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Enhancing Material Efficiency in Construction through BIM-Based Circular Economy Approaches: A Framework for Sustainable Building Design

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Research aim and tasks

The research aim:

Introduce an innovative decision-making approach that integrates Circular Economy (CE) principles into Building Life Cycle Assessment (LCA), enhancing sustainability across the entire building life cycle for increased resource efficiency and circularity in construction.

Research Tasks:

1. Develop a comprehensive understanding of the circular economy's relationship with sustainability in construction.

2. Propose a Building Information Modeling (BIM) model for Latvian office buildings with three alternative design possibilities.

3. Execute a Building Life Cycle Assessment (LCA) following sustainability principles, considering societal costs, carbon emissions, and Life Cycle Inventory Analysis (LCIA).

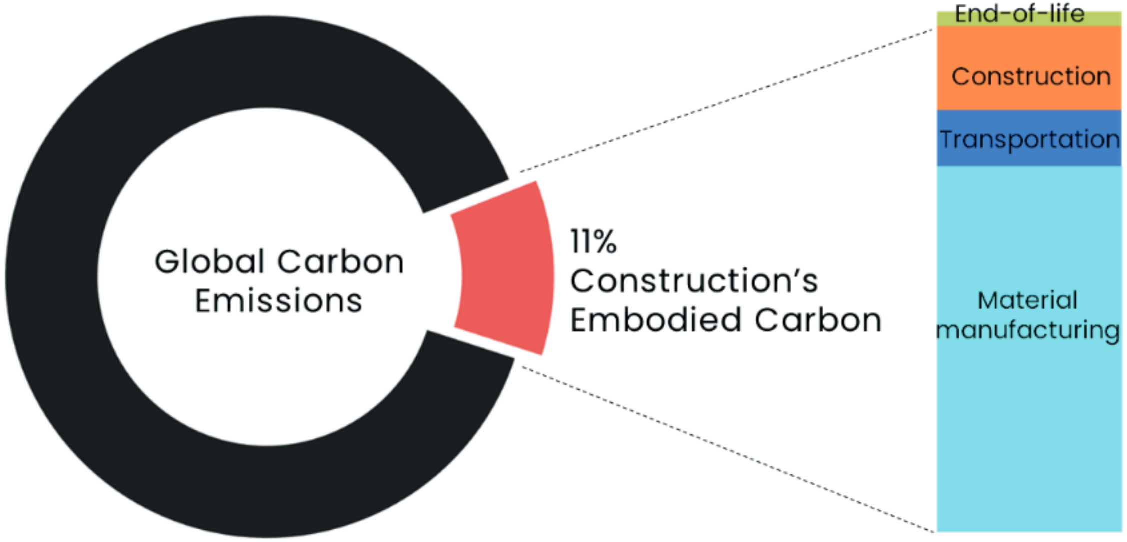
4. Systematically rank design categories using the Best Worst Decision-Making (BWM) approach and TOPSIS, recommending prioritization of highly ranked findings for early design stages.

Research Terminology

- **Best Worst Decision-Making (BWM):** A method for systematically ranking alternatives based on identified best and worst criteria.
- **Building Information Modeling (BIM):** A digital 3D model-based process for efficient building design, construction, and operation.
- **Circular Economy:** An economic model promoting resource regeneration, waste reduction, and sustainable product design.
- **Circular Economy Integration:** Incorporating circular economy principles into business, design, and production for sustainability.
- **Green Building Design:** Designing environmentally responsible structures using sustainable materials and energy-efficient systems.
- **Life Cycle Assessment (LCA):** A systematic evaluation of a product's environmental impact throughout its entire life cycle.
- **Reusability:** The ability of a product or material to be used again without significant degradation in performance, promoting sustainability.
- **EPD:** An Environmental Product Declaration (EPD) is a standardized document providing information on the environmental impact of a specific building material. It facilitates easy comparison of environmental data, aiding in informed choices for sustainable construction practices.

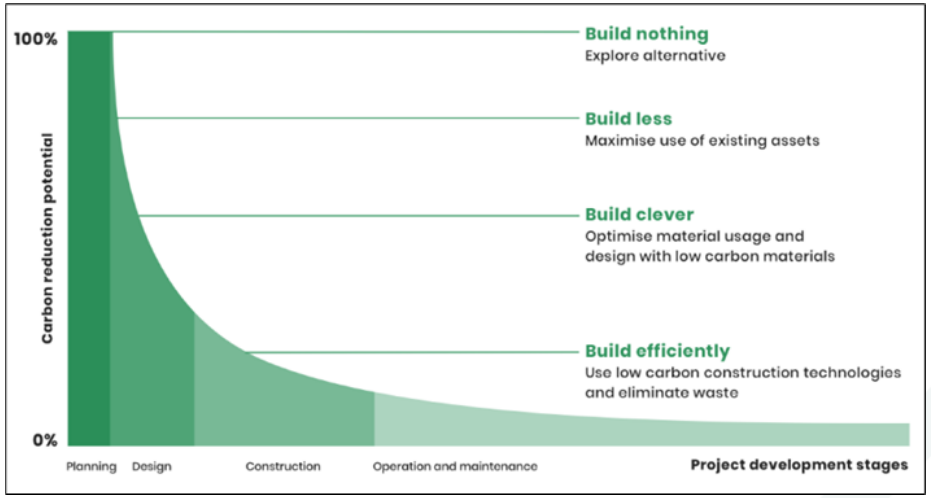
The Role of Design Phase on Embodied Carbon Impact

Contribution of embodied carbon



Life Cycle Stages, 2023

Embedded carbon reduction opportunities decrease with project advancement



(Decarbonizing construction, 2021, WBCSD) (Building Life Cycle Assessment Ebook - One Click LCA® Software, n.d.)2)

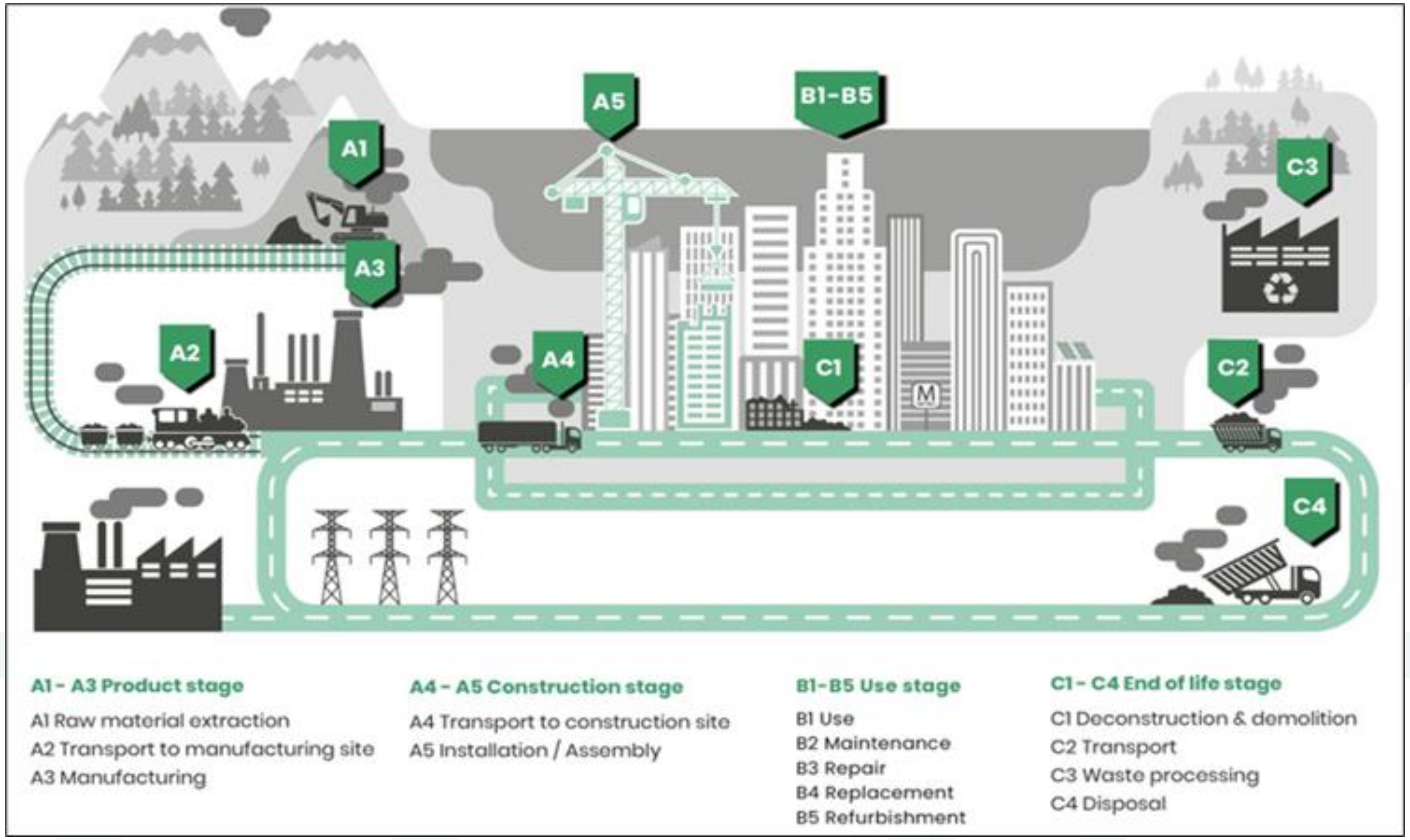
Embodied Carbon Impact: Encompasses emissions across the entire life cycle of building materials (extraction to disposal), contributing to 11% of global CO2.

Shifting Focus: Traditionally, efforts targeted operational carbon, but due to energy sector decarbonization, attention is now on embodied carbon.

Global Urgency: With construction responsible for 39% of global CO2 emissions, countries are setting limits to urgently reduce embodied carbon in the sector.

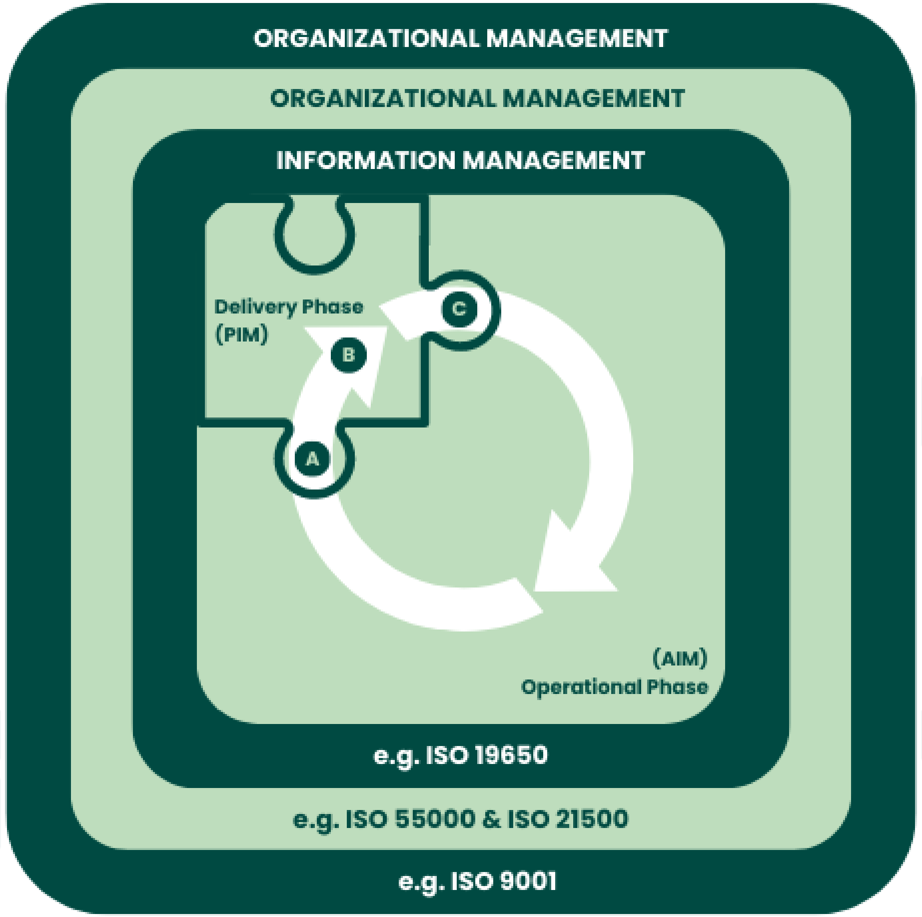
Building Life cycle

- Pre-construction (A1–A3): Involves raw material collection, processing, production, and delivery. Construction (A4 and A5): Building components are built, assembled, and installed on-site. (B1–B7): Represents the building’s operational phase, including energy consumption and maintenance. End of Life (C1-C4): Involves deconstruction, dismantling, and disposal or recycling of building materials.



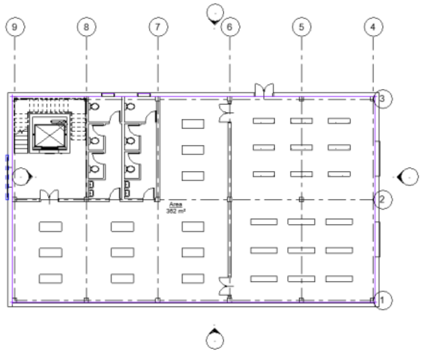
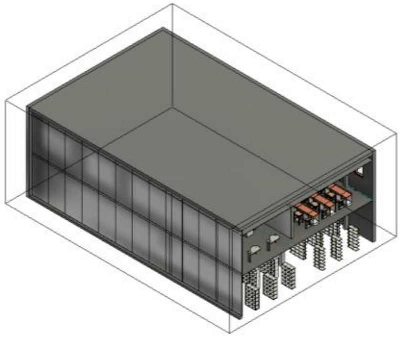
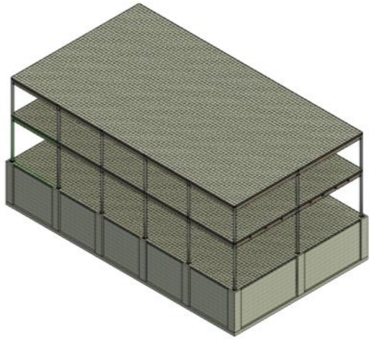
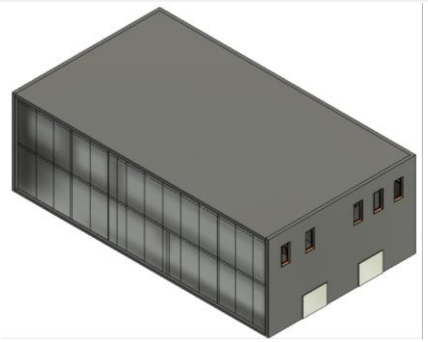
ISO 19650, the Role of BIM in Building Life Cycle

- BIM, according to the BIM Dictionary, encompasses technologies, methods, and rules facilitating collaborative design, construction, and operation within a virtual environment.
- ISO 19650 part 1 characterizes "BIM" as a collaborative digital representation of a built asset, enhancing efficiency across design, construction, and operation phases, providing decision-makers with a robust foundation.
- BIM is essentially a product of digital progress in the construction industry and the built environment, as highlighted by X. Pan et al. in 2023.
- Seamless communication and collaboration during design, construction, and use are facilitated by the integration of BIM authoring software (Revit) and specialist design software, centralizing all processed data.

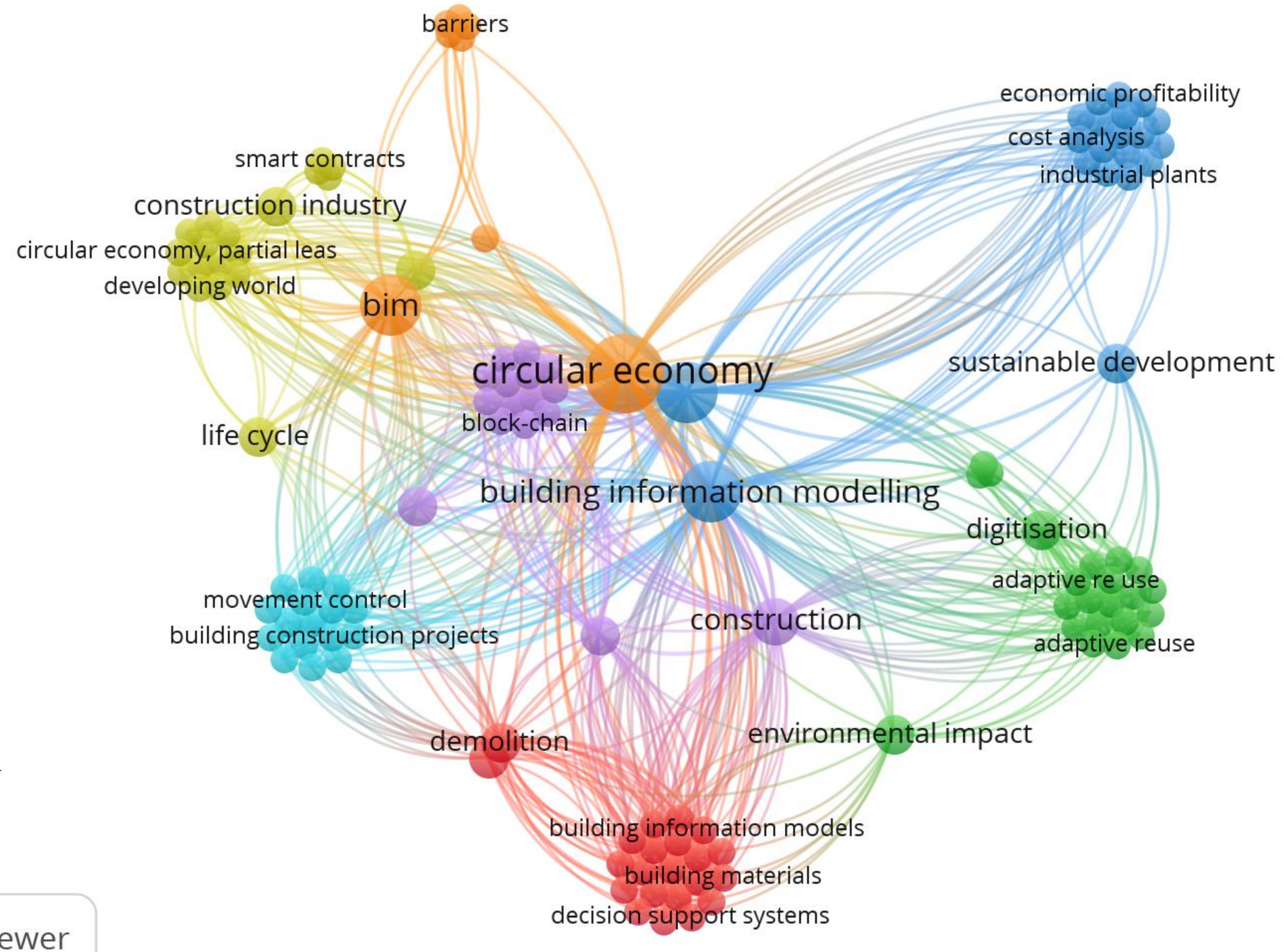


https://catenda.com/glossary/iso-19650/

Proposed Model

	Concept Design	*Detailed Design*	*Procurement*	*Use Stage*
Construction Stages	 Sketch or Concept	 BIM Model	 Construction Phase	 Use & Adaption
Material Quantities	Data can be obtained from cost estimation or early design tools	In this stage the material can be identified. The level of design (LOD) can affect on results	Benchmarking select best products from manufactures EPDs	Actual quantities
Possible Solutions	Carbon Designer Baseline	Compare Designs	Benchmarking select best products from manufactures EPDs	Interior fit outs and refurbishments

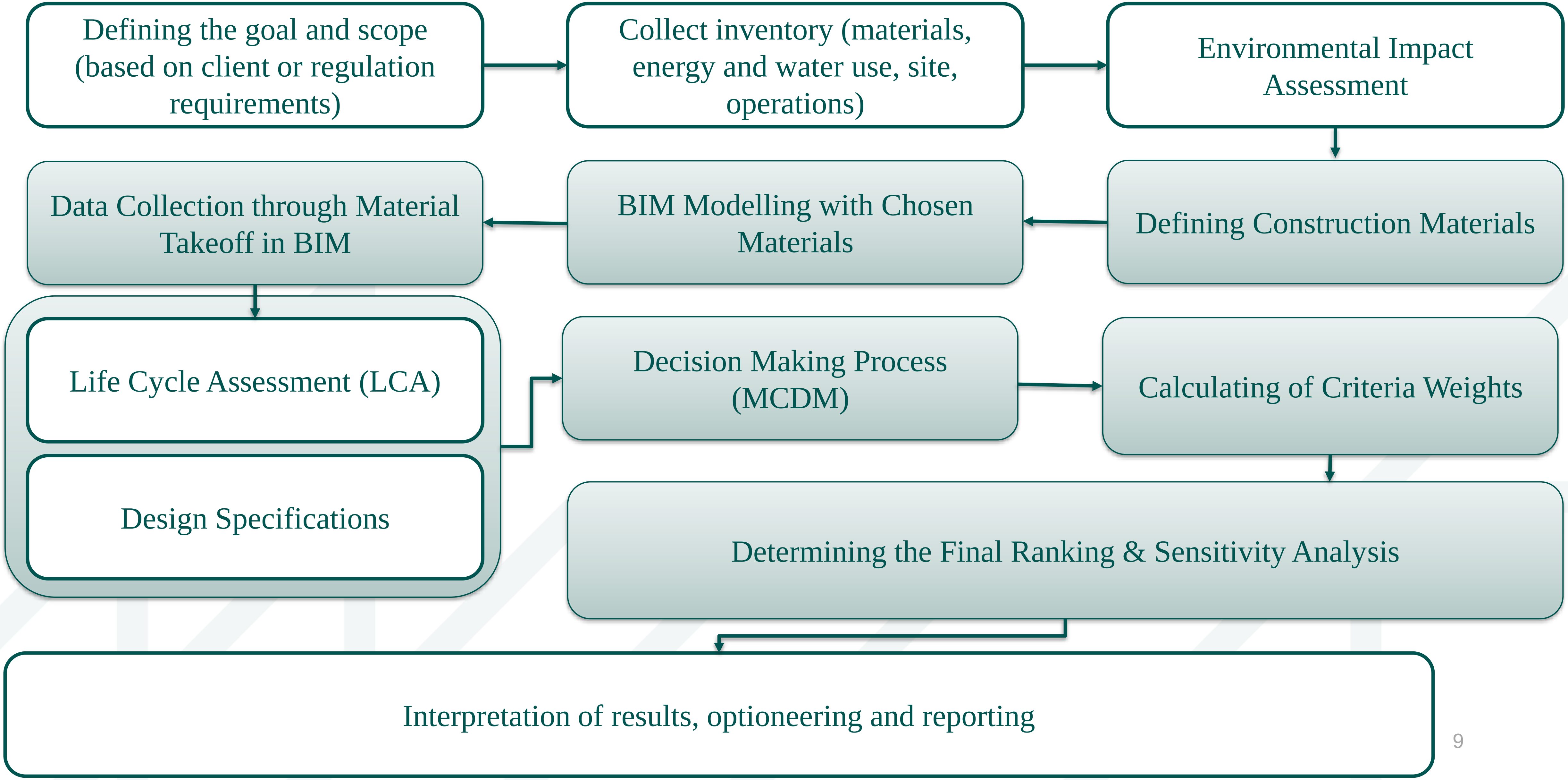
Most Keywords Used by Authors from 2020 to 2024



Most Keyword used by authors

VOSviewer

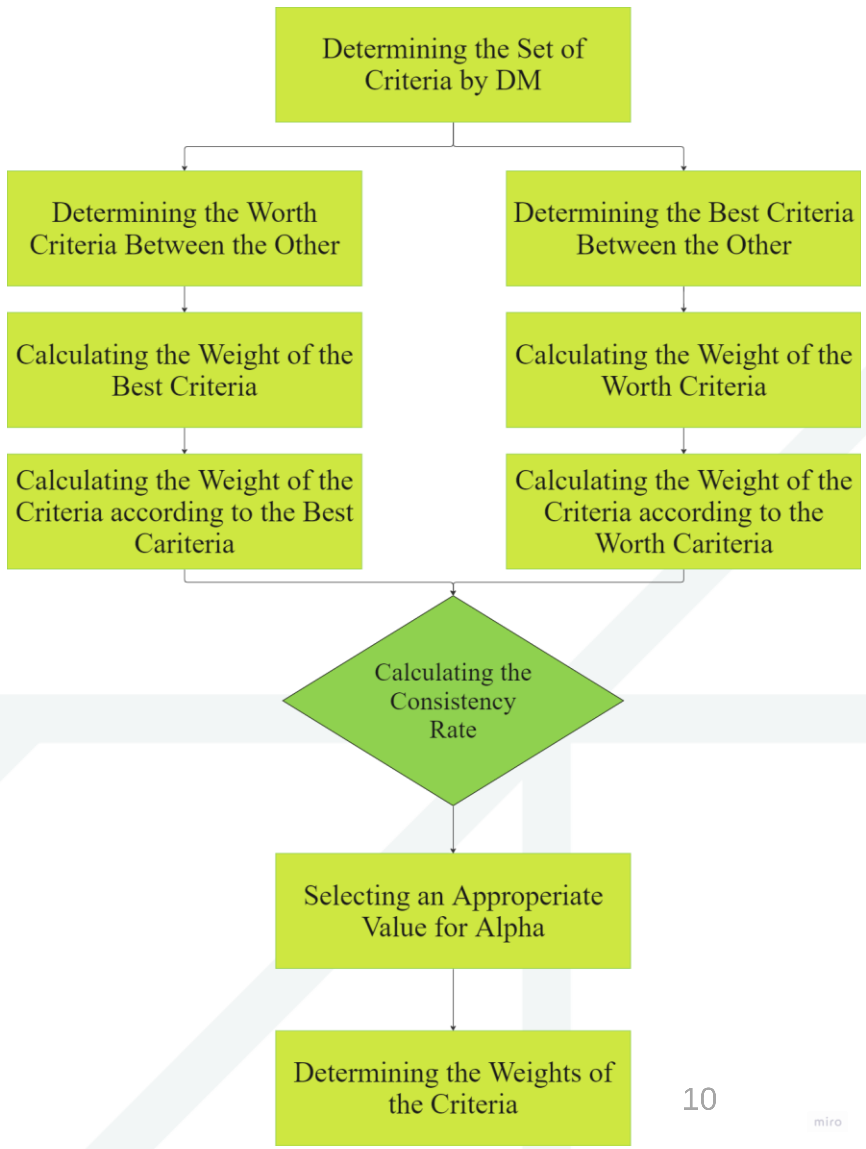
Suggested Flow Chart



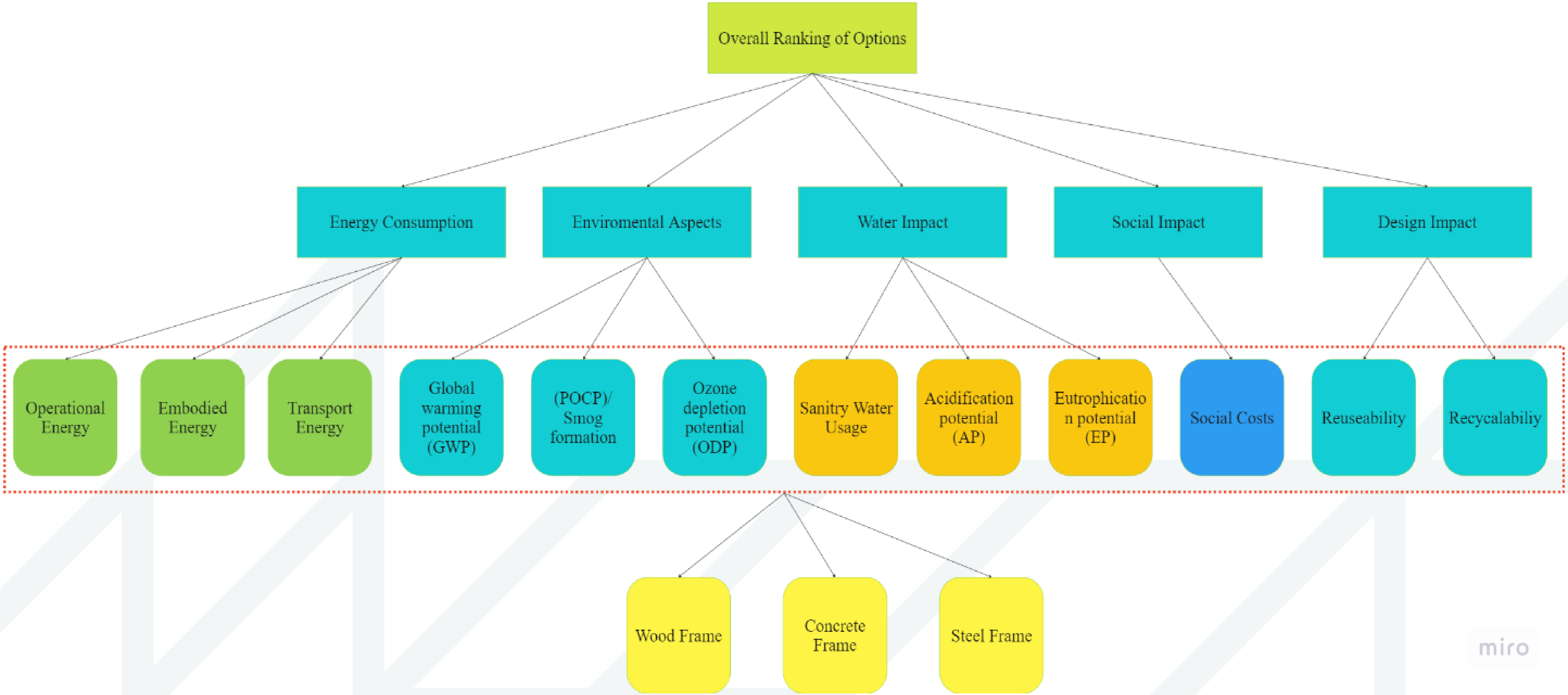
Best Worst Decision-Making Method

- **Criteria Identification:** Define criteria relevant to the decision context.
- Selection of Best and Worst: Determine the best and worst criteria among the identified set.
- **Weight Assignment:** Assign weights to each criterion based on its importance relative to others.
- **Scoring Alternatives:** Score alternatives against each criterion.
- **Calculation:** Compute overall scores for alternatives using the assigned weights.
- **Ranking:** Rank alternatives based on their total scores.

- **Pairwise Comparison in Decision-Making:** Decision-maker expresses preference strength and direction for option i over option j. Typically straightforward for decision-makers to articulate preferences (Rezaei, 2015). Nevertheless, articulating the intensity of one's choice is a challenging endeavor and serves as a primary contributor to incongruity. (Rezaei, 2015).



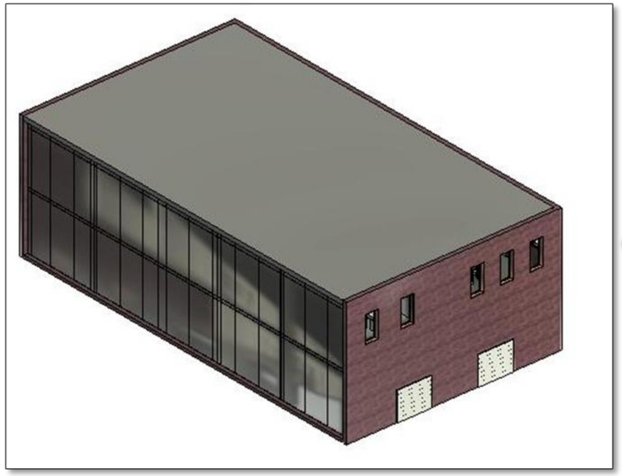
Development a Solution

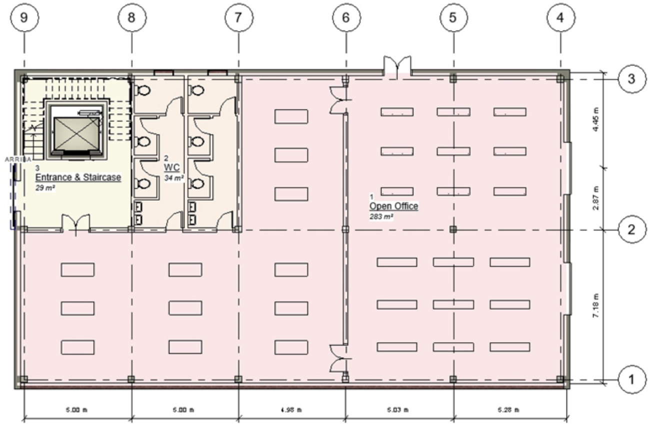


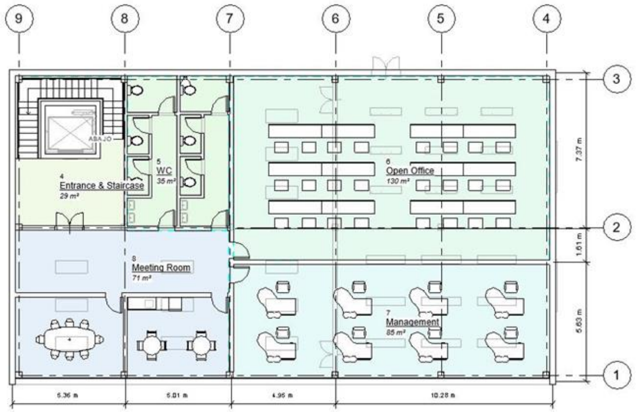
Model Description

Number of People	15 people
Average Lighting Power Density	10.76 W / m²
Average Equipment Power Density	13.99 W / m²
Specific Fan Flow	4.4 LPerSec / m²
Specific Fan Power	1.256 W / LPerSec
Specific Cooling	13 m² / kW
Specific Heating	5 m² / kW
Total Fan Flow	1,356 LPerSec
Total Cooling Capacity	24 kW
Total Heating Capacity	56 kW
Energy Use Intensity (EUI)	1,858 MJ / m² / year
Annual Electric Usage	48,285 kWh
Annual Fuel Usage	393,742 MJ
Annual Peak Demand	14.5 kW

Introduces a two-story residential building modeled as an office space with a ground floor area of 362 m2 and three structural scenarios (steel, concrete, timber).



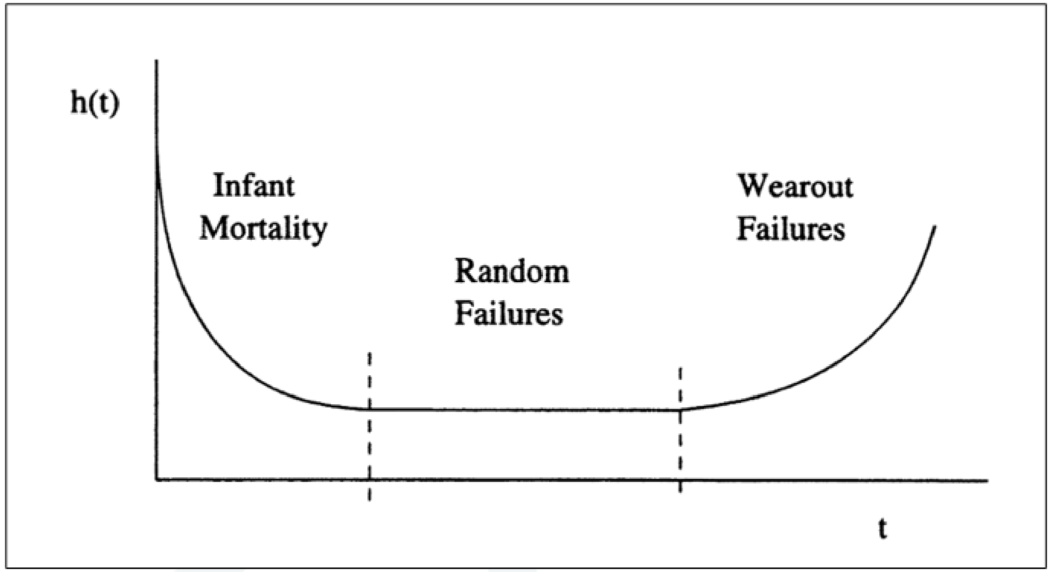




Office Room Schedule

Name	Level	Area (m^2)	Perimeter (m)
Open Office	Level 1	282.94	109.65
WC	Level 1	33.88	23.74
Entrance & Staircase	Level 1	28.51	24.44
Entrance & Staircase	Level 2	28.52	24.44
WC	Level 2	35.30	24.29
Open Office	Level 2	130.22	48.43
Management	Level 2	85.14	42.01
Meeting Room	Level 2	71.02	34.37

Weibull Distribution Function used for Modelling



$$F(t) = 1 - exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right),\ t \geqslant 0$$

α is scale parameter, β is shape parameter and t is time

$$S_{ru} = \left(\beta\frac{ndc}{nc} + \gamma\frac{nfb}{ne} + \mu\frac{\nu\bar{S}_f}{\nu m} + \rho\frac{\nu\bar{h}_t}{\nu m}\right) * \left(1 - e^{t-\alpha} - \frac{t}{10*\alpha}\right)$$

$$S_{rc} = \left(1 - \left(\beta\frac{ndc}{nc} + \gamma\frac{nfb}{ne} + \mu\frac{\nu\bar{S}_f}{\nu m} + \rho\frac{\nu\bar{h}_t}{\nu m}\right)\right) * \left(1 - e^{t-\alpha} - \frac{t}{10*\alpha}\right)$$

ndc is the specified number of demountable connections in a design and nc is the total number of connections in a building. (fb) is the proportion of prefabricated assemblies used to total number of building elements. nfb represents the number of prefabricated assemblies, and ne represents the total number of building elements. T is the average building life expectancy. Sf is the ratio of the volume of materials without secondary finishes to the total volume of materials used for the building and ht shows the ratio of the volume of materials free of hazardous and toxic materials to the total volume of building material

Modelling in software (Revit 2024)

D	E	F	G	
ial: Volume	Count	Reuseable	Recycable	De
	1	☑	☑	☑
	1	☑	☑	☑
	1	☑	☑	☑
	1	☑	☑	☑
	1	☑	☑	☑
	1	☑	☑	☑
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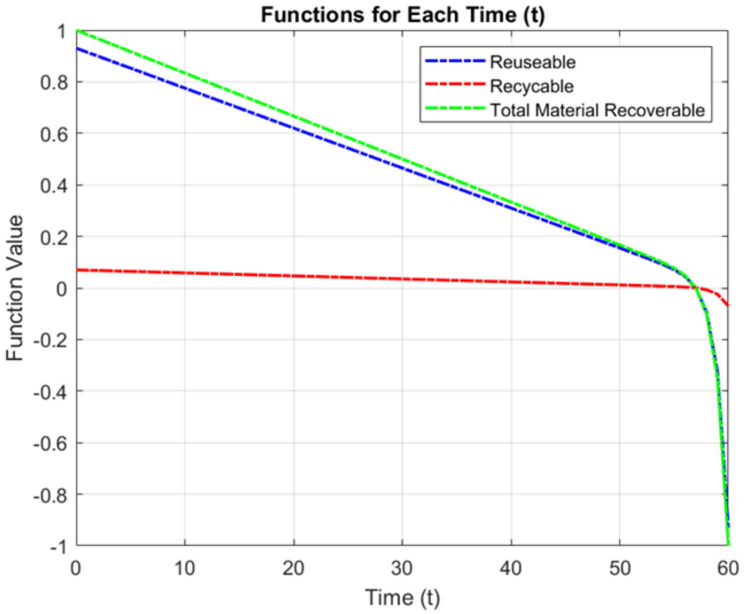
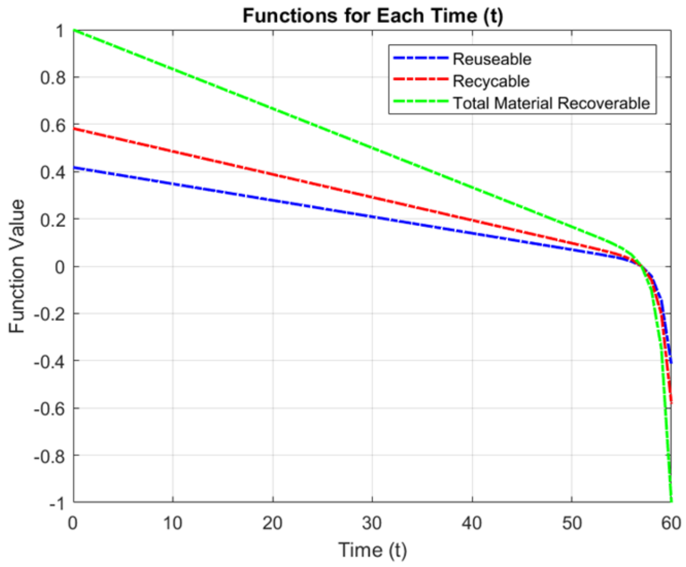
	1	☑	☑	☑
	1	☑	☑	☑
	1	☑	☑	☑

Systems and options	Recyclable (r_1)	Reusable (r_2)	Toxic (x)	Sec. Finish (s)
1. Structural Foundations				
H-Pile foundation	✓	✓	×	×
Concrete ground beam	✓	×	×	×
Concrete with mastic tanking	✓	×	×	×
2. Floor system				
Insitu Concrete floor with ceramic tiles	✓	×	×	×
Precast Concrete slab with carpet	✓	×	×	×
Timber floor with ceramic tiles	✓	✓	×	×
3. Structural frame system				
Exposed Steel with fixed connections				
Concrete Encased Steel with fixed connections	✓	✓	×	×
Exposed Steel with bolted connections	✓	×	×	×
Concrete Encased Steel with bolted connections	✓	✓	×	×
Timber with bolted connections	✓	✓	×	×
Timber with nailed connections	✓	×	×	×
Reinforced Concrete with bolted connections	✓	✓	×	✓
4. Wall system				
Demountable dry internal wall – Steel				
Curtain wall	✓	✓	✓	✓
Brick/block cavity wall	✓	✓	×	×
Cladded timber cavity wall	✓	×	×	✓
Steel framed wall	✓	×	×	✓
5. Doors and windows				
Glass with aluminium frame				
Timber with timber frame – Softwood	✓	✓	×	×
Timber with timber frame – Hardwood	✓	✓	×	✓
6. Ceiling system				
Aluminium strips with steel frame	✓	×	×	✓
Soffit plaster and paint	✓	✓	×	×
Timber planks with timber frame	✓	✓	×	✓
Ceiling tiles with metal frame	✓	✓	×	✓
7. Roof system				
Flat galvanised steel on Z profile beams	✓	✓	×	×
Reinforced concrete roof with sand/cement screed	✓	✓	×	×
Pitched roof timber structure	✓	×	×	✓
Tiles covering on pitched roof	✓	✓	×	×

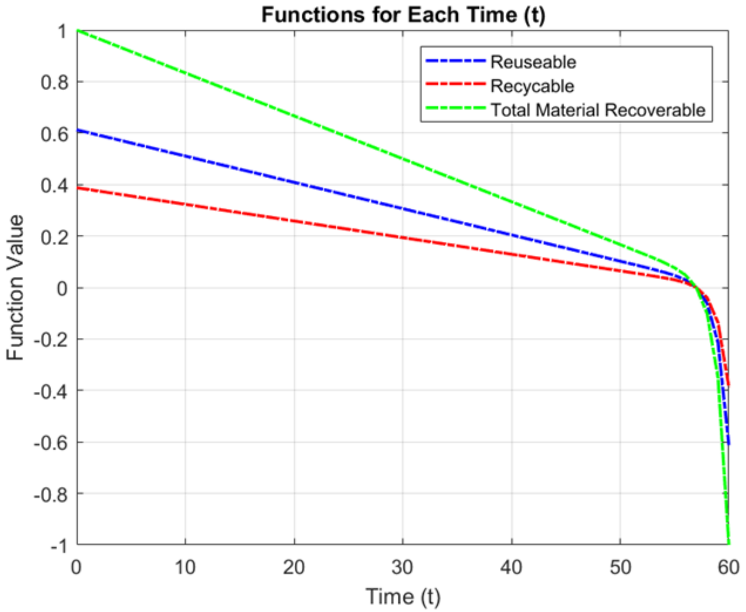
Design specification Related Graphs sample



Steel Structure



Concrete Structure



Wood Structure

Compare Elements by Category

Carbon Footprint Comparison:

- Steel frame exhibits the highest global warming potential, while wood structure has a lower and more balanced carbon footprint. Concrete frame shows a carbon footprint comparable to steel.

Key Contributors:

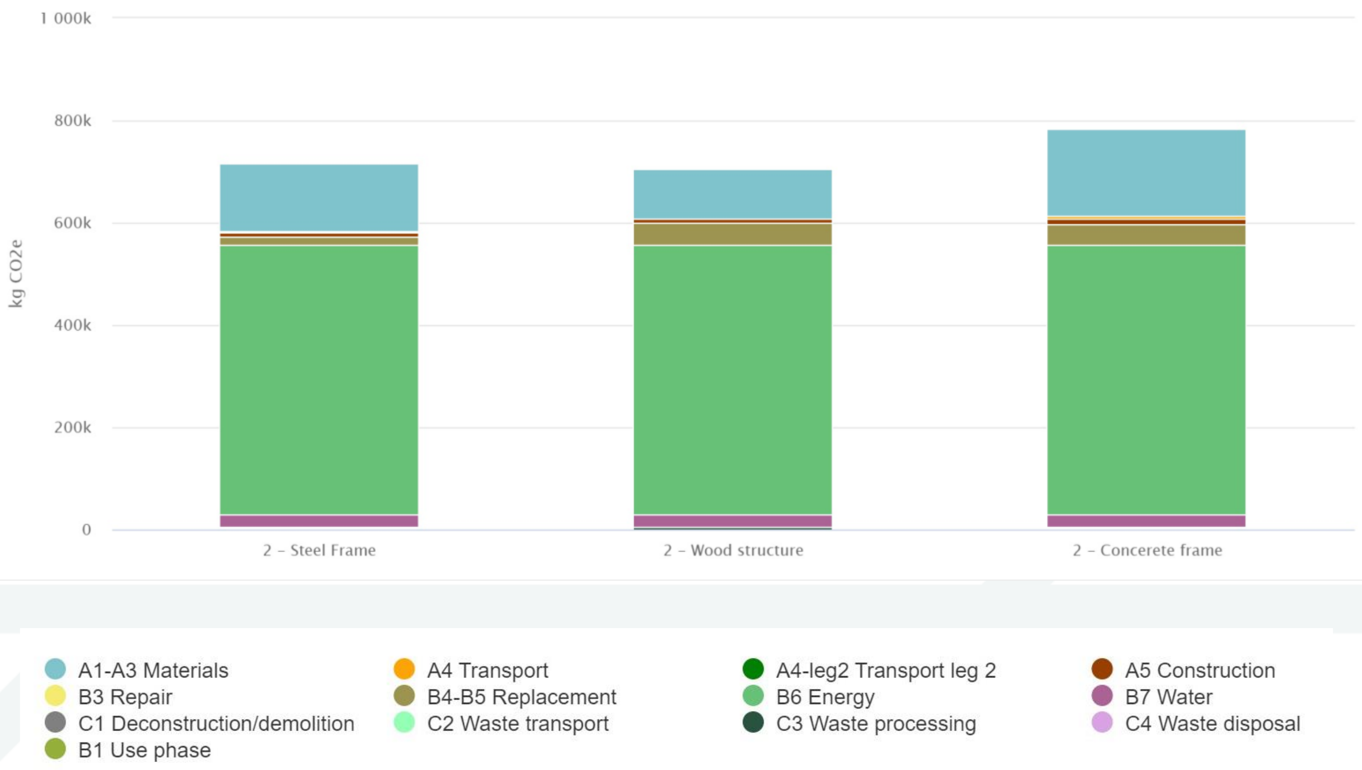
- Frame, internal walls, and external wall systems are major contributors to emissions in both steel and concrete structures. Wood structure displays a more evenly distributed impact across categories.

Energy Focus:

- Electricity use is a significant factor in the carbon footprint for all structures. Wood structure, though lower overall, has higher impacts in hot water distribution and electricity use.

Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO2e - Life-cycle stages

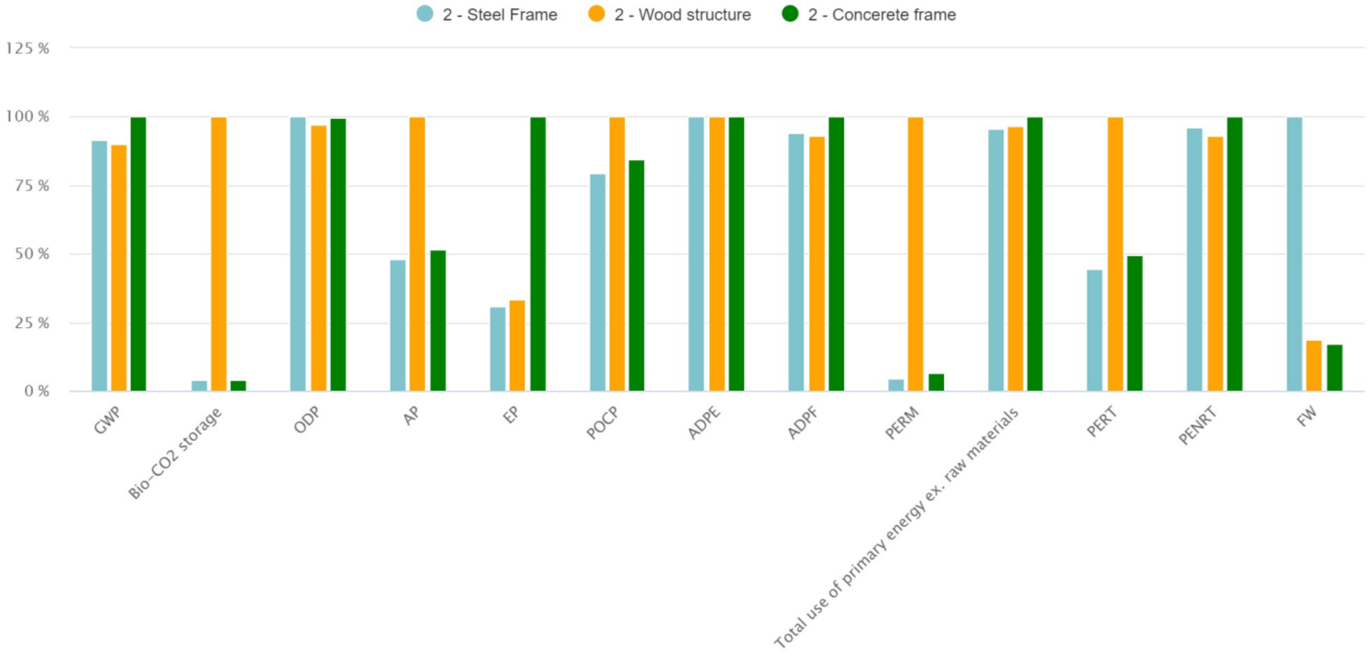
Materials Production (A1-A3): Steel frame has the highest emissions, followed by concrete and wood structures.
Transport (A4): Steel has lower transport emissions than wood, with concrete in between.
Construction (A5): Concrete frame exhibits the highest emissions during construction, followed by steel and wood.
Energy Use (B6): Steel has the highest energy-related emissions, and the use phase significantly contributes to all structures.
Replacement (B4-B5): Wood has higher emissions during replacement, while concrete shows higher emissions in deconstruction/demolition.
Waste Handling (C2-C3): Steel demonstrates lower emissions in waste transport and processing.
Transport Leg 2
(A4-leg2): All structures show relatively low impact in transport efficiency.



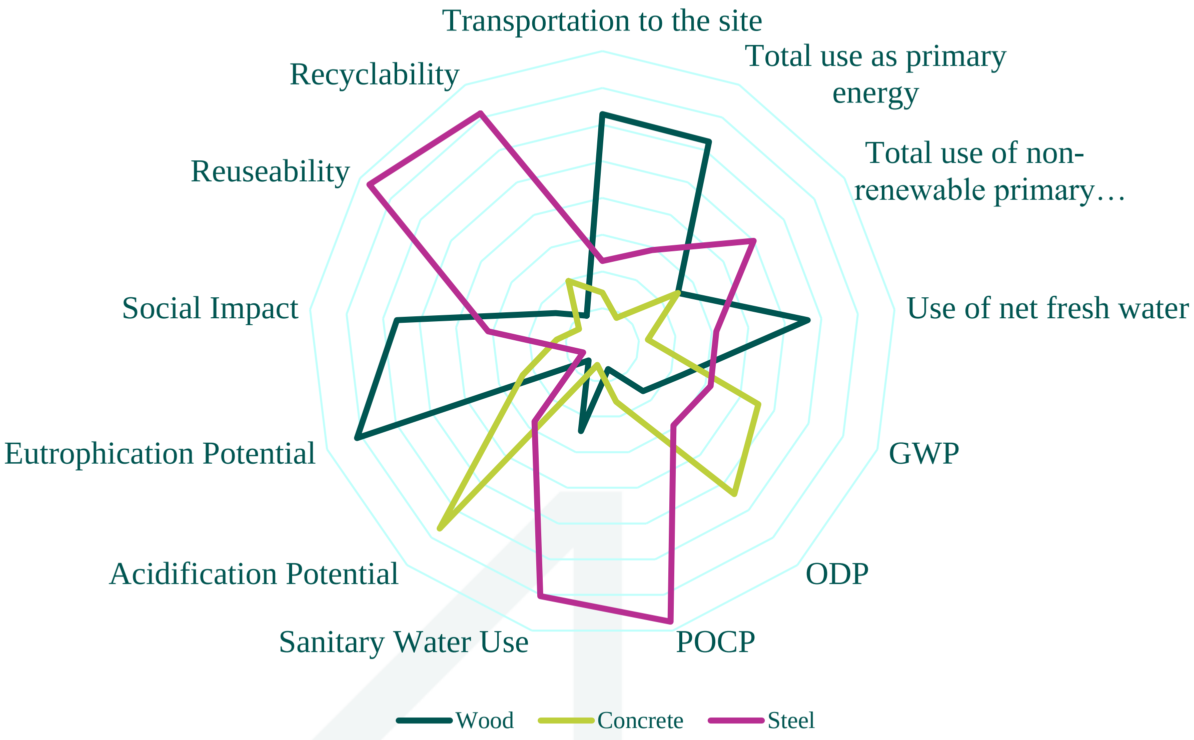
Life cycle assessment (EN15804 +A1) - All impact categories

- Wood Structure generally performs well across multiple impact categories, especially in Bio-CO2 storage, EP, and ADPE.
- Steel Frame excels in PERT and PENRT, showcasing a better balance of renewable and non-renewable energy use.
- Concrete Frame exhibits higher impacts in GWP, AP, and FW, indicating potential environmental concerns in these areas.

Level(s) assesses building sustainability via EN15804 +A1 LCA. Comparing three construction options, Wood Structure excels in Bio-CO2 storage, Eutrophication, and ADPE. Steel Frame balances renewable energy use, while Concrete Frame shows higher impacts in GWP, Acidification, and Freshwater Consumption.



Topsis Method for Ranking the Results

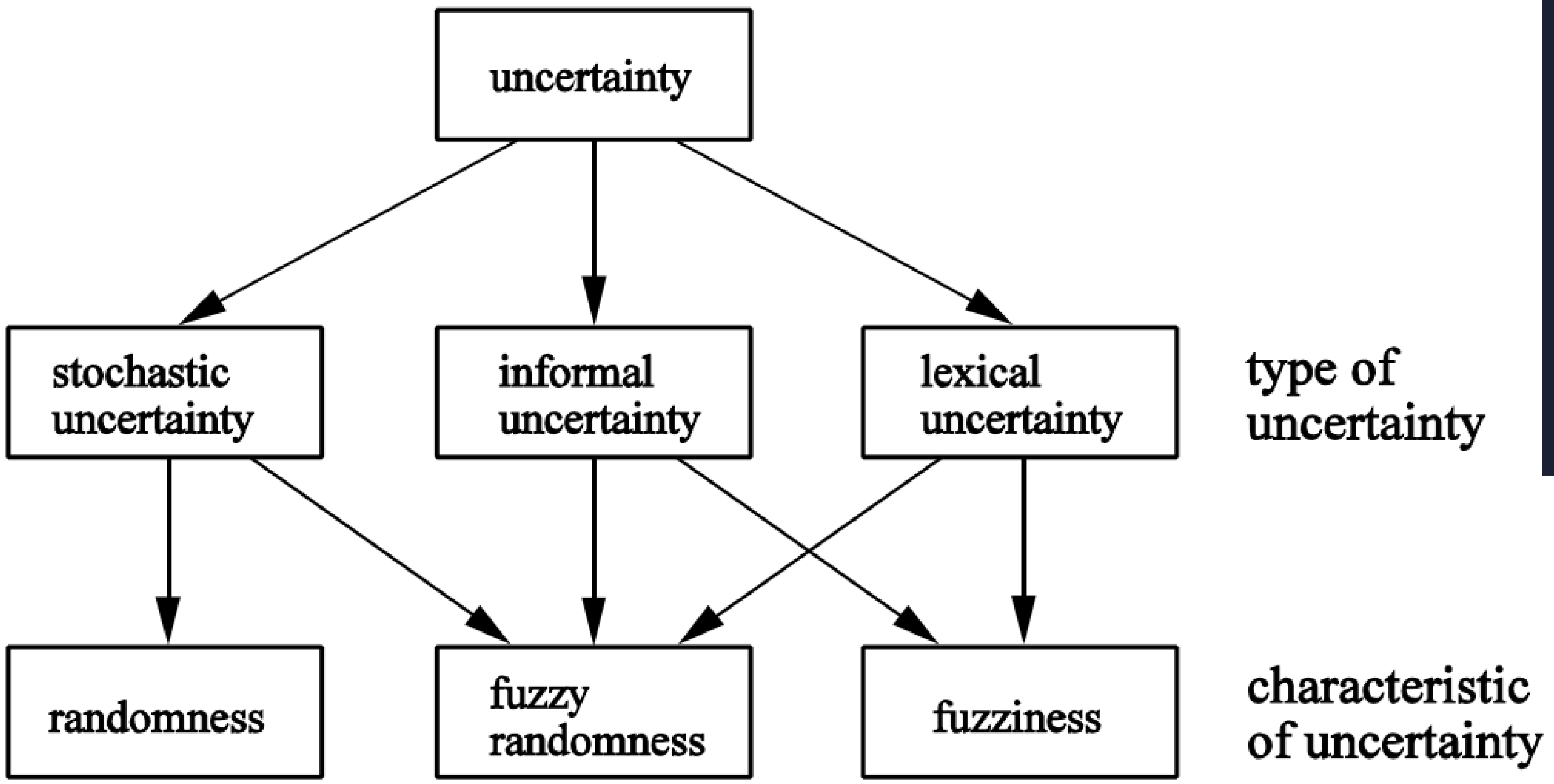


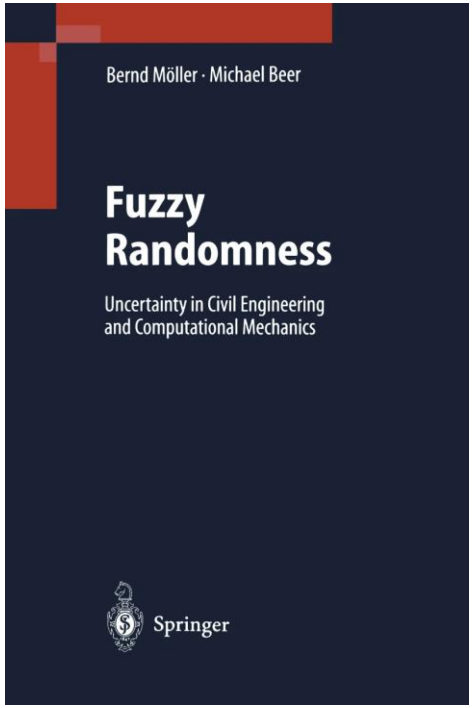
Category	TOPSIS	Rank
Transportation to the site	0.236167	12
Total use as primary energy	0.527092	1
Total use of non-renewable primary energy	0.227162	13
Use of net fresh water	0.510657	2
GWP	0.311228	11
ODP	0.50776	3
POCP	0.355578	10
Sanitary Water Use	0.367798	7
Acidification Potential	0.473107	4
Eutrophication Potential	0.45303	5
Social Impact	0.384497	6
Reusability	0.364694	9
Recyclability	0.365496	8

This study employs optimal and suboptimal weights for criteria, crucial for a fair and comprehensive assessment of Wood, Concrete, and Steel frames using TOPSIS ranking. Total use as primary energy holds the highest Shannon Weight, emphasizing its impact on project sustainability. Notably, Wood structures emit less carbon, positioning them as low-carbon structural materials. Shannon Entropy highlights the significance of energy-efficient design and water consumption throughout the building's life cycle. Prioritizing "Reusability" and "Recyclability" supports a circular economy, promoting green and socially responsible construction decisions for architects and builders.

How the Approach should Be?

Classification of Uncertainty





Fuzzy Normal Distribution Function

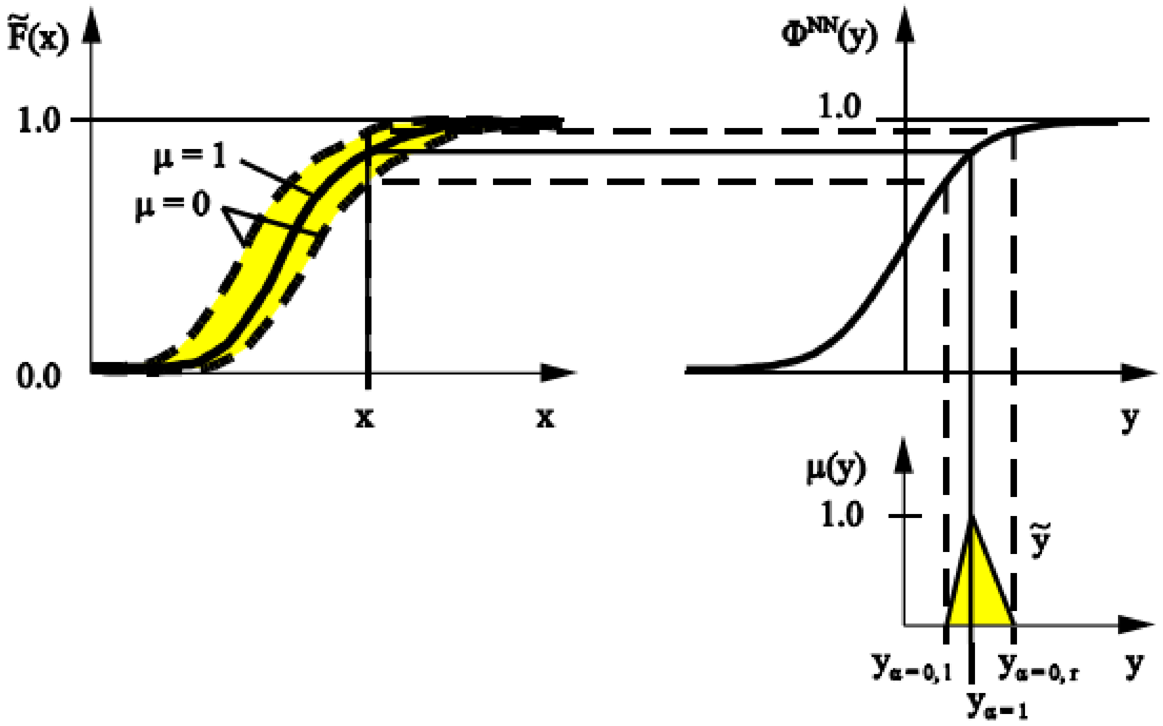


Fig. 8 Transformation of fuzzy random variables into standard normalized random variables

Fuzzy Limit state Function

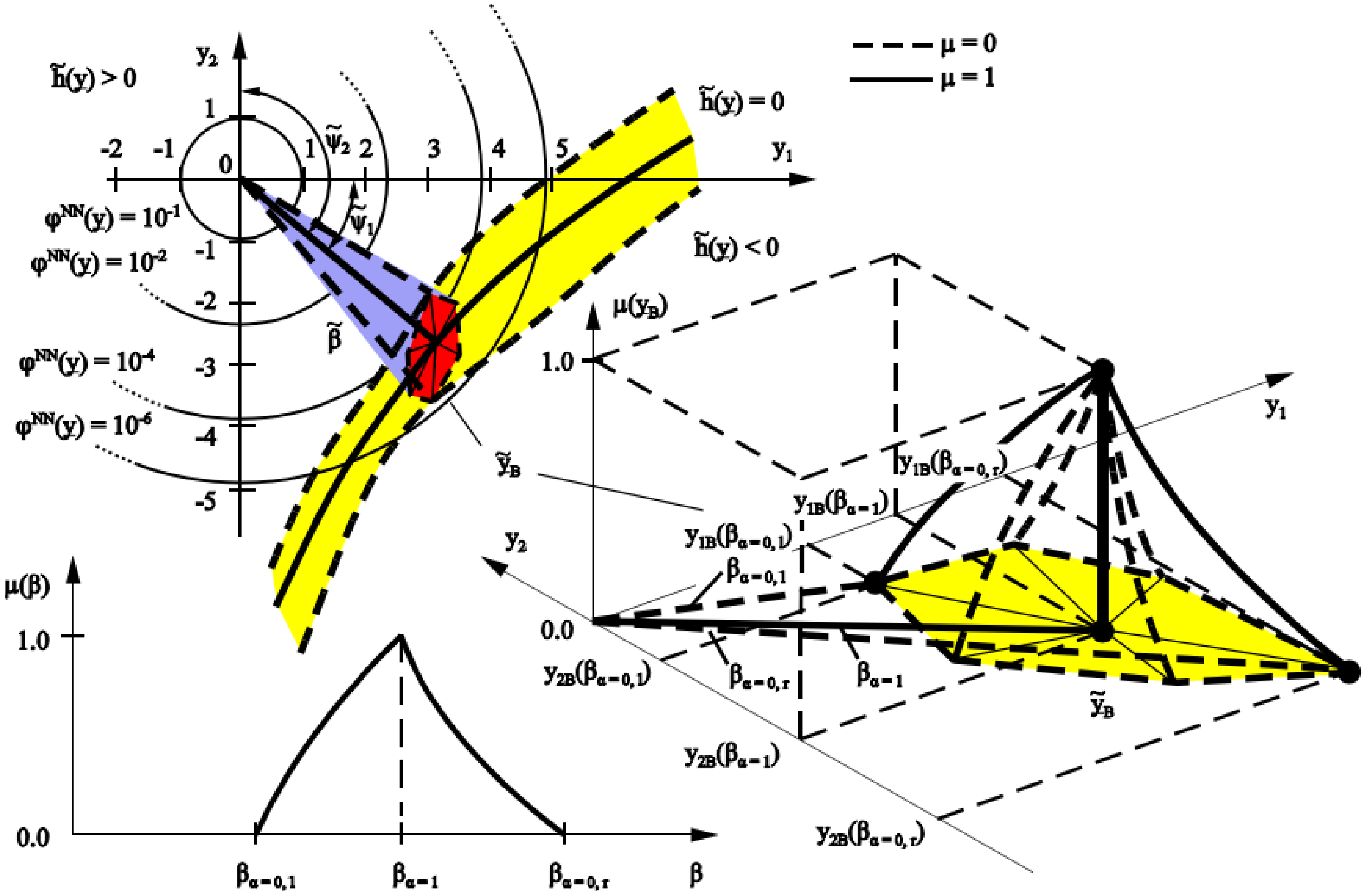


Fig. 9 Fuzzy limit state surface $\tilde{h}(\underline{y}) = 0$, fuzzy design point $\tilde{\underline{y}}_B$ and fuzzy reliability index $\tilde{\beta}$

Conclusions

1. Integration of Life Cycle Assessment (LCA) is crucial for circular economy principles in construction design.
2. Accurate interpretation of LCA data, especially in scenario analysis, is vital for informed decision-making.
3. Scenario analysis should align with specific goals, considering factors like ozone depletion, carbon emissions, and water use.
4. Construction software addresses diverse life cycle stages, supporting circular economy building needs.
5. Best Worst Decision-Making is recommended for efficiency in large dataset handling and improved decision-making.
6. The study utilized Revit 2024 and One Click LCA to enhance research, evaluating models for energy performance and environmental impacts.
7. Environmental impact complexities highlight the importance of analyzing multiple categories for informed circular economy decisions.
8. Key sustainability factors include total energy usage, net freshwater use, and social impact in project design.
9. Wood, concrete, and steel have pros and cons, emphasizing the need for holistic sustainability considerations.
10. Conclusions stress the importance of prioritizing sustainability, environmental protection, and social responsibility in building material selection.

Proposals

Integration of LOD in BIM for LCA Precision:

- Enhances LCA precision through BIM's Level of Development (LOD). Provides accurate representations for informed sustainable design decisions.

Optimal LOD Levels for Sustainable Design:

- Investigates best LOD for varied sustainable projects. Balances accuracy and resource efficiency to meet standards.

Incorporating LCC Analysis into LCA:

- Includes Life Cycle Costing (LCC) for economic sustainability. Considers environmental and economic impacts for holistic insights.

Circular Economy Principles in Building Design:

- Examines pros and cons of circular economy principles. Aims to reduce waste, align methods with sustainability goals, and promote closed-loop practices for environmental and economic sustainability.

Combining LCA, LCC, and Social Costs for Sustainability:

- Explores merging LCA, LCC, and social costs for a comprehensive sustainability evaluation. Aims to develop decision-making tools for environmental, economic, and social aspects.

Dynamic LCA for Building Adaptation:

- Assesses dynamic LCA approaches for evolving building materials and technology. Adapts sustainable design to industry changes and environmental concerns.

Occupant Behavior's Influence on Sustainability:

- Focuses on how occupant behavior impacts environmental and social performance. Emphasizes behavior-driven strategies for improved building sustainability.

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Thank you for your attention!