

Article

From Simplicity to Sustainability: Structuring Minimalist Housing with SDG Metrics

Duygu Yildiz  and Ilkim Markoc * 

Construction Management and Building Production Unit, Department of Architecture, Faculty of Architecture, Yildiz Technical University, 34349 İstanbul, Turkey; duygu.yildiz2@std.yildiz.edu.tr

* Correspondence: ilkim@yildiz.edu.tr; Tel.: +90-533-463-8100

Abstract

The increasing construction-driven growth in urbanization requires innovative and holistic design approaches for sustainable housing. This study examines the relationship between Minimalist Design Principles (MDPs) and the UN SDGs and develops a multi-stage decision-support model to operationalize these links. The research adopts a five-stage mixed-methods design. It includes content analysis based on a systematic literature review, conceptual mapping, a two-round Delphi method (N = 56), Fuzzy AHP for criteria weighting, and SEM for model validation. A total of 13 MDPs were mapped against 17 SDGs and 169 subtargets, revealing particularly strong linkages with SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production). The SEM results confirm the structural validity of the proposed model. Among the minimalist principles, those associated with “resource, material, and process simplification” and “user needs, functional flexibility, and quality of life” emerged as the most influential factors for the SDGs. This study proposes a measurable, multidimensional decision-support model in sustainable architecture that clarifies how MDPs influence the SDGs.

Keywords: minimalism; sustainable development goals; housing production; Delphi technique



Academic Editors: Amjad Almusaed, Raad Z. Homod and Asaad Almssad

Received: 26 August 2025

Revised: 1 October 2025

Accepted: 11 October 2025

Published: 17 October 2025

Citation: Yildiz, D.; Markoc, I. From Simplicity to Sustainability: Structuring Minimalist Housing with SDG Metrics. *Sustainability* **2025**, *17*, 9232. <https://doi.org/10.3390/su17209232>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The construction sector ranks among the leading contributors to global environmental degradation and resource consumption, accounting for approximately 36% of total energy use and over 50% of natural resource utilization [1]. In this context, the United Nations' 2030 Sustainable Development Agenda, launched in 2015, provides a multidimensional paradigm for the built environment, encompassing environmental, social, economic, and governance-oriented sustainability principles [2]. In sustainable housing production, balancing cost efficiency, energy performance, and spatial flexibility remains an unresolved challenge in the literature. Addressing this gap requires linking minimalist design principles with sustainability goals, which represents a critical gap in the literature.

Aligning the construction sector with these goals requires not only technological innovation but also a fundamental re-thinking of design approaches and production models. At this point, minimalist design emerges as a distinctive strategy, directly aligning with sustainability principles through its emphasis on simplified forms, functional integration, resource efficiency, and environmental sensitivity. Beyond being an esthetic trend, minimalism represents a systematic approach that enhances energy efficiency, reduces material consumption, streamlines construction processes, and lowers life-cycle costs [3].

The study by Hasan et al. (2024) [4] revealed the multidimensional structural links between lean construction principles and the Sustainable Development Goals (SDGs), demonstrating how simplified design approaches contribute to sustainable development. In particular, the lean principles of “reducing non-value-adding elements,” “focusing on all processes,” and “continuous improvement” exhibit strong alignment with the SDGs and provide a core framework for reducing environmental impacts [4]. Similarly, Dagilgan and Ercan (2025) [5] identified themes such as energy use, occupational health and safety, as well as governance and financial performance, as key determinants of sustainability performance in the sector. Their findings offer a guiding foundation for the thematic prioritization of decision-support models in housing production.

Quantitative work connecting MDPs to the SDGs is scarce, and current studies often consider sustainability and lean production separately, without a unifying SDG-based framework [1]. To address this gap, the present study structures and empirically tests the relationship between minimalist principles and the 2030 SDG framework in the context of sustainable housing production (Section 2, Materials and Methods). A five-stage methodological design was adopted: (1) conducting a systematic literature review and content analysis to establish the conceptual foundation, (2) developing a conceptual model aligned with the SDGs, (3) implementing a two-round Delphi method (Round 1: N = 56; Round 2: N = 15) based on expert opinions, (4) determining criteria weights using Likert-based Fuzzy Analytic Hierarchy Process (FAHP), and (5) validating the model statistically through Structural Equation Modeling (SEM), detailed in Section 3 (Methodology).

The decision-support model developed in this study establishes strong structural linkages particularly with SDG 11–12–13. Furthermore, the model’s validation through CFI, RMSEA, and χ^2/df fit indices confirms the conceptual and statistical robustness of the proposed framework (Section 4, Findings). In this regard, the research offers a multidimensional, applicable, and scalable decision-support model for sustainability in the architecture and construction sectors, providing both methodological and theoretical contributions to the literature (Section 5, Discussion; Section 6, Conclusions).

2. Materials and Methods

2.1. Minimalist Design Approaches and Its Intersection with Housing Production

The increasing pace of urbanization, population density, and scarcity of resources on a global scale has made sustainable housing production, particularly for low- and middle-income groups, a critical challenge in metropolitan areas. Traditional building production processes often conflict with the United Nations Sustainable Development Goals (SDGs) due to material waste, high energy consumption, and prolonged construction periods [1]. Therefore, housing production must be re-evaluated from environmental, economic, and social perspectives.

Minimalist architecture emerges as a design approach offering a holistic contribution to environmental, economic, and social sustainability through its principles of simplicity, functionality, and resource efficiency [6]. Beyond an esthetic orientation, minimalist design provides tangible benefits such as reducing construction costs, shortening project timelines, lowering energy consumption, and minimizing life-cycle expenses [7,8]. As the construction sector transitions toward low-carbon development, integrated approaches to sustainable architecture and material selection have become increasingly important [9]. In urban regeneration housing projects, minimalist design principles, functional spatial organization, and material efficiency have become key strategies for lowering costs and improving access to quality housing for low-income populations [10].

Moreover, this approach has the potential to drive behavioral transformation among users. The minimalist lifestyle promotes functionality and simplicity over excessive con-

sumption, contributing to a reduced environmental footprint [7]. This aligns with SDG 12.1 (promoting sustainable consumption patterns) and SDG 13.3 (enhancing individual action against climate change).

In recent years, data-driven natural language processing (NLP) approaches have enabled the modeling of sustainability parameters beyond architecture, incorporating social dimensions as well. For instance, Alqahtani et al. (2022) [11] showed how NLP and big data analytics reveal social, economic, and environmental dimensions of housing. Thus, NLP-based analytics can also be employed to model the societal dimensions of sustainable housing policies.

Furthermore, the integration of digital distribution and production diversification techniques focused on energy efficiency into early design phases enhances the feasibility of minimalist strategies [12]. This enables the proliferation of low-energy, user-friendly, and adaptable housing typologies with scalable applications.

Defining Minimalist Design: Distinction from Lean Construction

Minimalist architectural design deliberately includes only elements that serve essential functions and prioritizes simplification across formal, structural, and operational dimensions to optimize usability, spatial efficiency, and resource use [7]. It is user-centric and performance-oriented rather than purely esthetic. Lean construction likewise values efficiency but focuses on post-design production workflows and site operations [1,4]. Table 1 summarizes the main distinctions.

Table 1. Comparative framework: minimalist design versus lean construction.

	Minimalist Design [6–10]	Lean Construction [1,4,7]
Focus Phase	Early design and conceptual development; spatial and functional decision-making	Construction and site operations; workflow management
Core Objective	Functional clarity, spatial reduction, formal and material simplification	Waste elimination, value maximization, process flow optimization
Primary Domain	Design principles affecting form, space, and user experience	Managerial and operational principles affecting labor, time, and material use
Shared Values	Efficiency, resource optimization, user-centered outcomes	Efficiency, reduced variability, continuous improvement
Typical NVA Examples	Excessive detailing and redundant facade elements Over-complex circulation and spatial repetitions	Waiting time, rework, and unnecessary transport Excess inventory and overproduction

Created by the authors.

As shown in Table 1, minimalist design acts early on form/space/user experience, whereas lean targets site-level workflows share efficiency/waste-minimization yet operate in complementary domains.

2.2. Transformation of Housing Production in the Context of the SDGs

The 17 UN SDGs (2015) and 169 subtargets seek to balance social, economic, and environmental dimensions of global development, with the construction sector directly linked to these goals [1,4]. In housing, reducing life-cycle costs and optimizing material use are consistent with SDG priorities. Because land-use and urbanization choices strongly influence carbon outcomes, effective strategies must also extend beyond the building

scale [13]. The reuse of demolition waste in cement supports both resource reduction and carbon mitigation [14].

Furthermore, studies examining the spatial-temporal distribution of regional carbon emissions suggest that consumption-based compensation mechanisms can contribute to the achievement of the SDGs [15]. In particular, SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) foreground the themes of social equity, resource efficiency, and carbon footprint reduction in the construction sector. MDPs intersect directly with these themes, offering effective solutions for enhancing sustainability in housing production.

El-Husseiny and El-Setouhy (2022) show that low-tech, local techniques reduce environmental impacts and strengthen community identity, supporting social sustainability [16]. The revival of low-tech construction modules as a sustainability strategy demonstrates that design simplicity holds esthetic, functional, and social value. The use of local materials and knowledge systems directly aligns with SDG 11.1 (access to safe and affordable housing for all) and SDG 16.7 (inclusive and participatory decision-making processes). Similarly, Salihbegovic and Salihbegovic (2020) highlighted that reintroducing natural materials into contemporary architecture in Bosnia and Herzegovina significantly reduces both construction costs and carbon emissions [17]. These practices are particularly relevant to SDG 12.2 (sustainable management of natural resources) and SDG 13.2 (integration of climate change measures into national policies).

Kamali and Hewage (2017) find modular systems outperform traditional methods on environmental and operational sustainability [8]. This finding supports SDG 9.4 (modernization of infrastructure for environmental sustainability) and SDG 12.5 (substantially reducing waste generation through recycling and reuse). Moreover, both structural and material-focused strategies, along with nature-based solutions that enhance spatial quality, contribute to achieving sustainability objectives. Specifically, the integration of green spaces into collective housing developments within urban areas has positive impacts on climate change adaptation, ecosystem service continuity, and social well-being [18].

2.3. Development of the Conceptual Model

M1–M13 were mapped to the SDGs in four steps: each principle was defined; its causal pathway was specified; measurable indicators were assigned (energy intensity, material/waste intensity, rework rate); and the result was linked to SDG targets. For example, M1 corresponds to reductions in waste and energy use and aligns with SDG 9.4 and SDG 12.2. Using these pathways and indicators, principles were then associated with the relevant SDG targets and subtargets. For illustration, M1 (elimination of non-value activities) operates through material and energy waste reduction and is measured by material intensity per m², waste intensity, and rework ratio; this pathway aligns with SDG 9.4 (resource-efficient industry) and SDG 12.2 (sustainable management of natural resources).

The protocol was validated via a two-round Delphi panel (Round 1: N = 56; Round 2: N = 15). Expert feedback between rounds led to refinements that strengthened agreement, rendering a third round unnecessary. Detailed consensus thresholds and statistical results are reported in the Methodology section.

2.4. Hypothesis Development and Justification of the Conceptual Framework

The primary aim of this research is to model the conceptual relationship between MDPs and the SDGs and to demonstrate the statistical validity of this relationship through testable hypotheses. The literature shows that minimalist design contributes to sustainability in multiple dimensions: environmental, economic, social, and esthetic.

In particular, the pressures of urbanization, resource scarcity, and climate crises reveal that conventional housing production models do not align with sustainable development objectives. MDPs hold the potential to address this gap through functionality, process simplification, material efficiency, and the use of local production techniques. Within this context, the hypotheses developed to construct a model testable at both theoretical and empirical levels are systematically presented in Table 2.

Table 2. Hypotheses, Theoretical Rationales, and Alignment with the SDGs.

Hypothesis	Theoretical Rationale	Relevant SDG's	Reference
H1	Minimalist design principles contribute to sustainable development goals.	12.2, 13.3, 9.4	[7,19]
H2	The mean scores of MDPs and related SDG indicators differ significantly across demographic groups.	4, 5, 10, 11	[20]

Created by the authors.

These hypotheses add rigor and allow quantitative testing of policy alignment with concrete SDG targets. The next section details the methods.

3. Methodology

To test the structural relationships between MDPs and SDG targets in sustainable and affordable housing, we used a mixed-methods design that integrates multi-criteria decision-making and structural modeling techniques recommended in the literature [1,4,8]. The study proceeded in five-stages: (1) a systematic literature review and content analysis to establish the conceptual framework; (2) development of an SDG-aligned conceptual model; (3) a two-round Delphi with experts (N = 56) to elicit judgments; (4) Likert-based FAHP to derive criteria weights; and (5) SEM to validate the model (Figure 1).

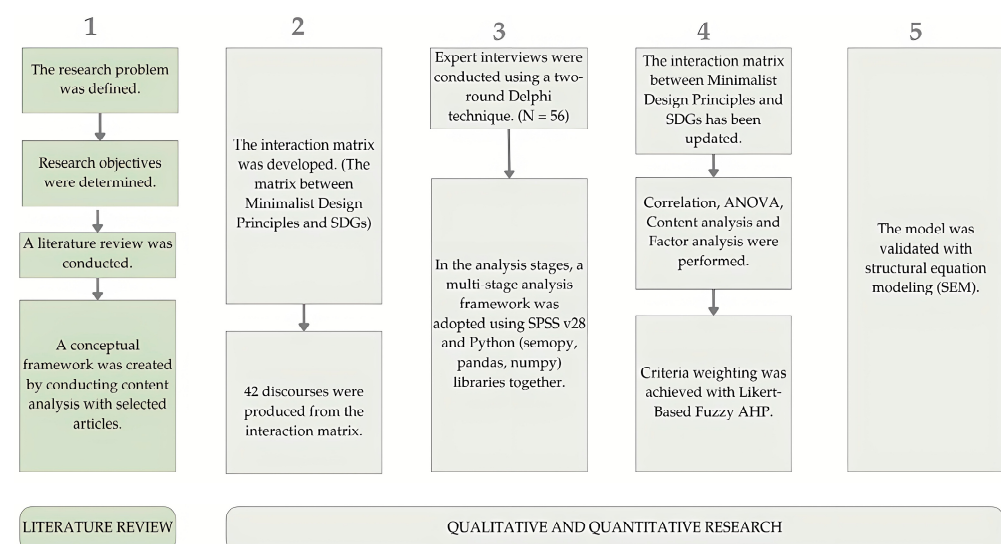


Figure 1. Research methodology.

Based on a 2010–2025 systematic review of minimalism, sustainable architecture, lean production, and eco-friendly housing. Inclusion required explicit treatment of minimalism and sustainability in housing design; excluded were non-peer-reviewed sources, purely esthetic discussions, and works outside the housing scale. The coding process was carried

out independently by two researchers using a double-blind protocol to minimize subjective bias. Each study was evaluated across 13 MDPs (M1–M13), which were synthesized from recurring themes such as functional clarity, material efficiency, and user-centered simplicity. While some principles have appeared in earlier literature, their integration into a coherent and systematic framework was achieved for the first time in this study.

Inter-coder agreement was assessed using Cohen’s Kappa statistic, yielding perfect agreement for M4 and M9 ($\kappa = 1.000$), and substantial agreement for M1 ($\kappa = 0.811$) and M3 ($\kappa = 0.759$). Principles such as M7, M11, and M12 also demonstrated strong reliability ($\kappa > 0.65$). The overall average Cohen’s Kappa was calculated as $\kappa = 0.650$, indicating a good level of coding consistency.

Python-based tooling supported preprocessing, statistical text analysis, topic modeling, and visualization. The 13 principles were organized into four dimensions aligned with sustainability themes:

- Resource, material, and process simplification (M1, M4, M5, M8).
- User needs, functional flexibility, and quality of life (M2, M3, M6).
- Transparency, locality, and cultural coherence (M7, M12).
- Technological flexibility, ease of intervention, modularity, and maintenance advantages (M9, M10, M11, M13).

Therefore, the conceptual network developed from the content analysis reveals the multidimensional relationships between MDPs and sustainability themes in detail. Figure 2 presents the concept map of themes, key concepts, and relevant literature.

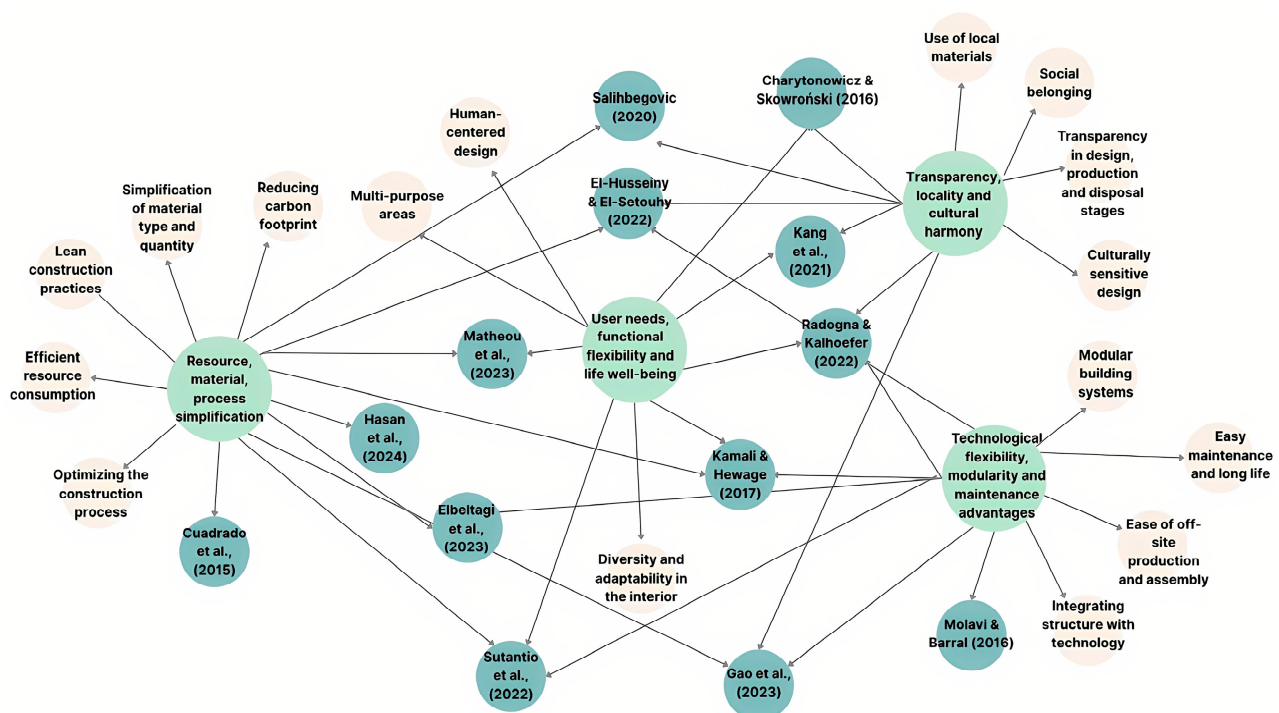


Figure 2. Concept map. Created by the authors. (References: [4,7,8,12,16,17,21–27]).

Figure 2 maps the relationships between the MDPs and sustainability themes, with clusters and key sources. The principles identified within this framework are grounded in both the content analysis findings and expert evaluations, representing the core components of sustainable housing design. Table 3 offers a detailed description of the 13 MDPs, each systematically coded to operationalize the proposed conceptual framework.

Table 3. Minimalist design principles.

Code	MDPs
M1	Eliminating non-value-generating actions throughout the design lifecycle.
M2	Focusing on core human needs and the promotion of holistic well-being.
M3	Mitigating ambiguity and functional complexity throughout the design process.
M4	Integrating improvements by streamlining the construction timeline and lifecycle.
M5	Minimizing environmental impact by streamlining operational processes, material usage, and spatial design to reduce resource demand, carbon output, and construction-related waste.
M6	Achieving a diversity of living environments by enabling functional adaptability within spatial design.
M7	Promoting clarity and operational transparency throughout the design process to facilitate better decision-making and collaboration.
M8	Embedding lean principles throughout the entire lifecycle, from design and manufacturing to end-of-life deconstruction, to maximize efficiency and minimize waste
M9	Proactively identifying potential points of intervention and optimizing outcomes through streamlined, low-complexity solutions
M10	Leveraging modular and off-site construction methods to enhance build-time efficiency and streamline on-site construction workflows
M11	Maximizing design effectiveness through the minimization of tool dependency.
M12	Locality (Use of natural materials and cultural compatibility)
M13	Ease of maintenance and durability

Created by the authors.

Each principle (M1–M13) was derived from thematic intensity and conceptual coherence across the reviewed studies and is used here as a data-driven, operational framework for sustainable housing. Consequently, the M1–M13 principles gain a functional and strategic character, rather than a purely esthetic one, contributing directly to sustainability objectives [3]. Table 4 summarizes the article-level coding schema and the mapping from thematic clusters to M1–M13.

The conceptual framework developed in this study reinterprets minimalist housing design in line with sustainability objectives. Its simplification principles, grounded in the literature and linked to resource reduction, functional flexibility, and user-responsive design, were explicitly defined to clarify their practical implications. A practical reflection of this conceptual framework within the design process is exemplified through the application of Principle M1: Eliminating non-value activities is treated not merely as a production tactic but as an early-design decision filter. Addressing non-functional spatial repetitions, unnecessary material specifications, and excessive detailing at design time prevents later time and cost losses. We distinguish these design-stage wastes from site-level inefficiencies (delays, surplus materials, underutilized labor) and embed lean logic in the design itself. Thus, minimalism is positioned not as an esthetic preference but as a strategy for efficiency and systemic optimization.

The M1–M13 principles then informed the survey items used in subsequent stages. Items tied to specific sustainability dimensions were converted to a Likert scale to as-

sess adoption levels, providing a theoretically coherent measurement basis and the data infrastructure for quantitative analyses.

Table 4. Article-based content analysis table.

Variable	Purpose	Method	Sustainability Dimension	Thematic Focus	Thematic Clusters	Related M1–M13
Kamali & Hewage (2017) [8]	Comparing modular and traditional construction.	Mixed (Survey + Analysis)	Environmental, Economic, Social	Construction method	1, 2, 4	M4, M6, M10, M11, M12
Kang et al. (2021) [7]	Investigating the relationship between minimalism and sustainable consumption.	Quantitative	Environmental, Social	Way of living	2, 3	M2, M6, M7
Cuadrado et. al. (2015) [21]	Sustainable decision-making in industrial buildings.	Conceptual + AHP	Environmental, Economic	Construction method	1	M1, M5, M8,
Matheou et al. (2023) [22]	Contributing to sustainability with transformable buildings.	Quantitative	Environmental	Architectural design	1, 2	M4, M3, M6
Molavi & Barral (2016) [23]	Improving sustainability through procurement methods.	Conceptual	Environmental, Economic	Construction method	4	M10, M11
Radogna & Kalhoefer (2022) [24]	Conducting flexibility analysis for new housing needs.	Theory + Case	Environmental, Social	Housing policy	2, 3, 4	M6, M7, M13
El-Husseiny & El-Setouhy (2022) [16]	Measuring the sustainability impact of low-tech construction.	HBIM+ Observation	Environmental, Social	Local Architecture	1, 3, 4	M7, M8, M12, M13, M9
Salihbegovic (2020) [17]	Analyze the use of natural materials.	Case study	Environmental	Material use	1, 3	M5, M12
Sutantio et al. (2022) [25]	Developing a sustainable housing model.	Mixed	Environmental, Economic, Social	Housing policy	1, 2, 4	M1, M4, M5, M6, M10
Hasan et al. (2024) [4]	Assessing the contribution of lean construction to the Sustainable Development Goals.	Mixed (Delphi+ Literature)	Environmental, Economic, Social	Construction method	1	M1, M4, M8,
Gao et al. (2023) [26]	Investigating the effect of minimalist consumption on low-carbon innovation behavior.	Quantitative (2 experiments+ survey)	Environmental, Social	Consumer Behavior	1, 3, 4	M5, M7, M11,
Carvajal-Arango et al. (2019) [19]	To evaluate the contribution of lean construction practices to sustainable construction.	Literature Review	Environmental, Economic, Social	Construction method	1, 2	M3, M4, M5, M8
Charytonowicz & Skowroński (2016) [27]	Examining the relationship between ergonomics and sustainable design.	Theoretical	Social	Design Ergonomics	2, 3	M2, M6, M12
Elbeltagi et al. (2023) [12]	Analyzing the contribution of integrated design processes to sustainable projects.	Case study+ BIM	Environmental, Economic,	Project Management	1, 4	M4, M9, M10, M11

The authors used Python with pandas, NumPy, NLTK, spaCy, scikit-learn, and gensim for data processing, text analysis, and topic modeling.

The principles cover strategic themes such as functional simplicity, process optimization, human-centered design, modularity, local adaptation, ease of maintenance, and resilience. Figure 3 shows their mapping to the 17 SDGs and 169 subtargets; these links, supported by sustainability indicators, were consolidated into a multidimensional evaluation matrix.

Figure 3 maps the relationships between the MDPs and the SDGs across environmental, social, and economic dimensions. The links were operationalized into indicators and sub-targets and compiled in Table 5.

The Delphi technique is a widely recognized method for expert-based consensus building and for validating conceptual frameworks [28]. In this study, a two-round Delphi was conducted to assess and refine the framework. Round 1 used purposive sampling

of 56 experts in architecture and civil engineering, ensuring variation in age, gender, and region; this stage explored practitioner insights and reduced an initial pool of 42 items. Round 2 engaged 15 experts (selected for subject expertise and response consistency) to rate 12 refined items and answer three open-ended questions, combining Likert ratings with qualitative thematic analysis (following Braun & Clarke’s framework [29]). The two-stage design, with a larger exploratory round followed by a smaller expert-focused round, is consistent with Delphi methodological standards and ensures both breadth and depth of input while supporting validity of the final framework.

Table 5. M1–M13 × SDGs: targets, subtargets, indicators, and references.

Code	MDPs	Related SDGs	Related SDG Subtargets	References
M1	Eliminating non-value-generating actions throughout the design lifecycle.	SDG-9; SDG-12	9.4 12.2	[4,21,25]
M2	Focusing on core human needs and the promotion of holistic well-being.	SDG 1 SDG 3; SDG 11	1.4; 3.8; 11.1	[7,27]
M3	Mitigating ambiguity and functional complexity throughout the design process.	SDG-3; SDG-9; SDG-11	3.8; 9.4; 11.3	[19,22,24]
M4	Integrating improvements by streamlining the construction timeline and lifecycle	SDG-9; SDG-11; SDG-12; SDG-13	9.1; 11.1; 12.2; 13.2	[4,8,12,19,22,25]
M5	Minimizing environmental impact by streamlining operational processes, material usage, and spatial design to reduce resource demand, carbon output, and construction-related waste.	SDG-7; SDG-12; SDG-13	7.2; 12.5; 13.2	[17,19,21,25–27]
M6	Achieving a diversity of living environments by enabling functional adaptability within spatial design.	SDG-3; SDG-11	3.9; 11.1; 11.3	[7,8,22,24,25,27]
M7	Promoting clarity and operational transparency throughout the design process to facilitate better decision-making and collaboration.	SDG-8; SDG-16; SDG-11	16.6; 11.3; SDG-8	[7,16,24,26]
M8	Embedding lean principles throughout the entire lifecycle—from design and manufacturing to end-of-life deconstruction—to maximize efficiency and minimize waste	SDG-12; SDG-13	12.4; 12.5; 13.2	[4,16,19,21,27]
M9	Proactively identifying potential points of intervention and optimizing outcomes through streamlined, low-complexity solutions	SDG-9; SDG-11; SDG-13	9.5; 11.b.2; 13.1	[12,16]
M10	Leveraging modular and off-site construction methods to enhance build-time efficiency and streamline on-site construction workflows	SDG-9; SDG-11; SDG-12; SDG-13	9.4; 11.1; 12.2; 12.5; 13.2	[8,12,23,25]
M11	Maximizing design effectiveness through the minimization of tool dependency.	SDG-11; SDG-12; SDG-13	11.1; 12.2; 12.6; 13.2	[8,12,23,26]
M12	Locality (Use of natural materials and cultural compatibility)	SDG-11; SDG-12; SDG-15	11.4; 12.2; 15.1; 12.b	[8,16,17,27]
M13	Ease of maintenance and durability	SDG-9; SDG-11; SDG-12	9.1; 11.6; 12.5	[8,12,16,23]

Developed by the authors.

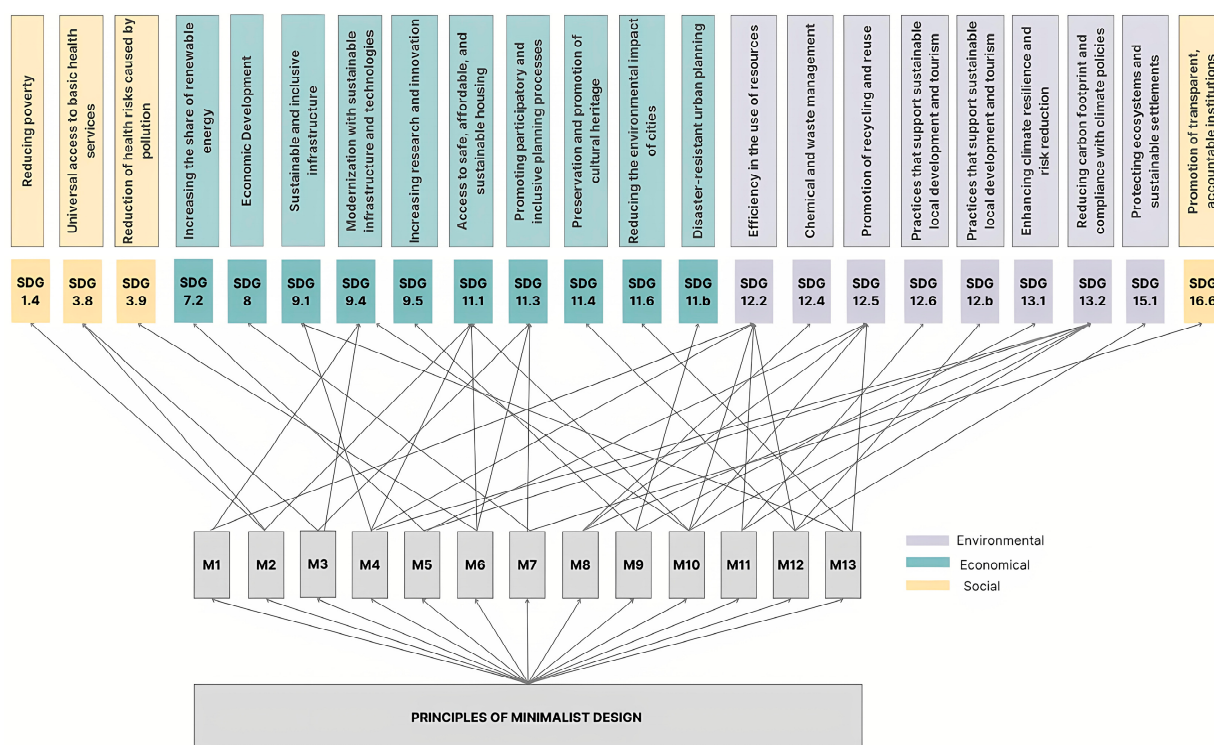


Figure 3. Conceptual mapping of MDPs to SDG targets. Reference: Developed by the authors from [4].

A priori thresholds were $IQR \leq 1.0$ and $\geq 70\%$ of responses $\geq 4/5$. We tracked panel convergence with Kendall's W, which improved from 0.39 to 0.52. In Round 2, 9/13 principles achieved $IQR \leq 1.0$, and the majority met the $\geq 70\%$ agreement threshold; therefore, a third round was not required.

Quantitative data analysis followed a multi-layered structure. First, descriptive statistics were calculated using SPSS v28, reliability was assessed with Cronbach's α (Section 4.4). Exploratory Factor Analysis (EFA) was conducted to determine structural validity. EFA in the first stage ($N = 56$) identified eight first-order factors, while confirmatory factor analysis (CFA) within SEM subsequently supported the aggregation of these factors into three higher-order constructs.

FAHP transformed Likert data into Triangular Fuzzy Numbers (TFNs) (Python 3.11: NumPy, pandas, Matplotlib) to derive principle weights; these weights then served as inputs to SEM, linking expert priorities to statistical validation. SEM was implemented in Google Colab with semopy; fit indices met acceptable thresholds. For data quality control, missingness was $<5\%$; we applied mean imputation, and Little's MCAR indicated data were completely random. The study received ethics approval from Yildiz Technical University (Protocol 20250605687); informed consent was obtained from all participants. All Delphi instruments (Rounds 1–2) are provided as Supplementary Materials for transparency. The Delphi panel is non-probabilistic and region-bounded; it supports expert consensus but is not statistically representative of all stakeholders.

Figure 4 summarizes the mixed-methods workflow linking theory building and hypothesis development to data collection and analysis (Delphi + FAHP for prioritization; SEM for structural validation; ANOVAs as contextual sensitivity checks).

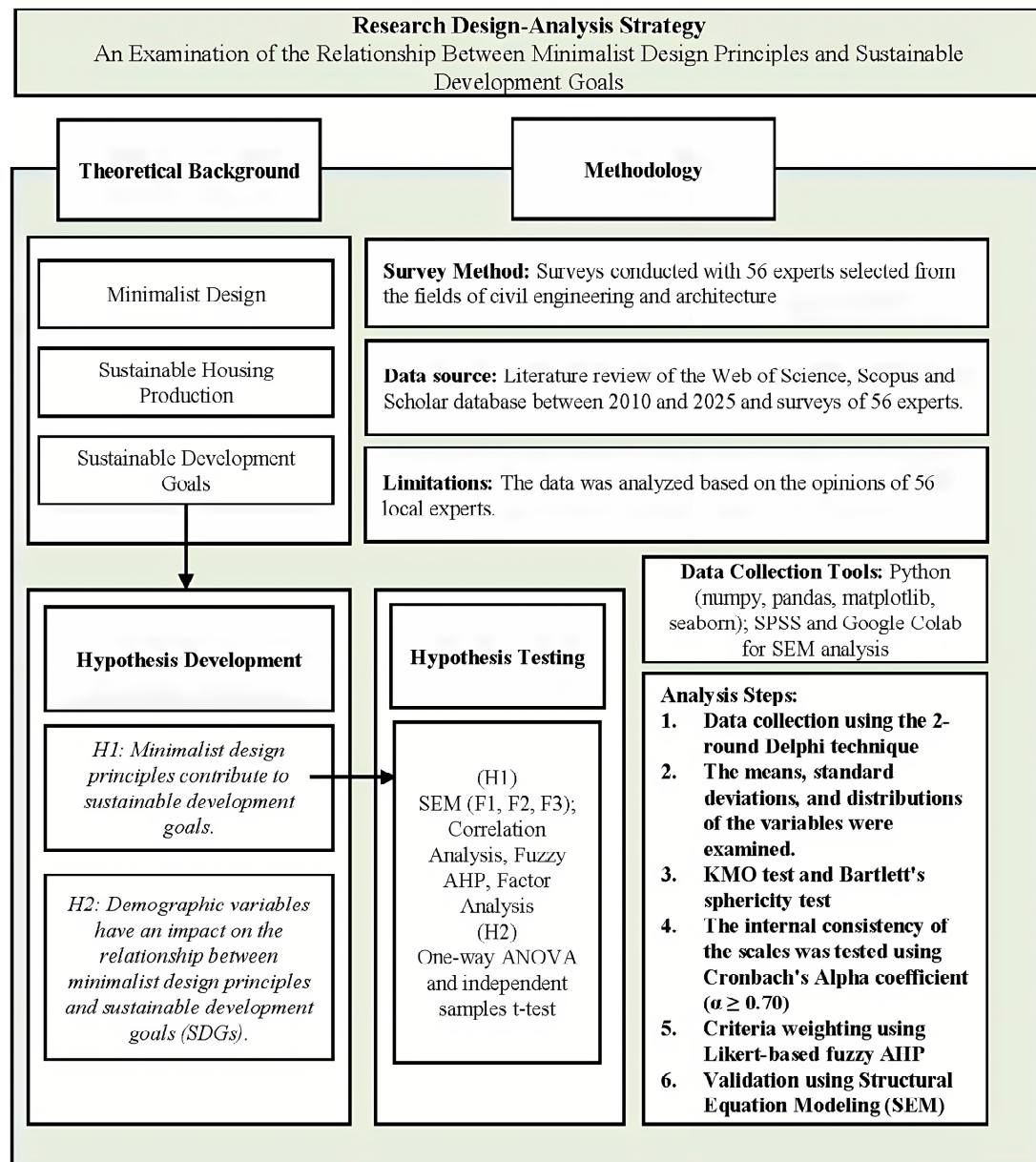


Figure 4. Research design. Created by the authors.

Following this design framework, the next section presents the participant profile and demographic characteristics.

Participant Profile and Demographic Characteristics

The study involved a two-stage expert panel. In Round 1 (N = 56), participants from architecture, engineering, and sustainability fields contributed to identifying the factor structure and developing the preliminary model. In Round 2 (N = 15), a subset of experts was selected based on subject-matter expertise and response consistency to validate the model. Panel composition criteria included disciplinary expertise, professional experience, and stable response patterns. As shown in Table 6, the sample ensured diversity across gender, age, education, professional experience, and place of residence, thereby strengthening the representativeness and applicability of the findings.

As shown in Table 6, the study sample ensured both representativeness and diversity across professional backgrounds, supporting the validity of the model. The following section presents the study's findings in detail.

Table 6. Participant demographic distribution (first and second stages).

Variable	Category	First Stage (N = 56)	%	Second Stage (N = 15)	%
Gender	Female	33	58.9	8	53.3
	Male	23	41.1	7	46.7
Age	22–30	31	55.4	5	33.3
	31–40	15	26.8	4	26.6
	41–50	8	14.3	5	33.3
	51–60	1	1.8	1	6.6
	61–70	1	1.8	-	-
Discipline	Architecture	43	76.8	10	66.6
	Civil Engineering	13	23.2	5	33.4
Educational Level	Bachelor's Degree	31	55.4	7	46.6
	Master's Degree	19	33.9	7	46.6
	Ph.D	5	8.9	1	6.8
Professional Experience	1–5 Year	26	46.4	5	33.3
	6–10 Year	18	32.1	3	20
	11–20 Year	7	12.5	5	33.3
	21–30 Year	4	7.1	2	13.4
	31+ Year	1	1.8	-	-
Place of Residence	Istanbul	43	76.8	11	73.4
	Outside of Istanbul	13	23.2	4	26.6

Demographic distribution of participants was analyzed and tabulated using SPSS. Data were collected by the authors.

4. Findings

Experts' ratings on a 5-point Likert scale were normalized to [0–1] for visualization. Figures 5 and 6 show heatmaps where cell values and color intensity indicate agreement levels (≈ 0.85 – 1.00 very high [0.1 h, 0.70–0.85 high, 0.50–0.70 moderate; <0.50 low / none).

Targets	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13
SDG 1		M2-1 1.9464											
SDG 3		M2-2 1.5536	M3-3 2.0714			M6-3 1.8571							
SDG 7					M5-2 1.7957								
SDG 8							M7-2 2.1071	M8-3 1.6727					
SDG 9	M1-1 3.1071		M3-1 2.0179	M4-2 2.1818 M4-1 2.2143				M8-3 1.6727	M9-3 1.7857	M10-2 2.1964			M13-3 1.6786
SDG 10						M6-1 1.7143							
						M6-4 2.0357							
SDG 11		M2-3 2.4464	M3-2 2.1250	M4-1 2.2143 M4-5 2.5714		M6-2 1.5536 M6-4 2.0357	M7-3 1.9464 M7-2 2.1071			M10-1 1.8393	M11-2 2.2500	M12-4 1.6071	M13-1 1.8393 M13-3 1.6786
SDG 12	M1-2 1.8214			M4-4 1.9821 M4-1 2.2143 M43 2.0000	M5-1 2.3571			M8-1 2.2857	M9-1 2.1250	M10-2 2.1964	M11-3 1.9286	M12-3 1.6607	M13-2 1.7407
SDG 13				M43 2.0000	M5-1 2.3571	M5-3 1.6182		M8-2 2.0893	M9-2 1.6964	M10-3 1.7679	M11-1 2.0357		
SDG 15												M12-1 1.6786	
SDG 16							M7-1 2.1964						

Figure 5. Heat maps of average scores for SDGs and MDPs (stage 1). Data analyzed in SPSS and visualized in Python. Colors correspond to the value ranges shown in the color bar.

Targets	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13
SDG 1		6.M2 2.1333											
SDG 4												10.M12 1.8000	
SDG 7			2.M3 2.4667	7.M4 1.6667									
SDG 9	1.M1 3.7333									8.M10 2.0000			
SDG 10		5.M2 2.0000											
SDG 11		5.M2 2.0000	2.M3 2.4667		11.M5 2.0000					8.M10 2.0000		9.M12 2.0000	
		6.M2 2.1333										10.M12 1.8000	
SDG 12				7.M4 1.6667	11.M5 2.0000	12.M6 2.4667					4.M11 2.0000	9.M12 2.0000	
SDG 13						12.M6 2.4667					4.M11 2.0000		

Figure 6. Heat maps of average scores for SDGs and MDPs (stage 2). Data analyzed in SPSS and visualized in Python. Colors correspond to the value ranges shown in the color bar.

The highest scores concentrated on SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). The statements associated with these goals were found to be highly correlated with multiple MDPs (M1.1, M3.1, M10.2, M11.1, M13.2). The findings are structured around descriptive statistics, reliability analysis, exploratory factor analysis (EFA), correlation tests, analysis of variance (ANOVA), the Fuzzy Analytic Hierarchy Process (FAHP), and structural equation modeling (SEM) (Table 7).

Table 7. Findings section- strategic summary table.

Subsection	Analytical Approach	Purpose of Analysis	Key Findings/ Interpretation Area
4.1 Correlation Analysis	Pearson Correlation Coefficient	Examine direction/strength of relationships	Significant positive/negative associations among minimalist design criteria.
4.2 ANOVA (one-way)	Multiple group comparisons	Test group differences by demographics	Effects of age, gender, and education on factor scores; η^2 effect sizes reported.
4.3 Qualitative Content Analysis	Thematic & conceptual coding	Analyze semantic patterns in open-ended data	Themes, keyword clusters, and content intensity (network visualizations).
4.4 Descriptive Statistics	Descriptives & reliability (Cronbach's α)	Profile participants and dataset	Means, SDs, and Cronbach's α indicate acceptable reliability.
4.5 Factor Analysis (EFA & CFA)	Comprehensive factor analysis	Test scale validity and dimensional structure	KMO, Bartlett, variance explained, and factor loadings support structure.
4.6 FAHP	Fuzzy MCDM (TFN method)	Derive criteria weights from expert judgments	Normalized weights, decision hierarchy, and impact rankings.
4.7 Structural Equation Modeling (SEM)	Confirmatory structural modeling	Test theoretical model with empirical data	Model fit confirmed (CFI, TLI, RMSEA, SRMR).
4.8 Hypothesis Testing	Multi-method statistical validation	Evaluate hypotheses via multiple methods	Significance established via SEM and ANOVA.

Created by the authors.

4.1. Correlation Analysis

Pearson correlations among MDPs showed significant positive associations, indicating strong thematic coherence across items. Overall coefficients ranged $r = 0.42\text{--}0.83$ ($p < 0.05$). Illustrative links include M10.1–M10.2 (modular systems-prefabrication, $r = 0.784$), M6.1–M6.2 (functional flexibility-spatial diversity, $r = 0.690$), and M13.1–M13.2 (durability-resource conservation, $r = 0.714$). Simplified spatial solutions also correlated with social inclusivity discourse ($r = 0.83$, $p < 0.001$) and, more moderately, with broader sustainability outcomes ($r = 0.65$, $p < 0.01$). These patterns provide a solid empirical basis for the subsequent SEM.

4.2. Group Differences (ANOVA)

As an exploratory step, we ran one-way ANOVAs across gender, education, discipline, years of experience, and region to test item-score differences. Where present, effects were small-to-moderate and did not alter FAHP priorities or SEM paths. Despite the modest sample (Round 1, $N = 56$), several differences reached significance, indicating that demographic factors can shape perceptions.

For gender, significant differences emerged for spatial flexibility (M6.3) and user-centered comfort (M2.2), with women reporting higher agreement, $F(1, 54) = 5.96$, $p = 0.018$; $F(1, 54) = 4.99$, $p = 0.029$. By discipline, perceptions differed for local materials / carbon reduction (M12.3), $F(1, 54) = 4.21$, $p = 0.045$. By education, participants with master's/doctoral degrees showed greater awareness of M12, while those with longer experience emphasized life-cycle-based design (M4.2), $F(1, 54) = 7.91$, $p = 0.007$. By region (Istanbul vs. non-Istanbul), the M12 composite was lower (stronger agreement) among Istanbul participants ($n = 47$, $M = 1.64$, $SD = 0.79$) than non-Istanbul ($n = 16$, $M = 1.92$, $SD = 0.97$), but the difference was not significant, $F(1, 61) = 1.31$, $p = 0.257$, $\eta^2 = 0.021$ (small). Item-level contrasts for M12.3 showed a similar non-significant pattern, $F(1, 61) = 1.83$, $p = 0.181$, $\eta^2 = 0.029$.

Taken together, perceptions of sustainability and minimalist design vary across demographic groups, yet the ANOVAs should be read as contextual signals given the modest sample. The results add nuance, especially by gender, discipline, and experience, and can inform the design of larger, confirmatory studies.

4.3. Qualitative Content Analysis

The qualitative component analyzed responses to three open-ended questions to deepen insight into how participants perceive MDPs in sustainable housing. Participants' responses to three open-ended questions were analyzed using the six-phase thematic analysis approach proposed by Braun and Clarke (2006) [29] and implemented preprocessing and analytics in Python (NLTK, spaCy, scikit-learn):

1. **Code Development:** Text segments were divided into meaning units, from which open codes were derived and then grouped into categories based on content similarity. A combination of open coding and axial coding techniques was used. Additionally, the TF-IDF algorithm was employed to identify salient terms, ensuring that the codes were informed by both surface-level repetitions and contextually meaningful expressions.
2. **Theme Formation:** Code clusters were categorized into overarching themes based on conceptual similarity. Besides frequency density, contextual co-occurrence and discourse patterns were also considered. Code similarities were assessed using Python's pandas and scikit-learn libraries, while the resulting clusters were reviewed by the researcher for content consistency.
3. **Theme Review:** Generated themes were revisited and examined alongside Python outputs. Overlaps among themes were assessed using the Jaccard similarity index to ensure conceptual clarity.

4. Theme Definition: The finalized themes were re-labeled based on their content, with the researcher defining the meaning domains of each theme represented.
5. Reporting: We documented themes with direct quotations. The researchers made final selections to balance rigor and interpretive depth.

The thematic distribution for each question, along with their numerical representations, is presented in Table 8.

Table 8. Thematic coding distribution for open-ended questions.

Question Title	Minimalism and Sustainability	Challenges in Design Processes	Local Elements and Strategies
Sustainability and Resource Use	8	7	5
Minimalist Approach and Lifestyle	10	4	3
Design Process and Cultural Elements	1	10	2
Local and Cultural Elements	3	5	11
User-Centeredness	0	4	2
Education and Awareness	5	2	5

The analysis was conducted using Python tools, including NLTK, spaCy, scikit-learn, and TF-IDF algorithm for preprocessing, coding, and theme extraction.

Table 8 summarizes the thematic distribution per question. Responses cluster around sustainability, design processes, and local strategies. Emphasis on “Minimalist Approach and Lifestyle” and “Local and Cultural Elements” links minimalist housing to cultural values and sustainability priorities. Python tooling ensured a replicable workflow while preserving qualitative depth.

A word co-occurrence network (Figure 7) was built from the cleaned corpus (CountVectorizer→co-occurrence matrix; NetworkX→graph; Matplotlib→visualization). Node size = frequency; edge weight = co-occurrence intensity. Central nodes include “sustainability,” “environment,” “minimalism,” “locality.” The network indicates that participant discourse centers on minimalist lifestyles, environmental impact, local identity, and user needs.

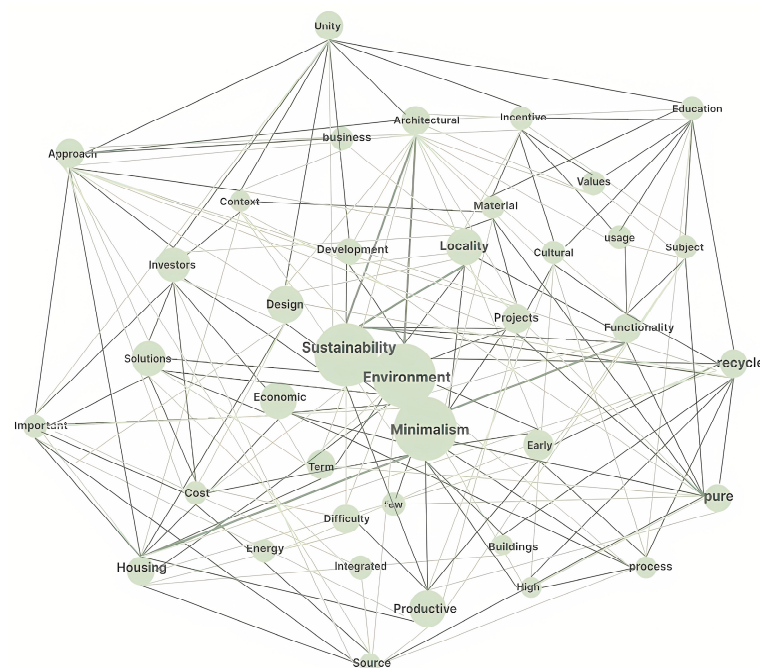


Figure 7. Conceptual network map. Analysis supported by Python (NLTK, scikit-learn, CountVectorizer, NetworkX, Matplotlib); thematic method per Braun & Clarke (2006) [29].

The content analysis revealed three key insights. First, participants perceived minimalist approaches both as a spatial strategy and as a tool for lifestyle transformation. Second, the local context emerged as a strong conceptual domain in terms of cultural adaptation, material selection, and climate-responsive design. Third, the simplification process was conceptualized as a transformation prioritizing environmental and economic gains without compromising user comfort.

4.4. Descriptive and Reliability Analysis

The 42-item scale showed excellent internal consistency in Stage 1 (Cronbach's $\alpha = 0.968$) and high reliability in Stage 2 ($\alpha = 0.839$), indicating consistent responses aligned with the intended constructs.

4.5. Exploratory Factor Analysis (EFA)

An Exploratory Factor Analysis (EFA) was conducted to examine the latent structure of the MDPs and assess scale validity. KMO = 0.849 indicated sampling adequacy, and Bartlett's test was significant ($\chi^2 = 3501.72$, $p < 0.001$), supporting factorability. Principal Component Analysis with Varimax rotation explained 79.21% of the variance, well above the ~60% benchmark. Items with loadings ≥ 0.40 were retained, yielding eight first-order factors (Table 9).

Table 9. Factors obtained as a result of factor analysis.

Factor No	Factor Name	Content Themes
F1	Resource and Energy Efficiency	Energy conservation, prevention of material waste, reduction in life-cycle costs
F2	Functionality and User Experience	Flexibility, comfort, accessibility, spatial efficiency
F3	Esthetic Purity and Planning Clarity	Open planning, simple form language, architectural clarity
F4	Structural Durability and Economic Sustainability	Long-lasting structures, low maintenance requirements, cost-effectiveness
F5	Local Materials and Cultural Adaptation	Use of local materials, cultural context, local production techniques
F6	Environmental Awareness and Early Design Decisions	Consideration of sustainability criteria in the early stages of design
F7	Elimination of Unnecessary Elements	Lean production processes, elimination of non-functional elements
F8	Material Selection and Ecological Compatibility	Preference for natural, recyclable, low carbon footprint materials

Factors were extracted via PCA (Varimax) in SPSS; only items with loadings $\geq .40$ were retained.

For SEM (Section 4.7), these were aggregated into three higher-order constructs, Resilience/Performance, Social/Cultural Adaptation, and Environmental Contribution, capturing broader latent dimensions while preserving the EFA structure.

4.6. FAHP-Based Weighting of Criteria

To estimate the relative importance of the MDPs within a sustainability context, we applied a Likert-based FAHP [30,31]. Expert judgments collected via a Likert-scale survey were converted into Triangular Fuzzy Numbers (TFNs), defined by the lowest (l), most likely (m), and highest (u) values, to capture uncertainty in decision-making.

$$M_i^g = (l_i, m_i, u_i)$$

Aggregated TFNs were calculated using the geometric mean operator, and defuzzification was performed via the centroid method. The weighting procedure was implemented in Python following [30] extent analysis approach, which models expert comparisons through triangular fuzzy numbers.

For each criterion, a fuzzy synthetic extent value was defined as:

$$s_i = \frac{\sum_{j=1}^m M_{ij}^g}{\sum_{i=1}^n \sum_{j=1}^n M_{ij}^g}$$

Comparison of two fuzzy numbers is expressed as:

$$V(M_1 \geq M_2) = \begin{cases} 1, & \text{if } m_1 \geq m_2 \\ \frac{(u_2 - l_1)}{(m_1 - l_1) - (m_2 - u_2)}, & \text{if } l_2 \leq u_1 \leq m_2 \\ 0, & \text{if } u_1 \leq l_2 \end{cases}$$

The minimum degree of possibility for each criterion was then computed as:

$$(A_i) = \min_{k \neq i} V(S_i \geq S_k)$$

and the final normalized weight vector was:

$$W = (d(A_1), d(A_2), \dots, d(A_n))^T$$

Unlike classical AHP, the Likert-based FAHP avoids pairwise-matrix burden while preserving flexibility for subjective judgements [32]. Because the eigenvalue Consistency Ratio (CR) is not directly defined for FAHP, we computed an approximate CR from the defuzzified weights; its near-zero value indicates high logical consistency of expert evaluations. In order to determine the relative importance levels of the MDPs in the context of sustainability, FAHP was employed.

Results indicate that “Only elements with functional contributions should be prioritized in design processes” (m1.1) obtained the highest weight ($\bar{x} = 3.1071$), highlighting functionality as the most critical dimension of sustainable housing. “Design focusing on simplicity reduces carbon emissions and waste generation” (m5.1, $\bar{x} = 2.3571$) also ranked highly, reinforcing minimalism’s environmental role, especially for SDGs 12 and 13. Conversely, criteria such as “Priority should be given to user comfort” (m2.2), “Spaces should allow flexible rearrangements” (m6.2), and “Buildings should require minimal maintenance over time” (m13.3) received lower weights, suggesting that social and operational considerations were evaluated as secondary to environmental efficiency and process optimization.

The normalized weights and rankings for all 13 principles are given in Table 10; these priorities provided the exogenous weights used in the subsequent SEM, linking expert-based valuation to statistical validation of MDP-SDG relations.

Table 10. Ranking of MDPs.

Ranking	MDPs	Average Normalized Weight
1	M1—Eliminating non-value-generating actions throughout the design lifecycle.	0.0297
2	M4—Integrating improvements by streamlining the construction timeline and lifecycle.	0.0264
3	M3—Mitigating ambiguity and functional complexity throughout the design process.	0.0258
4	M7—Promoting clarity and operational transparency throughout the design process to facilitate better decision-making and collaboration.	0.0251
5	M11—Maximizing design effectiveness through the minimization of tool dependency.	0.0249
6	M2—Focusing on core human needs and the promotion of holistic well-being.	0.0239
7	M10—Leveraging modular and off-site construction methods to enhance build-time efficiency and streamline on-site construction workflows	0.0233
8	M8—Embedding lean principles throughout the entire lifecycle, from design and manufacturing to end-of-life deconstruction, to maximize efficiency and minimize waste	0.0226
9	M9—Proactively identifying potential points of intervention and optimizing outcomes through streamlined, low-complexity solutions	0.0225
10	M5—Minimizing environmental impact by streamlining operational processes, material usage, and spatial design to reduce resource demand, carbon output, and construction-related waste.	0.0225
11	M6—Achieving a diversity of living environments by enabling functional adaptability within spatial design.	0.0216
12	M13- Ease of maintenance and durability	0.0211
13	M12—Locality (Use of natural materials and cultural compatibility)	0.0207

FAHP weights were computed with Chang's extent analysis in Python; weights normalized to $\Sigma = 1.000$.

Table 10 reports the normalized weights and the resulting priority order of the 13 principles; higher values indicate greater expert-assessed importance. These priorities provide a practical basis for design planning and resource allocation. The FAHP weights were then used as exogenous inputs to the SEM, linking expert-based priorities to statistical tests of the hypothesized relationships between MDPs and sustainability criteria.

4.7. Structural Equation Modeling (SEM)

A three-factor SEM was estimated in Python (semopy) to test the proposed framework. The latent factors were Resilience/Performance (F1), Social/Cultural Adaptation (F2), and Environmental Contribution (F3). EFA (Section 4.5) indicated eight first-order factors. To align with theory and improve parsimony, CFA/SEM grouped these into three higher-order

constructs after considering content overlap, explanatory power, and overall fit. All factor loadings were significant, indicating adequate measurement (Figure 8).

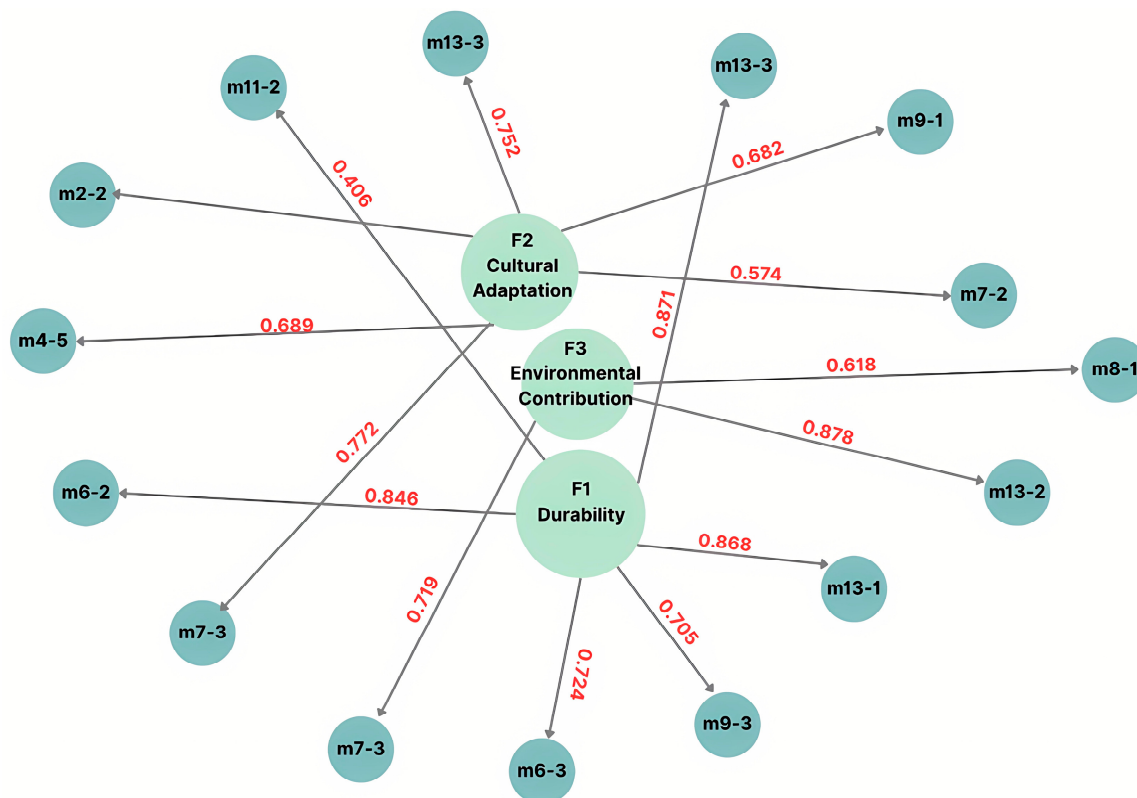


Figure 8. SEM 3-factor model structure. SEM was created by the authors using Python.

In the evaluation of model fit, the Comparative Fit Index (CFI) was calculated as 0.865 and met the acceptable fit level. The SRMR value was obtained as 0.08, which also shows that the overall fit level of the model is satisfactory. However, the Tucker–Lewis Index (TLI) remained at the level of 0.729 and fell below the ideal threshold value (≥ 0.90). Similarly, the RMSEA value was found to be 0.132, indicating a level below that of strong fit. Within structural equation modeling, some fit indices (RMSEA and TLI) tend to yield lower values in small samples. Kenny et al. [33] noted that such indices are highly sensitive to sample size. In cases with $N < 100$, RMSEA may not fully reflect structural validity. Since the sample size in this study ($N = 56$) was selected according to academic expertise criteria, it remained limited; this led to deviations in the RMSEA and TLI indices.

However, the fact that the CFI and SRMR values exceeded the threshold values supports that the overall fit of the model is at an acceptable level. It was observed that the correlation coefficients between the factors ranged between 0.40 and 0.57. This shows that the three proposed factors are conceptually related to each other, but at the same time differ sufficiently in measurement terms and present distinguishable structures. Thus, both the internal consistency and the discriminant validity of the model were ensured.

The SEM statistically supports the theorized links between MDPs and SDG-aligned outcomes, providing the empirical basis for hypothesis testing.

4.8. Hypothesis Testing

Finally, the study examined two hypotheses in its theoretical framework. H1 was examined with SEM, correlations, FAHP, and factor analyses (EFA/CFA) and was supported. H2 was tested with one-way ANOVA and was supported. The confirmed relationships indicate that the principle clusters, functional simplicity, human-centered design, and

lean production align with SDG outcomes. Overall, results show that minimalist design functions as an integral component of environmental, social, and cultural sustainability. The results are presented in Table 11.

Table 11. Hypothesis result.

Code	Hypothesis	Method	Result
H1	MDPs significantly influence SDGs	SEM, Correlation, FAHP, Factor Analysis (EFA&CFA)	Significant
H2	The mean scores of MDPs and related SDG indicators differ significantly across demographic groups.	ANOVA	Significant

Analyses conducted by the authors.

These findings corroborate the empirical and structural validity of the framework and provide a multidimensional evidence base for sustainable housing aligned with development goals. The next section discusses implications, limitations, and contributions.

5. Discussion

Minimalist Design Principles (MDPs) serve as a systematic strategy for sustainable housing production rather than a purely esthetic stance [3,7,8]. They create impact at functional, environmental, and behavioral levels. They generate multidimensional effects, ranging from environmental sustainability and social accessibility to economic efficiency and life-cycle awareness. Both quantitative analyses and qualitative interpretations support these results, forming an interdisciplinary validation structure.

Sustainable architectural approaches were linked with participants' demographic characteristics, statements, and experiences. According to survey data (N = 56), age, gender, discipline, education, and professional experience affected attitudes toward minimalist approaches. Most participants were women (58.9%), architects (76.8%), and young professionals with 1–10 years of experience. This reflects a sample with high environmental and functional sensitivity. The online survey format increased the participation of digitally literate young individuals, making them dominant in the sample.

The highest scores clustered around functionality, resource efficiency, and lean production. This profile positions minimalism within an operational/production-centered understanding of sustainability. In particular, the item “only elements with functional contribution should be prioritized” (aligned with SDG 9) reflect participants' anti-consumerist preferences and expectations for process simplicity in design and construction. These findings can guide thematic prioritization in decision-support models for housing. Convergence with sectoral analyses is evident: Dagilgan and Ercan (2025) identified energy use, occupational health and safety, and governance/management as high-impact themes in construction, paralleling the present results [5].

However, the M12 code (Locality/Cultural Coherence), which received the lowest weight in the FAHP analysis, shows a contrasting contrast with the qualitative findings, where the “locality” node exhibits high conceptual centrality. This divergence likely stems from (i) the relatively broad and generalized wording of the M12 items and (ii) the composition of the expert panel, which was predominantly Istanbul-based and architecture-oriented. To address this, we recommend expanding M12 to include clearer sub-themes such as local materials, climatic context, and cultural continuity, and increasing regional diversity in future panels to obtain more comprehensive evaluations of locality-based design principles.

To reconcile this conceptual prominence with the lower quantitative weight, we propose a set of candidate sub-items that more precisely operationalize M12 for future scale refinement and sensitivity tests. These items were not used in the present weighting; they are provided to facilitate replication and robustness checks. Specifically, we outline four sub-dimensions: M12.1 Climatic and Geographic Responsiveness (designs explicitly respond to local climatic conditions and site geography, orientation, shading, ventilation, topography); M12.2 Traditional/Vernacular Construction Techniques (revisiting traditional/vernacular methods and details as context-appropriate, resource-efficient alternatives); M12.3 Local Supply Chains and Economic Impact (prioritizing local sourcing to reduce transport emissions and support regional economies); and M12.4 Cultural Heritage Integration (thoughtful integration of heritage elements and place-specific identity into contemporary design without compromising functionality). For future surveys, we recommend a 5-point agreement scale (1 = strongly agree; 5 = strongly disagree) for each sub-item.

FAHP rankings (Tables 9 and 10) show technically and operationally oriented principles, M1 (eliminating non-value activities) and M4 (process/life-cycle streamlining), outweighing social/cultural principles such as M2 (user needs/quality of life) and M12 (locality/cultural compatibility). This suggests panel priorities favored process and functional optimization over socio-cultural considerations, consistent with (i) incentive structures framed by environmental-efficiency metrics and (ii) a technically oriented cohort profile. ANOVA sensitivity checks indicated modest demographic effects that did not undermine the FAHP-SEM structure.

However, such prioritization risks under-weighting social and cultural components of sustainability. Outcomes more closely captured by M2 and M12, including SDG 11.4 (heritage safeguarding), SDG 16.7 (inclusive/participatory decision-making), and SDG 12.b (local values and sustainable tourism), may receive insufficient emphasis in practice. Qualitative coding nonetheless revealed frequent references to “locality,” “cultural coherence,” and “user lifestyle,” indicating conceptual awareness that exceeds their quantitative weights. These patterns argue for panel diversification and wording-sensitive robustness checks (re-estimating FAHP with M12 sub-items and reporting subgroup stability), and for calibrated decision flows (Figure 9) that up-weight social-cultural principles where warranted.

Links between lean construction and SDGs, particularly process orientation and continuous improvement, were highlighted by Hasan et al. (2024) [4]; related evidence from Charytonowicz & Skowroński [27] shows that lean-oriented material strategies reduce energy demand and life-cycle costs. The present findings align with sector-level priorities identified by Fei et al. [1] (SDGs 9, 11, 13) and extend them by operationalizing effects at the housing scale through FAHP weights and SEM pathways. Still, relatively lower scores for social sustainability imply that sustainability is often evaluated primarily in environmental and economic terms, possibly reflecting gaps in architectural education’s coverage of social dimensions. While Markoc and Cinar [10], found social norms decisive for environmental attitudes, the present results indicate that social sustainability remains under-prioritized in design-oriented applications.

SEM indicated strong linear relationships among MDPs; “functional simplicity,” “long-lasting construction,” and “avoiding unnecessary consumption” contributed to sustainability through both direct and indirect effects. The behavioral-transformation potential of minimalism emphasized by Kang et al. [7] also resonates here: respondents tended to simplify not only spaces but also daily practices.

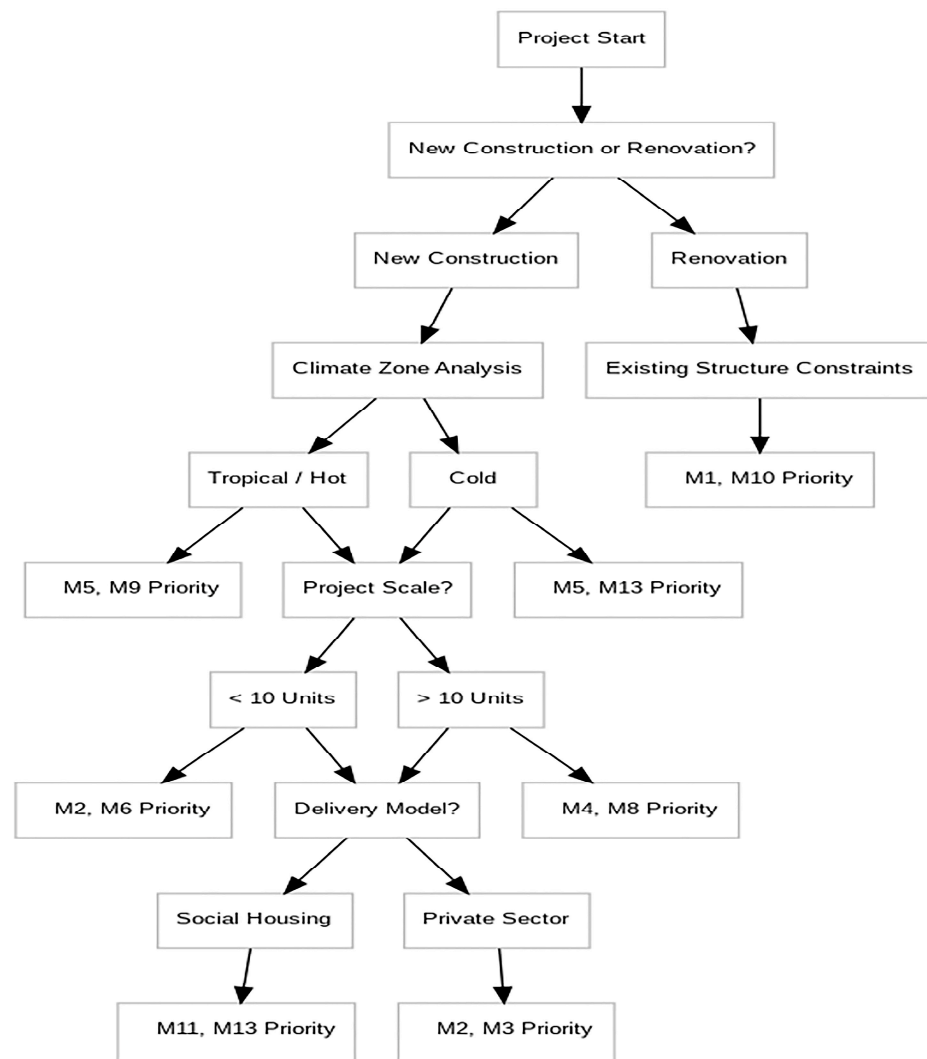


Figure 9. Decision flowchart for context-based reweighting of MDPs. Nodes indicate trigger conditions; outgoing arrows specify M-code groups recommended for up-weighting/down-weighting.

Demographic analyses showed significant effects for gender and age on selected items; women and older participants expressed more positive attitudes toward minimalism. This pattern suggests minimalism is not a transient youth aesthetic, but rather a practice associated with maturing sustainable-living preferences over time.

Qualitative evidence reinforced the numerical structure at a thematic level. The highest-scoring statements focused mainly on environmental awareness, simple living, local-resource sensitivity, and recyclable systems. Frequently co-occurring concepts, such as “balance,” “reduction,” “adaptation,” and “efficiency”, indicate that MDPs are internalized as a performative value system.

Overall, the findings indicate a transition from minimalism as an esthetic option to a multidimensional sustainability instrument in housing. Whereas much of the literature treated minimalism conceptually, the present study grounds it in a data-driven model; the integration of FAHP and SEM demonstrates a feasible interdisciplinary structure for architectural research. The hypothesis tests support this interpretation: H1 confirmed significant effects of MDPs on SDG-aligned outcomes [7,19], and H2 confirmed demographic differences (with more positive attitudes among women and older participants) [20].

From a global perspective, the integration of minimalist housing principles with SDGs provides solutions to critical problems in rapidly urbanizing world cities. These cities share common challenges such as resource scarcity, informal settlements, and environmental

degradation, making the framework of this study highly transferable. Aligned with UN-Habitat strategies, the proposed model contributes to SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action), ensuring that local interventions align with global sustainability agendas.

5.1. Theoretical Contributions

This study offers several contributions to scholarship on sustainability, architecture, and multi-criteria decision-making (MCDM). First, it formally links MDPs to the Sustainable Development Goals (SDGs) by structuring minimalism into 13 core criteria and aligning them with the 17 goals and 169 targets. In a literature that has largely treated minimalism as an esthetic stance or lifestyle choice, this work provides a conceptualized, criteria-based mapping that enables multi-stage analytical verification of minimalism's contribution to sustainability objectives.

Second, the research integrates Delphi, Likert-based FAHP, and Structural Equation Modeling (SEM) into a single framework, balancing qualitative judgment with quantitative validation. This MCDM-informed SEM offers a reproducible model for Architecture and Building Sciences, strengthening both statistical and conceptual validity.

Third, as one of the most comprehensive analyses in the Turkish context, the study examines how theories developed in Western settings travel to local conditions. The thematic evidence demonstrates how global sustainability goals are interpreted locally—through cultural, climatic, and economic lenses—thereby filling an important gap in the literature on contextualized sustainability.

Overall, the study reinterprets sustainable design through a minimalist lens, advancing theory both by its modeling architecture and by its conceptual structuring of minimalism as a multidimensional, operational pathway to SDG-aligned outcomes.

5.2. Practical Contributions

The findings provide strategic guidance and implementable tools for policymakers, local governments, and practitioners. The M1–M13 evaluation framework offers a scalable guide that moves beyond aesthetics to address functionality, cost-effectiveness, resource efficiency, and social inclusivity. FAHP weights supply a data-driven priority order, with the highest weight for “only elements with functional contribution should be prioritized,” underscoring the prominence of simplicity and efficiency in sustainable housing.

Policy and practice recommendations include: (i) municipal design checklists aligned with SDG 11.1/11.3 and SDG 12.2; (ii) green public-procurement scoring and fast-track permitting for projects meeting high-weight criteria; (iii) mandatory LCA plus durability/maintenance reports for M5/M13; (iv) minimum adaptable-plan ratios (M2/M6) for social housing; and (v) integration of FAHP weights into tender scoring templates to ensure transparent evaluation.

The SEM model clarifies structural links between design inputs and user perceptions and can function as an analytical decision-support system for municipal agencies, social-housing developers, and policy institutions. Reported path coefficients and correlation patterns enable more holistic and evidence-based strategies.

Finally, the online sampling and young-professional profile reflect emerging user preferences, providing a useful basis for future user-centered housing projects. Overall, the study serves as a practical reference for academia, design practice, governance mechanisms, and behavior-informed policy design.

5.3. Applicability Limits and Recalibration Guidelines

The decision-support model is intended for broad use, yet several conditions warrant recalibration. Project type matters: in renovation, existing structures can limit the

applicability of M1 (eliminating non-value activities) and M10 (modularity), whereas M12 (locality) and M13 (maintainability) typically gain weight. Climate also reshapes priorities: in tropical and very cold zones, energy performance dominates, elevating M5 and M9 and aligning the model with SDG 7 and SDG 13. In practice, this translates to passive ventilation, shading, and light-weight assemblies in the tropics; and compact forms, thermal insulation, and renewable integration in cold climates. Project scale shifts emphasis as well: small social-housing projects foreground M2 (user needs) and M6 (functional flexibility), whereas large programs call for M4 (process optimization) and M8 (life-cycle orientation). Delivery model further modulates priorities: publicly funded/social-housing schemes tend to privilege M11 (reduced tool dependency) and M13, while private-sector projects emphasize M3 (esthetic simplicity) and M2. Social sustainability is reinforced when recalibration toward M12 supports local materials and craftsmanship, and when M2 sustains inclusivity and adaptability in diverse communities.

Figure 9 synthesizes these conditions into a decision flow: starting from project type, then climate, scale, and delivery model, each node indicates when specific principles (M1, M5, M13) should be up or down-weighted so that prioritization remains sensitive to local needs, environmental conditions, and implementation models. For architects and planners, this yields concrete outcomes such as, in new construction, M10 supports standardized typologies and faster assembly; in renovation, M12 guides the integration of cultural heritage within existing fabrics.

For practical deployment, the model can be operationalized through a small set of quantitative targets that align MDPs with the SDGs and can be recalibrated by context: final energy use should be $\leq 45 \text{ kWh/m}^2/\text{year}$ to enact M5 (SDG 7/13); the gross-to-net area ratio should be ≤ 1.25 under M1 (SDG 12); adaptable floor area should reach $\geq 20\%$ for M2 (SDG 11); process and life-cycle optimization under M4/M8 should deliver $\geq 10\%$ reduction in 30-year life-cycle cost (SDG 12/13); in new builds, prefabricated/modular components should comprise $\geq 40\%$ for M10 (SDG 9/11); and local content, materials and workmanship, should be $\geq 30\%$ for M12 (SDG 11).

These thresholds are governed by the decision flow in Figure 9, which sequences the four contextual nodes, project type (new build vs. renovation), climate zone, project scale, and delivery model (PPP, social housing, private), and, at each node, specifies which principle groups (M1/M4/M8 vs. M2/M12/M13) should be emphasized. Typical outcomes include a shift from modularity (M10) to locality/maintainability (M12/M13) in renovation; elevation of M5/M9 in hot-humid climates (passive ventilation, shading, envelope performance); and emphasis on M2/M6 in small-scale social housing versus stronger M4/M8 signals in large, multi-stakeholder projects.

The central contribution of this work is the Minimalist Design Principles Framework (M1–M13). Beyond serving as an SDG mapping device, the framework provides a reusable, theory-grounded scaffold that can be operationalized across contexts (new build/renovation, climates, delivery models). Consequently, it enables cumulative research, comparable evaluation, and policy translation in sustainable architectural design.

6. Conclusions

This study presents a structured, generalizable framework for minimalist architectural design (M1–M13). By specifying principle $\rightarrow$ mechanism $\rightarrow$ indicator linkages and providing open materials for replication, the framework functions as shared research infrastructure rather than a one-off case. The evaluation model integrates this framework with the United Nations Sustainable Development Goals through a sequential program of literature synthesis, SDG mapping, Delphi-based expert consensus, FAHP weighting, and SEM validation, linking 13 principles to 17 SDGs and 169 targets within a decision-oriented architecture.

Findings indicate that minimalism functions as a multidimensional paradigm, not merely an esthetic stance. Core principles, functional simplicity, resource efficiency, modularity, and the avoidance of unnecessary consumption, exert strong effects across environmental, economic, and social dimensions, supporting minimalism as both a behavioral and design strategy. Practically, the framework offers policymakers, municipalities, architects, and developers a measurable tool for prioritizing design strategies, allocating resources, and improving user outcomes.

Overall, the proposed model positions minimalist design as a holistic and actionable pathway for advancing SDG-aligned housing. It establishes a robust foundation for policy and practice while inviting continued empirical testing and interdisciplinary application to maximize impact. Findings reflect consensus from a purposive, regionally bounded expert panel and should be treated as analytical generalizations pending replication across geographies, populations, and stakeholder groups.

Several limitations qualify these conclusions. First, the reliance on expert judgments ($N = 56$) constrains generalizability. Although this design yields high information density, it limits socio-demographic breadth, especially for socially oriented sustainability dimensions. Future work should recruit larger, heterogeneous, and representative samples to enable broader, multidimensional assessment.

Second, the panel was discipline-skewed toward architecture and civil engineering, foregrounding technical perspectives. Because sustainable housing also hinges on user behavior, social equity, and spatial justice, greater interdisciplinary diversity (planning, sociology, public health, economics) is needed to enrich interpretation and policy relevance.

Third, the exclusive focus on the Turkish context means the model embeds specific socio-cultural, economic, and climatic conditions. Given the global scope of the SDGs, subsequent studies should conduct cross-country replications, assess contextual transferability, and incorporate culturally sensitive adaptations, including settings in developing countries where priorities may differ.

Methodologically, several SEM fit indices approached borderline thresholds, consistent with small-sample behavior. Future research should validate the model with larger datasets and explore methods that relax linearity assumptions, such as neural networks, fuzzy clustering, fsQCA, or Bayesian networks, alongside robustness checks (bootstrapping, multi-group invariance tests).

Finally, evidence is cross-sectional. Because sustainability outcomes unfold over time, longitudinal designs are essential to track life-cycle effects, monitor policy/design interventions, and observe durable changes in user behavior. These directions will strengthen external validity, expand theoretical scope, and refine the model's practical utility for SDG-aligned housing.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su17209232/s1>, File S1: Reproducible Python Workflow (PDF); Table S1: Coders Comparison (XLSX); File S2: Cohen's Kappa Inter-Coder Agreement Report (PDF); Table S2: Conciliation Report (XLSX); Dataset S1: Full-Dataset (CSV/XLSX); Code S1: Python Analysis Files (ZIP: scripts and notebooks).

Author Contributions: Conceptualization, I.M. and D.Y.; Formal analysis, I.M. and D.Y.; Investigation, I.M. and D.Y.; Methodology, I.M. and D.Y.; Resources, I.M. and D.Y.; Software, I.M. and D.Y.; Validation, I.M. and D.Y.; Visualization, I.M. and D.Y.; Writing—original draft, I.M. and D.Y.; Writing—review & editing, I.M. and D.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Ethical review and approved by the YTU Social Sciences Institute Scientific Research and Publication Ethics Board (Protocol No: 20250605687).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are contained within the article.

Acknowledgments: This article is part of a master's dissertation research at Yildiz Technical University, Department of Architecture, Construction Management and Building Production.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of Variance
AHP	Analytic Hierarchy Process
AGFI	Adjusted Goodness of Fit Index
CFI	Comparative Fit Index
CFA	Confirmatory Factor Analysis
EFA	Exploratory Factor Analysis
FAHP	Fuzzy Analytic Hierarchy Process
GFI	Goodness of Fit Index
KMO	Kaiser-Meyer-Olkin Criterion
MCAR	Missing Completely at Random
MCDM	Multi-Criteria Decision-Making Method
NLP	Natural Language Processing
SDG	Sustainable Development Goals
M1–M13	Minimalist Design Principles (MDPs)
RMSEA	Root Mean Square Error of Approximation
SEM	Structural Equation Modeling
SPSS	Statistical Package for the Social Sciences
SRMR	Standardized Root Mean Residual
TLI	Tucker–Lewis Index
TFN	Triangular Fuzzy Numbers
χ^2/df	Chi-square / Degrees of Freedom

References

1. Fei, W.; Opoku, A.; Agyekum, K.; Oppon, J.A.; Ahmed, V.; Chen, C.; Lok, K.L. The Critical Role of the Construction Industry in Achieving the Sustainable Development Goals (SDGs): Delivering Projects for the Common Good. *Sustainability* **2021**, *13*, 9112. [\[CrossRef\]](#)
2. Wu, J.; Guo, S.; Huang, H.; Liu, W.; Xiang, Y. Information and communications technologies for sustainable development goals: State-of-the-art, needs and perspectives. *IEEE Commun. Surv. Tutor.* **2018**, *20*, 2389–2406. [\[CrossRef\]](#)
3. Yildiz, D.; Markoc, I. Redefining minimalism in housing: Introducing the M1-13 evaluation framework via NLP and multi-scale criteria. *J. Sustain. Eng. Appl. Technol. Dev.* **2025**, *8*, 61–76. [\[CrossRef\]](#)
4. Hasan, S.; Isik, Z.; Demirdögen, G. Evaluating the Contribution of Lean Construction to Achieving Sustainable Development Goals. *Sustainability* **2024**, *16*, 3502. [\[CrossRef\]](#)
5. Dağilgan, S.; Ercan, T. Developing a Sustainability Reporting Framework for Construction Companies: Prioritization of Themes with Delphi Study Approach. *Sustainability* **2025**, *17*, 3014. [\[CrossRef\]](#)
6. Yildiz, D. Evaluation of the Relationship between the Minimalist Housing Design Approach and the Sustainable Development Goals. Master's Thesis, Yildiz Technical University, Istanbul, Turkey, 2025.
7. Kang, J.; Martinez, C.M.J.; Johnson, C. Minimalism as a sustainable lifestyle: A structural equation modeling approach. *Sustain. Prod. Consump.* **2021**, *27*, 802–813. [\[CrossRef\]](#)
8. Kamali, M.; Hewage, K. Development of performance criteria for sustainability evaluation of modular versus conventional construction methods. *J. Clean. Prod.* **2017**, *142*, 3592–3606. [\[CrossRef\]](#)

9. Li, Y.; Chen, H.; Yu, P.; Yang, L. Development and Challenges of Low-Carbon Cities in China: Current Situation, Influencing Factors, and Sustainability Strategies. *Buildings* **2025**, *15*, 350. [\[CrossRef\]](#)
10. Markoç, İ.; Cinar, C. Loss of social belonging, displacement and social exclusion in the neighborhood: Urban redevelopment in Sarıgöl, Istanbul, Turkey. *Megaron* **2018**, *13*, 169. [\[CrossRef\]](#)
11. Alqahtani, E.; Janbi, N.; Sharaf, S.; Mehmood, R. Smart Homes and Families to Enable Sustainable Societies: A Data-Driven Approach for Multi-Perspective Parameter Discovery Using BERT Modelling. *Sustainability* **2022**, *14*, 13534. [\[CrossRef\]](#)
12. Elbeltagi, E.; Wefki, H.; Khallaf, R. Sustainable Building Optimization Model for Early-Stage Design. *Buildings* **2023**, *13*, 74. [\[CrossRef\]](#)
13. Kumar, A.; Singh, P.; Kapoor, N.R.; Meena, C.S.; Jain, K.; Kulkarni, K.S.; Cozzolino, R. Ecological Footprint of Residential Buildings in Composite Climate of India—A Case Study. *Sustainability* **2021**, *13*, 11949. [\[CrossRef\]](#)
14. Kaptan, K.; Cunha, S.; Aguiar, J. A Review: Construction and Demolition Waste as a Novel Source for CO2 Reduction in Portland Cement Production for Concrete. *Sustainability* **2024**, *16*, 585. [\[CrossRef\]](#)
15. Zhang, Z.; Qi, S.; Abulizi, A.; Zhang, Y. Habitat Quality Evolution and Multi-Scenario Simulation Based on Land Use Change in the Tacheng Region. *Sustainability* **2025**, *17*, 6113. [\[CrossRef\]](#)
16. El-Husseiny, M.-A.; El-Setouhy, H. Reviving Low-Tech Modes of Construction as a Method for Sustainability. *Sustainability* **2022**, *14*, 13762. [\[CrossRef\]](#)
17. Salihbegovic, A.; Salihbegovic, A. Natural materials in contemporary low-tech architecture. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *960*, 042012. [\[CrossRef\]](#)
18. Vinczeová, Z.; Tóth, A. Urban Green Spaces and Collective Housing: Spatial Patterns and Ecosystem Services for Sustainable Residential Development. *Sustainability* **2025**, *17*, 2538. [\[CrossRef\]](#)
19. Carvajal-Arango, D.; Bahamón-Jaramillo, S.; Aristizábal-Monsalve, P.; Vásquez-Hernández, A.; Botero, L.F.B. Relationships between lean and sustainable construction: Positive impacts of lean practices over sustainability during construction phase. *J. Clean. Prod.* **2019**, *234*, 1322–1337. [\[CrossRef\]](#)
20. Lozano, R.; Ceulemans, K.; Seatter, C.S. Teaching organisational change management for sustainability: Designing and delivering a course at the University of Leeds to better prepare future sustainability change agents. *J. Clean. Prod.* **2015**, *106*, 205–215. [\[CrossRef\]](#)
21. Cuadrado, J.; Zubizarreta, M.; Rojí, E.; García, H.; Larrauri, M. Sustainability-related decision making in industrial buildings: An AHP analysis. *Math. Probl. Eng.* **2015**, *2015*, 157129. [\[CrossRef\]](#)
22. Matheou, M.; Phocas, M.C.; Christoforou, E.G.; Müller, A. New perspectives in architecture through transformable structures: A simulation study. *Front. Built Environ.* **2023**, *9*, 1051337. [\[CrossRef\]](#)
23. Molavi, J.; Barral, D.L. A construction procurement method to achieve sustainability in modular construction. *Procedia Eng.* **2016**, *145*, 1362–1369. [\[CrossRef\]](#)
24. Radogna, D.; Kalhoefer, G. Environmental and technological flexibility for new housing needs. *VITRUVIO* **2022**, *7*, 30–45. [\[CrossRef\]](#)
25. Sutantio, A.; Anwar, N.; Wiguna, I.P.A.; Suryani, E. Developing a model of sustainable construction for condominium projects in developing countries; case of Indonesia. *GEOMATE J.* **2022**, *23*, 85–94. [\[CrossRef\]](#)
26. Gao, J.; Tang, L.; Lyu, Y. Impact of minimalism on consumers' low-carbon innovation behavior: Interactive role of quantitative behavior. *Chin. J. Popul. Resour. Environ.* **2023**, *21*, 82–91. [\[CrossRef\]](#)
27. Charytonowicz, J.; Skowroński, M. Re-consumption of materials in architecture. In *Advances in Human Factors and Sustainable Infrastructure, Proceedings of the AHFE 2016 International Conference on Human Factors and Sustainable Infrastructure, Florida, USA, 27–31 July 2016*; Springer: Cham, Switzerland, 2016; Volume 493, pp. 75–83. [\[CrossRef\]](#)
28. Skulmoski, G.J.; Hartman, F.T.; Krahn, J. The Delphi method for graduate research. *J. Inf. Technol. Educ. Res.* **2007**, *6*, 1–21. [\[CrossRef\]](#)
29. Braun, V.; Clarke, V. Using thematic analysis in psychology. *Qual. Res. Psychol.* **2006**, *3*, 77–101. [\[CrossRef\]](#)
30. Chang, D.Y. Applications of the extent analysis method on fuzzy AHP. *Eur. J. Oper. Res.* **1996**, *95*, 649–655. [\[CrossRef\]](#)
31. Saaty, R.W. The analytic hierarchy process—What it is and how it is used. *Math. Model.* **1987**, *9*, 161–176. [\[CrossRef\]](#)
32. Buckley, J.J. Fuzzy hierarchical analysis. *Fuzzy Sets Syst.* **1985**, *17*, 233–247. [\[CrossRef\]](#)
33. Kenny, D.A.; Kaniskan, B.; McCoach, D.B. The performance of RMSEA in models with small degrees of freedom. *Sociol. Methods Res.* **2015**, *44*, 486–507. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.