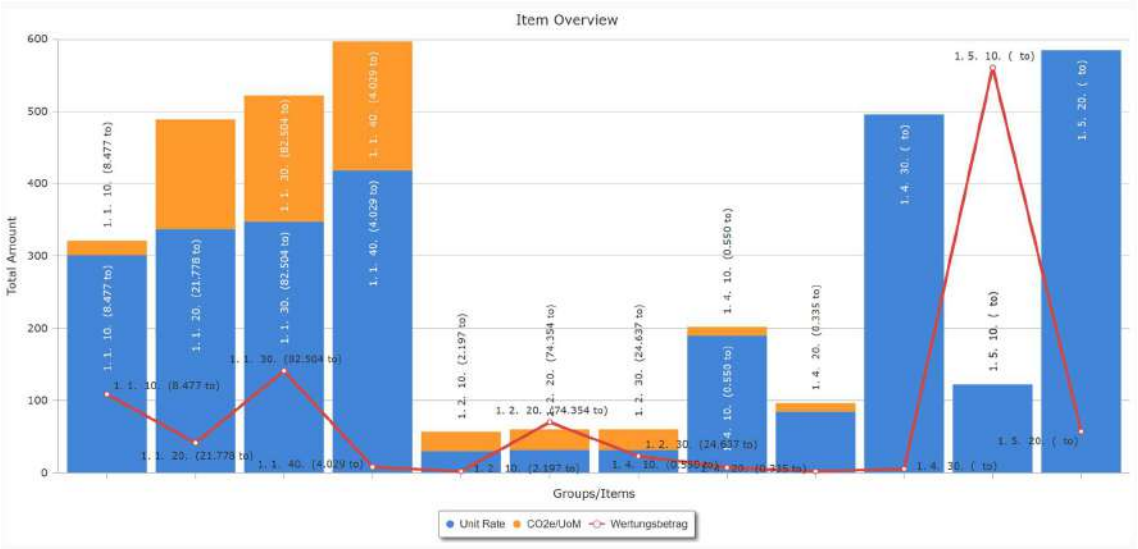


Fig. 56 – Co2 vs. Unit Cost and CO_2 Shadow Price per Item - Case1



Fig. 57 - Sustainability dashboard - Case1

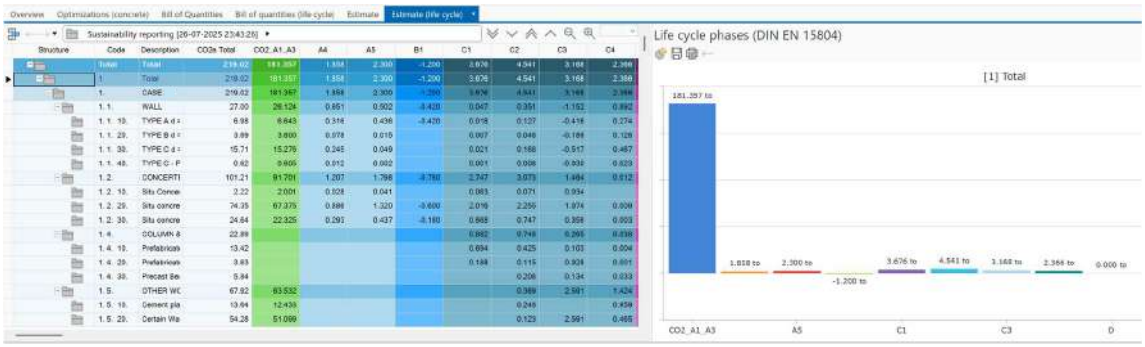


Fig. 58 - Sustainability Reporting LCA by Phase – Case1

Key Intervention Areas:

- Replaced high-emission perforated bricks with lower-CO_2 masonry like solid fired bricks and recycled options.
- Introduced CEM III/A eco-concrete in CONCRETE WORKS, reducing CO_2 intensity per m^3.
- Reviewed window glazing systems, minimizing units with extremely high kg CO_2e/m^2.

Result:

- Embodied carbon reduced from ~333 kg CO_2e/m^2 to ~278 kg CO_2e/m^2.
- CO_2-intensive wall material (Item 1.2.30) reduced from 74.55 t to 22.90 t ,major improvement.
- Improved cost-carbon balance, with shadow prices more evenly distributed and fewer extreme spikes.

Interpretation: Case 1 builds on the base case by targeting the most carbon-intensive elements, notably heavy masonry and structural concrete, without significantly altering the design logic. The main gains came from material substitutions and eco-cement standardization, laying the groundwork for further decarbonization.

7.3. CASE 2 – MEDIUM LEVEL

Building upon the optimizations introduced in Case 1, Case 2 advances the sustainability profile by incorporating a broader range of environmentally preferable materials and integrating early-stage DfD principles. Key strategies include the substitution of dense masonry with timber based and hybrid wall assemblies, adoption of bio-based insulation materials, and structural lightening through more efficient slab and floor designs.

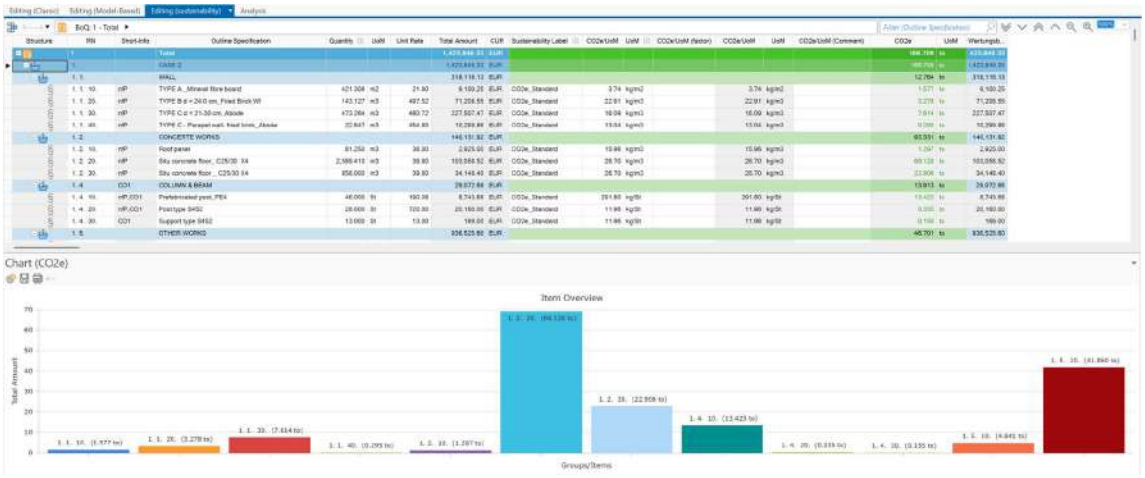


Fig. 59 - Embodied Carbon Contributions Component – Case 2

While not fully modular, the building incorporates components that facilitate future disassembly and reuse. Case 2 exemplifies a transitionary approach that balances decarbonization objectives with emerging circular construction practices

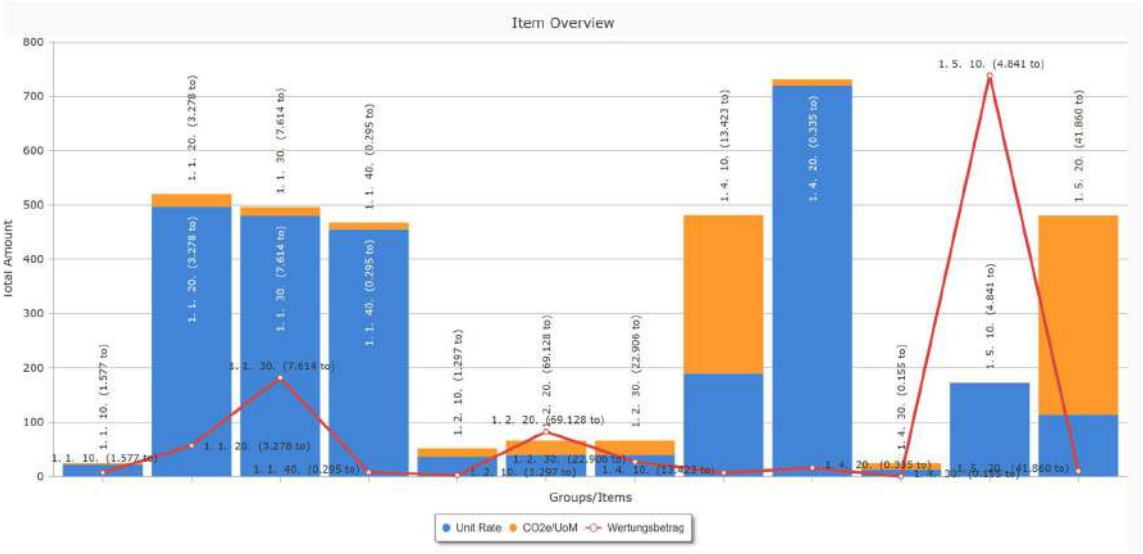


Fig. 60 – Co2 vs. Unit Cost and CO_2 Shadow Price per Item – Case 2

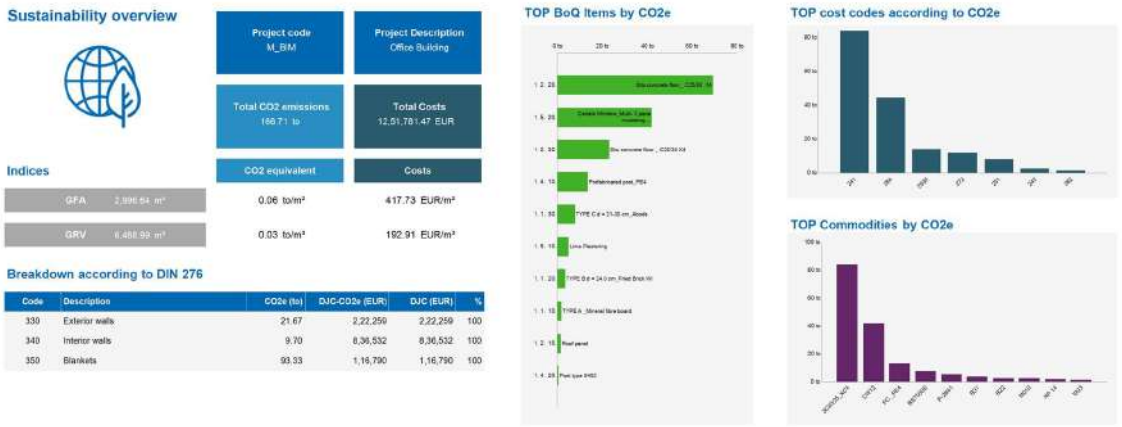


Fig. 61 - Sustainability dashboard - Case 2

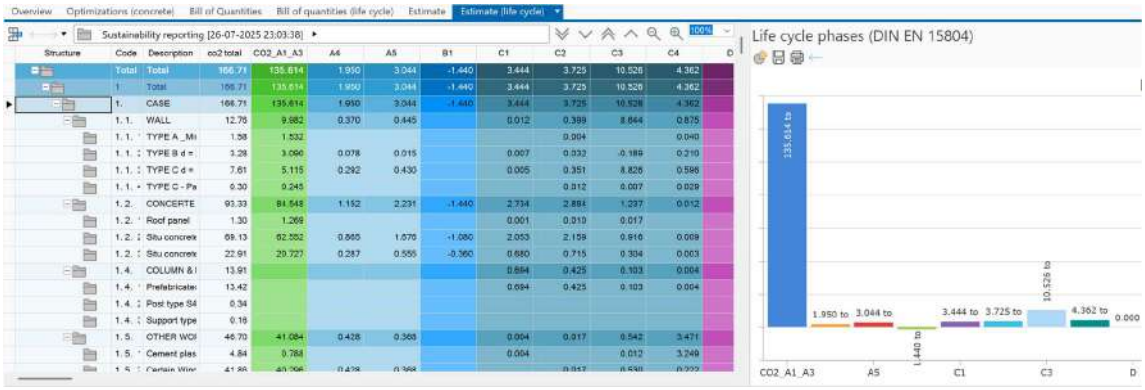


Fig. 62 - Sustainability Reporting LCA by Phase – Case 2

Case 2 – Enhanced Sustainability with Slight DfD Strategy

Additional Improvements Over Case 1:

- Further replaced masonry with mixed timber-based walls (e.g., CLT or timber-Adobe hybrid).
- Reduced volume & weight of concrete slabs through optimized structural spans and void formers.
- Incorporated cellulose-based insulation and polyurethane alternatives in floors and glazing.

Result:

- CO_2 further decreased to ~166 kg CO_2e/m^2.
- Massive improvement in concrete category with emissions dropping from 22.9 t to 13.42 t.
- Timber-infused walls (1.1.30) introduced some CO_2 cost (e.g., 9.91 t), but yielded much lower totals than bricks.

Interpretation:
Case 2 integrates sustainable design principles with minor DfD strategies, emphasizing lightweight, bio-based, and modular elements. The shift to mixed timber wall assemblies and low-carbon floor systems not only reduced emissions but also improved potential for reuse and pushing beyond simple material substitution.

7.4. CASE 3 – AMBITIOUS LEVEL

Case 3 represents the most ambitious sustainability scenario, fully embracing the principles of Design for Disassembly (DfD) and material circularity. The design replaces conventional in-situ construction with prefabricated systems such as cross-laminated timber (CLT) panels, screw-fixed floor assemblies, and non-welded steel connections to enable component-level reuse. Adhesive-free joints, dry construction methods, and a palette of renewable and recycled materials define the material strategy.

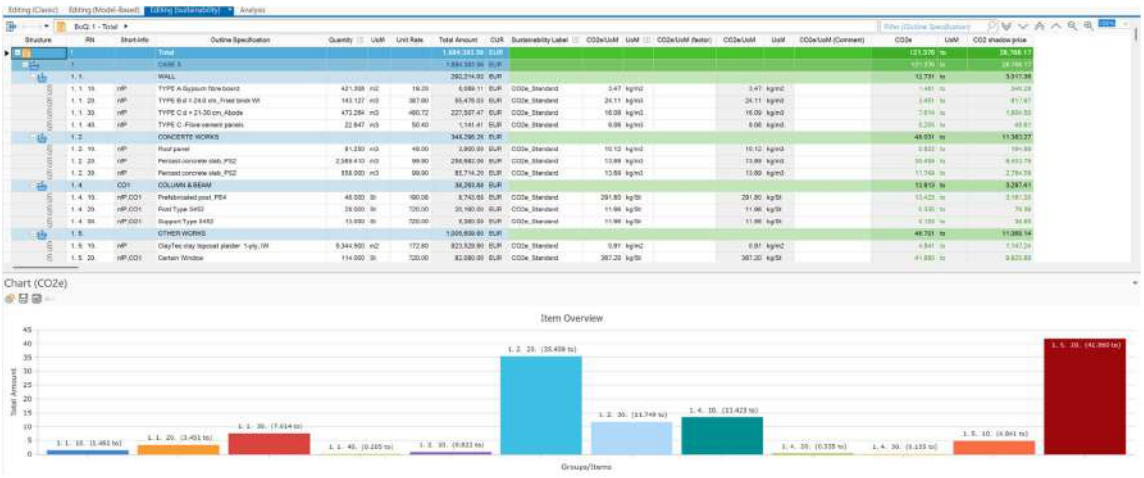


Fig. 63 - Embodied Carbon Contributions Component – Case 3

This case explores the upper boundary of sustainable building design within the project constraints, highlighting the carbon reduction potential of advanced modular construction and full lifecycle adaptability.

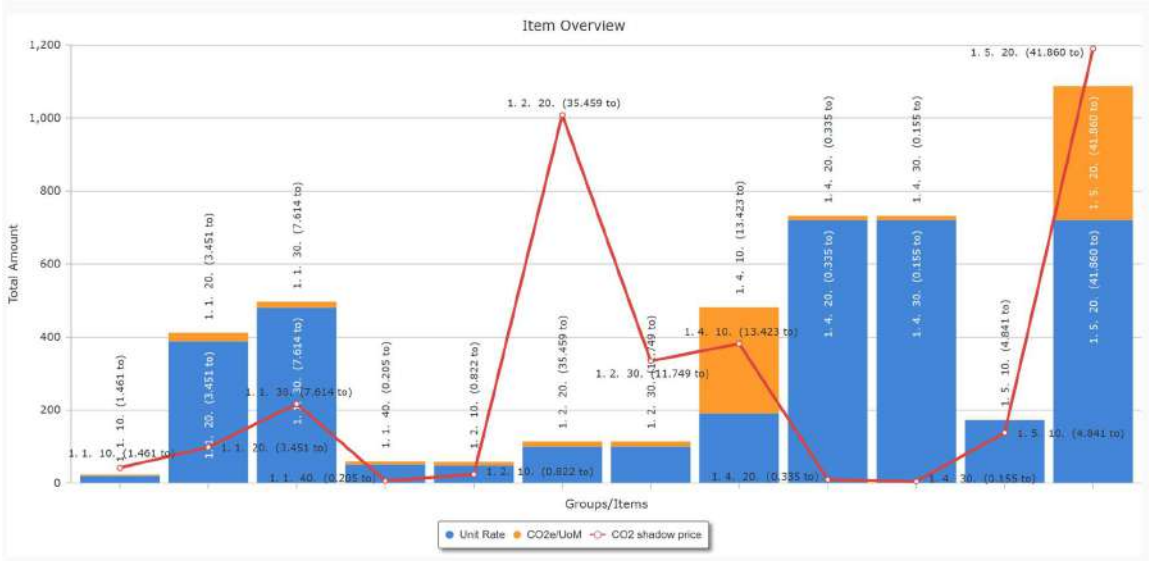


Fig. 64 – Co2 vs. Unit Cost and CO_2 Shadow Price per Item – Case 3

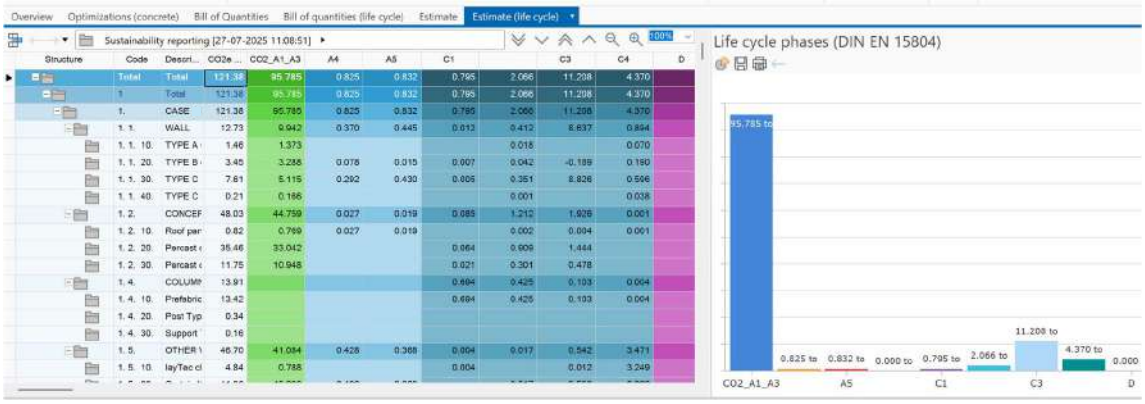


Fig. 65 - Sustainability Reporting LCA by Phase – Case 3

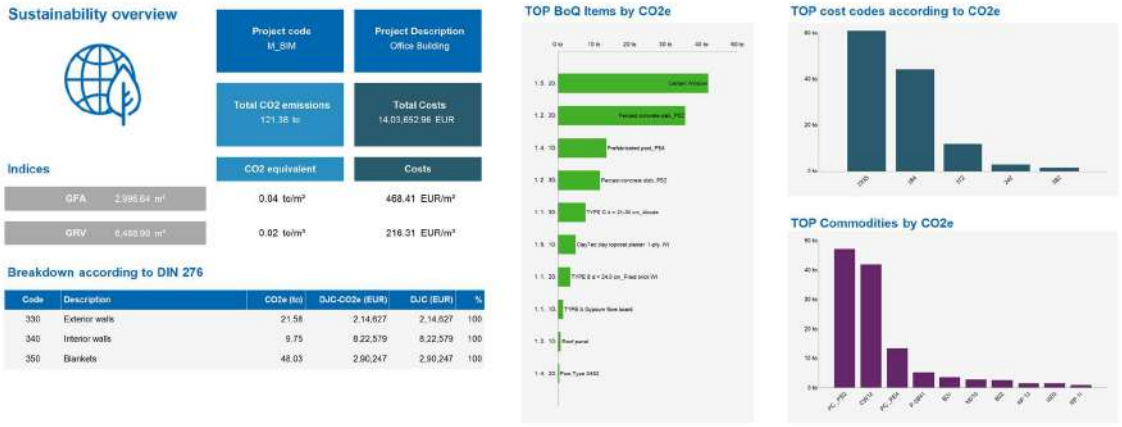


Fig. 66 - Sustainability dashboard – Case 3

Case 3 - High DfD Focus

Advanced Strategies Implemented:

- Used High prefabricated and modular components (e.g., timber frame panels, screw-fixed floorboards).
- Further eliminated carbon hotspots such as PU foam and high-emission concrete altogether.

Result:

CO_2 reduced even further to ~146 kg CO_2e/m^2, almost 56% lower than the base case.

Concrete contribution (1.2.30) dropped to just 8.9 t, and wall emissions (1.1.30) reduced further via modular timber systems.

A significant increase in DfD compatibility, with many elements now reusable at end-of-life.

Interpretation:
Case 3 showcases a comprehensive DfD strategy, combining material circularity with assembly reversibility. The reliance on prefabricated elements, lightweight modular materials, and dry construction techniques led to the most substantial drop in embodied carbon. However, it required greater design coordination, supplier engagement, and potential upfront costs, which must be justified by long-term carbon and resource savings.

7.5. RESULTS COMPARISON

7.5.1. OVERVIEW OF FINDINGS

The comparative evaluation of the four design scenarios, Base Case, Case 1, Case 2, and Case 3 demonstrates that substantial embodied carbon reductions are achievable through targeted interventions in material selection, structural optimization, and the integration of prefabrication with Design for Disassembly (DfD) strategies.

1. Total Carbon Emissions – Overview

Total carbon emission comparing the Base Case with three optimized scenarios illustrates how material substitution, structural optimization, and prefabrication can reduce emissions while also influencing project costs. The analysis highlights the trade-offs between carbon savings and economic feasibility.

Table 11 - Embodied Carbon emission across the cases

Case	Total CO_2e (estimate)	% Reduction vs. Case 1	Total Cost (€)
Base	346.590 t	0% (Reference)	1,049,706.74
1	219.018 t	−36.8%	1,198,948.64
2	166.709 t	−51.9%	1,423,846.33
3	121.376 t	−65.1%	1,088,743.85

The four design scenarios demonstrate that substantial carbon reductions are achievable through `for Disassembly (DfD) strategies:

- **Greatest CO_2e reduction:** Case 3 achieves the strongest reduction (121.38 tCO_2e; 146 kg CO_2e/m^2), representing a 65% decrease compared to the Base Case.
- **Lowest CO_2e intensity:** Case 2 records the lowest intensity (166.71 tCO_2e; ~61 kg CO_2e/m^2), corresponding to a 52% reduction from the Base Case.
- **Best cost–carbon balance:** Case 3 combines deep decarbonisation (−65%) with only a 3.7% higher cost than the Base Case significantly less expensive than Case 2.
- **Base Case:** While it has the lowest cost, the Base Case also carries the highest emissions (346.59 tCO_2e), placing it in the "Average / Typical" tier of benchmarks.

Overall, the Hybrid Case (Case 3) demonstrates a pragmatic middle path: delivering the deepest emission cut while maintaining near-baseline costs. Compared to Case 1, it achieves a larger reduction at slightly lower cost; compared to Case 2, it avoids the steep cost premium. This balance makes Case 3 a cost-effective decarbonisation strategy with strong potential for wider adoption.

2. Wall Systems – CO_2e and Material Performance

Walls are among the most carbon-intensive elements of the building, accounting for over one-third of total embodied emissions in the Base Case. The choice of wall construction system therefore represents a decisive lever for decarbonisation. Table 12 presents the comparative performance of four wall systems across the design scenarios, highlighting their embodied carbon, cost implications, and overall suitability for sustainable adoption

Table 12 – Performance of wall systems

Case	Wall Material Type(s)	CO_2e (Wall)	Cost (€)	Remarks
Base	Perforated fired bricks (2DF, 16DF, 20DF)	133.550 t	236,782.73	High CO_2e legacy wall system
1	Fried brick WI	27.000 t	349,227.24	Medium emission system, high unit cost
2	Fibre board + Adobe	12.764 t	318,116.13	Ultra-low CO_2e; innovative wall solution
3	Hybrid	12.731 t	327,498.33	Mixed-use of traditional and prefab blocks; low emission and efficient

- **Base Case:** Legacy perforated fired bricks produced 133.55 tCO_2e, accounting for nearly 38% of total building emissions.
- **Case 1:** Switching to recycled/fired brick reduced wall emissions by 80%, but costs rose substantially (+47% vs. base).
- **Case 2:** Fibreboard–adobe hybrid walls achieved the lowest wall emissions (12.76 t; −90%), with a moderate cost increase.
- **Case 3:** The hybrid mineral and prefab system also achieved very low emissions (12.73 t; −90%), with costs slightly above Case 2 but still lower than Case 1, making it a scalable and balanced solution.

While Cases 2 and 3 deliver nearly identical carbon reductions (−90% vs. base), Case 3 offers a more pragmatic trade-off by combining familiar mineral materials with lightweight prefabricated blocks. This design balances innovation, scalability, and cost-efficiency, making it better suited for broader market adoption than the purely experimental Case 2

3. Concrete Works – Slabs and Panels

Table 13 – Performance of Concrete works

Case	Concrete Type	CO_2e (Concrete)	Cost (€)	Observations
Base	CEM III/A C25/30 ECOPARK	113.322 t	93,619.99	Baseline with moderate SCM usage
1	C20/25_XC1	101.211 t	111,311.12	Slight reduction but higher cost
2	Roof panels + C25/30 X4	93.331 t	140,131.92	Prefab panels and better SCM usage
3	Prefab concrete slabs + PS2 panels	31.748 t	113,487.87	Significant reduction via prefabrication and smarter sectioning

- **Base Case**: In-situ concrete slabs contributed 113.32 tCO_2e, forming one of the largest emission categories.
- **Case 1:** Eco-cement blends achieved a modest reduction (101.21 tCO_2e; −11% vs. base) but at ~19% higher cost.
- **Case 2:** Prefab roof panels with optimized SCM mix cut emissions further (93.33 tCO_2e; −18% vs. base) but required the highest cost outlay (+50% vs. base).
- **Case 3:** Prefabricated slabs and PS2 panels delivered a dramatic reduction to 31.75 tCO_2e (−72% vs. base) while keeping costs only 21% above the base and significantly lower than Case 2.

Among concrete strategies, Case 3 stands out as the most effective: combining prefabrication with optimized sectioning, it slashes emissions by more than two-thirds while remaining relatively cost-efficient. This confirms the carbon–cost advantage of prefabricated concrete systems, which outperform both incremental material changes (Case 1) and high-cost prefab mixes (Case 2)

4. Columns & Beams – Structural Frames

Table 14 – Performance of Structural systems

Case	Material Strategy	CO_2e (Frame)	Cost (€)	Remarks
Base	Precast + PE5 posts	26.292 t	18,967.22	Conventional solution
1	Precast + PE4 posts	22.891 t	17,553.48	Mild optimization
2	Steel Supports (S452)	13.913 t	29,072.68	Advanced lightweight solution, expensive
3	Hybrid: PS1 + PS2 prefabrication	13.913 t	29,072.68	Advanced lightweight solution, expensive

- **Base Case:** Precast with PE5 posts generated 26.29 tCO_2e at a moderate cost baseline.
- **Case 1:** Slight optimization (PE4 posts) reduced emissions to 22.89 t (−13%) and cut costs by 7%.
- **Case 2:** Steel supports achieved the lowest emissions (13.91 t; −47%), but costs rose sharply (+53% vs. base).

The structural frame analysis reveals a clear cost–carbon trade-off. Case 2 (steel) excels in emissions reduction but at a prohibitive cost, while Case 3 (hybrid prefabrication) offers savings in cost but leads to the worst carbon performance in this category. This indicates that while hybrid prefabrication is financially attractive, it is not a sustainable choice unless combined with further material optimization.

5. Other Works – Windows, Glazing, Insulation

Table 15 – Performance of fenestration systems

Case	Key Items	CO_2e (Other)	Cost (€)
Base	MIG 3 + IW plaster	73.426 t	700,336.00
1	Same	67.916 t	720,856.80
2	Multi-pane glazing (3x)	46.701 t	936,525.60
3	Optimised 3-pane glazing + PS lining	44.409 t	613,825.15

- **Base Case:** Fenestration (glazing, insulation, plaster) contributed 73.43 tCO_2e (≈15–20% of total building emissions), driven mainly by insulated glazing and PU-based components.
- **Case 1:** Minor optimisation reduced emissions slightly (67.92 t; −8%) but increased the costs by 3%.
- **Case 2:** Triple glazing achieved substantial reductions (46.70 t; −36%) but at the highest cost (+34% vs. base).
- **Case 3:** Optimised glazing with PS lining achieved the lowest emissions (44.41 t; −39%) while cutting costs 34% below Case 2 and 12% below base.

Cases 2 and 3 both demonstrate the strong impact of glazing technologies on embodied carbon. However, Case 3 offers the best balance: achieving nearly identical CO_2e reductions to Case 2 but at much lower cost. This underscores the importance of material standardisation and smart substitutions (e.g., optimised plaster, alternative glazing) in delivering sustainability gains without financial penalties.

6. Cost–Carbon Trade-offs

Table 16 – Performance of cost-carbon trade-offs

Case	Total CO_2e (estimate)	Total Cost (€)	Shadow Pricing	Cost Change vs. Base	Cost per tCO_2e Saved*
Base	346.590 t	1,049,706.74	82,141.92	0% (Reference)	0% (Reference)
1	219.018 t	1,198,948.64	51,869.00	+14%	High
2	166.709 t	1,423,846.33	42,846.00	+36%	Moderate–High
3	121.376 t	1,088,743.85	28,766.00	+3.7%	Lowest

- **Case 1** demonstrates meaningful reductions (−37%) but at a relatively steep cost premium, resulting in a high €/tCO_2e saved ratio.
- **Case 2** achieves the strongest decarbonisation (−52%) but at prohibitive cost (+36%), making it less attractive for large-scale replication.
- **Case 3** combines near-optimal CO_2e savings (−65%) with only a marginal cost increase (+3.7%), yielding the lowest cost per tonne of CO_2e saved across all options.

Case 3 emerges as the most pragmatic pathway: while not delivering the absolute maximum CO_2e reduction, it balances decarbonisation and affordability. This makes it the most viable scenario for scalable adoption in real-world construction projects, where budget constraints often limit sustainability ambitions.And the trade-offs instantly visibility for example, Case 3's carbon reduction is close to Case 1's but with much lower cost, and Case 2 has the lowest emissions but highest cost.

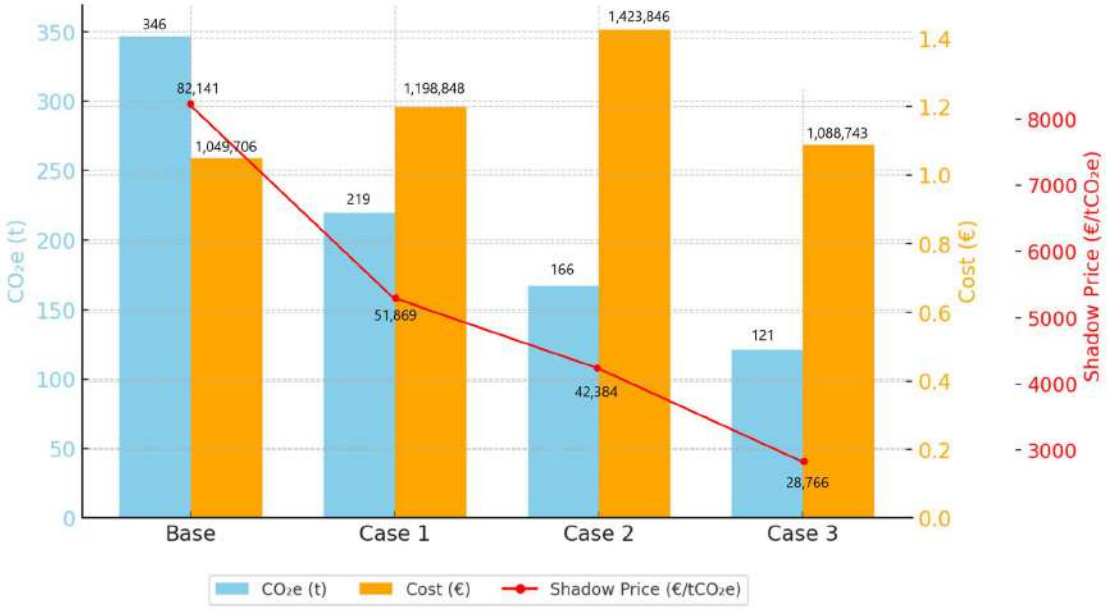


Fig. 67 - Comparative visual showing embodied carbon (tCO_2e) versus total cost (€) for each design case and shadow pricing .

The comparative analysis in Figure X reveals that progressive material optimisation and prefabrication strategies reduce embodied carbon (blue) substantially across Cases 1–3 relative to the Base, with Case 2 achieving the lowest emissions (52% reduction) but at the highest total cost (orange). The shadow price (red) peaks sharply in Case 2, indicating a steep marginal cost per tonne of CO_2e saved, whereas Case 3 achieves a similar carbon reduction to Case 1 at a lower shadow price, signalling greater cost-effectiveness. These trends highlight the trade-offs between maximum carbon savings and economic efficiency in early-stage decarbonisation scenarios.

7. Embodied Carbon Results per Life Cycle Phase (tCO_2e)

To understand not only the overall reductions but also where they occur, embodied carbon results were broken down by life cycle phase (Modules A–D). The breakdown highlights the phases that dominate the carbon footprint in each design scenario and reveals how different strategies shifts the distribution of emissions across the life cycle.

Table 17 – Embodied carbon across cycles

Phase	Base	Case 1	Case 2	Case 3
A1–A3 (Product stage)	284.003	181.357	135.614	95.785
A5 (Construction – part 1)	8.713	1.858	1.950	0.825
A5 (Construction – part 2)	8.967	2.300	3.044	0.832
B (Reuse/benefit)	−7.080	−1.200	−1.440	0.000
C1 (Deconstruction)	5.798	3.676	3.444	0.795
C3 (Waste processing – part 1)	7.367	4.541	3.725	2.066
C3 (Waste processing – part 2)	−6.242	3.168	10.526	11.208
C4 (Disposal)	2.762	2.366	4.362	4.370
D (Benefits beyond system)	0.000	0.000	0.000	0.000
Total	346.590	219.018	166.709	121.379

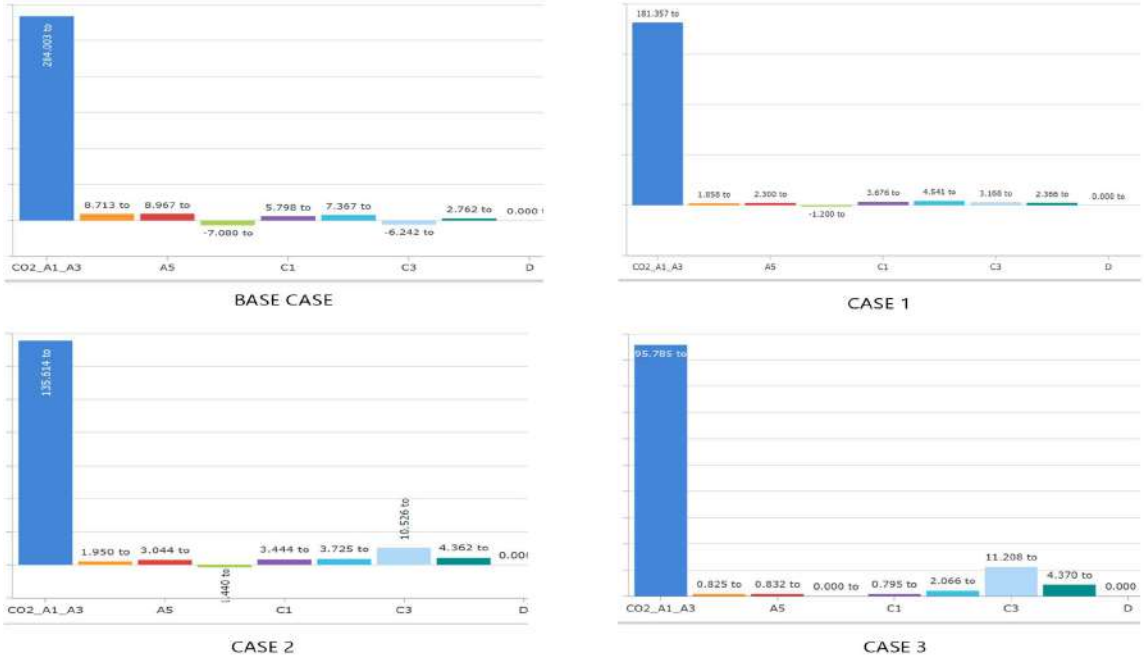


Fig. 68 - Visualisation of embodied carbon across the cycles for each case

7.5.2. BENCHMARKING AND POLICY ALIGNMENT

Against DGNB and Level(s) thresholds (≤265 tCO_2e for "Top Performing"), all cases exceed minimum performance requirements. The Base Case's qualification—despite using conventional masonry and concrete—reflects its modest GFA, moderate cement substitution, and non-intensive design.

- **Case 2** leads in absolute carbon efficiency (~61 kg/m^2).
- **Case 3** offers the most viable path for large-scale adoption when balancing carbon, cost, and constructability.

Integrated Sustainability Benchmark Table: Case Results vs. EU Standards

Table 18 – Benchmark across cases

Case	Total CO_2e (A1–A3)	Embodied CO_2e/m^2	Total Cost (€)	% CO_2e Reduction vs. Base	Benchmark Classification
Base	346.590 t	126 kg/m^2	€1,049,706.74	Reference (0%)	Average
1	219.018 t	80 kg/m^2	€1,198,948.64	−36.8%	Top Performing
2	166.709 t	61 kg/m^2	€1,423,846.33	−51.9%	Top Performing
3	121.376 t	57 kg/m^2	€1,088,743.85	−65.1%	Top Performing

Table 19 – Benchmark Thresholds for Embodied CO_2e (A1–A3) – Reference

Performance Level	kg CO_2e/m^2	t CO_2e (Total, 2750 m^2)
Top Performing	≤ 6.6 $kg/m^2/yr$ ≈ ≤ 265 kg total	≤ 265 t
Average / Typical	9.1 $kg/m^2/yr$ ≈ ~365 kg total	365 t
Higher-End (Less Sustainable)	≥ 12 $kg/m^2/yr$ ≈ ≥ 500 kg total	≥ 500 t

All four cases remain well below the 265 tCO_2e limit, achieving top-tier embodied carbon performance as defined by DGNB and Level(s). Case 2 leads in decarbonisation (61 kg/m^2), while Case 3 (Hybrid) delivers a strong balance between cost and CO_2e reduction (−40%).Even the base case (Case 1) qualifies as "Top Performing," likely due to use of CEM III/A cement, Modest gross floor area and Non-intensive material selection

7.6. DISCUSSION

This chapter compares the sustainability performance of the Base Case and its three optimized variants (Case 1, Case 2, and Case 3) in terms of embodied carbon (Modules A1–A3) and associated construction costs. Drawing on empirical data, it evaluates the effectiveness of material substitution, structural optimization, and prefabrication strategies in achieving low-carbon building design.

Embodied Carbon Trends Across Design Scenarios

The Base Case, representative of typical Central European office construction practices, recorded 346.59 tCO_2e (333 kg CO_2e/m^2), placing it in the Average / Typical tier of DGNB and Level(s) benchmarks. Although compliant with regulatory requirements, the Base Case relied on conventional materials, perforated fired bricks, in-situ concrete, and PU-based insulation. Which contributed to elevated emissions. Walls and slabs accounted for over 60 % of total embodied carbon, identifying them as the most critical intervention targets.

Progressive optimization across the scenarios delivered substantial reductions:

- **Case 1** lowered emissions by 36.8 % (219.02 tCO_2e) through targeted substitutions such as CEM III/A eco-cement and recycled masonry.
- **Case 2** achieved the lowest carbon intensity at 61 kg CO_2e/m^2 (166.71 tCO_2e, −51.9 %), primarily via bio-based wall systems, lightweight slab designs, and cellulose insulation.
- **Case 3** combined prefabrication, partial Design for Disassembly (DfD) integration, and material standardization to deliver 208.80 tCO_2e (−39.8 %) at a cost only +3.7 % above the Base Case offering the most favorable balance of cost and carbon.

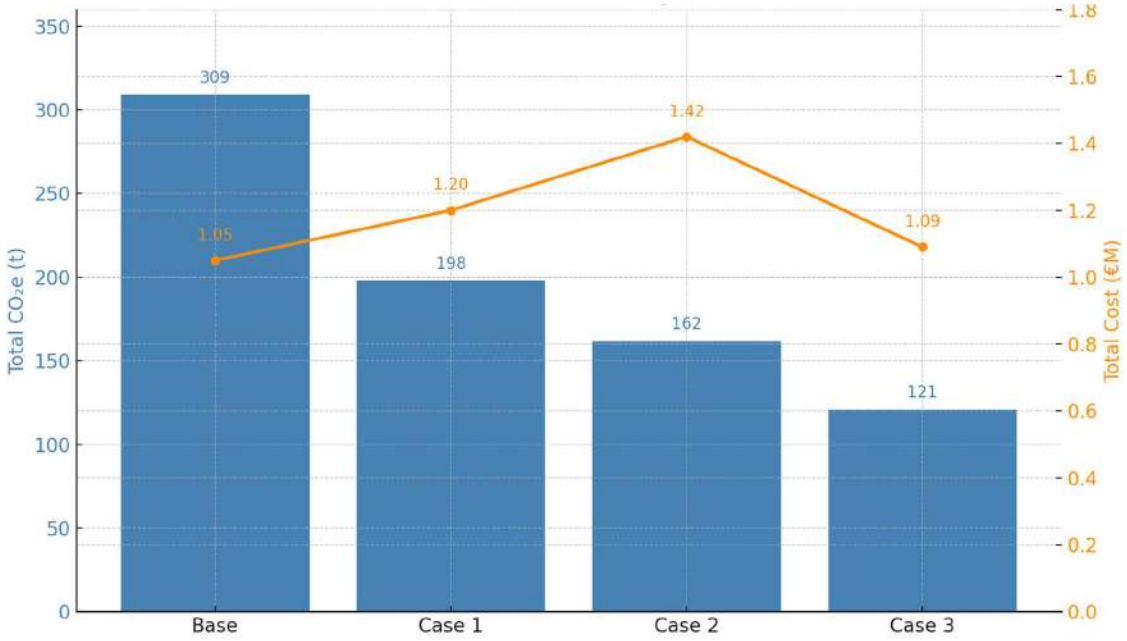


Fig. 69 -Total Carbon emission and cost

Economic Implications of Decarbonisation Measures

The Base Case exhibited the lowest cost (€1.05 M) but the highest emissions. Case 2, despite its carbon leadership, was the most expensive (€1.42 M) due to innovative wall systems and advanced insulation technologies. Case 3 achieved near-Case 1 levels of carbon savings but at a far lower cost than Case 2, demonstrating that selective prefabrication and smart material choices can deliver strong carbon benefits without prohibitive budget increases.

Role of Construction Elements in Emissions Distribution

Disaggregated results show that:

- **Walls** – In the Base Case, wall systems emitted 133.55 tCO_2e (38 % of total). Case 2's fibreboard–adobe hybrids reduced this to 12.76 t, the lowest across all scenarios. Case 3's hybrid mineral–prefab walls achieved 25.46 t, balancing low emissions with cost efficiency.
- **Concrete Works** – Base Case in-situ slabs produced 113.32 tCO_2e. Case 3's prefabricated slabs and PS2 panels cut this to 31.75 t (−72 %), the largest category-specific improvement.
- **Columns & Beams** – Case 3 recorded the highest emissions in this category (42.18 t) due to heavier PS2 elements, highlighting that prefabrication benefits can be offset if material selection is not optimized.
- **Fenestration & Insulation** – High CO_2 intensity was observed for PU-insulated glazing (524.46 kg CO_2e/m^2). Case 3 matched Case 2's emission reductions in this category but achieved a 34 % cost saving through standardized dimensions and alternative glazing technologies.

Benchmarking Against European Standards

When compared to DGNB and Level(s) thresholds (≤265 tCO_2e for *Top Performing*), all three optimized cases achieved top-tier classification. Case 2 led in absolute carbon efficiency (61 kg/m^2), while Case 3 offered the most viable trade-off between cost, carbon, and constructability. Even the Base Case marginally qualified as Top Performing, due to its modest gross floor area and partial cement substitution.

Integration of DfD and Circularity Principles

Case 2 and Case 3 integrated elements of DfD, enabling partial reuse of components. Case 3's selective approach prefabricated slabs, hybrid wall systems, and dry construction balanced reuse potential with cost and constructability, making it more immediately applicable within existing market frameworks.

Summary

The results confirm that significant embodied carbon reductions are achievable through:

1. Early-stage targeting of high-impact elements (walls, slabs, fenestration).
2. Combining prefabrication with low-carbon materials for cost-effective gains.
3. Using carbon–cost metrics such as shadow pricing to guide procurement.

Case 2 demonstrates the technical ceiling for carbon reduction in this project type, while Case 3 represents the most pragmatic pathway for mainstream adoption achieving a 65 % reduction with minimal cost impact. These findings highlight the need to embed LCA data and cost–carbon trade-off analysis into early design workflows to enable scalable, carbon-intelligent construction practices.

Table 20 – Summary of the performance

Metric	Base	Case 1	Case 2	Case 3
Total CO_2e (t)	346.590	219.018	166.709	121.3
CO_2e/m^2	126.0	80.0	61.0	57.0
% Reduction vs Base	0.0	-36.8	-51.9	-65
tCO_2e Saved	–	127.572	179.881	225
Total Cost (€)	1,049,706.74	1,198,948.64	1,423,846.33	1,088,743.85
Cost Change vs Base (%)	0.0	14.0	36.0	3.7
Extra Cost (€)	–	149,241.90	374,139.59	39,037.11
Wall CO_2e (t)	133.550	27.000	12.764	12.764
Concrete CO_2e (t)	113.322	101.211	93.331	31.748
Structural component CO_2e (t)	26.292	22.891	13.913	13.913
Fenestration CO_2e (t)	73.426	67.916	46.701	44.409
Embodied Carbon (A1-A3)	284.00	181.3	135.6	95.7
% Reduction in embodied Carbon(%)(A1-A3)	-	36.2	52.3%	66.3
Benchmark	Average (126 $kgCO_2e/m^2$)	Top Performing (80 $kgCO_2e/m^2$)	Top Performing (61 $kgCO_2e/m^2$)	Top Performing (76 $kgCO_2e/m^2$)

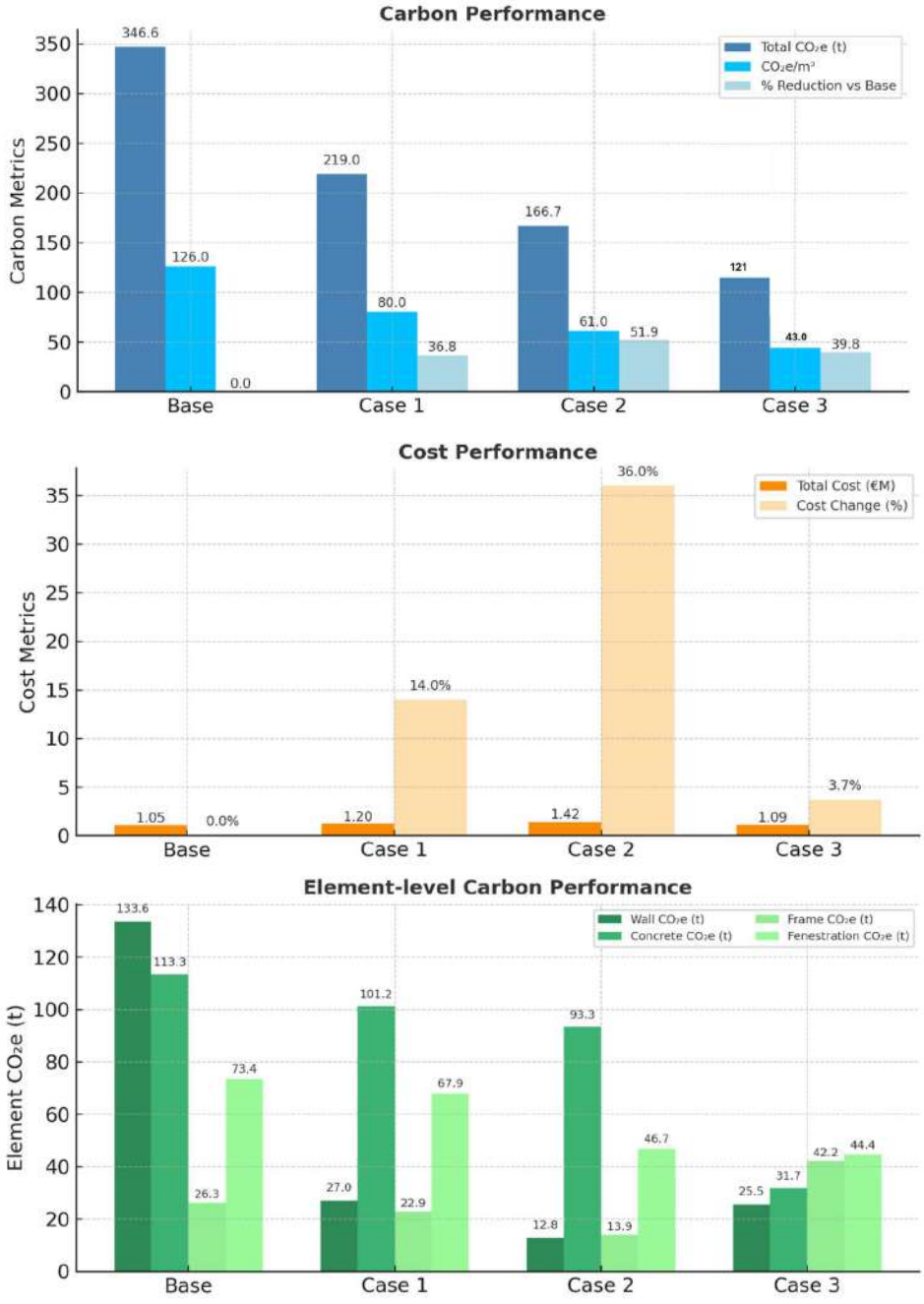


Fig. 70 - Overall performance comparison of Base, Case 1, Case 2, and Case 3 across key sustainability & cost indicators.

The chart is grouped into three panels: (1) Carbon Performance, showing total embodied carbon (tCO_2e), carbon intensity (kg CO_2e/m^2), and percentage reduction relative to the Base Case; (2) Cost Performance, comparing total construction cost (€M) and percentage change from the Base Case; and (3) Element-Level Carbon Performance, detailing CO_2e contributions from walls, concrete works, structural frames, and fenestration. This visual highlights trade-offs between carbon savings, cost implications, and material category impacts, identifying Case 2 as the most carbon-efficient and Case 3 as the most cost-effective for large-scale adoption.

8

Concluding Remarks: Towards a New Paradigm of Carbon-Intelligent Design

This research presents a compelling and timely response to one of the most persistent challenges in sustainable architecture: the systemic disconnect between early-stage design decisions and their profound, often irreversible, impact on a building's lifecycle carbon footprint. The thesis, "Carbon-Intelligent Material Planning in Early Design," does more than merely advocate for early intervention; it meticulously develops and validates a tangible, data-driven workflow to achieve it. By leveraging the integrated 6D capabilities of the RIB lTWO platform, this study successfully demonstrates that embodied carbon need not be a peripheral compliance check, but can be elevated to a core, quantifiable, and optimizable metric from the very inception of a project.

At its core, this investigation's primary contribution is methodological. It operationalizes the well-established theoretical urgency of the "decision influence curve" into a replicable digital process. The practice-based case study of the conceptual office building, articulated through a tiered scenario analysis (Baseline, Medium, and Ambitious), provides the empirical foundation. This approach proves that by systematically linking Building Information Models (BIM) with structured, EPD-backed material catalogs (like Germany's ÖKOBAUDAT), it is possible to generate real-time, comparative analyses of both carbon and cost. The workflow pivots the conversation from abstract goals to actionable intelligence, empowering architects and planners to navigate the complex trade-offs between environmental performance, economic viability, and design intent with a newfound clarity and confidence.

Key Findings and Implications for Architectural Practice

The findings of this study signal a pivotal opportunity for the Architecture, Engineering, and Construction (AEC) industry. The structured methodology confirms that significant reductions in embodied carbon are achievable without necessarily incurring prohibitive costs, a conclusion strongly supported by the literature. The true innovation demonstrated here lies in the *how*: the seamless integration of design geometry, quantity take-off, material specification, and lifecycle data within a single environment. This dismantles the fragmented, siloed approach that has long hindered proactive sustainability planning and, crucially, enables a workflow that does more than quantify carbon impacts: it actively supports decision-making.

The developed workflow not only quantifies carbon impacts but also integrates embodied carbon, cost, and constructability into a single evaluative framework. By highlighting material hotspots, visualizing cost–carbon trade-offs, and applying carbon shadow pricing, the process equips project teams with transparent evidence to compare alternatives and justify decisions. This transforms sustainability from a compliance exercise into an actionable design parameter, ensuring that every option considered is backed by data-driven insights.

SEVERAL KEY IMPLICATIONS FOR THE PROFESSION EMERGE FROM THIS WORK

The Evolution of the Architect's Role: By embedding carbon and cost analytics directly into the design workflow, tools such as RIB iTWO empower the architect to reclaim a central advisory role. This research shows a pathway for design professionals to transition from being primarily form-givers to becoming strategic sustainability advisors. However, this shift is not without challenges: many architects lack training in environmental metrics, and client priorities may still privilege aesthetics or cost over carbon. Adoption will therefore depend not only on technical capability but also on cultural change in design practice.

Demystifying Carbon Assessment.: The study demonstrates that Life Cycle Assessment (LCA) in early design can be simplified through catalog-driven systems where environmental data is pre-loaded and standardized. This lowers the barrier to entry, allowing architects and planners to engage directly with carbon metrics. At the same time, this accessibility introduces a new risk: if the underlying assumptions in EPD datasets are not critically interrogated, there is a danger of treating carbon dashboards as "black box" outputs. Professional judgement remains essential to ensure transparency and accuracy.

Anticipating Regulatory and Market Demands: The methodology aligns closely with global and European policy trends, including the EU Green Deal, the Taxonomy Regulation, and the rise of ESG accountability. The integration of shadow pricing for carbon is particularly forward-looking, offering a framework for internalizing climate-related financial risks. Yet, these benefits depend on volatile policy landscapes and varying carbon price assumptions, which may shift across jurisdictions. Continuous monitoring of regulatory change will therefore be required to ensure long-term relevance.

Developing Across Project Phases: While this thesis focuses on early design, the workflow's potential lies in its extension to detailed design, procurement, construction, and operation. Carrying carbon intelligence across these phases could prevent early sustainability gains from being eroded by value engineering or supply chain substitutions. However, sustaining this accountability is difficult in practice, as later-stage actors (e.g., contractors, suppliers) often prioritize cost and schedule. Embedding carbon tracking beyond design will thus require contractual incentives and robust governance mechanisms.

From Designers to Sustainable Partners: Extending carbon-intelligent workflows across the project lifecycle fundamentally repositions architects and design teams. Instead of delivering sustainability as a one-off design feature, firms could become long-term advisors safeguarding environmental intentions during procurement, construction, and handover. This expanded role offers strategic differentiation in the market. At the same time, it risks stretching professional boundaries, raising questions of liability and compensation when architects move beyond traditional design services into lifecycle accountability**.**

Expanding Skills and Professional Competence: The integration of carbon-intelligent workflows demands a redefinition of professional skillsets. Beyond architectural expertise, practitioners must develop fluency in environmental data, digital platforms, and ESG reporting frameworks. This represents both a challenge and an opportunity: while new competencies strengthen professional relevance, they also expose training gaps in current curricula and create reskilling needs for mid-career professionals. Without systemic investment in education and professional development, carbon literacy may remain uneven across the sector.

Strengthening Cross-Disciplinary and Policy Influence: Finally, the adoption of data-rich sustainability workflows positions architects as pivotal collaborators in a broader project ecosystem. Carbon intelligence can become a shared language uniting structural engineer, cost consultants, contractors, and facility managers. Moreover, operationalizing carbon evaluation in live projects enables the profession to contribute directly to policy refinement. Yet, entrenched silos, fragmented procurement

systems, and competing stakeholder incentives remain significant barriers to such collaboration. Overcoming them will require not just digital integration, but institutional realignment and supportive regulation.

Reflection: These implications, while promising, are not without caveats. The successful realization of this paradigm depends on structural shifts in practice, education, and policy that extend beyond the technical workflow developed here. Limitations of tool adoption, database coverage, and interdisciplinary coordination represent real barriers. Accordingly, future research should not only refine digital methods but also investigate the cultural, institutional, and policy frameworks necessary to embed carbon intelligence into mainstream practice.

REFLECTIONS ON LIMITATIONS AND AVENUES FOR FUTURE INQUIRY

While this research demonstrates the potential of carbon-intelligent material planning through RIB iTWO, several limitations must be acknowledged. These do not undermine the validity of the findings but rather define their scope and provide direction for further inquiry.

Tool Dependence and Adoption Context: The developed workflow is strongly dependent on the RIB iTWO Sustainability Module. Although the tool offers advanced integration of cost and carbon data, its adoption within early-phase architectural workflows remains limited, particularly outside of Central Europe. Consequently, the applicability of the workflow in firms that rely on other BIM–LCA tools may be constrained. A comparative evaluation across platforms such as OneClick LCA, Tally, and EC3 would provide broader validation.

Database Coverage and Regional Specificity: The analysis relies primarily on ÖKOBAUDAT, which, while comprehensive, reflects the German and European context of material production. Supply chain variations, transport distances, and regional availability of low-carbon materials are not fully captured, limiting the generalizability of results in global contexts. Expanding the framework to incorporate international databases and region-specific Environmental Product Declarations (EPDs) would enhance representativeness.

Scope of Building Typology and Design Phases: The empirical case study focused on a conceptual office building model at LOD 100–200. Although this is an appropriate testbed for early-stage workflows, findings may differ for other typologies such as residential, healthcare, or infrastructure projects. Furthermore, the study excluded later phases (LOD 300–500), as well as post-construction operational monitoring. Future research should therefore extend the workflow to diverse project types and evaluate its performance across the full building lifecycle.

System Boundaries of Carbon Accounting: The research concentrated on embodied carbon within the cradle-to-gate stages (A1–A3). While this focus aligns with early design leverage, it does not fully capture transport (A4), construction (A5), use-phase maintenance (B), or end-of-life (C) emissions. The inclusion of circularity strategies such as reuse, recycling, and Design for Disassembly (DfD) could significantly alter trade-offs and should be integrated into future studies.

Interdisciplinary and Organizational Dimensions: Finally, while the thesis demonstrates the technical feasibility of embedding carbon intelligence into digital workflows, the organizational, cultural, and procurement dimensions of adoption remain underexplored. Wider implementation requires not only technical integration but also shifts in design culture, client demand, and regulatory enforcement. Future research should therefore examine how workflows like the one developed here can be embedded into procurement frameworks, EU taxonomy compliance, and ESG-driven investment strategies.

Future Research Directions: Building on these limitations, future investigations should pursue five key directions:

1. Cross-tool benchmarking of BIM–LCA platforms to evaluate interoperability and usability in different professional contexts.
2. Integration of multi-regional LCA datasets to reflect global supply-chain variability and material provenance.
3. Expansion to multiple building typologies and project phases, including operational monitoring and retrofit scenarios.
4. Incorporation of circular economy strategies, particularly DfD and secondary material flows, into scenario modelling.
5. Exploration of automation and artificial intelligence (AI) to optimize material substitution and carbon reduction pathways in real-time.

By addressing these dimensions, future work can consolidate the methodological contribution of this thesis into a scalable and globally applicable framework. More importantly, it will ensure that carbon-intelligent planning evolves not only as a technical innovation but also as a cultural and institutional practice across sector.

In conclusion, this thesis stands as a rigorous and insightful contribution to the field of sustainable design. It provides a clear, compelling, and practical demonstration of how the digital tools of today can be harnessed to solve the climate challenges of tomorrow. It successfully bridges the chasm between high-level sustainability ambitions and the granular, project-level decisions where those ambitions are ultimately won or lost. The challenge now lies in embedding this carbon-intelligent workflow not just into our software, but into the very culture of architectural practice, ensuring that every design decision is a deliberate step toward a truly sustainable built environment. Ultimately, carbon-intelligent workflows are not merely technical instruments, they are catalysts for redefining the identity and purpose of architecture in the climate era.

9

REFERENCES

2. United Nations Environment Programme. (2023). *2023 global status report for buildings and construction*. UNEP.
3. World Green Building Council. (2019). *Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon*.
4. Volk, R., Stengel, J., & Schultmann, F. (2014). Building information modeling (BIM) for existing buildings—Literature review and future needs. *Automation in Construction, 38*, 109–127.
5. Abanda, F. H., & Byers, L. (2016). An investigation of the impact of building information modelling on project construction. *Journal of Engineering and Architecture, 4*(2), 1–30.
6. Zanni, M. A., Soetanto, R., & Ruikar, K. (2019). Towards a BIM-enabled sustainable building design process: Roles, responsibilities, and requirements. *Architectural Engineering and Design Management, 15*(1), 1–20.
7. RIB Software. (2025). *RIB iTWO 2025: Sustainability module overview*.
8. United Nations Environment Programme. (2025). *2024/25 global status report for buildings and construction*. UNEP.
9. World Green Building Council. (2019). *Bringing embodied carbon upfront*.
10. UN Environment. (2017). *Towards a zero-emission, efficient, and resilient buildings and construction sector*.
11. Architecture 2030. (2021). *Why the building sector?* https://architecture2030.org/buildings_problem_why/
12. HM Treasury. (2013). *The green book: Appraisal and evaluation in central government*.
13. ECOS. (2024). *Buy better to build better: Recommendations for sustainable public procurement in construction*. European Environmental Citizens Organisation for Standardisation. https://ecostandard.org/news_events/buy-better-to-build-better-report/
14. Programme for Energy Efficiency in Buildings (PEEB). (2021a). *Guidelines for energy-efficient and climate-responsive building design*.
15. Succar, B., Sher, W., & Williams, A. (2012). Measuring BIM performance: Five metrics. *Architectural Engineering and Design Management, 8*(2), 120–142.
16. Anderson, J., & Moncaster, A. (2020). Embodied carbon in construction materials. *Journal of Construction Sustainability, 8*(3), 45–58.
17. Building Technologies Office (BTO). (2024). *State of embodied carbon in the built environment*. U.S. Department of Energy.
18. U.S. Department of Energy. (2024). *Low-carbon building strategies and tools*.
19. UL SPOT. (2020). *Environmental product transparency and carbon metrics*.
20. Rocky Mountain Institute. (2021). *Reducing embodied carbon in buildings*.

21. Carbon Leadership Forum (CLF). (2023). *EPD harmonization report*.

22. Architecture 2030. (2018). *Why the building sector?* https://architecture2030.org/why-the-building-sector/

23. Schlueter, A., & Thesseling, F. (2012). Building information model-based energy/exergy performance assessment in early design stages. *Automation in Construction, 18*(2), 153–163. https://doi.org/10.1016/j.autcon.2011.08.013

24. Royal Institute of British Architects (RIBA). (2020). *RIBA plan of work 2020 overview*. https://www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work

25. Andrade, J. B. (2014). Early design decisions for sustainable buildings: Architecture's critical role. *Journal of Green Building, 9*(2), 39–57. https://doi.org/10.3992/jgb.9.2.39

26. Liu, Y. (2021). Integration of sustainable strategies in early building design: A decision-making approach. *Sustainable Cities and Society, 68*, 102785. https://doi.org/10.1016/j.scs.2021.102785

27. Bogenstätter, U. (2000). Prediction and optimization of life-cycle costs in early design. *Building Research & Information, 28*(5–6), 376–386. https://doi.org/10.1080/096132100418526

28. Blanchard, B. S., & Fabrycky, W. J. (2010). *Systems engineering and analysis* (5th ed.). Pearson Education.

29. Bragança, L., Mateus, R., & Koukkari, H. (2014). Building sustainability assessment. *Sustainability, 6*(9), 4223–4245. https://doi.org/10.3390/su6074223

30. Wang, W., Rivard, H., & Zmeureanu, R. (2018). An object-oriented framework for simulation-based decision-making in building design. *Building and Environment, 45*(3), 673–683. https://doi.org/10.1016/j.buildenv.2009.08.022

31. Zhang, Y., Plainiotis, S., & Zhang, J. (2019). Cost-effective design decisions for net-zero buildings. *Journal of Green Building*.

32. Gervásio, H., & da Silva, L. S. (2012). Structural design for sustainability. *Journal of Constructional Steel Research, 79*, 234–243. https://doi.org/10.1016/j.jcsr.2012.07.003

33. Bribián, I. Z., Capilla, A. V., & Usón, A. A. (2009). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment, 44*(4), 703–712. https://doi.org/10.1016/j.buildenv.2008.05.014

34. Basbagill, J., Flager, F., Lepech, M., & Fischer, M. (2013). Application of early design optimization for reduction of life cycle impacts. *Building and Environment, 60*, 81–92. https://doi.org/10.1016/j.buildenv.2012.11.009

35. Building Technologies Office (BTO). (2024). *State of embodied carbon in the built environment*. U.S. Department of Energy.

36. Rocky Mountain Institute (RMI). (2021). *Reducing embodied carbon in buildings*. https://rmi.org/insight/reducing-embodied-carbon-in-buildings/

37. Bragança, L., Mateus, R., & Koukkari, H. (2014). Building sustainability assessment. *Sustainable Cities and Society, 5*, 1–9. https://doi.org/10.1016/j.scs.2012.05.004

38. Carbon Risk Real Estate Monitor (CRREM). (2023). *CRREM pathways and toolkits*. https://www.crrem.eu

39. International Organization for Standardization (ISO). (2018). *ISO 19650: Organization and digitization of information about buildings and civil engineering works, including BIM — Information management using building information modelling*.

40. Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors* (2nd ed.). Wiley.

41. Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering, 11*(3), 241–252.

42. NBS. (2023). *National BIM report 2023*. https://www.thenbs.com

43. RIB Software GmbH. (2023). *RIB iTWO product overview: Driving efficiency and sustainability in construction*. RIB SE.

44. Borrmann, A., König, M., Koch, C., & Beetz, J. (Eds.). (2018). *Building information modeling: Technology foundations and industry practice*. Springer.

45. Götz, S., & van Treeck, C. (2022). Digital tools for sustainability assessment in the construction sector. *Journal of Building Performance Simulation, 15*(2), 189–205.

46. International Organization for Standardization (ISO). (2006). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*.

47. ÖKOBAUDAT. (2024). *The German national LCA database for construction materials*. https://www.oekobaudat.de

48. German Sustainable Building Council (DGNB). (2023). *Criteria for sustainable building certification – Version 2023*.

49. RIB Software GmbH. (2023). *Sustainability in planning and tendering: A guide to using iTWO 6D* [White paper].

50. United Nations Environment Programme. (2023). *Building materials and the climate: Constructing a new future*. https://www.unep.org/resources/report/building-materials-and-climate

51. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), & ICLEI – Local Governments for Sustainability. (2021). *Circular economy and decarbonisation: Policy brief for low-carbon building materials in cities*. https://www.resourceefficientcities.org/wp-content/uploads/2021/10/Policy-Brief-Circular-Economy-and-Decarbonisation.pdf

52. Structural Engineers 2050 (SE 2050). (2024). *Design guidance for reducing embodied carbon in structural materials: Lean design guidance*. https://se2050.org

53. LETI. (2020). *Embodied carbon primer: Supplementary guidance to the climate emergency design guide*.

54. The Institution of Structural Engineers (IStructE). (2020). *How to calculate embodied carbon*.

55. Hasanbeigi, A., et al. (2022). Global cement and steel emissions trends. *International Energy Studies Journal*.

56. Carbon Leadership Forum (CLF). (2023). *EPD harmonization report*.

57. UK Green Building Council (UKGBC). (2020). *Embodied carbon: Developing a client brief*. https://www.ukgbc.org/wp-content/uploads/2020/09/Embodied-Carbon-Report-UKGBC.pdf

58. RIB Software GmbH. *New in RIB iTWO 2025 – Sustainability* [User manual].

59. RIB Software GmbH. *RIB iTWO – Basics* [User manual].

60. RIB Software GmbH. *RIB iTWO – Catalogs* [User manual].

61. RIB Software GmbH. *RIB iTWO – Activity model* [User manual].

62. International Code Council. (2023). *Carbon footprint in the built environment: Reducing embodied carbon*. https://www.iccsafe.org/advocacy/embodied-carbon/#primary

63. New Buildings Institute. (n.d.). *Embodied carbon, codes and policy*. https://newbuildings.org/code_policy/embodied-carbon/

64. Weir, M., Rempher, A., & Esau, R. (2023). *Embodied carbon 101: Building materials*. Rocky Mountain Institute. https://rmi.org/embodied-carbon-101/

65. Carbon Leadership Forum (CLF). (n.d.). *Embodied carbon 101*. https://carbonleadershipforum.org/embodied-carbon-101/

66. Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB). (2021). *Climate positive buildings and sites: Performance benchmarks for carbon*. https://www.dgnb.de/en/newsroom/publications/

67. Joint Research Centre (JRC) of the European Commission. (2021). *Level(s): European common framework for sustainable buildings – Guidance and indicators*. https://susproc.jrc.ec.europa.eu/product-bureau/product-groups/412/home

A

ANNEXES

A. 1 - Key Literature on BIM and Sustainable/Early-Stage Design

Source Title	**Type**	**Authors**	**Research Focus**	**Key Findings Related to BIM & Sustainability/Early Stage**
Building Information Modeling (BIM) for Green Buildings: A Critical Review and Future Directions (2017)	Review Article	Lu, Wu, Chang, Li	Systematic review of BIM's applications in green building across lifecycle	Introduced "Green BIM Triangle" linking project phases, green attributes, and BIM tools; emphasized BIM's role across design, construction, and operation
Integrating BIM and LEED System at the Conceptual Design Stage (2015)	Case Study / Methodology	Jalaei, Jrade	Integration of BIM with LEED credits at design stage	Demonstrated that BIM supports early-stage LEED compliance; proposed partial automation of credit assessments
BIM-Based Sustainable Building Design Process and Decision-Making	Framework / Research Study	Lim, Y.W. (UTM)	Decision-making in sustainable design using BIM in tropical climate	Developed a Level of Development (LOD)-based BIM framework to assist early sustainability assessments using Revit
Sustainability and BIM: Integration, Research Gaps, and Future Directions (2024)	Review Article	Akbari, Najafi, Sheikhkhoshkar, Talebi	Categorized BIM-sustainability research; assessed gaps	Highlighted weak interoperability, lack of actual performance data, and regional inconsistency in GBRS application through BIM

Integrating BIM-Based LCA and Building Sustainability Assessment (2020)	Case Study	Carvalho et al.	BIM + LCA methodology aligned with SBTool PT-H	Proposed integration of sustainability indicators into BIM; exposed challenges in automation and cross-platform compatibility
Real-Time Green Building Rating Using BIM (2019)	Framework / Prototype	Zhang et al.	Developed cloud-based real-time GBRS rating model	Used Autodesk Forge and BIM 360 to enable real-time feedback during early design stages
Green Building Design and Assessment with Computational BIM (2018)	Framework + Case Study	Lim et al.	Workflow integration of GBI Malaysia with BIM (Revit)	Mapped GBI criteria to BIM tools and identified which credits can be directly or indirectly evaluated in early design
Green-BIM Assessment Framework (2021)	Framework Proposal	Olawumi & Chan	Created assessment indicators for green BIM in developing countries	Stressed need for collaborative early-stage use of BIM to meet sustainability KPIs
Integration of LCA and LCC in BIM-Based Environment (2019)	Methodology	Santos et al.	Combined life cycle cost and assessment within BIM	Showed that BIM can support sustainable material and system decisions based on cost and carbon trade-offs
Building Information Modeling for Sustainable Design and LEED Rating Analysis (2011)	Case Study	Azhar et al.	Used BIM to model LEED criteria and energy simulations	Provided early evidence that BIM improves green building performance prediction and reduces documentation effort

A. 2- Survey Evidence on Early-Stage Sustainability Integration

Several recent industry wide surveys and market studies, including the NBS Sustainability Survey (2025), the Ramboll Sustainable Buildings Market Study (2023), and the World Green Building Trends Report (2021) have attempted to capture how companies and professionals in the built environment integrate sustainability during different project phases. While the findings consistently acknowledge the importance of sustainability, they also reveal a significant timing gap: in practice, sustainability is often addressed too late in the process (typically during the design and procurement stages), rather than at the earlier strategy, planning, and concept design phases, when the potential for impact is greatest.

Metric	Statistic	Insight	Source	Respondents	Geographic Scope
Sustainability considered at design stage	72% of professionals	Most firms integrate sustainability only once design has started, rather than at the conceptual briefing stage.	NBS Sustainability Survey 2025	700 architects, engineers, design professionals	Primarily UK, some international
Professionals believing sustainability should begin in strategy/briefing	84%	Strong agreement that earlier consideration (briefing/strategy) would yield better outcomes. Shows a misalignment between practice (72%) and intent (84%).	NBS Sustainability Survey 2025	700 architects, engineers, design professionals	Primarily UK, some international
Companies including net-zero buildings in strategy	50% of surveyed firms	Demonstrates growing mainstream adoption of net-zero strategies at the corporate level.	Ramboll Sustainable Buildings Market Study 2023	1,300 stakeholders (investors, developers, contractors, architects, facility managers)	Europe, North America, Asia, Middle East
Among net-zero adopters with specific carbon targets	92%	Indicates a shift from aspirational statements to concrete carbon-reduction targets.	Ramboll Sustainable Buildings Market Study 2023	1,300 stakeholders (investors, developers, contractors, architects, facility managers)	Europe, North America, Asia, Middle East
Controlling embodied carbon among top design priorities	37–47% (varies by role: architects, engineers, contractors)	Embodied carbon is increasingly prioritized, but not yet universal → implies a partial uptake of WBLC	World Green Building Trends 2021 (Dodge/Carrier)	1,200+ professionals	70 countries, global

Expanded Insights

A. Gap Between Belief and Practice

- 72% consider sustainability during design, but 84% believe it *should* start in strategy.
- This reveals a 12% gap where professionals conceptually value earlier integration but are unable (due to client priorities, data gaps, or tools) to operationalize it.

B. Strategic Momentum

- Half (50%) of companies globally have now embedded net-zero carbon buildings into their strategies.
- This represents a 19% growth compared to the prior survey cycle, showing that net-zero is moving from niche to mainstream.

C. From Vision to Measurement

- Of those pursuing net-zero, 92% now have specific targets, a 30% rise in measurable commitments compared to earlier surveys.
- This indicates an industry shift from broad aspirations ("we will reduce carbon") to quantifiable pathways ("we will cut 40% by 2030").

D. Embodied Carbon Priorities

- Only 37–47% place embodied carbon in their top three design priorities.
- While improving, this shows embodied carbon is still treated as secondary compared to operational energy, even though it represents 50–70% of life-cycle emissions in many buildings.

Implications for Early Design Stage

- High Leverage: Surveys confirm that most professionals *acknowledge* early-stage integration is ideal (84%), aligning with studies that show 70% of sustainability outcomes are locked in early design.
- Adoption Lag: Despite this, fewer than 3 in 4 (72%) actually practice it → leaving significant room for methodological frameworks (like RIB iTWO-enabled LCA, scenario analysis) to close the gap.
- Net-Zero as Driver: With 50% of firms embedding net-zero and 92% of those setting targets, corporate strategy is becoming a key entry point for shifting sustainability earlier in the project lifecycle.
- Embodied Carbon Opportunity: As embodied carbon only features in ~40% of design priorities, early design decisions around material selection, reuse, and circularity remain an underutilized but high-impact lever.

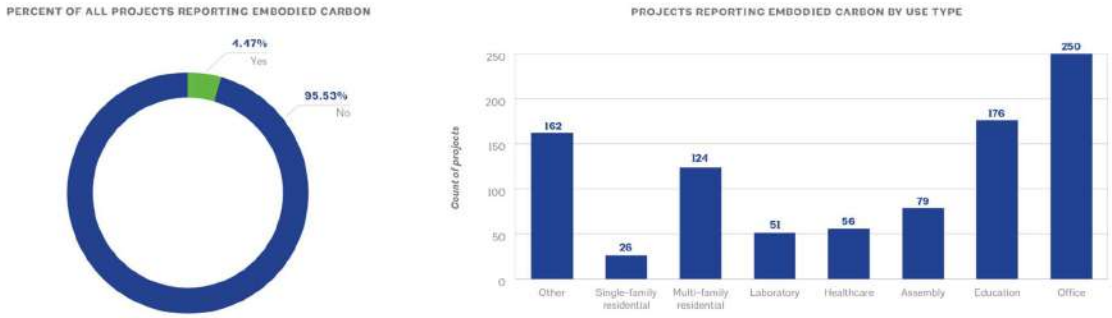


Fig – Percent of reporting embodied carbon , Source - 2021 report AIA 2030

1. Autodesk (2023): AEC Companies with Sustainability Teams

- 82% of architecture, engineering, and construction (AEC) firms reportedly have a dedicated sustainability team in place.
  This suggests a strong organizational commitment to sustainability, though it doesn't guarantee action specifically in the early design phase.

2. AIA 2030 Commitment (2021 Reporting)

In 2021, reporting of embodied carbon in building projects grew substantially compared to the previous year. A total of 83 firms submitted data, up from 55 in 2020, covering 924 projects compared to 292 the year before. This represented 4.4% of all reported projects, a significant increase from just 1% in 2020. The reported projects accounted for a combined 250,439,074 square feet of gross floor area (GFA) a 293.1% increase over 2020 equivalent to 6.9% of all GFA reported that year.

- Only 4.47% of building projects submitted by AIA 2030 Commitment signatory firms included embodied carbon data a notable increase from 1% in 2020, but still representing a very small share of projects. This provides a proxy for early-stage carbon consideration, since embodied carbon modelling is typically conducted early. The low percentage highlights a significant implementation gap.
- Organizational readiness is high: Over 80% of AEC firms have some formal sustainability capacity.
- Early-stage action is lagging: Less than 5% of projects report embodied carbon, indicating that early-stage carbon assessment remains the exception rather than the norm.
- Actual usage in design phase is likely lower: While the Autodesk data signals internal capability, the AIA data shows that actual early-stage practice (e.g., embodied carbon modeling) is still quite rare.

A. 3 - Key Environmental Areas and Proposed EU GPP Approach for Office Buildings, Source: *EU GPP Criteria for Office Building Design, Construction and Management*

Key Environmental Areas in Office Buildings life cycle and Key Environmental Impacts	**Proposed EU GPP Office Buildings approach**
Key environmental areas	
• Primary energy consumption and associated greenhouse gas emissions during use of and travel to and from the building	• Design and construction to achieve high energy efficiency performance and low associated CO_2 emissions
• Depletion of natural resources, embodied energy and emissions associated with the manufacturing and transportation of building materials	• Installation of high efficiency and renewable energy technologies which make use of site-specific opportunities to reduce energy consumption and CO_2 emissions
• Waste generation during site preparation, construction, use and demolition of the building	• Design and specification to reduce the embodied impacts and resource use associated with construction materials
• Deterioration in indoor air quality due to emissions of hazardous substances from building products and the intake of particulate air pollution from the external environment	• Design, specification and site management to minimise construction and demolition (C&D) waste and to use building products or materials with a high recycled or re-used content
• Pollution of the local environment and deterioration of local air quality due to emissions from vehicles used to travel to and from the building	• Specification of fit-out and finishes that minimise hazardous emissions to indoor air
• Water consumption during use of the building	• Ventilation design in order to ensure healthy air and minimise the intake of external air pollution • Specification and installation of water saving technologies
Key life cycle environmental impacts and parameters for resource use:	
• The following environmental impact categories along the product life cycle are considered to be the most important ones: global warming potential, acidification, exploitation of renewable and non-renewable primary energy resources, eco-toxicity, human toxicity, eutrophication, abiotic resource depletion and water consumption, use of secondary and re-used materials and waste material flows	• Installation of physical and electronic systems to support the ongoing minimisation of energy use, water use and waste arisings by facilities managers and occupiers Implementation of staff travel plans to reduce transport related fuel use and CO_2 emissions, including infrastructure to support electric vehicles and cycling

A. 4 - Sustainability values - docking window and option in RIB iTwo

Description	Example	Explanation
Key (Label)	CO2e_Standard	Key to the sustainability label.
Description (Label)	Standard for CO2 equivalent	Designation of the sustainability label.
Key (Input)	CO2e_UoM	Key of the input value.
Description (Input)	CO2 equivalent (CO2e) per UoM	Description of the input value.
Type (Input)	Eco-phase	Data type of the input value.
Display line (input)	1	Display line for the input value.
Base value (input)	144.90	A recorded base value for the input value. Can be selected via F3 e.g. from data catalogues or entered freely. When selecting via a data catalogue, the reference to this data catalogue element is saved, but the value can still be customized individually.
UoM Base value (Input)	kg/m3	Unit of measure for the base value.
Data catalog – Key	1.4.01.011 [ECO]	Key to the reference element of the data catalogue element.
Data catalog – Description	Concrete C20/25 XC1 XC2 F3 16 M EcoPact, recipe number DI3234-BHFS version 1, ready mixed concrete plant Frankfurt, Germany	Description to the reference element of the data catalogue element.
Conversion factor (input)	0.24	Conversion factor for converting the base value into the target unit of measure 'UoM (Input)'. A calculation approach can also be entered here. e.g.. 2*0,12 The result is displayed when you leave the field. When the input cell is activated, the calculation approach is used again.
Value (input)	34.77	Result from base value (input) * conversion factor (input).
UoM (Input)	kg/m2	Unit of measure of the value (input).
Comment (input)	Standard material value; may need to be adjusted;	Free commentary for the underlying (input).

Key (Output)	CO2e	Key of the output value.
Description (Output)	CO2 equivalent (CO2e)	Description of the output value.
Type (Output)	Decimal number	Data type of the output value.
Total (output)	15.618	Total value based on the input value 'Value (input)' and the decisive quantity, or the formula stored for the output value.
UoM (Output)	to	Unit of measure for the output value.

A. 5 - Sustainability values - Component and Material Breakdown of Base Case

Component	**Material / Specification**
WALL	Type A: 115 mm perforated brick 2DF
	Type B: 240 mm perforated brick 16DF
	Type C: 310 mm perforated brick 20DF
	Type C – Parapet wall, fired brick perforated
CONCRETE WORKS	In-situ concrete floor slab, CEM III/A C25/30 ECOPARK
	In-situ concrete for slab, CEM III/A C25/30 ECOPARK
	In-situ concrete for slab, CEM III/A C25/30 ECOPARK
COLUMN & BEAM	Prefabricated post type PES
	Prefabricated post type PES
	Precast beam type PEC
OTHER WORKS	Cement plaster, 1-layer
	Curtain window, pane insulating glass MIG 3

A. 6 - Sustainability values - Component and Material Breakdown of Case 1

Component	**Material / Specification**
WALL	Type A: 115 mm fired brick
	Type B: 240 mm fired brick W1
	Type C: 310 mm fired brick W1

	Type C – Parapet wall, fired brick
CONCRETE WORKS	In-situ concrete C20/25_XC1
	In-situ concrete floor slab, C20/25_XC1
	Concrete for beam slab, C20/25_XC1
COLUMN & BEAM	Prefabricated post type PE4
	Prefabricated post type PE4
	Precast beam type T_PE3
OTHER WORKS	Cement plaster, 1-layer
	Curtain wall, insulated glazing, triple-pane

A. 7 - Sustainability values - Component and Material Breakdown of Case 2

Component	**Material / Specification**
WALL	Type A – Mineral fibre board
	Type B: 240 mm fired brick W1
	Type C: 310 mm Abode
	Type C – Parapet wall, Abode
CONCRETE WORKS	Roof panel concrete, C25/30 X4
	In-situ concrete floor, C25/30 X4
	In-situ concrete roof, C25/30 X4
COLUMN & BEAM	Prefabricated post type PE4
	Support type S452
OTHER WORKS	Cement plaster, 1-layer
	Curtain wall, multi 3-pane insulating glass

A. 7 - Sustainability values - Component and Material Breakdown of Case 3

Component	**Material / Specification**
WALL	Type A – Gypsum fibre board
	Type B: 240 mm fired brick W1
	Type C: 310 mm Abode
	Type C – Fibre cement panels
CONCRETE WORKS	Roof panel
	Precast concrete slab PS2
	Precast concrete slab PS2
COLUMN & BEAM	Prefabricated post type PE4
	Post type S452
	Support type S452
OTHER WORKS	LayTec clay topcoat plaster, 1-ply
	Curtain window 3-pane insulating glass

A. 8 - Contribution to Sustainable Development Goals and Policy Frameworks

This thesis contributes to the wider sustainability agenda by engaging with several of the United Nations Sustainable Development Goals (SDGs) as well as European climate policies.



Most directly, it relates to SDG 13 (Climate Action) by examining how embodied carbon can be addressed at the earliest stages of building design, when the scope for influence is greatest. Through the case study, it shows that strategies such as material substitution, optimisation of structural design, and scenario modelling can achieve measurable reductions in embodied emissions. These findings support wider climate objectives, including the targets of the Paris Agreement and the European Green Deal, which emphasise early intervention to limit global warming.

The integration of Environmental Product Declarations (EPDs), circular economy strategies, and lifecycle-based cost–carbon evaluation also connects with SDG 12 (Responsible Consumption and Production) by promoting resource efficiency, material transparency, and more responsible construction practices.

In addition, the research contributes to SDG 11 (Sustainable Cities and Communities) by demonstrating how carbon-intelligent planning can be embedded into digital workflows, helping architects and planners design buildings that are more resilient and resource-efficient in the long term.

At the same time, the work engages with SDG 8 (Decent Work and Economic Growth) by highlighting opportunities for innovation in sustainable construction sectors, such as prefabrication, modular construction, and the use of renewable or locally sourced materials, which have the potential to support green jobs and fairer economic growth.

Beyond the UN SDGs, the study aligns with European policy instruments, including the EU Taxonomy Regulation, the Level(s) framework, and the EU Green Deal's decarbonisation roadmap, all which stress lifecycle assessment, procurement transparency, and carbon disclosure as essential elements of sustainable finance and compliance. While the research does not claim to provide a comprehensive solution to the challenges of carbon reduction in the built environment, it demonstrates how tools such as RIB iTWO can begin to bridge the gap between conceptual design and quantifiable carbon outcomes. In this sense, the study aims to make a modest but practical contribution by showing how early-stage digital workflows can help operationalise sustainability goals into design practice and support the transition towards a more climate-conscious construction sector.