

## A NEW FRAMEWORK FOR THE QUANTIFICATION OF SUSTAINABILITY, INCLUSIVENESS, AND AESTHETICS OF STRUCTURES AND URBAN AREAS

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**Abstract.** The construction industry accounts for approximately 40% of Europe's total energy consumption, emphasizing the urgent need for more sustainable urban areas. Various building sustainability rating systems have been developed worldwide to address environmental impacts. However, inconsistencies in their application, due to differences in climatic conditions, building typologies, and policy frameworks, pose challenges for effective implementation. Beyond sustainability, rapid industrialization and urbanization have amplified socioeconomic disparities, underlining the necessity for inclusive and aesthetically pleasing designs that reflect modern community standards. To address these challenges, the European Union launched the New European Bauhaus (NEB) initiative in 2020. NEB aims to harmonize sustainability, inclusiveness, and aesthetics within the built environment through interdisciplinary collaboration among engineers, architects, researchers, businesses, and citizens. This study proposes a comprehensive framework to enable the self-assessment of buildings in alignment with NEB goals. The framework adopts a flexible weighting system based on fuzzy logic, ensuring regional relevance and adaptability. The framework employs an arithmetic aggregation method, which balances strong and weak performance areas, ensuring a holistic assessment of both new projects and existing urban areas. It is structured hierarchically to facilitate a multi-level evaluation of building performance. At the foundational level, sub-indicators capture detailed metrics addressing specific aspects of a project, such as energy efficiency, material sustainability, and community integration. These sub-indicators are aggregated to form indicators, which provide a more integrated evaluation of performance areas, including resource efficiency, accessibility, and design quality. The next level involves dimension indices, which consolidate indicators into three major dimensions, i.e., sustainability, inclusiveness, and aesthetics, representing the core principles of NEB. At the top of this hierarchy is the NEB Performance Index, which quantifies a project's overall performance in meeting NEB's goals. The validation process is integral to the framework. The quantified scores of dimension indices are compared to predefined benchmark thresholds. Projects failing to meet thresholds undergo an iterative redesign process to address deficiencies in underperforming dimensions, refining designs until compliance is achieved. By integrating NEB principles of sustainability, inclusiveness, and aesthetics, this framework provides a

robust tool for guiding and assessing building projects, fostering the creation of environmentally responsible, socially equitable, and visually inspiring spaces across Europe.

## 1 INTRODUCTION

The industrial revolution begun in the late 18th century in Europe. It brought about massive changes in technology, transportation, and manufacturing of building industries. Currently, we are entering the fifth industrial revolution that focuses on combining advanced technologies like AI and robotics with a human-centered approach. They accelerate productivity and innovation in the construction sector, including automation in design and building processes, advanced analytical modeling, and enhanced decision-making tools. As a result, project timelines were shortened and overall construction quality improved outcomes [1]. Additionally, the expansion of global transport and communication networks enabled broader industry growth and international integration. However, the progress driven by industrial development has come at a significant environmental cost.

The construction industry alone is responsible for approximately 40% of total energy consumption in Europe [2] [3], [4]. It also generates 30–40% of global solid waste (Rodriguez-Morales et al., 2024) and contributes 40% of global carbon emissions [5]. Beyond construction, buildings consume more than 50% of global electricity, and nearly 75% of the EU’s building stock is classified as energy inefficient [6]. These statistics emphasize the urgent need for sustainable practices in construction and urban development.

In response, numerous assessment tools have been introduced to guide the design, evaluation, and retrofitting of buildings with reduced ecological footprints. Among the most widely adopted are LEED (USA), BREEAM (UK), and CASBEE (Japan), which benchmark building performances across various environmental domains. These frameworks are built around predefined indicators, which can be either quantitative or qualitative, and are used to simplify complex environmental data into actionable insights [7]. Indicators may be derived directly or through combinations of sub-indicators, forming broader metrics that capture performance across multiple aspects [8]. While sustainability rating systems have integrated the environmental factors into building practices, several limitations exist that hinder their broader applicability. Studies have highlighted significant inconsistencies in indicators, scoring systems, weighting schemes, and qualification criteria across frameworks like LEED, BREEAM, and CASBEE [9], [10], [11].

In parallel, recent industrial transformations have introduced new social and aesthetic challenges in the built environment. The rise of automation, AI-driven design, and prefabrication methods has reshaped construction practices, often at the expense of traditional labor roles, cultural expression, and social inclusion [12]. These emerging issues highlight the need for a broader definition of sustainability one that encompasses not only environmental performance, but also social equity and aesthetic quality. In response to these multidimensional challenges, the European Commission launched the NEB initiative in 2020 [13]. Inspired by the original Bauhaus movement, the NEB emphasizes the integration of sustainability, inclusion, and aesthetics in shaping the built environment. It envisions a future where construction projects are not only ecologically sound but also culturally enriching, socially just, and visually inspiring.

Despite the strong conceptual foundation of NEB, there is currently no formalized framework to operationalize its goals in infrastructure design and evaluation. Existing tools fall short in capturing the full scope of NEB values and fail to provide a structured methodology for performance assessment. This gap underscores the need for a new self-assessment framework that is aligned with NEB principles, adaptive to regional contexts, and capable of delivering consistent, multidimensional evaluations.

## **2 OBJECTIVES AND CONTRIBUTIONS**

The core objective of this research is to develop a novel self-assessment framework that enables the evaluation of infrastructure projects in alignment with the NEB values. This framework is designed to be multidimensional, capturing sustainability, inclusiveness, and aesthetics, the three foundational pillars of the NEB initiative. By doing so, it addresses the current gap in assessment tools that fail to fully incorporate these integrated values.

Specifically, the study aims to:

- Formulate a structured and adaptable methodology for deriving measurable indicators and sub-indicators across the NEB dimensions;
- Develop a hierarchical aggregation process that translates diverse metrics into a unified performance score, the NEB Performance Index ( $PI_{NEB}$ );
- Design a flexible weighting system, informed by expert input through a fuzzy TOPSIS approach, to reflect the relative importance of each indicator;
- Enable applicability to both new and existing infrastructure projects, ensuring relevance across varied European contexts and planning stages.

This is the first self-assessment framework explicitly developed to operationalize the NEB values through a performance-based evaluation tool. Unlike existing sustainability rating systems, which focus predominantly on environmental metrics, the proposed framework introduces a holistic assessment model that also embraces cultural, social, and experiential quality compatible with the values of the NEB. This novelty positions the framework as a practical and forward-looking tool for stakeholders aiming to implement NEB principles in real-world projects.

## **3 THE NEW EUROPEAN BAUHAUS PROJECT**

The NEB is an interdisciplinary initiative launched by the European Commission to bridge the gap between science, technology, and the arts by promoting sustainable, inclusive, and aesthetically enriching environments. Rooted in the principles of the European Green Deal, NEB aims to inspire innovation in the built environment while fostering a stronger sense of community and cultural identity. It is created from three main dimensions:

- **Sustainability:** It emphasizes enhancing the performance and resilience of buildings while minimizing environmental impact. It promotes the use of fewer and renewable resources to achieve ultra-high-performance structures and aims to support sustainable land use and transportation in alignment with regional planning. Additional goals include reducing waste, boosting construction efficiency, and ensuring safety at construction sites. Long-term objectives focus on extending building lifespans and maintaining structural safety during regular use and in response to extreme events.
- **Inclusiveness:** the inclusion goals revolve around fostering equity and accessibility throughout all stages of project development. It encourages the consideration of diverse user backgrounds and needs, ensuring that built environments cater to all segments of

society. A key aspect is the provision of sustainable and affordable mobility options that improve access and usability for everyone, especially underrepresented or vulnerable populations.

- **Aesthetics:** this dimension focuses on improving design quality and construction excellence through innovative architectural and engineering approaches. It encourages projects that promote spatial and social interaction within communities, fostering cohesion and shared identity. Furthermore, aesthetic strategies are expected to respect and harmonize with regional architectural traditions, urban design norms, and cultural landscapes, ensuring that new developments are both contextually relevant and visually integrated.

#### 4 INDICATOR-BASED FRAMEWORK DESIGN

The proposed framework adopts an indicator-based architecture to systematically assess infrastructure performance in alignment with the NEB dimensions namely, sustainability, inclusion, and aesthetics. The assessment model follows a hierarchical structure, enabling the transformation of diverse data sources into a unified performance score,  $PI_{NEB}$ .

The evaluation process is structured across four hierarchical levels:

1. **Sub-indicators:** These represent detailed, measurable components of a specific concept (e.g., air permeability, daylight autonomy).
2. **Indicators:** Aggregations of related sub-indicators reflecting broader metrics (e.g., Indoor Airflow Control).
3. **NEB Dimension Indices:** Indicators grouped under the three NEB pillars—Sustainability, Inclusiveness, and Aesthetics.
4.  **$PI_{NEB}$ :** A composite index combining the three dimension indices into a single, comprehensive performance score.

Figure 1 illustrates this hierarchy, emphasizing the structured flow of data from granular sub-indicators to the final  $PI_{NEB}$  value.

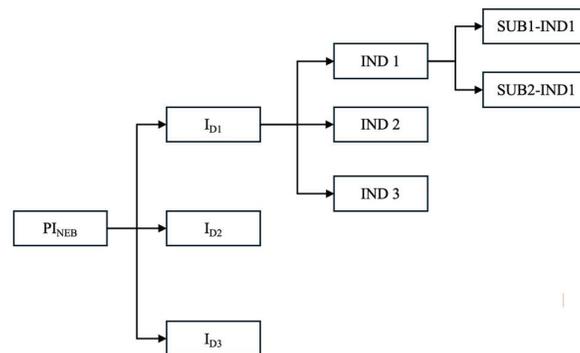


Figure 1. Hierarchy and structure of data in the framework.

##### 4.1 Indicator identification and selection

The effectiveness of any indicator-based framework depends on the relevance, validity, and completeness of its indicators. Therefore, a systematic protocol was established in this study to identify and classify indicators aligned with the three NEB dimensions. A comprehensive review of existing literature, frameworks, standards, and policy reports was conducted using the PRISMA review protocol (Preferred Reporting Items for Systematic

Reviews and Meta-Analyses). This approach ensured that the identification process was structured, reproducible, and unbiased.

*Identification:* A wide search was performed across academic databases such as Scopus and Google Scholar, using keywords related to each NEB dimension (e.g., “construction sustainability,” “inclusiveness in infrastructure,” “aesthetic quality in urban design”).

*Screening:* Duplicate entries and unrelated studies were removed based on titles and abstracts.

*Eligibility:* Full-text documents were assessed to determine the relevance and quality of the indicators presented.

*Inclusion:* Only studies offering quantifiable, well-documented, and NEB-aligned indicators were retained for analysis.

From the eligible literature, a list of potential indicators and sub-indicators was extracted. For each, the following data were compiled:

- Indicator name and ID
- Definition and scope
- Unit of measurement
- Quantification methodology
- Relevant benchmarks or threshold values
- Technology Readiness Level (TRL)
- Corresponding references

In particular, each indicator was evaluated for its TRL to ensure practical applicability in the field and discard the theoretical indicators that are in the initial stage of application. Based on TRL scoring, further refinement of extracted indicator was performed:

- TRL 6–9: Well-established, validated indicators (included directly).
- TRL 4–5: Emerging indicators (included with caution).
- TRL 1–2: Early-stage indicators (excluded or considered future work).

Additionally, the indicators were further classified into:

- Quantitative (numeric, measurable)
- Qualitative (perceptual or categorical, e.g., design harmony)

At the next step, all indicators were then mapped to one of the three NEB dimensions based on their primary objective and alignment with the initiative’s values. For example, *Sustainability indicators* included metrics like structural resilience, whole-life carbon footprint, and energy demand. *Inclusion indicators* addressed aspects such as universal accessibility, workforce equity, and affordable mobility. *Aesthetic indicators* captured factors related to spatial cohesion, visual comfort, and integration with cultural context. A full list of selected indicators are presented below:

*Table 1. List of extracted aesthetics indicators.*

<b>Aesthetics (D2)</b>		
Compactness of geographic shape (IND1)	Spatial and social cohesion (IND2)	Quality improvement by novel technology: (IND3)
Balance (IND4)	Classic Proportion (IND5)	Simplicity (IND6)
Unity (IND7)	Symmetry (IND8)	Contrast (IND9)
Color Harmony (IND10)		

Table 2. List of concluded sustainability indicators.

Sustainability (D1)		
Automation in construction (IND1)	Offsite manufacturing integration (IND2)	Supply sustainability (IND3)
Sustainable mass utilization (IND4)	Renewable material (IND5)	Bio-based material (IND6)
Standard occupancy space (IND7)	Eco-friendly material (IND8)	Indoor airflow control (IND9)
Whole-life carbon footprint (IND10)	Material certification (IND11)	Material-health influence metric (IND12)
Sustainable workforce training (IND13)	Economic sustainability in construction (IND14)	SHM Integration (IND15)
Acoustic Comfort (IND16)	Workforce safety (IND17)	Thermal Comfort (IND18)
Energy-Sustainability nexus (IND19)	Visual comfort (IND20)	Structural resilience (IND21)
Adaptation-enhanced properties (IND22)		

Table 3. Indicators defined for inclusiveness.

Inclusiveness (D3)		
Physical disability (IND1)	Sensory disability (IND2)	Intellectual disability: (IND3)
Neurodiversity (IND4)	Gender (IND5)	Elderly (IND6)
Children (IND7)	Race (IND8)	Poverty (IND9)
The non-human (IND10)		

## 4.2 Indicator Normalization, Weighting, and Aggregation

To ensure consistency and comparability, all indicators are first normalized using one of two approaches:

- Continuous Rescaling: Applied to quantitative indicators using the following equation:

$$S_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \quad (1)$$

where  $S_i$  is the sub-index score,  $X_i$  the actual value, and  $X_{\max}, X_{\min}$  are the threshold bounds. For cost-related indicators (where lower is better), the equation is inverted.

- Categorical Scaling: Used for qualitative indicators or when precise data is unavailable. Sub-indicators are grouped into ranked classes (e.g., “very poor” to “excellent”), each mapped to a value within a 0–1 scale.

To reflect the relative importance of each indicator in the final assessment, the framework employs a multi-criteria decision-making approach. Among the various MCDA techniques, the fuzzy Technique for Order of Preference by Similarity to Ideal Solution (fuzzy TOPSIS) was selected for its ability to handle uncertainty and linguistic judgments in a mathematically robust manner. Fuzzy TOPSIS is an extension of the traditional TOPSIS method, allowing the inclusion of linguistic variables (e.g., "high importance," "low importance") and their conversion into triangular fuzzy numbers. This method is selected for weighting the indicators since it allows for the integration of multiple, often conflicting criteria from its dedicated survey

and processing method. One of its key strengths is its ability to accommodate diverse expert preferences that make it compatible with the NEB's inclusive and participatory spirit. By applying TOPSIS to survey or questionnaire data collected across various European regions, the method can reflect the cultural, environmental, and social values of different communities. This ensures that the final outcomes are not only technically sound but also aligned with the pluralistic vision of the NEB initiative.

To determine the weight of extracted indicators, a structured questionnaire was distributed via a web survey platform (e.g., Google Forms), targeting a diverse group of experts in construction, sustainability, and policy. Respondents were asked to rate the importance of each indicator using five-point linguistic scales, as well as to propose threshold values for each NEB dimension index.

The steps taken to attain the final weight are summarized below:

1. Conversion of linguistic inputs to fuzzy triangular numbers.
2. Normalization of fuzzy values to eliminate unit inconsistencies.
3. Construction of the weighted normalized matrix by applying equal or expert-defined weights to respondents.
4. Calculation of the Positive Ideal Solution (PIS) and Negative Ideal Solution (NIS) using defuzzied values.
5. Computation of the closeness coefficient for each indicator
6. Normalization of closeness coefficients to obtain the final weights.

To determine the final index related to the NEB performance, it is necessary to combine the values obtained from each indicator and sub-indicators. Each sub-indicator is calculated based on either direct input data, simulation models, or expert evaluation, and then normalized using the continuous or categorical scaling methods. Then, normalized sub-indicators are aggregated to form indicators using an arithmetic average:

$$IND_k = \frac{1}{n} \sum_{i=1}^n SUB_{i,IND_k} \quad (2)$$

where  $IND_k$  is the score of the  $k^{\text{th}}$  indicator and  $SUB_{i,IND_k}$  are the associated sub-indicator scores. This equal-weighted average ensures comparability across indicators with differing numbers of sub-indicators (Cutter et al., 2010).

Each NEB Dimension Index is then calculated by applying weights  $w_j$  obtained from the TOPSIS analysis to the corresponding indicator using the following relation:

$$I_{DIM} = \sum_{j=1}^m w_j \cdot IND_j \quad (3)$$

where  $I_{DIM}$  is the dimension index (sustainability, inclusion, or aesthetics), and  $m$  is the number of indicators under that dimension. A threshold validation is performed for each dimension. If any index fails to meet its assigned minimum threshold (based on expert-defined cutoffs), the framework triggers an iterative redesign phase, where the project is refined to improve performance in that dimension.

The final step is to compute the NEB Performance Index ( $PI_{NEB}$ ), which aggregates the three dimension indices:

$$PI_{NEB} = \sum_{d=1}^3 w_d \cdot I_{DIM_d} \quad (4)$$

$I_{DIM_d}$  refers to the index of each dimension and  $w_d$  are their respective weights. If no prioritization exists between dimensions, equal weights can be applied to maintain neutrality. This modular structure allows for flexible application across varied project contexts, supports transparency in decision-making, and aligns with NEB's holistic evaluation goals. This score serves as an overall assessment of how well the project aligns with NEB values. Based on the resulting percentage, the project is categorized into performance tiers such as:

Exceptional, superior, highly satisfactory, adequate, unsatisfactory.

## 5 IMPLEMENTATION STRATEGY AND APPLICATION

The proposed NEB self-assessment framework is designed to be flexible and adaptable, allowing its application across a wide range of infrastructure types and development stages. It can be implemented for:

- New structures, by integrating the framework during the planning and design phase;
- Existing structures, through retroactive data acquisition and evaluation;
- Adapted or modified structures, such as renovations, extensions, or reuse projects, where updates are made to improve environmental performance, accessibility, or aesthetics.

Implementation begins with the collection of essential input data, which varies slightly depending on the project type:

- For new structures, inputs include architectural plans, structural design models, Building Information Models (BIM), technical and urban planning specifications, and hazard mitigation requirements.
- For existing structures, available documentation must be supplemented with performance data (e.g., energy audits, material condition assessments).
- For adapted structures, both the original design data and the proposed modifications must be considered, including the rationale for design updates and their projected impact on NEB dimensions.

The developed framework is applied to an existing project in this section. The case study, Mjøstårnet is an 18-storey mixed-use timber structure located in Brumunddal, Norway. Completed in March 2019, it has been officially recognized by the Council on Tall Buildings and Urban Habitat (CTBUH) as the tallest timber building in the world. The tower accommodates a variety of functions, including office spaces, 72 hotel rooms, 33 residential apartments with private balconies, a ground-floor restaurant, conference facilities, and a rooftop terrace. An architectural pergola crowns the building, reaching a total height of 85.4 meters above ground level.

To explore the applicability of the NEB framework to adaptive retrofitting of various projects, a structural adaptation scenario was designed for the Mjøstårnet case study. The original configuration included traditional concrete floor slabs across top 7 stories. To reduce the overall structural mass while maintaining the same performance under wind loads, the concrete floors were removed and replaced with a lightweight Tra8 flooring system. Moreover, three magnetorheological (MR) dampers were introduced to enhance the dynamic response and ensure continued structural safety.

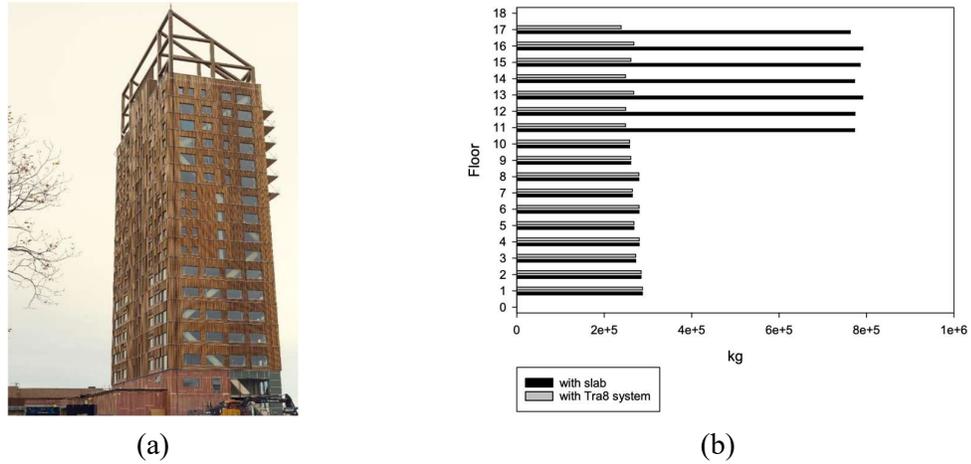


Figure 2. Case study and structural adaptation, (a) Mjøstårnet tower, (b) Comparison of floor weight with traditional concrete slabs and Tra8 lightweight system.

As shown in Figure 2, the substitution of concrete slabs with the Tra8 system produced a significant reduction in floor-wise mass, particularly in the upper levels of the structure. The reduction in mass contributes to both sustainability, through material efficiency and aesthetics, by preserving the architectural integrity of the original design while enabling improved structural performance.

In the adaptation process, a FE model of the building was developed to extract its modal properties and evaluate the dynamic performance before and after the adaptation. The integration of MR dampers was optimized using a hybrid fuzzy logic and Whale Optimization Algorithm (WOA). This approach enabled the fine-tuning of damper to achieve desired damping characteristics without compromising the structural response to wind loading. The energy efficiency of this optimization approach is demonstrated in Figure 3.

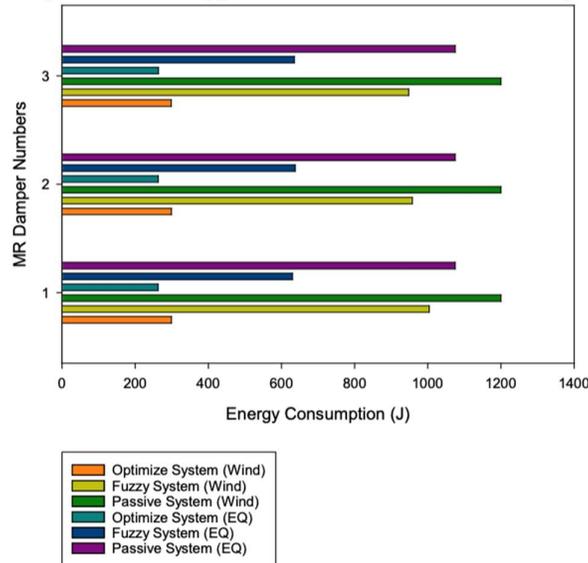


Figure 3. energy consumption of designed adaptive MR dampers.

To elaborate on the practical applications, some examples for indicator calculations are presented in this section. The first indicator is Offsite manufacturing integration (D1-IND2). It measures the extent to which, offsite assembling techniques are integrated into the construction process. It result in better control over materials through precision manufacturing, minimizing overordering and on-site losses. In addition, it can enhance the sustainable design since producing elements in a factory reduces the energy needed for heating or cooling compared to on-site operations. The indicator is quantified as the Pre-Manufactured Value (PMV). It presents the const attributed to pre-manufactured components and processes over the gross construction cost in a project.

$$PMV (\%) = \frac{Pre - manufactured\ value}{Gross\ construction\ cost} * 100 \quad (5)$$

For the current case study, we didn't have direct access to the financial details. Therefore, the cost is estimated based on the weight of pre-manufactured elements.

In the initial building configuration, the input parameters are derived and summarized below:

- Glulam (Limtre): volume: 1,328.90 m<sup>3</sup>, density: 480 kg/m<sup>3</sup>, weight: 637,872 kg
- Concrete Slabs (7 floors): area: 3,482.99 m<sup>2</sup>, thickness: 0.30 m, volume: 1,044.9 m<sup>3</sup>, density: 2,400 kg/m<sup>3</sup>, weight: 2,507,753 kg
- Prefabricated Modules: 400,000 kg
- Other Materials (est.): 600,000 kg
- Total Building Weight: 637,872 + 2,507,753 + 400,000 + 600,000 = 4,145,625 kg.
- Pre-manufactured Elements Weight: 637,872 + 400,000 = 1,037,872 kg.

Based on the above input, the estimated PMV would be:

Proportion of Pre-manufactured Weight:

$$PMV (\%) = \frac{1,037,872}{4,145,625} * 100 \approx 25\%$$

After Replacing Concrete Slabs with Glulam the input parameters changed as:

- Weight of New Glulam Floors (7 floors): 169 kg/m<sup>2</sup> × 497.57 m<sup>2</sup> = 84,089 kg/floor
- Total: 588,625 kg
- Updated Building Weight: (4,145,625 - 2,507,753 + 588,625) = 2,226,497 kg
- Updated Pre-manufactured Elements Weight: 1,037,872 + 588,625 = 1,626,497 kg

Therefore, the final PMV after the structural adaptation is:

$$PMV (\%) = \frac{1,626,497}{2,226,497} * 100 \approx 73\%$$

Another indicator calculated in this section belong to simplicity indicator in the aesthetics dimension (D2-IND6). This indicator refers to the human preference for easily interpretable, minimal, and aesthetically clear forms. It emphasizes clarity by removing unnecessary elements and focusing on the core components in design. Simplicity is evaluated through two sub-indicators:

- The number of attributes (D2-IND6-SUB1): it can be determined using the following relation:

$$Simplicity_N = 1 - \frac{N_r}{N} * 100 \quad (6)$$

Where  $N_r$  is the number of attributes in styling, color or texture design, and  $N$  is total number of elements.  
 As illustrated in Figure 44,  $N_r$  is 4 (2 styles, 1 color, 1 texture), and total value of  $N$  is 177.  
 Thus, the value of this sub-indicator is 0.98.

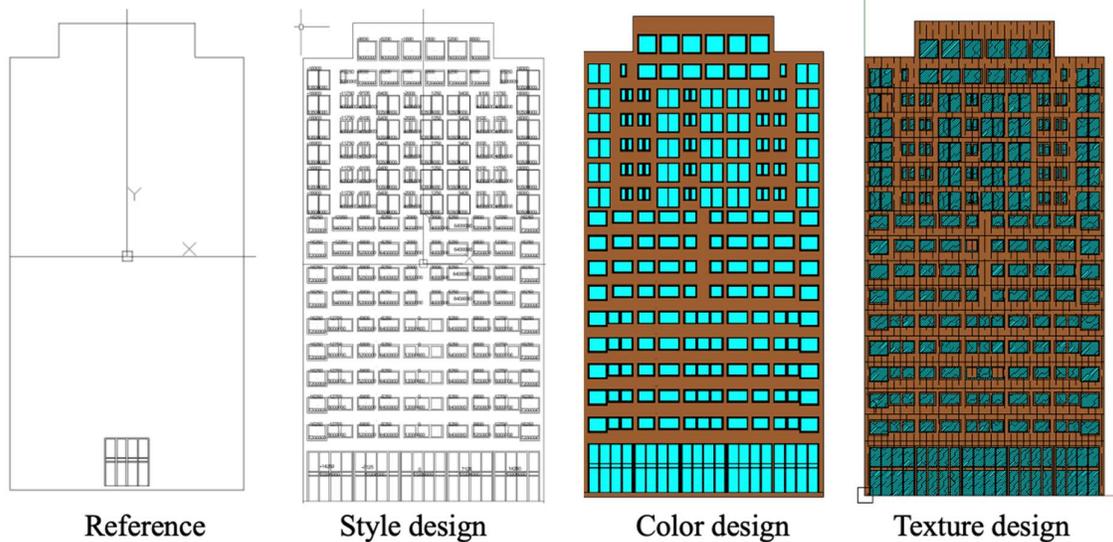


Figure 4. simplicity analysis of the case study.

## 6 CONCLUSIONS

This study presents a novel self-assessment framework tailored to the goals and values of the NEB initiative. The framework is designed to evaluate infrastructure projects holistically, integrating sustainability, inclusion, and aesthetics into a unified performance model. Through a multi-level hierarchical structure, it enables the systematic aggregation of sub-indicators into a single score, thereby transforming qualitative principles into quantifiable, actionable insights. The framework incorporates:

- A robust indicator selection process based on literature and policy review;
- Flexible normalization and aggregation methods to handle diverse data types;
- An adaptive weighting scheme using fuzzy TOPSIS, grounded in expert input;
- A modular design, allowing application to new, existing, and adapted structures.

By addressing the gaps in current sustainability assessment tools, this framework contributes to the advancement of inclusive and regenerative design practices across Europe.

Future work will focus on the following directions:

- Validation through real-world case studies, applying the framework to urban and rural projects across different EU regions;
- Development of a digital tool or software interface to automate the framework's application and improve accessibility;
- Integration with BIM platforms and other digital construction workflows to support dynamic, real-time assessments;
- Expansion of the indicator database, including emerging metrics from circular economy, smart infrastructure, and cultural heritage domains.

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