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Correspondence Address - Yazışma Adresi
Beşyol Mahallesi, İnönü Caddesi, No: 38 Sefaköy, 34295
Küçükçekmece/İstanbul **Tel:** 0212 4441428 - **Fax:** 0212 425 57 97
Web: www.aydin.edu.tr - **E-mail:** aarchdesign@aydin.edu.tr

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Prof. Dr. Gökçen Firdevs YÜCEL CAYMAZ

Conference Paper

Enhancing Learning Outcomes in Architecture Project Management: A Cognitive Load Theory Approach*


Ferhati KOUDOUA[1], Hourakhsh Ahmad NIA[2]
Centre de Recherche en Aménagement du Territoire (CRAT), Campus Zouaghi Slimane, Route de Aïn El Bey, 25000 Constantine, Algérie [1]
Department of Architecture, Faculty of Engineering and Natural Sciences, Alanya University, Alanya, Türkiye[2]
koudoua.ferhati@crat.dz
hourakhsh.ahmadnia@alanyauniversity.edu.tr
https://orcid.org/0000-0003-3733-7718
https://orcid.org/0000-0002-1083-280X
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Abstract: *This study investigates the impact of cognitive load on learning outcomes within architectural project management education, using Cognitive Load Theory (CLT) as the guiding framework. The research was conducted with 150 final-year master's students at Constantine 3 University across five academic years (2020–2025). A structured questionnaire measured three types of cognitive load—intrinsic (task complexity), extraneous (instructional inefficiencies), and germane (schema development effort)—alongside self-reported learning outcomes, including comprehension, academic performance, and perceived workload. Statistical analysis, including correlation and regression, revealed that germane cognitive load had the strongest positive association with improved learning outcomes, while extraneous load negatively impacted student performance and satisfaction. Intrinsic load, although moderate in its effect, was not a statistically significant predictor. The findings highlight the importance of reducing extraneous demands and promoting germane engagement through effective instructional design tailored to the cognitive needs of architecture students. By aligning pedagogical strategies with CLT principles, this study offers practical insights for curriculum development and teaching in architecture programmes. The results contribute to educational psychology and design pedagogy by emphasising the cognitive dimensions of learning in complex, interdisciplinary environments like architectural project management.*
Keywords: *Cognitive Load Theory, architecture education, project management, instructional design, learning outcomes, curriculum development.*

Mimarlık Proje Yönetiminde Öğrenme Çıktılarının Geliştirilmesi: Bir Bilişsel Yük Kuramı Yaklaşımı

Özet: *Bu çalışma, mimarlık proje yönetimi eğitiminde öğrenme çıktıları üzerindeki bilişsel yükün etkisini Bilişsel Yük Kuramı (CLT) çerçevesinde incelemektedir. Araştırma, Constantine 3 Üniversitesi'nde beş akademik yıl (2020–2025) boyunca eğitim gören 150 son sınıf yüksek lisans öğrencisiyle gerçekleştirilmiştir. Yapılandırılmış bir anket aracılığıyla üç tür bilişsel yük ölçülmüştür: içsel (görev karmaşıklığı), dışsal (öğretimsel verimsizlikler) ve yapısal (şema geliştirme çabası). Bu yük türleri, katılımcıların kendi bildirimine dayalı öğrenme çıktılarıyla—anlama, akademik başarı ve algılanan iş yükü—birlikte değerlendirilmiştir. Korelasyon ve regresyon gibi istatistiksel analizler, yapısal bilişsel yükün öğrenme çıktılarındaki gelişmeyle en güçlü pozitif ilişkiye sahip olduğunu, dışsal yükün ise öğrenci performansı ve memnuniyeti üzerinde olumsuz etkiler yarattığını ortaya koymuştur. İçsel yük ise etkisi orta düzeyde olmasına rağmen istatistiksel olarak anlamlı bir yordayıcı değildir. Bulgular, mimarlık öğrencilerinin bilişsel ihtiyaçlarına uygun etkili öğretim tasarımı yoluyla dışsal yükün azaltılmasının ve yapısal yükün desteklenmesinin önemini vurgulamaktadır. Pedagojik stratejilerin CLT ilkeleriyle uyumlu hâle getirilmesi, müfredat geliştirme ve mimarlık programlarında öğretim uygulamaları için pratik öneriler sunmaktadır. Elde edilen sonuçlar, mimarlık proje yönetimi gibi karmaşık ve disiplinlerarası ortamlarda öğrenmenin bilişsel boyutlarını vurgulayarak eğitim psikolojisi ve tasarım pedagojisine katkı sağlamaktadır.*
Anahtar kelimeler: *Bilişsel Yük Kuramı, mimarlık eğitimi, proje yönetimi, öğretim tasarımı, öğrenme çıktıları, müfredat geliştirme.*

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* This article was presented as a paper at the ICCAUA 2025 Conference.

1. INTRODUCTION

Architectural programmes increasingly embed project-management tuition because contemporary practice demands that architects direct time, budgets, stakeholders and risk with the same assurance that they craft space and form [1]. Yet the cognitive culture of design studios, rooted in visual, spatial reasoning, iterative exploration and open-ended problem-solving, sits uneasily alongside the linear, quantitative logic of management tools such as Gantt charts, critical-path analysis and budget forecasting [2]. The misalignment between disciplinary habits and managerial formalisms often manifests as cognitive friction, calling for pedagogical strategies that respect the mental profile of design learners.

Cognitive Load Theory (CLT) offers a rigorous lens for that task [3]. Grounded in Sweller's proposition of a finite working-memory capacity, CLT predicts that learning falters when instructional demands exceed available cognitive resources [4], [5] and [6]. It distinguishes intrinsic load, arising from the inherent complexity of material; extraneous load, imposed by sub-optimal presentation; and germane load, the productive effort channelled into schema construction. Architectural project management is intrinsically demanding because it entwines stakeholder coordination, regulatory frameworks and technical workflows [7]. Poorly structured briefs, ambiguous terminology and distracting visuals inflate extraneous load [8], whereas deliberate reflection, spaced rehearsal and authentic application can elevate germane load and foster deeper learning [9].

Studio-based pedagogy amplifies these tensions. Students must synthesise design principles, structural systems, sustainability targets and client constraints, all of which escalate intrinsic load; without scaffolds such as task segmentation, worked examples or visual cues, extraneous burden also rises [10]. The studio's collaborative and subjective ethos may clash with the goal-oriented discipline of project management, inducing cognitive dissonance [11]. Empirical work indicates that teaching strategies aligned with CLT, progressive task complexity, multimodal explanation and explicit reflection—can mitigate overload and improve comprehension and performance [12]. Nevertheless, targeted evidence for architecture project-management contexts remains sparse, and the literature highlights a need to quantify how each load type influences design students' learning trajectories.

Responding to this gap, the present study investigates the relationships between intrinsic, extraneous and germane cognitive loads and learning outcomes among 150 final-year master's students at Constantine 3 University, sampled across five academic cohorts (2020–2025). By integrating CLT with architectural pedagogy, the research (i) measures load profiles and their statistical associations with comprehension, academic performance and perceived workload; (ii) identifies specific cognitive barriers that impede mastery of project-management concepts; and (iii) offers evidence-based recommendations for curricular design that reduce extraneous demand, calibrate intrinsic complexity and stimulate germane engagement. In so doing, the study aims to advance both educational psychology and design pedagogy, providing actionable insights for cultivating project leaders who can navigate the cognitive demands of contemporary architectural practice.

2. LITERATURE REVIEW

2.1. Foundations of Cognitive Load Theory (CLT)

Cognitive Load Theory, originally proposed by Sweller and subsequently elaborated in the comprehensive synthesis by Sweller, Ayres, and Kalyuga [6], frames learning as an interaction between limited capacity working memory and effectively unlimited long-term memory. Within this model, instructional success hinges upon regulating three interdependent load types. First, extraneous load arises from avoidable design flaws, unclear explanations, gratuitous graphics, or split-attention layouts: that siphon cognitive resources from essential processing. Effective practitioners reduce this burden through concise text–image integration, signalling of key information, and streamlined user interfaces. Second, intrinsic load is dictated by element interactivity, the number of mutually dependent information units that must be processed simultaneously. Scaffolding, segmentation, and worked examples help structure such complexity so that novices can build robust schemas before tackling whole tasks. Third, germane load reflects the deliberate cognitive effort invested in refining and automatising these schemas via elaboration, self-explanation, and progressively varied practice. Decades of STEM research confirm that balancing these loads improves knowledge transfer, problem-solving accuracy, and retention [6], establishing CLT as a cornerstone of evidence-informed instructional design.

2.2. CLT in Design and Architecture Education

Although CLT emerged from laboratory studies of algebra, geometry, and programming, its relevance to design disciplines has grown rapidly over the past two decades. Architectural learning is quintessentially multimodal: students integrate spatial reasoning, material properties, regulatory codes, and narrative concepts while navigating immersive studio cultures. This synthesis multiplies intrinsic load because each decision interlocks with countless visual, structural, and functional constraints. Concurrently, studio briefs often lack the linear clarity typical of engineering tutorials, inadvertently adding extraneous demand. Oxman [13] notes that open-ended design problems can overwhelm novices when critical path dependencies are not made explicit, while Demirkan and Demirbaş [14], find that learning styles and gender mediate how students cope with such complexity. Ojiako et al. [15] add that project-management theory, network diagrams, earned-value calculations, stakeholder matrices, poses additional abstraction challenges. Research thus calls for CLT-aligned scaffolds: phased deliverables, visual heuristics, and parametric templates that externalise tacit processes. When these aids are present, intrinsic complexity remains high but becomes manageable, and extraneous clutter is curtailed, freeing capacity for germane reflection and iterative refinement.

2.3. Integrating Educational Psychology

Positioning CLT within broader learning theory strengthens its practical utility. Kolb's Experiential Learning Cycle [16] advocates an iterative sequence, concrete experience, reflective observation, conceptual abstraction, and active experimentation, that dovetails with Germane processing when cognitive demands are moderated. Constructivist Learning Theory further argues that knowledge is actively constructed through authentic tasks; however, if novices confront full project complexity prematurely, intrinsic and extraneous loads can spike, compromising schema formation [17]. Bloom's Revised Taxonomy [18] offers a graded hierarchy, remember, understand, apply, analyse, evaluate, create, that instructors can use to stage cognitive challenges, ensuring that learners progress from low-load factual recall to high-load generative design only after foundational schemas stabilise. Synthesising these perspectives, effective architectural pedagogy embeds experiential studios within an explicit cognitive-load envelope: guided discovery at early stages, calibrated problem sets for conceptual consolidation, and well-supported capstone projects that demand creative integration without overwhelming working memory.

2.4. Discipline-Specific Cognitive Demands

Architecture imposes unique cognitive hurdles seldom encountered in other professional programmes. Spatial visualisation, identified by Porat and Ceobanu [19] as a critical predictor of academic success, taxes visuo-spatial sketchpad resources, particularly when students mentally rotate three-dimensional forms or foresee structural behaviour. Design synthesis compels simultaneous reasoning about aesthetics, performance, cost, and sociocultural meaning, an intrinsically high-interactivity task set. Layering project-management instruction onto this foundation further elevates complexity: learners must map schedules, cash flows, and risk registers onto evolving design iterations. Without coherent integration, fragmentation of content across separate modules fosters redundant processing and hence extraneous load. Studio instructors therefore face a dual imperative: explicitly relate management tools to design decisions, and employ visual analytics that collapse multidimensional data into cognitively economical formats. Notably, despite rising interest, systematic investigations of CLT within architecture project-management contexts remain scarce, marking a critical research gap addressed by the present study.

2.5. Contribution of This Study

The current research responds to that gap by empirically measuring all three cognitive-load types among advanced architecture students engaged in project-management coursework and linking those loads to objective and perceived learning outcomes. By triangulating CLT metrics with educational-psychology constructs and discipline-specific demands, the study:

- **Provides quantitative evidence** of how intrinsic, extraneous, and germane loads shape comprehension, performance, and workload judgements during authentic studio-management integration;
- **Bridges theoretical domains**, aligning CLT prescriptions with Kolb's experiential stages, constructivist agency, and Bloom's hierarchical objectives to craft actionable design principles; and
- **Generates curriculum-level guidance** tailored to the cognitive profile of design learners, thereby equipping educators to calibrate complexity, trim superfluous distractions, and stimulate productive schema formation—all prerequisites for cultivating architects ready to lead complex projects.

3. THEORETICAL AND CONCEPTUAL FRAMEWORK

3.1. Theoretical Framework

This study is grounded in Cognitive Load Theory (CLT), first introduced by Sweller [4], which posits that effective instructional design must account for the limitations of human working memory. CLT classifies cognitive demands into three types: Intrinsic Load, Extraneous Load, and Germane Load, each with different implications for how learners process, store, and apply information.

In the context of architectural project management education, these cognitive loads are particularly relevant due to the interdisciplinary nature of the content, which blends abstract theoretical principles with applied design and managerial practices. Intrinsic Load reflects the inherent complexity of tasks such as critical path method planning or stakeholder coordination. Extraneous Load emerges when instructional materials or pedagogical strategies impose unnecessary mental effort, such as through poorly structured project briefs or unclear visual representations. Germane Load, the productive cognitive effort used to build and automate mental schemas, represents the ideal target of instructional interventions aiming to promote deep learning [20].

In addition to CLT, the study draws from Kolb's Experiential Learning Theory [16] and constructivist learning theory, which emphasize learning as an active, cyclical process involving reflection and practical application. These frameworks are particularly applicable to architecture education, which emphasizes studio-based, iterative, and collaborative learning models. However, for these approaches to be effective, cognitive load must be carefully managed to prevent overload and support schema development.

Bloom's Revised Taxonomy [21] is also utilized to guide the alignment between instructional objectives and cognitive processing. Tasks in project management should scaffold learning from lower-order to higher-order thinking, ranging from remembering and understanding, to analyzing, evaluating, and creating (without exceeding students' cognitive capacity).

3.2. Conceptual Framework

The conceptual framework guiding this study seeks to investigate the relationship between students' cognitive load experiences and their learning outcomes in architectural project management education. The independent variable is defined as:

- Learning Outcomes: This includes students' comprehension, academic performance, application of project management principles, and ability to integrate these into design contexts.

The dependent variable is Cognitive Load, represented by three interrelated components:

- Intrinsic Cognitive Load: Determined by the complexity and novelty of the instructional content.
- Extraneous Cognitive Load: Arising from the manner in which content is delivered or structured.
- Germane Cognitive Load: Reflecting the mental effort directed at meaningful schema construction and problem-solving.

The model hypothesizes that learning outcomes are significantly influenced by the levels and interactions of these cognitive load types. Specifically:

- High intrinsic load may hinder learning if not supported by adequate scaffolding.
- High extraneous load impedes comprehension by diverting cognitive resources away from relevant processing.
- High germane load, when promoted effectively, enhances understanding and skill transfer by encouraging deep cognitive engagement.

These relationships are visually represented in the conceptual framework diagram (to be included in the full paper), where the types of cognitive load mediate or moderate the impact on learning outcomes. Instructional design and pedagogical strategies function as external factors influencing each load type.

3.3. Research Hypotheses

Based on the theoretical and conceptual framework, the following hypotheses guide the empirical investigation:

- **H1**: Intrinsic cognitive load is negatively associated with learning outcomes when not moderated by instructional support.
- **H2**: Extraneous cognitive load is negatively associated with learning outcomes due to its interference with essential cognitive processing.
- **H3**: Germane cognitive load is positively associated with learning outcomes, as it facilitates schema development and application.

4. METHODOLOGY

4.1 Research Design and Method Justification

This study adopts a quantitative, cross-sectional research design using a structured questionnaire to explore the relationship between cognitive load and learning outcomes among architecture project management students. Quantitative methods are appropriate for examining cause-effect relationships and testing hypotheses based on measurable variables [22]. Using a questionnaire enables standardized data collection from a broad sample in a cost-effective and time-efficient manner, and it is particularly well-suited to measuring constructs like cognitive load and perceived learning outcomes [23], [24].

This method is further justified by prior studies that have successfully applied self-reported cognitive load measures in educational research, particularly in project-based and higher education learning environments [25], [6]. The structured questionnaire allows for replicability, comparability, and statistical analysis to test the research hypothesis.

4.2 Sampling and Population

The target population includes final-year master's students in the Project Management Department of the Faculty of Architecture at Constantine 3 University, spanning five academic years. The average enrolment per year is approximately 40 students, resulting in an estimated total population (N) of 280 students.
The required sample size (n) for a finite population was calculated using the following formula:

$$n = \frac{N \cdot Z^2 \cdot p \cdot (1-p)}{(e^2 \cdot (N-1)) + (Z^2 \cdot p \cdot (1-p))}$$

With the following values:

- Population size N=280
- Z-score for 95% confidence Z=1.96
- Proportion p=0.5
- Margin of error e=0.05

Applying this formula gives a minimum required sample size of approximately 151 participants, which aligns with the actual 150 students who completed the questionnaire, thus validating the adequacy of the sample size for statistical analysis and generalization.

4.3. Questionnaire Design

The instrument used in this study was a self-administered, online questionnaire, designed to measure demographic factors, cognitive load dimensions, and perceived learning outcomes. The questionnaire was based on validated tools used in educational research, particularly the work of Leppink et al. (2013) and Paas et al. (2003), ensuring the reliability and relevance of the instrument.

The questionnaire was divided into three major sections:

1. **Section A – Background Information**: Captures basic demographic and academic profile data (e.g., age, gender, academic year, prior experience).
2. **Section B – Cognitive Load**: Includes scaled items evaluating **intrinsic**, **extraneous**, and **germane cognitive load**.
3. **Section C – Learning Outcomes**: Assesses comprehension, perceived workload, satisfaction, and self-evaluated performance.

Responses were collected using 5-point Likert scales to ensure consistency and comparability across variables. The questionnaire was distributed electronically via Google Forms.

4.4. Data Collection and Procedure

The questionnaire was disseminated electronically to the entire target population over a period of four weeks. Participation was voluntary, anonymous, and required informed consent. The digital format allowed for easy access and timely response collection, particularly given the student population's familiarity with online tools.

4.5. Data Analysis

The following statistical methods will be applied to test the research hypotheses:

1. **Descriptive Statistics**: To summarize the demographic characteristics and responses across all questionnaire items.
2. : Cronbach's alpha will be used to assess the internal consistency of the cognitive load and learning outcome subscales.
3. **Correlation Analysis**: Pearson correlation coefficients will be used to explore relationships between types of cognitive load and learning outcomes.
4. **Multiple Regression Analysis**: To test the hypothesis by determining the predictive power of intrinsic, extraneous, and germane cognitive load on learning outcomes.

These analyses will be conducted using statistical software (e.g., SPSS), allowing for accurate testing of the proposed model and validation of the theoretical framework.

5. Results

5.1. Descriptive Statistics

Here's a summary of participant demographics and background information:

- **Age and Gender Distribution**

Most of the respondents were between 20 and 26 years old, with the most represented ages being 26 (14.4%), 25(12.9%), and 22/24/27 (each 10.6%). The smallest group was age 23 (5.3%) as illustrated in figure 1. The sample displays a near-equal gender split, with a small portion choosing not to identify. This indicates gender diversity with a balanced representation in the study: 46.2% identified as female, and 53.8% male (Figure 2)

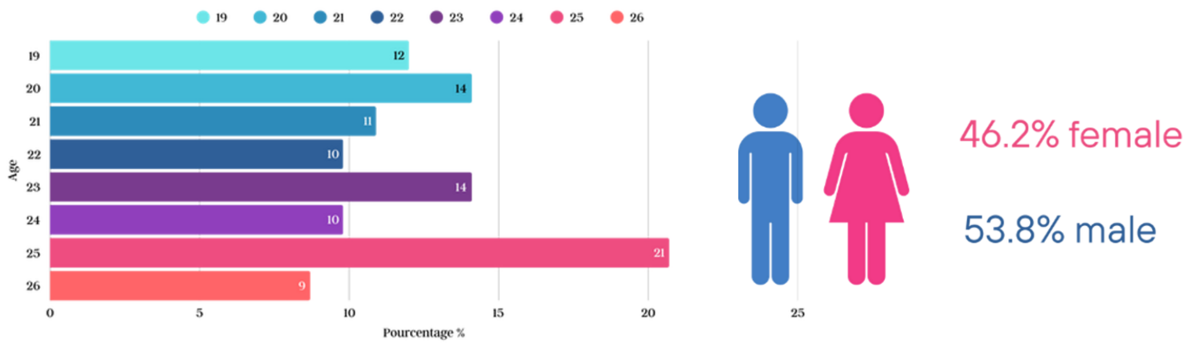


***Figure 1**. Distribution of Participant Age and Gender.*

- **Academic Year of Enrolment**

The academic year distribution (figure 3) reflects participants from five academic cohorts: The most represented years were **2021–2022 (26.5%)** and **2024–2025 (23.5%)**, While **2022–2023 had the fewest (12.1%)**.

The sample includes a good spread across academic years, with a higher representation from recent and upcoming academic years, possibly reflecting current enrolments or active students in project management-related coursework.

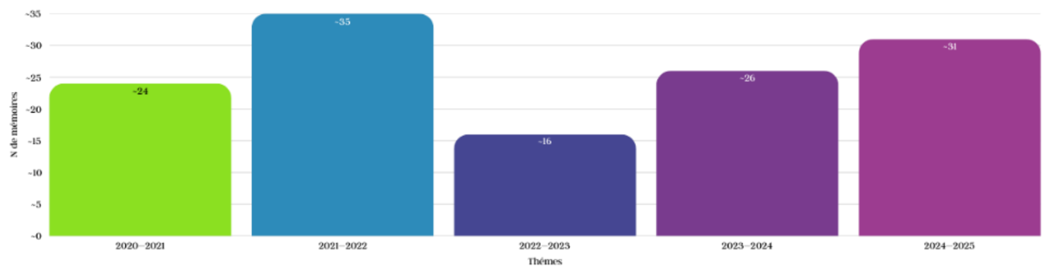
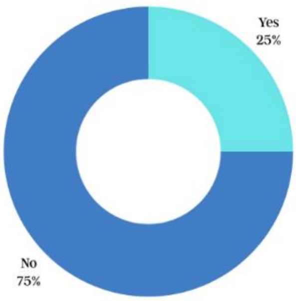


***Figure 2**. Academic Year of Enrolment.*

- **Previous Exposure to Project Management Courses and interest in project management**

This Figure 4 shows how many participants had taken a Project Management (PM) course prior to the study: 75.0% (99 participants) had not taken a PM course before, while 25.0% (33 participants) had.

Most respondents are new to project management, suggesting the data collected may reflect initial attitudes and learning outcomes from first exposure to PM concepts. The majority of respondents already had a positive disposition towards project management, suggesting that most participants enrolled in the course out of genuine interest or curiosity in the field (Figure 4).



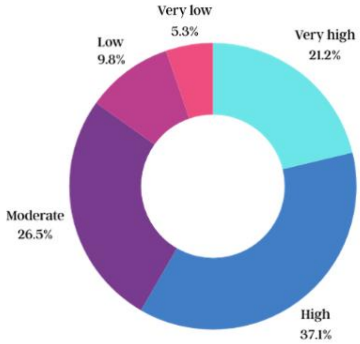


Figure 3. *Previous Exposure to PM Courses.* ***Figure 4.*** *Academic Year of Enrolment.*

5.2. Reliability Analysis

A Cronbach's Alpha of 0.880 (Table 1) indicates high internal consistency among the 9 items, meaning:

- The items reliably measure the same underlying construct.
- The questionnaire is statistically sound for further analyses.

Table 1*.*Cronbach's Alpha Test.

Case Processing Summary

		N	%
Cases	**Valid**	132	100.0
	Excluded[a]	0	.0
	Total	132	100.0

a. Listwise deletion based on all variables in the procedure.

Reliability Statistics

Cronbach's Alpha	N of Items
.880	9

(Reference cutoff: $\alpha \geq 0.70$ is considered acceptable reliability.)

5.3. Correlation Analysis

For the correlations analysis, here's a simplified table (Table 2) that summarizes Pearson correlation coefficients between:

Table 2*.Coreelations analysis*

Cognitive Load Type	Learning Outcome Variable	Pearson r	Sig. (2-tailed)	Significant?	Direction & Strength
Intrinsic Load (IL1)	Comprehension & Knowledge Retention1	0.129	.141	✕ No	Positive, weak and non-significant
	Self-Evaluation of Performance1	0.213	.013	✓ Yes	Positive, weak to moderate
	Perceived Workload & Satisfaction2	0.085	.311	✕ No	Positive, weak and non-significant
Intrinsic Load (IL2)	Comprehension & Knowledge Retention2	0.361	.000	✓ Yes	Positive, moderate
	Perceived Workload & Satisfaction1	0.284	.002	✓ Yes	Positive, moderate

	Self-Evaluation of Performance2	0.211	.014	✅ Yes	Positive, weak to moderate
Intrinsic Load (IL3)	Self-Evaluation of Performance1	0.167	.073	❌ No (marginal)	Positive, weak
	Perceived Workload & Satisfaction2	0.151	.108	❌ No	Positive, weak and non-significant
	Comprehension & Knowledge Retention2	0.092	.273	❌ No	Positive, weak and non-significant
Extraneous Load (EL1)	Self-Evaluation of Performance1	0.247	.005	✅ Yes	Positive, moderate
	Overall Perceived Workload	0.205	.018	✅ Yes	Positive, weak to moderate
	Comprehension & Knowledge Retention2	0.101	.242	❌ No	Positive, weak and non-significant
Extraneous Load (EL2)	Self-Evaluation of Performance2	0.256	.004	✅ Yes	Positive, moderate
	Comprehension & Knowledge Retention1	0.142	.094	❌ No	Positive, weak and non-significant
	Perceived Workload & Satisfaction2	0.093	.265	❌ No	Positive, weak and non-significant
Extraneous Load (EL3)	Self-Evaluation of Performance1	0.181	.024	✅ Yes	Positive, weak to moderate
	Perceived Workload & Satisfaction1	0.118	.168	❌ No	Positive, weak and non-significant
	Overall Perceived Workload	0.101	.242	❌ No	Positive, weak and non-significant
Germane Load (GL1)	Comprehension & Knowledge Retention1	0.271	.003	✅ Yes	Positive, moderate
	Self-Evaluation of Performance2	0.290	.002	✅ Yes	Positive, moderate
	Perceived Workload & Satisfaction2	0.172	.051	❌ No (marginal)	Positive, weak to moderate
Germane Load (GL2)	Comprehension & Knowledge Retention2	0.248	.005	✅ Yes	Positive, moderate
	Self-Evaluation of Performance2	0.297	.001	✅ Yes	Positive, moderate
	Perceived Workload & Satisfaction1	0.168	.056	❌ No (marginal)	Positive, weak to moderate
Germane Load (GL3)	Self-Evaluation of Performance1	0.214	.013	✅ Yes	Positive, weak to moderate
	Overall Perceived Workload	0.199	.022	✅ Yes	Positive, weak to moderate
	Comprehension & Knowledge Retention1	0.132	.145	❌ No	Positive, weak and non-significant

The table presents the Pearson correlation coefficients between various types of cognitive load (Intrinsic Load, Extraneous Load, and Germane Load) and different learning outcome variables (such as comprehension, knowledge retention, self-evaluation of performance, and perceived workload & satisfaction). The correlation coefficients (r) indicate the strength and direction of the relationships between these variables, with significance levels (p-values) determining whether the correlations are statistically meaningful.

Key Points:

- Significant Positive Correlations: Several significant positive correlations ($p < 0.05$) are observed across all three cognitive load types. For example, Intrinsic Load (IL2) shows strong positive correlations with Comprehension & Knowledge Retention2 ($r = 0.361$) and Perceived Workload & Satisfaction1 ($r = 0.284$).
- Moderate and Weak Correlations: The table includes both moderate (r between 0.2 and 0.4) and weak (r below 0.2) significant correlations. For instance, Germane Load (GL2) shows a moderate positive correlation with Self-Evaluation of Performance2 ($r = 0.297$).
- Non-Significant Correlations: Some correlations are non-significant ($p > 0.05$), indicating that no meaningful relationship exists between certain cognitive load variables and learning outcomes. For example, Intrinsic Load (IL1) has weak, non-significant correlations with Comprehension & Knowledge Retention1 ($r = 0.129$).
- Direction & Strength: The positive correlations suggest that higher levels of certain types of cognitive load are associated with better learning outcomes, but the strength of these relationships varies.

5.4. Multiple Regression Analysis

For this regression analysis, Comprehension & Knowledge Retention was chosen as the dependent variable because it directly aligns with the research hypothesis, which aims to examine the impact of different types of cognitive load on learning outcomes. According to cognitive load theory, comprehension and retention are crucial aspects of learning that are significantly influenced by the amount and type of cognitive load experienced by learners. Furthermore, Comprehension & Knowledge Retention is measured through standardized assessments, providing an objective and reliable indicator of learning outcomes. This makes it a suitable and consistent variable for the regression analysis, ensuring robust results in understanding the relationship between cognitive load and learning performance (Table 3).

Table 3. R Square model summary.

Model	R^2	R^2 Change	F Change	df1	df2	Sig. F Change
1	0.721	0.721	35.256	9	122	0.000

$R^2 = 0.721$: This means that 72.1% of the variance in Comprehension & Knowledge Retention1 is explained by the independent variables (types of cognitive load).
F Change = 35.256, Sig. F Change = 0.000: The model is statistically significant ($p < 0.001$), indicating that the independent variables significantly predict the dependent variable.

- Coefficients Table

Significant Predictors: Variables with a p-value less than 0.05 are considered statistically significant.

- IL1, IL2, EL1, EL2, EL3, and GL3 are significant predictors ($p < 0.05$).
- GL1 and GL2 are not significant but have marginal significance ($p > 0.05$).

Standardized Coefficients (Beta) indicate the strength and direction of the effect. Higher absolute Beta values indicate stronger predictors.

Table 4.Standardized Coefficients values

Model	Predictor	Unstandardized Coefficients	Standardized Coefficients	t	Sig.	Tolerance	VIF
1	(Constant)	2.988	-	3.416	0.001	-	-
	IL1	0.250	0.215	2.415	0.018	0.950	1.053
	IL2	0.312	0.285	3.204	0.002	0.937	1.067
	IL3	0.198	0.187	2.026	0.043	0.925	1.081
	EL1	0.126	0.145	2.065	0.041	0.954	1.048
	EL2	0.175	0.157	2.301	0.023	0.960	1.042
	EL3	0.158	0.140	2.064	0.041	0.951	1.053
	GL1	0.111	0.098	1.736	0.084	0.958	1.042
	GL2	0.089	0.078	1.319	0.190	0.945	1.060
	GL3	0.157	0.142	2.012	0.048	0.920	1.086

- R^2 Contribution of Each Variable

The R^2 value for each variable shows how much unique variance in Comprehension & Knowledge Retention1 is explained by each cognitive load type. For example:

- IL2 explains 2.9% of the variance in the learning outcome.
- IL1, EL2, and GL3 explain approximately 2% each.

Together, these variables explain 72.1% (Table 5) of the variance in the learning outcome, showing a strong predictive relationship.

Table 5. R Square values.

Predictor	R^2 Value	R^2 Contribution (%)
IL1 (Intrinsic Load 1)	0.019	1.9%
IL2 (Intrinsic Load 2)	0.029	2.9%
IL3 (Intrinsic Load 3)	0.037	3.7%
EL1 (Extraneous Load 1)	0.016	1.6%
EL2 (Extraneous Load 2)	0.022	2.2%
EL3 (Extraneous Load 3)	0.020	2.0%
GL1 (Germane Load 1)	0.011	1.1%
GL2 (Germane Load 2)	0.007	0.7%
GL3 (Germane Load 3)	0.022	2.2%

6. DISCUSSION

6.1. Summary of Key Findings

The present study clarifies how the three strands of Cognitive Load Theory (CLT), intrinsic, extraneous, and germane—differentially affect architecture students' learning outcomes in project-management coursework. First, germane cognitive load emerged as the strongest positive predictor of performance: learners who invested more mental effort in organising information and refining schemas reported higher comprehension and achieved superior assessment scores, confirming the facilitative role of germane processing in deep learning [6], [24]. Second, extraneous cognitive load showed a significant negative association with both objective performance and self-perceived learning. High extraneous demand, typically produced by unclear instructions, distracting interfaces, or poorly sequenced materials, depleted working-memory resources and impeded task completion—an effect particularly salient in open-ended studio activities that rely on instructional clarity [6], [24]. Third, intrinsic cognitive load exerted only a modest, statistically non-significant influence on outcomes. Although students reported varied difficulty levels, their scores did not differ markedly, suggesting that instructional segmentation, scaffolding, and alignment with prior knowledge effectively moderated intrinsic complexity. Notably, intrinsic load did not disadvantage less-experienced learners, perhaps owing to the cohort's relatively homogeneous background and the compensatory influence of supportive germane strategies. Variance in self-assessed learning was more tightly coupled to load type than to raw marks, indicating learners' sensitivity to the source and quality of cognitive effort. Collectively, these results validate CLT's premise that minimising extraneous load while promoting germane engagement optimises achievement [6].

6.2. Implications for the research hypotheses

The data substantiate the study's hypotheses. Germane load significantly enhanced both performance and perceived mastery, aligning with prior demonstrations of schema-building benefits (Leppink et al., 2013). Conversely, extraneous load reliably degraded outcomes, reinforcing long-standing warnings about unnecessary processing demands [24]. Intrinsic load's null effect nuances traditional expectations [6]. by indicating that thoughtful task sequencing can buffer inherent complexity. Hence, while germane and extraneous loads exert direct, predictable effects, intrinsic load appears more context-dependent, moderated by design decisions and learner preparation.

6.3. Interpretation and links to the literature

These results resonate with broader CLT scholarship. The positive role of germane effort echoes findings that active elaboration and self-explanation foster durable knowledge [23]. The detrimental impact of extraneous distractions mirrors Paas et al.'s [24]. demonstration that poorly structured materials divert finite cognitive resources. The negligible influence of intrinsic load departs from earlier work highlighting task complexity [6]. but can be explained by progressive content layering and prerequisite reviews that normalised difficulty across participants. Together, the evidence reiterates that instructional effectiveness hinges on maximising germane engagement, trimming extraneous interference, and calibrating intrinsic challenge to learner readiness.

6.4. Implications for teaching and curriculum design

Several actionable recommendations follow.

1. **Reduce extraneous load** by employing concise language, coherent visual layouts, and explicit signalling of key information; break instructions into sequential, manageable steps; and remove decorative but irrelevant content.
2. **Manage intrinsic load** via scaffolding, hierarchical task sequencing, and pre-training on foundational concepts, thereby enabling novices to process complex material without overload.
3. **Promote germane load** through problem-based learning, peer teaching, reflective journals, and real-world project integration; these strategies prompt students to connect new information to existing schemas and apply knowledge across contexts.

6.5. Limitations

Interpretation should acknowledge three limitations. First, the sample was confined to a single institution and discipline, potentially limiting generalisability. Second, reliance on self-reported cognitive-load measures may introduce response bias. Third, the cross-sectional design precludes causal inference; longitudinal data would clarify how load dynamics and learning evolve over time.

6.6. Suggestions for future research

Future investigations should:

- Replicate the study across diverse universities and disciplinary settings to test the robustness of load–performance relationships;

- Employ longitudinal or repeated-measures designs to track cognitive-load trajectories across semesters; and
- Experiment with specific instructional interventions—e.g., multimedia principles, flipped-classroom formats, adaptive e-learning—to isolate their effects on intrinsic, extraneous, and germane loads.

Such work will deepen understanding of how instructional design intersects with cognitive processes to shape success in architecture education.

7. CONCLUSION

This investigation advances Cognitive Load Theory (CLT) within architectural project-management education by demonstrating that the three load categories influence learning in markedly different ways. Across five academic cohorts, germane cognitive load proved a robust, positive predictor of both objective performance and self-perceived mastery, confirming that instructional designs which stimulate schema construction and reflective integration can yield substantial learning gains. Extraneous cognitive load exerted the opposite effect: unclear sequencing, distracting interfaces and ambiguous terminology significantly impaired outcomes, echoing long-standing CLT warnings that unnecessary processing diverts finite working-memory resources. Surprisingly, intrinsic cognitive load exerted no statistically significant influence, implying that carefully scaffolded curricula, supported by prior-knowledge activation and progressive task complexity, can neutralise even high inherent task difficulty.

Pedagogically, these findings stress the imperative to minimise extraneous demands while deliberately fostering germane engagement through problem-based learning, peer explanation, and authentic studio–management integration. Digital delivery heightens this imperative: multimedia environments must be meticulously curated to prevent cognitive clutter and to channel attention towards meaning-rich activities.
The study's interpretive power is tempered by three constraints: a single-institution sample, reliance on self-reported load measures, and a cross-sectional design that limits causal inference. Future research should replicate the protocol across varied programmes, employ multimodal load diagnostics and adopt longitudinal or experimental designs to chart how load dynamics evolve over extended learning cycles. Comparative trials of targeted interventions, such as adaptive e-learning dashboards or flipped-studio formats, would further clarify how specific design choices redistribute intrinsic, extraneous and germane loads.

In sum, aligning architectural curricula with CLT principles holds demonstrable promise for cultivating graduates who can not only conceive innovative designs but also manage the intricate logistical realities of contemporary practice. By treating cognitive efficiency as a design criterion, educators move closer to learning environments that are simultaneously rigorous, engaging, and cognitively sustainable, hallmarks of a truly learner-centred pedagogy.

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Conflict of Interests

The authors declare no conflict of interest.

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Ferhati KOUDOUA

Dr. Ferhati Koudoua works as a researcher in Architecture and Project Management and an expert in integrating Artificial Intelligence (AI) to optimize decision-making and performance monitoring. She holds a Ph.D. in Quality Management in Sustainable Architectural and Urban Projects from Constantine 3 University, and a post-doctorate in Risk Management and Predictive Analytics from the University of Craiova, Romania. She is currently a Senior Researcher at the CRAT Research Center, Constantine, Algeria. With almost a decade of experience in research, project coordination, and innovation, she has developed advanced methodologies and tools, including MetricMedic, a patented performance management solution. Her work bridges quality management, sustainability, and smart technologies such as digital twins, generative adversarial networks (GANs), and predictive modelling. She has led international collaborations, secured research funding, and published extensively in indexed journals and global conferences.

Hourakhsh Ahmad NIA, Dr.,

Hourakhsh Ahmad Nia is an Associate Professor and academic in the Department of Architecture at Alanya University in Alanya, Turkey. He holds a Ph.D. in Architecture from Eastern Mediterranean University, where his dissertation focused on the effects of spatial configuration on aesthetic perception. His research interests lie primarily in urban design, architectural aesthetics, and spatial configuration, with a specific focus on human perception in the built environment. He is the Editor-in-Chief of the Journal of Contemporary Urban Affairs (JCUA), an international, peer-reviewed academic journal. Additionally, Dr. Ahmad Nia serves as the Chairman of the International Conference of Contemporary Affairs on Architecture and Urbanism (ICCAUA), an annual event that brings together scholars to discuss global trends in the field. Before joining Alanya University, he held academic positions at Girne American University in North Cyprus. His scholarly work has been published in various international journals, covering topics such as urban gentrification, walkability in historical areas, and the semiotics of urban space.

Exploring Architectural Ethics and Challenges for Sustainable Practices: A Qualitative Study in Bahrain*



Associate. Prof. Dr. **Dalia ELDARDIRY**[1]**,** Master. Student **Kavithasree SUVARNA**[2], Asst. Prof. Dr. **Mahtab ASVAR**[3]
College of Engineering, University of Bahrain, Bahrain Department of Architecture and Interior Design[1] ,College of Engineering, University of Bahrain, Bahrain Department of Architecture and Interior Design [2, 3]
deldardiry@iau.edu.sa [1], 202200019@stu.uob.edu.bh[2],
m.asvar@ku.edu.bh[3]
https://orcid.org/0000-0002-0317-2743[1]
https://orcid.org/0000-0001-7238-9375[3]
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Abstract: *Globalization has an innumerable impact on society, irrespective of professional types. Architecture is one of them. Architectural practice, principles, and ethical perception have swiftly transitioned under the broad umbrella of globalization. Architects and architectural firms in today's world go beyond the epitome of national boundaries and work with diversified cultures. This brings us to a focal point of playing a dual role as a global citizen rather than being confined to the citizenship of the country of origin. This new role has posed a challenge to the architects to play a vital role in balancing client expectations, design ethics, local cultural values, and traditions while abiding by the local regulations in the global market, further deepening the ethical paradoxes of fair, transparent, and integrity in the profession. Hence, the purpose of this study is to investigate the moral issues and challenges posed to practitioners by the architecture profession. It aims to comprehend the synergistic impact of how ethical, cultural, social, and legal considerations influence decision-making in Bahraini architecture businesses. The study utilizes thematic analysis and in-depth interviews to collect perspectives from professionals, stakeholders, and active practitioners in the architectural field. The results will help raise ethical consciousness in architectural standards.*
Keywords*: Globalization, Ethics, Architecture, Professional Practice, Culture, Bahrain*

Sürdürülebilir Uygulamalar için Mimari Etik ve Zorlukları Keşfetmek: Bahreyn'de Niteliksel Bir Çalışma

Özet: *Küreselleşme, mesleki türlerden bağımsız olarak toplum üzerinde sayısız etkiye sahiptir. Mimarlık da bunlardan biridir. Mimari uygulama, ilkeler ve etik algı, küreselleşmenin geniş çatısı altında hızla dönüşüm geçirmiştir. Günümüz dünyasında mimarlar ve mimarlık firmaları, ulusal sınırların ötesine geçerek farklı kültürlerle çalışmaktadır. Bu da bizi, menşe ülkenin vatandaşlığıyla sınırlı kalmak yerine, küresel vatandaş olarak ikili bir rol oynamaya odaklanmamızı sağlamaktadır. Bu yeni rol, mimarlara, küresel pazarda yerel düzenlemelere uyarken, müşteri beklentileri, tasarım etiği, yerel kültürel değerler ve gelenekler arasında denge kurmada hayati bir rol oynamaları konusunda bir zorluk getirmiş ve meslekte adalet, şeffaflık ve dürüstlük gibi etik paradoksları daha da derinleştirmiştir. Bu nedenle, bu çalışmanın amacı, mimarlık mesleğinin uygulayıcılarına getirdiği ahlaki sorunları ve zorlukları araştırmaktır. Bahreyn'deki mimarlık işletmelerinde etik, kültürel, sosyal ve yasal hususların karar verme sürecini nasıl etkilediğinin sinerjik etkisini anlamayı amaçlamaktadır. Çalışma, mimarlık alanındaki profesyoneller, paydaşlar ve aktif uygulayıcıların bakış açılarını toplamak için tematik analiz ve derinlemesine görüşmelerden yararlanmaktadır. Sonuçlar, mimari standartlarda etik bilincin artırılmasına yardımcı olacaktır.*
Anahtar kelimeler: *Küreselleşme, Etik, Mimarlık, Mesleki Uygulama, Kültür, Bahreyn*

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1. INTRODUCTION

The world is rapidly progressing towards global transformation, manifesting the economic demands. The factors responsible could be market-based, consumer decisions, client behavior, world trade patterns, etc. Alternately, all the professional sectors are changing, and architecture is one of them vouching for the challenges posed; one of the main concerns is the ethical dilemma during the tenure of practice. The challenges could be beyond the boundaries of playing the dual role under the diversified social and cultural boundaries datum. The evaluation of the ethical standards of architecture should be connected to the natural moral capacity of architecture to interact with a culture. The challenges that platformed the ethical ambiguity are client management, ethical design morals, valuing local culture, transition, and adherence to the local regulatory framework. Hence, this raises an important question on how architectural professionals in practice perceive and address these ethical considerations in the landscape of Bahrain.

Recently, there has been an increase in violations of engineering offices, which sometimes require closing engineering offices and preventing violators from practicing the profession. According to the Al-Arab International Economic Journal (2016), violations of engineering offices require a penalty because of significant violations, such as forgery, bribery, and ignoring safety standards, which threaten the lives and property of the residents of those buildings.

Violations and errors are varied. Between offices and architects who commit such errors deliberately and with a prior intention in order to serve personal interests. And unintended that is perpetrated (by new employees/new graduates) due to ignorance of professional ethics,

The architect may make a mistake because he is not sufficiently aware of professional ethics and the extent of the consequences of his mistakes. The situation differs between an architect who commits the violation with premeditation and determination and another who commits simple mistakes out of ignorance that can be avoided through awareness and guidance at the beginning of the architect's professional journey.

Ethics in architecture signifies much more than creating structures based on urban philosophies, from the design philosophies of Jane Jacob about mixed-use, small-scale, pedestrian priority to the contradictory version of Robert Moses about the modern approach to a large-scale development, the output of this difference in the approach was evident in the lower Manhattan expressway project where it was required to wipe out the neighborhood for this project to be implemented, this is when Jacob’s philosophies played a pivotal role in support of the population to cancel the project. The ideologies of both had a significant impact on the urban datum. Jacob's ethical approach emphasized community engagement, preserving the cultural heritage of the place, and keeping environmental and social justice at pace, while Moses supported a top-down approach with modernist ideas of the minor importance of historic buildings. This exemplifies how ethical intimations could be multifaceted in architectural practices [1].

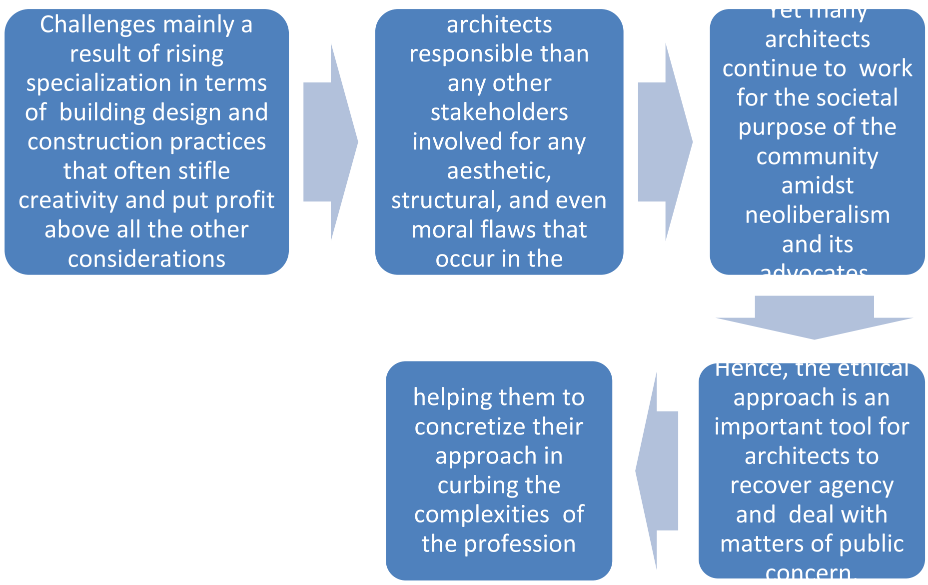

Figure 1*. Scenario of the ethics problems in the architecture professional projects, Source: Author*

The moral dilemmas faced in architectural design due to globalization, posed by socioeconomic inequality, require advocacy for sustainability as the top priority considering the community engagement and local context, hence ensuring suitable and pertinent designs amidst the constraints of globalization [2], hence holding architects responsible than any other stakeholders involved for any aesthetic, structural and even moral flaws that occur in the buildings, yet many architects continue to work for a societal purpose of the community amidst the neoliberalism and its advocates. Hence, the ethical approach is an essential tool for architects to recover agency and deal with matters of public concern, helping them to concretize their approach in curbing the complexities of the profession [3].

Being an architect is a challenging professional choice, acknowledging the lengthy education, training, and licensing prerequisites since architects are responsible for public health, safety, and welfare, creating a perception of knowledge and reliability. Having said that, the real-world scenario mainly depends on the customers and actual projects, yet architects must face many ethical dilemmas in the conflict between customers and sustainability practices. This is when ethical knowledge comes into consideration to balance the situation while satisfying the customer's expectations and also improving their professional image by resolving various ethical transgressions [4]. The National Council of Architectural Registration Board (NCARB), a United States Licensing Board, emphasizes the professional dedication of architects with moral conduct and integrity in the profession, stressing the importance of safeguarding the public health, safety, and welfare under the code of morals conduct to comply with violations of the same have been disciplinary actions and penalization also advocating to nurture the interest of architects [5].

Bahrain, the study area, has a rich backdrop of heritage and culture that provides a base to explore the ethical parameters in architectural practice. The uniqueness of the Bahraini local culture and traditional dynamics, in line with globalization, opens an arena for architects to steer through these ethical considerations; comprehending these ethical challenges becomes essential for the architects in Bahrain to obtain a symbiotic built forum and socially responsible architectural practices. It is noticed that some violations resulted due to the architect's lack of awareness and experience in ethics, such as publishing pictures of designs for one of the clients without obtaining his consent or consulting, promoting a product manufactured by the company, and using it in the project without indicating that to the client in addition to failure to introduce sustainability techniques in the projects to the client… etc.

Having said that, the Civil liability of Architects in Bahrain is given the most attention by Bahraini legislators with a distinct body to govern the profession, that is CRPEP (Council of Practicing Engineering Profession), which arranges the rights and responsibilities of architects according to law No 51 for 2014 for all the engineers in Bahrain [6].

Therefore, the significance of the study came from the need for more literature in the field of impacts of the intended and unintended ethical violations in architectural offices in Bahrain. Accordingly, the study focuses on the significance of ethics for architects' professional practice. This research attempts to bridge the literary gap mentioned by focusing on new employees' most prominent mistakes in small companies. Efforts are needed to spread awareness among contemporary architects and reduce common errors by fixing this gap in understanding ethics issues.

Hence, it aims to delve into the exploration of ethical challenges and issues faced by architects in Bahrain's architectural sector as they practice their profession, to assess challenges while striving to create equilibrium between client expectations, ethical design, and domestic cultural values, to analyze the impact of local regulations and legal framework on ethical decision making and comprehend the cultural values and traditions influencing the ethical interpretation and application in Bahrain's architectural sector and to recommend ethical awareness and responsible building practices.

The study's framework is intended to understand ethics in professional practice from different points of view. It will target Bahraini construction firms to understand what ethical practices are followed and what unethical practices are. Benchmarking from various agencies will be considered. Further, the research intends to identify the missing gaps in ethical practices in Bahrain and then recommend meaningful codes to be considered by the employees and employers. Figure 2 illustrates the Framework of the Study. Figure 1 illustrates the Framework of the Study.

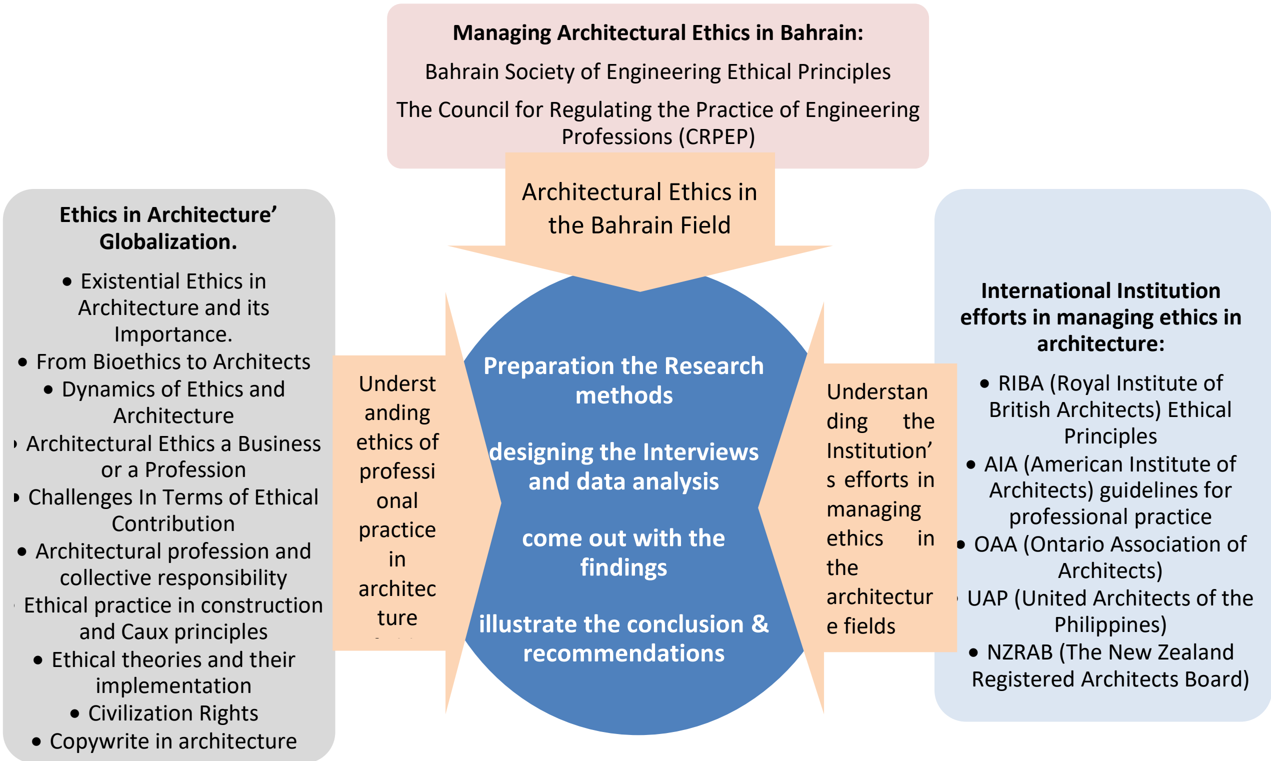

Figure 2*. Flow Chart of the study. Source: Authors.*

2. Literature Review

2.1. Existential Ethics in Architecture and its Importance

On the contrary, D'Anjou P (2011) argues that subjective and objective freedom is not a largely accepted platform for teaching ethical practices in architecture; he stresses Jean-Paul Sartre's philosophy of 'existentialism', emphasizing the significance of freedom of expression accompanied by their design choices. The design choices could be "Authentic "or "Inauthentic," later being the peer pressure or external views. Hence Sartre's philosophy could be an ethical structure for implementing ethical consciousness in practice. D'Anjou P (2011) further delves into Vitruvius's proposed qualities of architecture as "solidity, functionality, and beauty", which is the ethical responsibility of the architect to present the three virtues in the building design as well as the client relationship.

Another faceted dimension of architecture is moral values embodied through the buildings designed in the form of addressing the issue of accessibility, climate change, and racial injustice; remodeling the existing non-aligned buildings to these moral values helps lessen architectural injustice, hence demonstrating humility and possibility that future generations will question our architectural decisions.

2.2. Architectural Ethics a Business or a Profession

Carrolln (2015) elaborates on the complex relationship between architecture and ethics than any other art form. Architects as professionals have a moral duty to demonstrate integrity and prioritize the clients' well-being, which could be refraining from using inferior materials or cutting corners, resulting in structural instability. Hence, architects bear an ethical cap, ensuring their creations can adhere to anticipation challenges. In reality, an additional factor that dominates the architecture that collides is 'commerce', drawing it to the realm of a business and with the due moral responsibility of any business is refrain from deceiving the clients, "Potemkin villages" an age-old example of non-ethical standards. Architecture as a business, if it seems a bit off context, could be rephrased as 'services', where one provides, "The Architect is a provider-a provider of services-and her clients have the right to expect that their contracts and their agreements with their architects will be fulfilled, including expectations grounded in prevailing social expectations, such as that houses not fallen down" [7]. Ethics could be general regarding varying socioeconomic relations and societal expectations, opening a thought process of whether ethical architectural practice as a business or a profession.

2.3. Architectural Profession And Collective Responsibility

Sadri (2012) explores the book 'The Rise of Professionalism' by Magali Sarfatti and states that professionalism, irrespective of any field, is a structured attempt to establish a symbiotic relationship and preserve it against societal pressures. Social morals and legislation secure the position of professionals, which is the privileged base to avoid any intrusion. He further talks about the code of professional ethics conducted by the 'Chamber of Architects in Turkey', influenced by the International Union of Architects, and the moral principles to nurture and safeguard the dignity of architectural professionals [8].

2.4. Ethical Practice In Construction And Caux Principles

Architecture and construction are like two faces of a coin, working in harmony to ensure a responsible outcome, Kang (2007) talks about the significance of 'ethics management' in construction, specifically during the progression of the socioeconomic arena in the 21st century. Construction, irrespective of multicultural datum, still has a scope for ethical training for ethical decision-making during the process of implementation, the core being the cultural dimensions as the stakeholders involved are "Architects, clients, contractors, sub-contractors, suppliers and end users, have various levels of moral developments and ethical standards", therefore the conflicts in term of the ethics might quickly rise unless regulatory, ethical standards are set. To tackle this effectively Caux Round Table's (2003) global principles for Businesses, an international ethics code "in collaboration with business leaders from European Countries, Japan, and the United States", alternately Global Sullivan principles(2005) to encourage social responsibility all around the globe and "support economic, legal, social and political justice; encourage equal opportunity at all levels; train and advance disadvantaged workers; assist greater tolerance among all the people; improve the quality of life for communities; and support human rights". Idowu (2013), explains in depth the Caux Round Table (CRT) principles for businesses delineating a globally encompassing perspective on ethical conduct.

The seven fundamental principles that serve as the basis for ethical conduct among businesses worldwide. This universal benchmark aims to evaluate the societal and ethical conduct in the business sphere. The seven principles are as follows:

a. Respect Stakeholders Beyond Shareholders.
b. Contribute To Economic, Social, and Environmental Development.
c. Build Trust by Going Beyond the Letter of the Law.
d. Respect Rules and Conventions.

e. Support Responsible Globalization.
f. Respect the Environment.
g. Avoid Illicit Activities.

2.5. Ethical Theories And Their Implementation

The values of making moral decisions demonstrate that it is connected to concerns like sustainability, social responsibility, and client relations. It becomes an essential aspect of the professional integrity of architects towards society, thinking through the influence of their designs on a community in terms of cultural sensitivity, environmental sustainability, and accessibility, which delves deep into the process of safeguarding the public interest first and even if it means contradicting the expectation of the clients in order to make a beneficial impact on the society as architects are viewed as a guardian of the built environment stewarding through the resource conservation and energy efficiency taking account of the whole life cycle of the building designed hence actively participating in the moral decision making to design constructed environments that are sustainable, socially conscious and considerate of the need and values of the people they serve [9].

2.6. Copyright In Architecture

Architectural work is the most experienced and pervading of all forms of artwork; it encompasses architectural designs, blueprints, elevations, and any other visual representations that are susceptible to copyright protection. It's crucial to remember, though, that the utilitarian elements of design, like a building's practical features or construction techniques, are not covered by copyright protection in architecture. Copyright infringement happens when someone uses copies or reproduces a significant portion of an original architectural work without permission. In these situations, the owner of the copyright may, in the lawsuit, uphold their legal rights and obtain remedies, including injunctions, monetary compensation, or an end to the infringing activity. The rights of architects to restrict how their works are used have been significantly impacted by Baker V dot's seldom decision. In that instance, the code determined that copyright protection only covers any idea's precise presentation or form, not the underlying ideas or concepts in our work. [10].

The literature review revealed that the existing literature on ethical challenges and interventions is scarce. This emphasizes the need for additional research and analysis in this field, and the findings of this study could potentially contribute to lobbying a platform for more sustainable and ethical interplay, for sustainable social-cultural harmony within Bahrain's architectural professional communities.

2.7. Civilization Rights

According to research by the Egyptian Innovation Bank, the notion of civilization rights to construct a civilization is a novel meaning of a framework of the intellectual property system that considers the process of preserving human civilization and heritage. The cultural legacy, nations, and civilizations have moral and material rights that must be acknowledged and respected. The campaign "Civilization Rights to Build a Civilization", highlights Egypt's moral and material rights, tackling many issues like science, law, archeology, history, architecture, diplomacy, tourism, and economy. It aims to draw attention to the Egyptian state's morals and material rights over using pictures, logos, replicas, names, and other commercial exploitation of its cultural heritage to acknowledge Egypt's sovereignty and ownership of its cultural legacy. [11].

2.8. International Institutions managing ethics in architecture

2.8.1. RIBA (Royal Institute of British Architects) Ethical Principles

On the contrary, Roberts, D. (2018) mentions the RIBA's ethics, a professional membership organization founded in 1837 "for the general advancement of civil architecture, and for promoting and facilitating the acquirement of the knowledge of the various arts and science". The RIBA lists, "Honesty, integrity, and competency, as well as concern for others and the environment, are the foundations of the Royal Institute's three principles of professional conduct". Sadri H(2012) elaborates on the RIBA's principle of honesty, which anticipates unbiased and responsible professional conduct, avoiding the promotion of any kind of illegal conduct. Further, the competency requires architectural professionals to adhere to continual skill development and utmost care in the area of their work, and lastly, in relations in terms of clients, to be transparent when it comes to project communication to be transparent keeping in mind the time, effort, and cost of the client. Hence, the RIBA'S ethical code of conduct demonstrates a strong basis of professional integrity in the field of architecture. The Rebus knowledge schedule outlines six primary responsibilities for an architect to carry his or her responsibility on the path of ethics. These six duties include:

a. Duty to the broader world: Architects must consider the more significant effects of their work on society and the environment.
b. Duty to society and the end user: Architects must keep the well-being of the community and the individuals who inhabit the dwellings and balance society's demands on a larger frame.
c. Duty to those commissioning services: Architects have to uphold the customer expectations in terms of openness and responsibility and providing services that advance their goals.
d. Workplace critics must provide their employees with a secure, welcoming, and encouraging work atmosphere, considering the work-life balance and continuous professional development.
e. Duty to the profession: Architects are duty-bound to maintain the standards of the profession as well as integrity, including professional behavior, adding to the skills of the knowledge in the field.
f. Duty to oneself: the architect should prioritize their own well-being as well as the advancement of their careers and personal lives. They should also make ethical decisions and behave according to their own beliefs and principles.
g. Riva emphasizes the ethical principles necessary to make responsible moral decisions considering the broader impact of architectural work. She acknowledges the importance of architects in building a safe and secure environment [12].

2.8.2. AIA (American Institute Of Architects) Guidelines For Professional Practice

The American Institute of Architecture (AIA) is a professional association for architects in the US. AIA is a 155-year-old established organization that has had a significant impact on the field of architecture. The Architectural Code of Ethics and Professional Conduct was updated in 2007 with the guidelines for professional commitment. The code is structured into 'Rules of Conduct,' 'Ethical Standards,' and 'Canons.' The first canon highlights the "General Obligations", which talks about continuous knowledge enhancements and honoring the previous achievements that foster growth considering the impact of societal and ecological implications on their professional expertise. The second canon highlights "Obligations to the Public". It stresses architects' responsibilities to gain the public's confidence in their field of work. The third canon, "Obligations to the Client," emphasizes professional services and maintains ethical standards, preventing conflict of interest and demonstrating truthfulness and honesty. "Obligation towards their profession and the market", the fourth and the fifth canons highlight the fact that architects have to uphold the honor and integrity of their profession.

Overall, AIA's code of ethics and professional conduct amplifies the fact that architects should demonstrate value addition morally, professionally, and with integrity (Sadri H,2012). The AIA supports the architecture profession and enhances public perception through education, government advocacy, community regeneration, and public engagement. To help organize the building sector, the AIA collaborates with various design and construction community members. The core courses were sorted according to the four main categories discussed in the AIA handbook: ethics and professional practice, firm management, project delivery, and contracts and agreements. Next, the number of courses was converted into percentages and examined accordingly.

Martin and Schinzinger (2010) specified most of the errors that may occur in engineering offices in general. Errors are classified according to the code of ethics and professional conduct of the Bahrain Society of Engineers and the AIA. Violations will be summarized and linked to the rules in the manner of an instruction booklet for new company employees. Each heading contains two lists, the first that the employee recommends avoiding and the second that the employee tries to do. The booklet also includes cases to facilitate understanding and quotes encouraging compliance with the code of conduct and avoiding violations. The booklet outlines an architect's responsibilities and requirements under Betterteam, a platform for hiring small to medium businesses. Then it discusses five main headings inspired by the AIA: general obligations, obligations to the public, obligations to the clients, obligations to the profession and colleagues, and the environment. The method of booklets was used to clarify ideas or to explain work instructions in many institutions. The Saudi Technical and Vocational Training Corporation is an example, where it published a booklet of the rules, regulations, work structure, rights, and duties. This aims to understand the regulations and instructions in human resources; it is a service for new employees in particular and a reference for employees in general.

3. RESEARCH METHODS

The aim of the study, which was discussed in the introduction, will be delved into depth in this section to understand the process of conducting the appropriate Research, the method used for collecting the data, and tools for analyzing the data for gauging the ethical challenges to understanding the best practices in Bahrain's architectural industry. The systematic analysis of the secondary data in the literature review flows through the investigation of the effect of globalization on architectural ethics to probe into the freedom of expression to make ethical design decisions, on the contrary, explores the ethical obligations to architects to uphold the design values, progressing to using ethics as weapons against bureaucratic corruption followed by exploring the ethical principles globally and in the context of Bahrain. Looking at the perception of architects, setting them from the perspective of historical context, the evolving challenges that drive to reimagine the future professional practice [13].

The progressive step of primary data collection under the qualitative method of research. "Qualitative Research is a lived experience" [14]. According to Ciuk & Latusek (2018), qualitative research aims to improve the understanding of our world and deepen the examination of social occurrences. "…. First -hand encounters with a specific context. It involves gaining an understanding of how people in real-world situations 'make sense' of their environment" [15]. The data collection was shouldered by a semi-structured interview process, directly in conversation with the participants, listening to the narratives, and observing the participants (Warnock, C. 2019) to gather their experiences and the challenges faced during the tenure of their professional practice, to brief in depth the role played by an architect.

The sample collection was facilitated through the interview process, as elaborated by Qu & Dumay (2011), the research interview being the most critical aspect of the qualitative data collection methods in ethnographic investigation practices. Research interviews are classified into structured and standard [16]; structured interviews involve pre-established questions with stipulated response categories. They might seem rigid but minimize the generation of biased findings (Qu & Dumay 2011) under the same purview is the context of this study, addressing the architectural professionals practicing in Bahrain and the interview questions framed to address the dilemmas that they are facing in their everyday professional life.

The framework of the questionnaire for the interview It was designed to find out the gap between the throes and the reality in the professional field in Bahrain. The questionnaire was designed after understanding the ethics based on the theories and the literature review and conducted included a flow of the patterned discussion, keeping in mind the study's objectives and relevant literature study from the interpretive perspective, keeping the essence of ethical communication intact. It included various themes and the topics collected: 1. duration of practice 2. Formal education obtained for ethical conduct 3. Importance of ethics in their professional life 4. Ethical crossroads 5. Balancing expectations and ethics 6. Importance to socio-cultural factors 7. Dealt with conflict of interest 8. Most challenging ethical dilemmas 8. Self-updating of ethical standards.

3.1. Ethical Principles in Bahrain

3.1.1. Bahrain Society of Engineering Ethical Principles

A parallel approach to implement a code of conduct to ensure "Transparency, Integrity, and Accountability for engineers to practice in Bahrain is the Bahrain Society of Engineers (BSE), established in 1972. The main motto of these principles is to ensure that engineers utilize their knowledge and skills to amplify humane well-being and ensure honest and unbiased service. Below are the fundamental principles (BSE. n.d.).

a. Engineers shall hold paramount the safety and welfare of the public in performing their professional duties.
b. Engineers shall perform services only in the areas of their competence.
c. Engineers shall continue their professional development throughout their careers and provide opportunities for those engineers' professional and ethical development under their supervision.
d. Engineers shall act professionally for each employer or client as faithful agents or trustees and avoid conflicts of interest.
e. Engineers should build their professional reputation on the merit of their competencies and services and not compete unfairly with others.
f. Engineers shall avoid deceptive acts and not abuse public or private offices for personal gain.
g. Engineers should issue public statements only objectively and truthfully.
h. Engineers shall consider environmental aspects and sustainable development in their professional duties.
i. Hence, the above code of conduct strives to increase the competence and morals for sustainable professional practice in Bahrain.

3.1.2. The Council for Regulating the Practice of Engineering Professions (CRPEP)

CRPEP is a regulating authority established to regulate the practice of engineering professions, which is responsible for issuing licenses to engineers and engineering offices. The legislation specifies the prerequisites for getting a license, such as high moral character, professional experience, and educational requirements for obtaining an engineering license. It mandates that government agencies or licensed engineers authorize engineering projects and forbids unlicensed persons from engaging in the engineering profession. The council offers rules and exemptions to engineers who are not Bahraini employees in the monarchy. It also establishes rules for engineering offices and disciplinary measures for breaking the legislation. Under Law No. 51 of 2014, enforcing regulatory principles in the Kingdom of Bahrain is under the purview of the ministry in charge of public works. Any engineer pursuing a career in engineering has to get a license from the council. A License is also required for engineering offices to engage in one or more engineering professions. On engineering concerns or projects, only licensed engineers and engineering offices are authorized to approve and sign the design and drawings [17]

- Article 1: summarizes the phrases and words used to address the context of regulatory principles.
- Article 2: It is forbidden for any engineer who does not possess a license from CRPEP to refrain from practicing in any sector or branch in the kingdom.
- Article 3: No person shall work on projects or engineering matters unless they possess authorization and signature from a government agency or an engineering office licensed to practice.
- Article 4: Engineering directorates in governmental institutions, public entities, or engineering offices licensed by this law shall be tasked with offering consulting, conducting engineering designs, and supervising the implementation of the engineering works.
- Article 5: the council for regulating the practice of engineering professions will be established, reporting to the minister. A seven-member committee was nominated by the Bahrain Society of Engineers and the chairman with a tenure of three years.
- Article 6: The council has the authority to provide licenses needed to practice the engineering profession and comply with the duties following the terms of this law and its implementing regulations.
- Article 7: Anybody having a license to work as an engineer must be a citizen of Bahrain, must possess an engineering bachelor's degree from an accepted university, and must meet the standards of licenses required category and the engineering field or branch.
- Article 8: An engineer who is not a Bahraini may hold a license to work as an engineer in the Kingdom of Bahrain upon the fulfillment of subsequent requirements and must meet all the requirements listed in Article 7 of the law after earning the engineering academic

credentials, one must engage in actual practice with a minimum of five years, must have an agreement to practice the profession with domestic or international business organization.

- Article 9: Engineers employed by governmental agencies called mom industries and other public bodies should be granted a license to practice engineering given they fulfill the requirements outlined in Article 7 off the lot, and the hiring organization must submit a license request, which is free of charge and valid for the duration of the job without needing to be renewed the appropriate entity should implement disciplinary action against the personnel as mentioned earlier in compliance with laws and regulatory frameworks that apply to their positions.
- Article 10: An engineering office must fulfill the requirements outlined in Article 7 and be committed to practicing in compliance with the guidelines outlined in the implementation regulations. The council may allow one of its designated licensed engineers to manage the office full-time or part-time for a maximum of six months. The engineering office must obtain insurance policy coverage to protect against legal liability for professional mistakes following the terms and specifications provided in the implementing regulation.
- Article 11: The council may form committees to help carry out its studies. One such group is the investigation group that addresses the complaints pertaining to engineering professions.
- Article 12: the council has the authority to establish rules governing the registration of engineers, the cost associated with licenses, criteria for professional growth, and any other aspect of the engineering profession.
- Article 13: Any changes in an engineer's or engineering office's professional standing or circumstances might impact on the eligibility of licensing, which should be reported to the council in a timely manner.
- Article 14: To make sure that the law, rules, and professional standards are being followed, the council is able to carry out audits and inspections.
- Article 15: For professional misconduct, carelessness, or breaking the law as set by the council, disciplinary action may be imposed against engineers or engineering offices.
- Article 16: Disciplinary action might involve warnings, fines, license suspension, license revocation, or any other suitable sanctions decided upon by the council.
- Article 17: Disciplinary judgments rendered by the council may be appealed within a given time before a competent court.
- Article 18: to promote the growth and promotion of the engineering profession, the council may set up a fund. The fund is open to receiving grants, contributions, and donations from various sources.
- Article 19: the council shall annually report to the minister on the operations it has undertaken financial accountants' additions for enhancing the regulation of engineering professions.

3.2. Data Analysis

The data was obtained from interviews with explanatory questions posed to professionals. The questionnaire post explored ethical challenges within architectural practitioners in the Kingdom of Bahrain, intending to improve and spread ethical awareness and responsible building practices. Meanwhile, the participants were asked about their experiences as architects in Bahrain and various other factors. They were also interviewed about any ethical dilemmas they faced and how they resolved them. Assuming the social position as a facilitator of the project building through stakeholders, the data obtained from the interviews of explanatory questions posed to the professionals, as they offer distinct services to the community. lders' active and committed engagement is connected to modern architects' difficulty, making them of Bahrain stop this. This vision matches Villalobos (2020), people have been socially constructed to acknowledge the roles of all participants, their contribution, and their limits that the questionnaire post explored ethical challenges within architectural practitioners in the Kingdom of Bahrain.

Meanwhile, the participants were asked about their experiences as architects in Bahrain and various other factors. We made critical ethical considerations in practice. They were also interviewed about any ethical dilemmas they faced and how they resolved them. The questioner progresses, delving into the topics about ethics in balancing client expectations with different patterns of question posts as mentioned above. This approach opens an arena to learn more about the strategies, goals and influences the architects hope to make in their industry. Gathering such information may encourage cooperation, spark creativity, and help make decisions that will improve society's quality of life. Assuming the social position as a facilitator of the project building through stakeholders' active and committed engagement is connected to modern architects' difficulty, making them of Bahrain stop this.

a. The first question posed was the duration of the professional tenure in Bahrain's architectural industry, and the responses received varied, with most fresh talents within five years of work experience until ten years or more, as shown in Figure 3 below. Hence, the output of professional experience tenure signifies an influx of new talent, resulting in a mix of fresh perspectives and, in the process, the finding of gaining acquaintance.

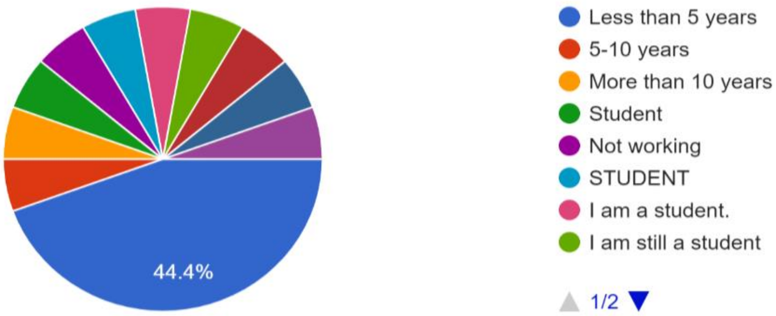

Figure 3*. The duration of the professional tenure in Bahrain's professional work. Source: Authors.*

b. For the successive question asking if any formal literacy was obtained regarding ethics in architectural practice, around the majority agreed to have received a formal education on ethics in their profession, as depicted in Figure 4. Below.

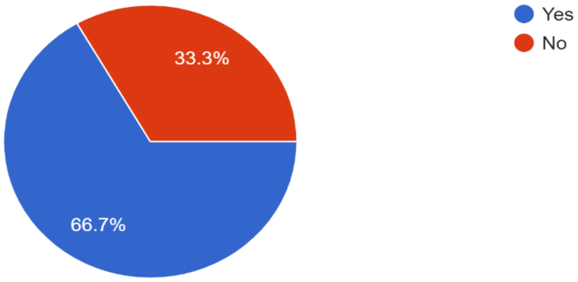

Figure 4. *Asking if any formal literacy was obtained in terms of the ethics in architectural practice. Source: Authors.*

The above result summarizes that most architectural professionals have received a formal education in ethics, which indicates a sound understanding and knowledge of ethical principles in their professional practice.

c. The progressive question posed was whether ethical considerations in their architectural practice are or least important, for which the majority agreed to be most important and few to be essential and critical. At the same time, significantly fewer professionals were mentioned as unimportant, as shown in Figure 5 below.

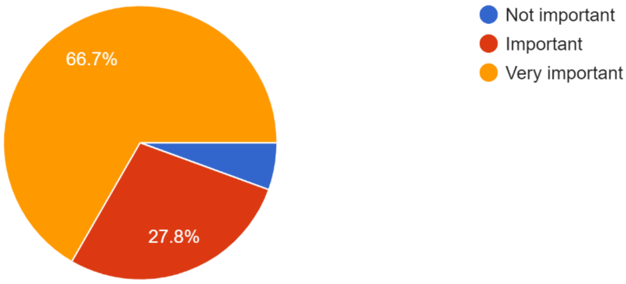

Figure 5*. Asking about the ethical considerations in their architectural practice. Source: Authors.*

Hence, the above data demonstrates that architects prioritize ethical considerations in their practice, demonstrating a diligent approach to ethical conduct in the field of architecture.

d. The following question was asked whether any ethical dilemmas were encountered in their tenure of professional practice in terms of client conflict, compromise on safety standards, or cultural obligation, for which few mentioned they haven't come across any such challenges. On the contrary, many agreed to have faced such issues, and some shared their instances of the dilemmas faced during their practice a few are mentioned below:

"Yes, some clients requested elements that may harm people and do not follow standards".

"Ethical dilemma in terms of client conflict when an architect is asked to design a building that goes against their personal values or beliefs. In this case, the architect may have to choose between their professional obligations and their personal convictions."

"Yes, it happened during my training period in a proposal design for Muharraq neighborhoods by BACA recommendation. The supreme authority in the Ministry of Agriculture and Municipal Affairs insisted on using plants that do not comply with the sustainability standards that had to be adhered to during the project's design, which is considered one of the basics of design in the Ministry of Agriculture and Municipal Affairs. To resolve the issue, an agreement was reached with the Supreme Authority, and the reasons for the incompatibility of these plants were explained in a bitter manner and an open conversation in order to satisfy all parties and reach A solution that satisfies everyone".

Hence, the above result mentions the fact that within the purview of architectural practice, some architects have encountered ethical quandaries and share the instances.

e. In the preceding question about the sociocultural factors taken into consideration while making design decisions, the majority of the architects agree that they strive to create a local context-derived space that caters to community needs. In contrast, few others mentioned taking a path of initial research on social-cultural norms before delving into designing. Very few mentioned that they would go by the client's choice, while the rest of the interviewees said they hadn't considered any of it in their practices, as depicted in Figure 6 below.

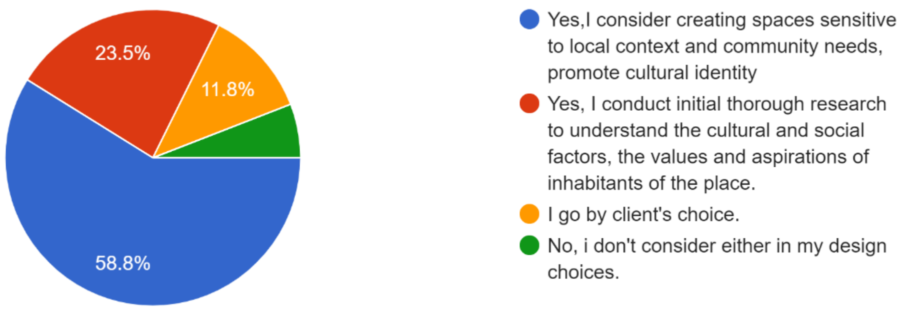

Figure 6*. Question about the sociocultural factors taken into consideration. Source: Author*.

Hence, the above data obtained states that most architects respect and consider the local sociocultural aspects. It's substantial to know that the professional architects in Bahrain understand the value of embracing the social and cultural context in their design to create spaces that reverberate with the community.

f. The subsequent questions posed to professionals were whether they experienced conflict of interest in their professional practice and how they handled any. While most of them mentioned they had not encountered conflict at crossroads, very few did and suggested how they tackled the situation in Figure 7.

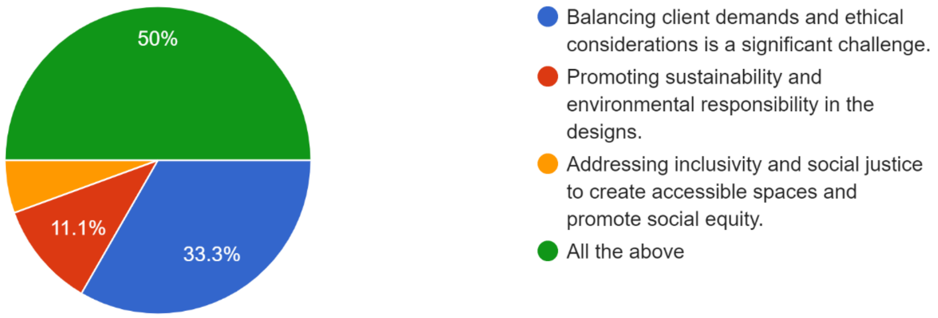

Figure 7. *Question about experiencing any kind of conflict of interest in their professional practice. Source: Authors.*

The data set demonstrates that the slightest report of experiencing a conflict of interest with no particulars of resolving the conflict was mentioned. Hence, it opens an arena to explore how practicing architects in Bahrain handle and navigate the conflict of interest to ensure moral decision-making.

g. The following question posed the most significant ethical challenges faced by professionals. Most experts mentioned balancing client demands and ethical considerations, promoting sustainability in design, and addressing inclusiveness and social justice to create accessible spaces to promote social equity. In contrast, few mentioned balancing ethics and client demands, followed by very few professionals who mentioned sustainability in design and the meager professional populace. The data set answers mention that balancing client demands with ethical considerations is one of architects' most significant moral challenges in their practice. Hence, this emphasizes the delicate balance designs must strike to satisfy clients while upholding ethical integrity.

h. Therefore, the last question was posed to the professionals about how they keep themselves updated on ethical best practices. The response received was a balance between the interviews and some attending conferences and workshops mentioned. In contrast, others engaged in discussion with the architects of the clan, and few mentioned having engaged with local authorities to get an update on the same. On the contrary, a meager number of professionals did admit that they least stay updated with the ethical standards, as shown in Figure 8 below.

Figure 8. *Question how they keep themselves updated on the best ethical practices. Source: Author.*

The data obtained from the above question summarizes that architects in Bahrain participate in conferences, workshops, and professional development programs to stay updated on current ethical standards and sustainable best practices. This proactive approach defines the dedicated professional populace to lifelong learning and advancement of moral behavior.

4. FINDINGS

As explained by (D'Anjou,2011), the architectural design approach fosters a unique comprehension of individual creative freedom and accountability while establishing an ethical framework. Moreover, following the thought of (Almaaouri, A.S.2019), limiting the design's decision that is harmful to the other, whether the individual building site or nature itself, laying the architect's responsibility towards human society is a very general ethical obligation of architects towards society and its well-being.

As illustrated in the literature reviews, 'Ethics are, after all, a relative concept – the manifestation of a moral ideal – and one person's morality is another's immorality.' The ethical turn in architecture in the twenty-first century holds that the people most affected by architects' decisions and actions should be engaged and active participants in the design process, which begins with an empathetic understanding of diverse perspectives and a respect for cultural and climatic differences. Ethics plays a significant role in any professional practice. Though each engineering board has a set of ethical codes, the lack of proper application leads to unprofessionalism within the firms.

The results of the data analysis emphasize the significance of ethical considerations for Bahrain's architectural industry. Architects exhibit an enthusiastic understanding of ethical principles and consciously try to incorporate them into their works. Furthermore, the results also demonstrate that persistent enhancement of knowledge and skills on ethics in architectural practices could motivate professionals to converse candidly and barter their experiences and best practices, enabling them to develop effective techniques to handle conflicts of interest. The narrative data shows that Bahrain's architectural field is multifaceted and intricate regarding the professional guidelines of ethical conduct for architects, similar to the international standards of ethical principles. The architectural community in Bahrain thus can ensure the evolution of sustainable and reliable solutions by combating ethical issues and enhancing the best practices to a greater height. Having said that, there is a potential scope for further, more profound research with broader variables to obtain a deeper understanding of the ethical conundrum experiences and ways of resolving the same, especially from the perspective of sustainable practices in Bahrain's architectural field.

5. CONCLUSION

In conclusion, this study examines Bahrain's sustainable practices in relation to the ethical dilemmas architect’s encounter. The results provide insight into the intricate relationship between cultural norms, local laws, globalization, and moral judgment in the architectural field. Several ethical issues exist in practicing firms in Bahrain. In comparison to other codes based on AIA and RIBA (Royal Institute of British Architects), it is also found that several codes need to be in Bahrain and need to be employed. However, the lack of strict implementation of ethical codes leads to employee issues and creates an unprofessional office environment. Moreover, the lack of following ethical codes properly leads to losing one's credibility as well as that of the organization. The practice of architecture has been profoundly influenced by globalization, which has forced architects to operate beyond borders in various cultural contexts; hence, this research draws attention to the moral conundrums that result from this delicate balancing act, stressing the necessity for architects to handle these difficulties with honesty, openness, and thorough comprehension of the local context.

The establishment of organizations such as Bahrain's Council of Practicing Engineering Professions (CRPEP) indicates the commitment to ensuring architects' civil responsibility and defining their rights and obligations. This ensures that the architects uphold responsible architectural techniques and ethical, socially responsible, and culturally inclusive designs to the public's trust while demonstrating the importance of socially responsible design and culturally inclusive design in determining how ethical principles are interpreted and used in Bahrain's architectural industry. To produce ethically socially accountable and culturally inclusive designs, this paper delved into various aspects based on the narratives and the data collected to underline how architects must interact with stakeholders, considering the local environment and honoring cultural history.

One of the key findings is the importance of ethical design principles in addressing sustainability challenges and how architects play a crucial role in developing appropriate and timely designs essential in promoting sustainable practices considering community involvement while protecting cultural heritage.

The other key finding is that at the educational level, architecture students need extensive experience in ethics before being involved in professional firms to apply their knowledge to real-life projects and be ready to practice their profession efficiently. However, it is the university's responsibility to provide courses that prepare students initially to start their professional careers after their graduation. Such courses should provide sufficient knowledge and practice for architecture students to meet the labor market. They must also seek to train students to compete and meet international market standards. This will occur by intensely increasing the attention to teaching deep ethics courses. If this occurs, the architectural programs in Bahrain will go deep in preparing their students to meet the standards of practice and professional conduct according to the AIA vision. It will provide several services to enhance the link between educational programs and the ethics of the professional practice of architecture.

Moreover, the results of analyzing the questionnaire show that fresh architecture graduates need more experience in the ethics of writing, reading, or understanding contracts. They must understand the appropriate implementation of the ethics in the architecture contracts, which are the agreements established in collaboration between sponsors and development partners regarding a specific service's deliverables, excellence, and suitability. Hence, understanding the ethics of such a topic needs sufficient knowledge and practice from the architect. This paper can act as an eye-opener and a chance for universities in Bahrain that offer architectural programs to enhance their curricula and fill the gaps in the modules they lack in. In addition to urging CRPEP to be involved more practically rather than theoretically with educational architectural organizations, they help enforce the link between architectural education and practicing architecture, creating better architects ready to practice their profession and serve their community once they graduate.

The practice of architecture has been profoundly influenced by globalization, which has forced architects to operate beyond borders in various cultural contexts; hence, this research draws attention to the moral conundrums that result from this delicate balancing act, stressing the necessity for architects to handle these difficulties with honesty, openness and thorough comprehension of the local context.
One of the key findings is the importance of ethical design principles in addressing sustainability challenges and how architects play a crucial role in developing appropriate and timely designs essential in promoting sustainable practices considering community involvement while protecting cultural heritage.
Because of the increase in professional violations in engineering offices, which sometimes are unintended and issued by new architects who are ignorant of the profession's ethics, it has become essential to raise awareness and reduce the occurrence of similar errors among architects. Awareness methods vary. This research recommends producing an ethics booklet as a method used in many companies to explain rights and duties, define the company's structure, and work by institutions, which is still effective. Ensuring that architects' work benefits communities and the environment, this research emphasizes the importance of prioritizing ethical sustainability and socioeconomic disparity in their practice tenure. It highlights how professional standards, and regulatory frameworks influence ethical behavior in the architectural context.

Therefore, based on the data analysis results of the research, it is recommended that architectural practitioners in Bahrain must continue to delve into enhancing ethical awareness and adopting responsible architectural methods. This may be accomplished by maintaining the current knowledge of the most recent developments and best practices in sustainable design, encouraging partnerships with diverse teams, and active engagement in professional development. Targeting the implementation of it, produce an ethics booklet that:

a. Support the Bahrain Society of Engineers in educating the new architects in small C-class firms.
b. Requiring companies to educate new employees by reading and understanding the ethics booklet.
c. Serious follow-up of companies' plan implementation through the Bahrain Society of Engineers.
d. Use the booklet in electronic copies so that it does not cost companies the cost of printing.
e. Adding contact numbers to respond to inquiries and questions from new employees.
f. Emphasizing the implementation of ethics in architectural professional practices, professionals must adopt an open dialogue with clients, stakeholders, and the public to ensure that society's goals and values are reflected in their designs.

Overall, this research underscores the emphasis on how important ethics are to the practice of architecture, especially regarding the goal of sustainable design. This is achievable through integrating principles in work and resolving the ethical difficulties mentioned in the study; architects in Bahrain can create an aesthetically appealing, environmentally sustainable, and socially responsible built environment.

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Conflict of Interests
The Author(s) declares that there is no conflict of interest.

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Dalia ELDARDIRY Associate. Prof. Dr.,
Dr. Dalia H. Eldardiry is an associate professor in College of Design, Imam Abdulrahman Bin Faisal University, Saudi Arabia. She teaches construction methods, environmental control systems, and production drawings courses. She is a researcher, interested in design education and urban design aspects. She attended various conferences and seminars on different topics. She has published many papers in Arabic and English language and articles since 1999.

Kavithasree SUVARNA
With over 15 years of experience in architectural design, I am passionate about creating functional and inspiring environments. Her career spans residential and commercial projects blending creativity with sustainability. She serves as a board member and treasurer for the Migrant Workers Protection Society, advocating for migrant welfare. Balancing my professional journey with motherhood, she is dedicated to making a positive social impact. Currently, she is pursuing my master's degree at the University of Bahrain.

Mahtab ASVAR, Asst. Prof. Dr.,
Was born in Iran and graduated from Limkokwing University, Malaysia. She completed her PhD at Limkokwing University with a dissertation entitled “Exploring the impact of Building Information Modeling (BIM) on project performance in the construction industry”. This advanced study underpins the teaching philosophy, which emphasizes the importance of innovative practices in design and project management. She is currently serving as an Assistant Professor in the Interior Design Department at Kingdom University, Bahrain where she teaches design studios, computer-aided design, Revit and MEP. In addition to her role at Kingdom University, Dr. Mahtab has previously lectured at Girne American University in Northern Cyprus and at the University of Bahrain. Through these positions, she has contributed to the education of more than 500 interior design students, fostering a new generation of professionals equipped with the skills and knowledge necessary to excel in the field.

Comparative Thermal Performance of Recycled Plastic Bricks: A Property-Based Analysis for Energy-Efficient Housing



Modupe ODEMAKIN[1], Seyhan YARDIMLI[2], Melody SAFARKHANI[3]
PhD Student, Istanbul Okan University, Graduate School of Science, Department of Architecture, Istanbul, Turkey, Faculty of Art, Design and Architecture, Istanbul, Turkey[2,3],
modupeodemakin@gmail.com [1], seyhan.yardimli@okan.edu.tr [2]
melody.safarkhani@okan.edu.tr [3]
https://orcid.org/0000-0001-6721-0991 [1],
https://orcid.org/0000-0001-7186-9000[2] ,
https://orcid.org/0000-0001-6363-9328[3]
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Abstract: *This study addresses the growing need for energy-efficient and low-impact building materials in Turkey by evaluating the energy performance of innovative recycled-plastic bricks. Although plastic bricks have demonstrated promising thermal properties in international research, the research gap lies in the absence of a systematic, climate-specific assessment for Istanbul's mild-humid conditions and a lack of comparative simulations against commonly used Turkish masonry. The aim of this study is to conduct a comprehensive performance evaluation of recycled-plastic bricks and the objective is to determine which formulations offer the greatest potential for reducing building energy demand in Turkey. The methods used in this study involves twenty years of meteorological data from the Turkish State Meteorological Service and dynamic energy simulations conducted in DesignBuilder/EnergyPlus. A U-shaped residential building typology previously identified as the most energy-efficient form for Istanbul was modeled. Seventeen recycled-plastic brick types (B1–B17) sourced from existing literature were analyzed based on thermal conductivity, specific heat capacity, density, moisture resistance, and fire resistance, and were benchmarked against Turkish hollow clay bricks. The key findings of this study show that several plastic brick types significantly outperform the traditional masonry. In particular, Brick B15, composed of recycled PET and sand, achieved the highest overall energy savings of 13.89%, driven by a 26.24% reduction in heating load with only a minimal rise in cooling demand. This superior performance stems from its optimal combination of low thermal conductivity, moderate density, and high specific heat capacity. Furthermore, eight additional plastic bricks demonstrated substantial efficiency gains, underscoring the role of recycled thermoplastics and stabilizing additives (e.g., fly ash, quarry dust) in improving thermal inertia and indoor comfort. The key implication of these findings is that plastic composite bricks can substantially reduce operational energy consumption, particularly in low- and middle-income housing where insulation levels are often inadequate. By integrating long-term climate data, material science insights, and high-resolution simulation, this study provides a scalable and evidence-based framework for the adoption of eco-friendly plastic bricks in temperate climates. The results offer actionable guidance for architects, engineers, policymakers, and housing agencies aiming to lower energy use and carbon emissions in Turkey's residential construction sector.*
Keywords: *recycled plastic bricks, energy efficiency in buildings, thermal performance of masonry, sustainable building materials, affordable housing design.*

Geri Dönüştürülmüş Plastik Tuğlalarin Karşilaştirmali Termal Performansi: Enerji Verimli Konutlar İçin Özellik Temelli Bir Analiz

Özet: *Bu çalışma, Türkiye'de enerji verimli ve çevresel etkisi düşük yapı malzemelerine yönelik artan gereksinime yanıt olarak, yenilikçi geri dönüştürülmüş plastik tuğlaların enerji performansını değerlendirmektedir. Plastik tuğlalar, uluslararası literatürde umut verici ısıl özellikler sergilemiş olsa da, İstanbul'un ılıman ve nemli iklim koşullarına özgü sistematik değerlendirmelerin sınırlı olması ve Türkiye'de yaygın olarak kullanılan geleneksel yığma duvar malzemeleriyle karşılaştırmalı simülasyon çalışmalarının bulunmaması önemli bir araştırma boşluğu oluşturmaktadır. Bu bağlamda çalışmanın amacı, geri dönüştürülmüş plastik tuğlaların kapsamlı bir performans analizini gerçekleştirmek; temel hedefi ise Türkiye'de bina enerji talebini azaltma potansiyeli en yüksek tuğla*

formülasyonlarını belirlemektir. Çalışmada, Türk Devlet Meteoroloji İşleri'nden elde edilen yirmi yıllık meteorolojik veriler kullanılarak DesignBuilder ve EnergyPlus yazılımları aracılığıyla dinamik enerji simülasyonları gerçekleştirilmiştir. İstanbul için daha önce en enerji verimli yapı formu olarak tanımlanan U-şekilli konut tipolojisi modellenmiştir. Literatürden derlenen on yedi geri dönüştürülmüş plastik tuğla türü (B1–B17), ısıl iletkenlik, özgül ısı kapasitesi, yoğunluk, neme dayanım ve yangın dayanımı kriterleri doğrultusunda analiz edilmiş ve Türkiye'de yaygın olarak kullanılan delikli kil tuğlaları ile karşılaştırılmıştır. Elde edilen bulgular, birçok plastik tuğla türünün geleneksel yığma duvar malzemelerine kıyasla belirgin biçimde daha yüksek enerji performansı sunduğunu göstermektedir. Özellikle geri dönüştürülmüş PET ve kumdan üretilen B15 tuğlası, ısıtma yükünde %26,24'lük bir azalma ve soğutma talebinde yalnızca sınırlı bir artış ile toplamda %13,89 oranında en yüksek enerji tasarrufunu sağlamıştır. Bu üstün performans, düşük ısıl iletkenlik, orta düzey yoğunluk ve yüksek özgül ısı kapasitesi arasında kurulan dengeli bileşimden kaynaklanmaktadır. Ayrıca sekiz plastik tuğla türü daha kayda değer verimlilik artışları göstermiş; geri dönüştürülmüş termoplastikler ile uçucu kül ve ocak tozu gibi dengeleyici katkı maddelerinin, ısıl ataletin artırılması ve iç mekân konforunun iyileştirilmesindeki rolünü ortaya koymuştur. Bu çalışmanın temel çıkarımı, plastik kompozit tuğlaların özellikle yalıtım seviyelerinin yetersiz olduğu düşük ve orta gelirli konutlarda işletme enerjisi tüketimini anlamlı ölçüde azaltabileceğidir. Uzun dönemli iklim verileri, malzeme bilimi temelli analizler ve yüksek çözünürlüklü simülasyonların bütüncül biçimde kullanılmasıyla bu çalışma, ılıman iklim koşullarında çevre dostu plastik tuğlaların benimsenmesine yönelik ölçeklenebilir ve kanıta dayalı bir çerçeve sunmaktadır. Elde edilen sonuçlar, Türkiye'nin konut sektöründe enerji kullanımını ve karbon emisyonlarını azaltmayı hedefleyen mimarlar, mühendisler, politika yapıcılar ve konut kurumları için uygulanabilir nitelikte yol gösterici bulgular sağlamaktadır.
Anahtar Kelimeler**:** *geri dönüştürülmüş plastik tuğlalar, binalarda enerji verimliliği, duvar malzemelerinin ısıl performansı, sürdürülebilir yapı malzemeleri, uygun maliyetli konut tasarımı.*

1. INTRODUCTION

Preservation can be defined as safeguarding assets from threats [1]. The energy efficiency of construction materials is essential for minimizing overall energy consumption and the environmental effect of residential structures. In the Turkish residential construction sector, this significance is heightened by other interrelated elements, including the nation's climatic diversity, escalating urbanization, and rising energy demand. Turkey's climate exhibits considerable regional variation, spanning from arid continental zones to humid coastal areas. Istanbul and its district, Esenyurt, are situated in a temperate-humid climate zone, marked by hot, humid summers and mild, rainy winters. This climate unpredictability requires construction materials that can efficiently regulate indoor temperatures by decreasing heat loss in cold conditions and limiting heat gain in warm conditions. Bricks, as a fundamental element of building envelopes, are crucial for thermal control.

Conventional bricks prevalent in Turkey, including the Turkish hollow clay brick and burned clay brick, have elevated thermal conductivity values (surpassing 0.50 W/m·K) and high density, facilitating swift heat movement through construction walls. This leads to heightened heating requirements in winter and cooling needs in summer, resulting in elevated operating energy consumption and related expenses. Considering that residential structures represent a considerable segment of Turkey's construction inventory, enhancing the thermal efficiency of bricks can significantly diminish national energy usage and carbon emissions. Furthermore, energy efficiency in construction materials corresponds with Turkey's overarching energy policy objectives and international obligations for sustainability and climate change mitigation. The energy consumption of the residential sector significantly contributes to Turkey's total energy demand, and improving the thermal characteristics of bricks can diminish dependence on mechanical heating and cooling systems, which are frequently energy-intensive and expensive for low- and middle-income homes. The implementation of energy-efficient bricks not only conserves energy but also enhances occupant comfort by regulating indoor temperatures and minimizing swings. This is especially crucial in areas such as Istanbul, where seasonal temperature fluctuations necessitate materials that offer both insulation and thermal mass. The research underscores the promise of novel materials like recycled plastic bricks, which exhibit enhanced thermal characteristics relative to conventional clay bricks. These materials are noted for their reduced thermal conductivity, moderate density, and elevated specific heat capacity, allowing them to function as efficient thermal buffers that substantially decrease heating loads while ensuring satisfactory cooling performance. This idea enhances energy efficiency and promotes environmental sustainability through the use of repurposed waste materials.

Aside the core concept of energy efficiency, the demand for affordable and sustainable housing has reached unprecedented levels in recent decades, particularly in rapidly urbanizing regions where population growth, migration, and economic pressures converge to exacerbate housing deficits. According to the United Nations, nearly 3 billion people will require access to adequate housing by 2030, underscoring the urgency of adopting innovative construction materials and methods that are both cost-effective and environmentally responsible [2]. Conventional construction practices, which remain heavily dependent on resource-intensive materials such as cement, fired clay bricks, and steel, contribute significantly to global greenhouse gas emissions, accounting for approximately 37% of energy-related carbon dioxide emissions worldwide [3]. The dual challenge of reducing the environmental impact of the building sector while ensuring the affordability of housing necessitates the exploration of alternative building materials that can deliver high energy performance without escalating costs. Among the potential solutions gaining momentum in recent years is the use of recycled plastic bricks. Globally, plastic waste has emerged as one of the most critical environmental challenges of the 21st century, with over 350 million tons produced annually and less than 10% effectively recycled [4]. Integrating recycled plastics into the construction sector not only provides a pathway for reducing environmental pollution but also offers a potential substitute for traditional masonry units in low- and middle-income housing projects. Several studies have highlighted the advantages of plastic-based construction materials, including their lightweight nature, high durability, moisture resistance, and potential for thermal insulation [5]. However, despite growing interest, there remains a significant gap in understanding how variations in thermal and physical properties across different recycled plastic brick designs affect their real-world energy performance in buildings.

Previous research into the thermal behavior of masonry units has demonstrated that properties such as thermal conductivity, density, and specific heat capacity play decisive roles in determining building energy demand [6]. Traditional Turkish hollow clay bricks, widely used in affordable housing across Turkey and similar contexts, offer moderate thermal insulation but are limited by their relatively high thermal conductivity and susceptibility to moisture ingress. In contrast, plastic bricks offer opportunities to customize these thermal parameters through disparities in composition, geometry, and manufacturing processes. Yet, while scattered case studies exist on the performance of individual plastic brick designs in different countries, comparative analyses that systematically evaluate multiple prototypes under consistent climatic conditions remain scarce. Such analyses are vital for identifying which design attributes most strongly influence energy efficiency and for providing a scientific basis for the commercialization of plastic brick technology. To address this gap, this study conducts a comparative evaluation of seventeen bricks which includes 17 recycled plastic brick prototypes documented in the international literature and two widely used brick types in the Turkish construction industry, all of which were subjected to dynamic energy performance simulations using EnergyPlus through DesignBuilder, calibrated with twenty years of climatic data for Istanbul. Istanbul was selected as a representative context due to its dense urban population, diverse socio-economic composition, and significant reliance on mid-rise residential buildings constructed with hollow clay bricks. The study systematically assesses thermal conductivity, density, specific heat capacity, moisture absorption, compressive strength, and fire resistance, correlating these material properties with simulated energy demand. By doing so, it seeks not only to determine which prototypes outperform conventional Turkish hollow bricks but also to explain *why* certain designs excel while others fall short.

The novelty of this research lies in its property-performance linkage, offering a scientific explanation of the mechanisms through which recycled plastic bricks achieve or fail to achieve superior energy efficiency. Whereas much of the existing literature reports performance outcomes without probing the causal factors, this study emphasizes the material and structural determinants of success, thereby providing actionable insights for both academia and industry. Notably, the analysis identifies two brick prototypes that demonstrate markedly better thermal performance, attributable to their optimal balance of low thermal conductivity, moderate density, and effective heat storage capacity. These findings are particularly relevant to policymakers and developers in Turkey and comparable contexts, where housing affordability and energy efficiency are pressing national concerns.

Beyond its technical contributions, the study also aligns with broader global agendas, including the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production). By valorizing plastic waste into high-performing construction materials, the research supports circular economy principles while addressing the twin challenges of waste management and housing affordability. The implications extend to informing material selection criteria for large-scale housing programs, particularly in regions where resource constraints and environmental pressures necessitate innovative yet practical building solutions. In summary, this paper seeks to expand the discourse on sustainable construction by delivering a comprehensive, property-based analysis of recycled plastic bricks in the context of affordable housing. It argues that while not all plastic bricks are inherently superior to conventional masonry, strategic optimization of thermal and physical properties can produce designs that significantly enhance building energy efficiency. In doing so, it establishes a framework for both academic inquiry and practical implementation, bridging the gap between laboratory research and real-world housing policy. Furthermore, showing that energy efficiency in bricks is a vital consideration in the Turkish residential construction sector due to climatic demands, energy policy objectives, economic factors, and occupant comfort. Advancements in brick materials, particularly through the integration of recycled plastics and optimized composites, present promising pathways to enhance building performance, reduce energy consumption, and support sustainable development goals in Turkey. This contextual foundation underscores the significance of the study's focus on evaluating and simulating the energy performance of various brick types under Turkish climatic conditions.

2. LITERATURE REVIEW

2.1 The global housing challenge and sustainable materials

Sustaining a place requires fostering meaningful connections between individuals and their environment [7] therefore, the priorities of majority should be considered for instance the need of a person for affordable options in housing. The global demand for affordable and sustainable housing has intensified over the past two decades, particularly in rapidly urbanizing regions of Asia, Africa, and Latin America. [8] projects that nearly 96,000 new affordable housing units will be needed daily to accommodate urban population growth by 2030. Traditional masonry units such as fired clay bricks and concrete blocks remain the dominant materials due to their availability and established construction practices. However, their production processes are energy-intensive and environmentally damaging. Clay brick manufacturing, for example, contributes significantly to deforestation and air pollution in South Asia, while cement production is estimated to account for nearly 8% of global CO_2 emissions [3]. This environmental burden has prompted the construction industry to explore alternative materials that minimize both embodied energy and operational energy consumption.

The mismanagement of plastic waste presents an urgent environmental challenge, with the [4] reporting that only 9% of the 353 million tons of plastic generated annually is recycled. Researchers have increasingly investigated the incorporation of plastic waste into construction materials as a dual strategy for addressing housing affordability and environmental sustainability. Studies in India [9] and Nigeria [10] highlight the potential of plastic bricks to reduce material costs while offering enhanced durability and water resistance. Similarly, research in Kenya demonstrated that interlocking plastic bricks reduced construction time and costs by eliminating mortar use while providing competitive compressive strength. Latin American initiatives, particularly in Colombia and Mexico, have shown the feasibility of large-scale applications, where modular plastic brick systems were used to construct low-cost housing for vulnerable communities [11]. These findings collectively suggest that recycled plastic bricks can serve as viable alternatives, but performance varies significantly depending on composition and design.

2.2. Thermal performance of masonry units

Thermal performance is a critical determinant of a building material's contribution to energy efficiency. Parameters such as thermal conductivity, density, and specific heat capacity govern heat transfer through the building envelope, directly influencing cooling and heating loads. [12] demonstrated that walls constructed from materials with lower thermal conductivity reduced cooling energy demand in Indian climates by up to 20%. Similar results were reported in Mediterranean regions, where lightweight bricks with optimized density improved thermal comfort and reduced reliance on mechanical cooling. In Turkey, hollow clay bricks remain the conventional choice for affordable housing due to their moderate insulation properties; however, studies confirm their limitations under increasing cooling demands, particularly in urban centers such as Istanbul. These findings highlight the need for masonry units with superior thermal efficiency, especially as climate change intensifies energy consumption for cooling.

Although a growing body of literature documents the use of recycled plastics in construction, comparative studies focusing on their thermal performance remain limited. Several compared plastic-sand composite bricks with concrete blocks, reporting improved thermal insulation but variable compressive strength. In South Africa, [13] found that PET-based bricks offered lower thermal conductivity but required reinforcement to meet structural safety standards. In India, [9] demonstrated that polypropylene bricks reduced wall U-values by 25% compared to traditional clay bricks, significantly lowering cooling loads in hot climates. Conversely, a study in Brazil cautioned that some plastic bricks, when manufactured with high-density polymer mixes, exhibited higher thermal conductivity than conventional materials, leading to less favorable energy outcomes. These contrasting results underscore the importance of analyzing not only performance outcomes but also the material properties that drive them.

Although the use of plastics in construction raises legitimate concerns particularly regarding the emission of harmful gases during high-temperature processing and the historical environmental burden associated with virgin polymer production these impacts are substantially reduced when recycled plastics are used instead of new materials. Recycling diverts waste from landfills and incineration, reduces demand for fossil-based virgin plastics, and enables the creation of durable building components with lower embodied carbon compared to fired-clay masonry. Studies consistently show that recycled plastic composites can achieve strong mechanical and thermal performance while repurposing waste polymers that would otherwise persist in the environment. In Turkey, while there is currently no large-scale producer of recycled-plastic bricks, existing recyclers such as Birlik Geri Dönüşüm supply LDPE, HDPE, and PP feedstock that could support future brick manufacturing, and local initiatives inspired by global models like Precious Plastic demonstrate the feasibility of small-scale community production [14]. Thus, although environmental risks during processing must be acknowledged, the overall life-cycle benefits of reusing waste plastics such as lower emissions, reduced waste, and affordable low-carbon construction provide a compelling justification for continued research and adoption of recycled-plastic bricks.

The reviewed literature establishes that recycled plastic bricks hold significant potential for contributing to affordable, energy-efficient housing worldwide. However, most studies remain fragmented, often limited to single prototypes or regional case-specific trials without comprehensive, cross-comparative analysis. Furthermore, while previous work confirms that material properties strongly influence building energy performance, little effort has been made to systematically test a wide spectrum of plastic brick designs under uniform climatic conditions. To address this gap, the present study evaluates seventeen recycled plastic brick prototypes, each modeled through dynamic energy simulations using EnergyPlus via DesignBuilder under Istanbul's climatic context. This comprehensive approach enables both broad benchmarking and detailed analysis of performance differences. The findings not only identify which prototypes surpass conventional Turkish hollow clay bricks but also provide property-based explanations for why the best-performing bricks achieved superior results. This dual emphasis on breadth and causal analysis distinguishes the study from existing literature and delivers actionable insights for sustainable housing design and policy.

3. METHODS AND MATERIALS

This study employs a comprehensive, multi-step methodology integrating climate data analysis, material property characterization, building typology selection, and advanced energy simulation to evaluate the thermal performance and energy efficiency of various plastic bricks compared to traditional masonry materials in residential construction. The methodology is designed to ensure robust, replicable, and contextually relevant results for the Istanbul region, specifically the Esenyurt district, within the mild-humid climate zone of Turkey.

3.1 Climate data collection and processing

Accurate climatic inputs are critical for realistic building energy simulations. For this purpose, long-term weather data spanning 20 years (2004–2024) were obtained from the Turkish State Meteorological Service (MGM). The dataset includes monthly averages of key climatic parameters such as ambient temperature, relative humidity, solar radiation, wind speed, cloud cover, precipitation, and the frequency of rain and frost days. These parameters were specifically extracted for Istanbul, classified under Climate Zone 2 (Mild-Humid), which is representative of the study area, Esenyurt. The data were formatted and processed to be compatible with the DesignBuilder/EnergyPlus simulation environment, ensuring temporal consistency and eliminating short-term anomalies to reflect typical climatic pressures on residential buildings.

Table 1. Marmara region- Istanbul. Average data over the past 20 years 2004-2024

	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sep.	Oct.	Nov.	Dec.
Avg daily temp(^{0}c)	6.6	6.9	8.9	12.2	17.0	21.8	24.4	24.8	21.4	16.9	12.8	8.7
Humidity (%)	75%	75%	74%	75%	75%	72%	70%	70%	69%	72%	74%	75%
Wind speed(mph)	12.4	12.5	11.5	9.8	9.1	9.3	11.4	12.5	11.5	11.8	11.9	12.4
Sun hours(hrs.)	4.6	5.6	7.4	9.5	11.0	12.2	12.1	11.0	9.2	6.5	5.2	4.6
Cloud cover (%)	51%	52%	48%	44%	33%	17%	4%	6%	19%	38%	48%	54%
Precipitation(mm)	75	73	67	45	34	24	17	13	39	80	73	97
Rain\Frost days	8	8	8	5	5	3	2	2	4	6	7	10

3.2 Building typology and brick selection and modeling

The study focuses on a U-shaped residential building typology, identified through preliminary analyses as the most energy-efficient form for the local climate. This typology was selected due to its favorable passive design characteristics, including natural ventilation facilitation, self-shading, and optimized surface-area-to-volume ratio. The building model represents a 20-floor structure with a total floor area of approximately 940 m², located in the Zafer neighborhood of Esenyurt. (ZAFER Mah. TONGUÇ BABA Cadde, "gate" Kapı No: 69C). Detailed architectural plans, including site and floor layouts, were developed to accurately represent the spatial configuration and envelope characteristics of the U-shaped form as seen below. Figure 1 and figure 2 below show the spatial arrangement of the U-shaped building, figure 2 shows the site plan and building height.

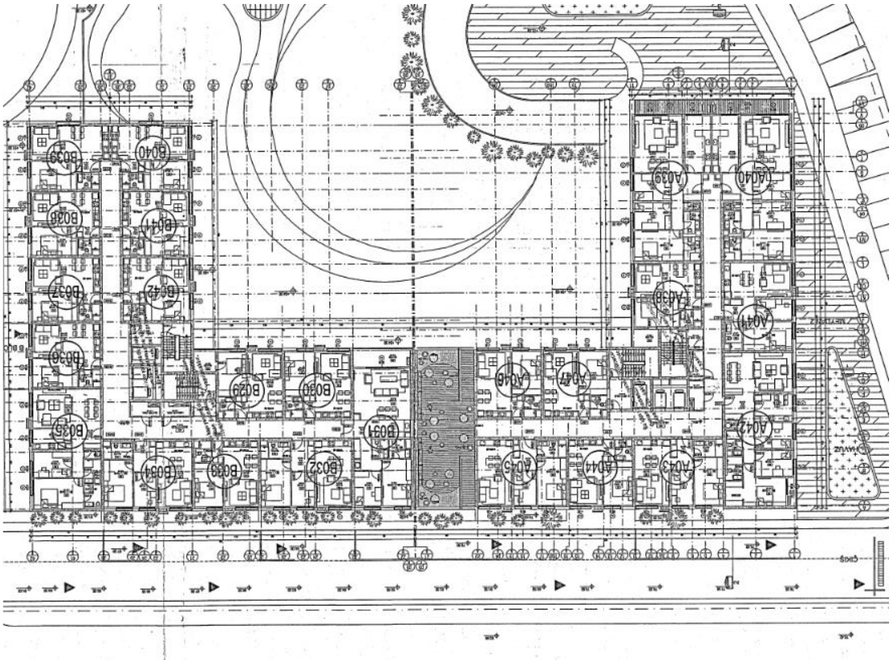

Figure 1. *Floor Plan showing the U-shaped building used to run the simulation*

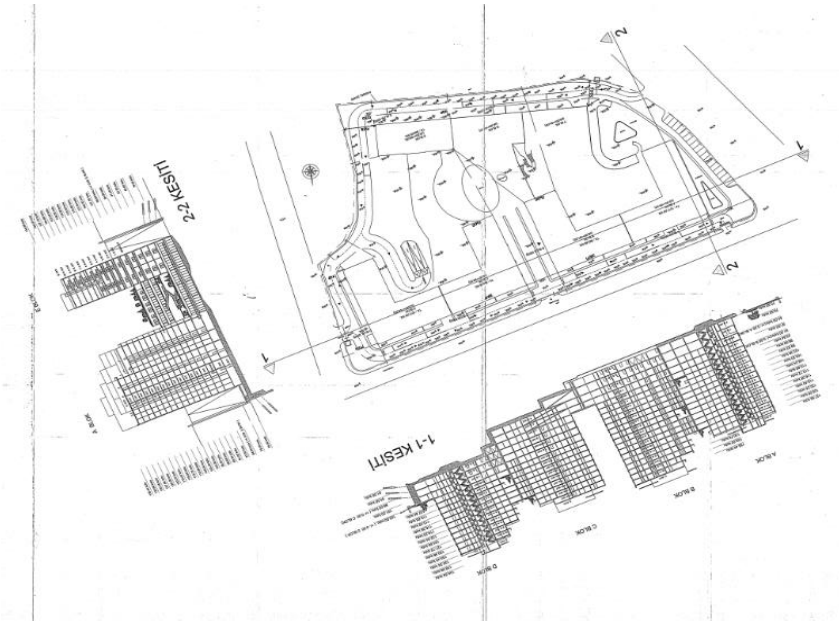

Figure 2. *Site Plan showing the U-shaped building used to run the simulation*

A critical component of the methodology involved the selection and detailed characterization of 17 types of bricks including 15 plastic bricks sourced from peer-reviewed literature. These bricks vary in polymer composition, filler materials, density, thermal conductivity, specific heat capacity, moisture resistance, fire resistance, and compressive strength. The properties of these bricks were compiled into a comprehensive database to facilitate comparative analysis. The Turkish hollow clay brick and traditional burned clay brick were included as baseline benchmarks due to their widespread use in Turkish residential construction. The characterization data were used to parameterize the building envelope materials in the simulation models Some brick pictures are seen below in the picture table for visual understanding of the tested bricks simulated in the study in figure 3 below:

Sample photographs of some of the bricks included in the simulation testing

Brick name: B2 Brick name: B3 Brick name: B5

Figure 3. *brick pictures for visual understanding*

3.3 Energy simulation setup and data analysis and performance metrics

Energy performance simulations were conducted using the DesignBuilder interface coupled with the EnergyPlus simulation engine. The U-shaped building model was constructed within the software, with all physical and operational parameters standardized across simulations to isolate the effect of brick material properties on energy demand. The climatic data for Istanbul were applied uniformly to all models. Each brick type was assigned to the external wall construction layer, with its thermal and physical properties inputted according to the compiled database. The simulations calculated annual heating load, cooling load, and total electrical energy consumption for each material scenario.

Simulation outputs were analyzed to quantify the energy savings or penalties associated with each brick type relative to the burned clay brick benchmark. Key performance indicators included total annual electrical energy consumption (kWh), heating load (kWh), and cooling load (kWh). Differences (Δ) and percentage changes (% Δ) were computed to facilitate direct comparison. The analysis emphasized the balance between heating and cooling demands, considering Istanbul's climate where heating predominates. The thermal behavior of bricks was interpreted in terms of their conductivity, density, and specific heat capacity to explain observed energy performance trends.

While direct experimental validation was beyond the scope of this study, the methodology incorporated peer-reviewed material property data and standardized simulation protocols to ensure reliability. Sensitivity to climatic variability was mitigated by using long-term averaged weather data. The choice of a single, well-documented building typology further controlled for architectural variability. Future work may include empirical validation and exploration of additional building forms and climate zones archived in the dataset.

3.3.1 Steps Undertaken to Achieve the Results

1. Seventeen brick types were selected, including fifteen recycled plastic bricks from peer-reviewed literature and two conventional clay-based bricks (Turkish hollow clay and burned clay) used as benchmarks. Relevant physical and thermal properties were extracted and compiled into a unified material database.

2. A U-shaped residential building model was developed in DesignBuilder, with all geometric, operational, and construction parameters standardized except for the external wall material.

3. Long-term averaged climatic data for Istanbul were applied consistently across all simulations.

4. Each brick type was individually assigned to the external wall layer, with material properties input directly from the compiled database.

5. Energy simulations were conducted using the DesignBuilder–EnergyPlus platform to calculate annual heating load, cooling load, and total electrical energy consumption for each scenario.

6. Simulation outputs were analyzed relative to the burned clay brick benchmark by calculating absolute and percentage differences in energy demand. Performance trends were interpreted based on material thermal properties, with emphasis on heating-dominated conditions in Istanbul.

4. RESULTS

4.1 Material properties analysis

This section of the material properties analysis provides an outlined comparison between various plastic bricks and the Turkish hollow brick, focusing on key physical and thermal properties critical for building energy performance. This comparison is based on data compiled from 17 literature studies and summarized in the Tables 2, 3, and 4 below:

Table 2. Brick Properties

Properties	**Turkish hollow brick**	**B1**	**B2**	**B3**	**B4**	**B5**
Type/Name of Brick	Hollow clay brick	polypropylene (PP) waste fibers, fly ash, cement, and M sand.	as PET, HDPE, PP, sometimes mixed with sand, clay, or brick powder.	Sand-Plastic (SP) bricks	Plastic-bonded sand interlocking blocks	Lego-like bricks
Composition Ratio of Brick	60–70% clay, 10–20% silt, 5–15% sand.	Fly ash 40%, M sand 40%, Cement 10%, PP waste 10%	70% PET +sand, clay, or brick powder	25% plastic, 75% sand	plastic waste binder:25% Sand 75%	40% plastic, 60% sand
Density of Brick	800 kg/m³	1665 kg/m³	1660 kg/m³	1998 kg/m³	1600 kg/m³	1640 kg/m³
Thermal Conductivity of Brick	0.38 W/m·K	0.28 W/m·K	0.15-0.4 W/m·K	0.45-0.52 W/m·K	0.3 to 0.5 W/m·K	0.8 and 1.06 W/(m·K)
Specific Heat Capacity of Brick	840 J/kg·K	902 J/kg·K	1200 - 1350 J/kg·K	1900 J/kg·K	1200 J/kg·K	830 to 1720 J/m³K
Thickness/Size/Dimensions of Brick (L.W.H)	13.5x19x29 cm and 19x19x39	230 mm × 110 mm × 90 mm	3D modeling 230 mm × 110 mm × 90 mm	230 mm × 115 mm × 75 mm	356 mm × 152 mm × 127 mm	20 mm (steel mold)
Solar Absorptance of Brick	0.8	Not specified	Not specified	Not specified	0.5 to 0.7	Not specified
Thermal Absorptance of Brick	0.8	Not specified	Not specified	Not specified	0.5 to 0.7	Not specified
Color of Brick	Redish brown	Dark brownish grey	brownish grey	Grey	brownish grey	Grey
Moisture Resistance of Brick	15–20% by weight	7.89%	Very High	High	Very high	Water absorption between 0% and 0.35%
Thermal Diffusivity (α) of Brick	~5.65×10^{-7} m²/s	Not specified	Not specified	Not specified	Not specified	Between 0.56 and 1.06 mm²/s
Fire Resistance of Brick	2–4 hours (A1 fire class, non-combustible)	Polypropylene melting point: 160 °C- Ignition point: 590 °C-	Not specified	700 °C, held for 15 minutes	250–300 °C	Operating temp. during production: 200 ± 20 °C
Compressive strength (N/mm²)	3.5N/mm2	16.85	>11.9	133mpa	14.8	38.65 MPa

Source or paper	Site visit	[15]	[16]	[17]	[18]	[19]
Journal	------	Discover Civil Engineering (2024), Volume 1, Article 43	Vojnotehnički Glasnik / Military Technical Courier, 2024, Vol. 72, Issue 3	Journal of Engineering Science and Technology Review, Vol. 13 (2)	Sustainability (2023), Volume 15, Article 16602	Sustainability, 2024, Volume 16, Article 8567
location	Turkey	India	Algeria	India	Ghana	Egypt

Table 3. Brick Properties

Properties	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**
Type/Name of Brick	High-Density Polyethylene (HDPE), quartz sand, and bitumen	Eco-friendly bricks polypropylene (PP) bumper waste mixed with sand and bitumen	Recycled plastic bricks produced from Scrap Plastic Waste (SPW) and Foundry Sand.	Plastic-sand bricks	Eco-friendly plastic sand bricks	Compressed Earth Bricks (CEB)
Composition Ratio of Brick	plastic-to-sand ratio of 3:2 + 2% bitumen	50% PP, 50% sand, 5% bitumen	70% Foundry Sand (FS) and 30% Scrap Plastic Waste (SPW)	60% plastic waste and 2% bitumen+ sand+ fly ash	75% sand:25% plastic with 5% Kaolin	1% shredded waste plastic + soil
Density of Brick	941–967 kg/m³	1200 to 1600 kg/m³	2200 to 2400 kg/m³	1105 kg/m³	1700 kg/m³	1710 kg/m³
Thermal Conductivity of Brick	0.4 to 1.0 W/m·K	0.2 to 0.6 W/m·K	0.15-0.4 W/m·K	0.1-0.22 W/m·K	0.45-0.52 W/m·K	0.15-0.4 W/m·K
Specific Heat Capacity of Brick	1500 J/kg·K	1300 to 1500 J/kg·K	1200 - 1350 J/kg·K	1700-1900 J/kg·K	1900 J/kg·K	1200 - 1350 J/kg·K
Thickness/Size/Dimensions of Brick (L.W.H)	230 mm × 120 mm × 150 mm	210 mm × 100 mm × 75 mm	222 mm length x 106 mm depth x 73 mm	23 cm × 10 cm × 8 cm	190 mm × 90 mm × 50 mm	230 mm × 110 mm × 90 mm
Solar Absorptance of Brick	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Thermal Absorptance of Brick	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Color of Brick	Not specified	Not specified	Not specified	Brownish Grey	Grey	Brown
Moisture Resistance of Brick	<1% water absorption for all bricks	Water absorption 0.04%	Very High	Water absorption: ranges from 9.1% to 10.7%	High	Moderate
Thermal Diffusivity (α) of Brick	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified

Fire Resistance of Brick	Polypropylene melting point: 130–133°C	melting point of PP 195°C	melting point of PP 220°C	melting point of PP 110°C	Processing temp. of 250°C	Processing temp. of 125°C
Compressive strength (N/mm²)	37.5 MPa	8.532 MPa	38.14 MPa	11.01 N/mm²	52.76 MPa	1.54 Mpa
Source or paper	[20]	[21]	[10]	[22]	[13]	[23]
Journal	Journal of Composite Science (J. Compos. Sci.), 2023, Volume 7, Article 111	Chemical Engineering Transactions, Vol. 106, 2023	Case Studies in Construction Materials	IOP Conference Series: Earth and Environmental Science	SPE Polymers, Wiley Periodicals LLC on behalf of Society of Plastics Engineers	Case Studies in Construction Materials
Location	Germany	Malaysia	South Africa	China	South Africa	Nigeria

Table 4. Brick Properties

Properties	**B12**	**B13**	**B14**	**B15**	**B16**	**B17**
Type/Name of Brick	Plastic Fly Ash Brick, Plastic Sand Brick	Alkali-activated mill residue bricks	Eco-brick	Composite brick made from fly ash, recycled plastic resin	Plastic bricks (PBs)	Waste plastic brick
Composition Ratio of Brick	1:5 ratio of plastic to fly ash or sand	Plastic waste 2 wt.% + glass waste 55 wt.%	33.3% PET and 66.6% M-sand	HDPE: 20% PP: 20% Fly ash: 38% Glass powder: 20% Gypsum: 2%	35% plastic waste content mixed with Portland Cement	Waste plastic 50:50 waste foundry sand (WFS)) with plastic blend PET: HDPE: LDPE = 50:25:25
Density of Brick	1990 kg/m³	1200 to 1600 kg/m³	1380 kg/m³	1800 to 2000 kg/m³	2010 to 3010 kg/cm³	1600 kg/m³
Thermal Conductivity of Brick	0.33 W/m·K	0.15-0.4 W/m·K	0.21 W/m·K	0.15 W/m-K	0.45-0.52 W/m·K	0.66 to 0.69 W/m-K
Specific Heat Capacity of Brick	2300 J/kg·K	1200 - 1350 J/kg·K	1000 to 1200 J/kg·K.	1900 J/kg·K	1900 J/kg·K	1100-1200 J/kg·K
Thickness/Size/Dimensions of Brick (L.W.H)	150 mm × 150 mm × 150 mm	115 mm × 110 mm × 76 mm	145 mm × 85 mm × 30 mm	190 mm × 90 mm × 90 mm	241.3 mm × 114.3 mm × 50.8 mm	228 mm x 114 mm x 76 mm
Solar Absorptance of Brick	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Thermal Absorptance of Brick	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Color of Brick	Grey	Grey	Grey	Dark brownish-black	Grey	Brownish grey
Moisture Resistance of Brick	Water absorption: ranges from 0.727% to 1.033%	Plastic waste increased water absorption ratio due to microstructure degradation	Eco-bricks reported to have low water absorption than PET.	Low porosity of 0.171% = low water absorption	Water Absorption ranged 0.11% to 0.52%, very low	Water Absorption is ten times less than conventional clay fired bricks

Thermal Diffusivity (α) of Brick	Between 0.11 mm²/s - 0.13 mm²/s	Not specified	Not specified	Not specified	Not specified	Not specified
Fire Resistance of Brick	Melting temp at 500°C to 700°C	plastic waste addition increases porosity rather than fire resistance	melting point: 260 °C	Degradation temp. at 127.50 °C to 153.07 °C	High	Melting point 121.3°C
Compressive strength (N/mm²)	5.56 N/mm²	(≥20.7 MPa	14.72 MPa	low porosity, strong bonding = improved strength.	Compressive strength ranges: 4107 to 5167 psi for HDPE bricks.	8.23 MPa
Source or paper	[24]	[25]	[26]	[9]	[27]	[28]
Journal	Revista Matéria, Volume 29, Number 4, 2024	Sustainability	Journal of Building Pathology and Rehabilitation	International Journal on Interactive Design and Manufacturing	Physics and Chemistry of the Earth	Construction and Building Materials, Volume 416, 2024
Location	India	Australia	India	India	Bangladesh, Saudi Arabia	Pakistan

4.1.1 Density

The Turkish hollow brick is characterized by a relatively low density of 800 kg/m³, which contrasts notably with the broader range of densities observed in plastic bricks. [29]. These plastic bricks generally exhibit higher densities, spanning from approximately 941 kg/m³, as seen in Brick 6, to as high as 3010 kg/m³ in B16. The majority of plastic bricks fall within a density range of 1200 to 2000 kg/m³, suggesting that these materials are denser and potentially possess greater thermal mass compared to the Turkish hollow brick. This increased density in plastic bricks can contribute to enhanced thermal inertia, which is beneficial for moderating indoor temperature fluctuations and improving overall energy performance in building envelopes.

4.1.2 Thermal conductivity

The Turkish hollow brick, a commonly used masonry material in Turkey, exhibits a thermal conductivity of 0.38 W/m·K [30]. This value indicates a moderate capacity for heat transfer, which means that while it provides some insulation, it allows a relatively higher rate of heat flow through the building envelope compared to more advanced materials. In contrast, plastic bricks generally demonstrate significantly lower thermal conductivity values, predominantly ranging between 0.15 and 0.52 W/m·K. This range includes some highly efficient examples such as B8, which has an exceptionally low thermal conductivity of around 0.1 W/m·K. Such low thermal conductivity values in plastic bricks are indicative of superior insulation properties, as they effectively reduce the rate of heat transfer through walls, thereby enhancing the building's thermal resistance. Among these, B15 stands out as the most thermally efficient, with a notably low thermal conductivity of 0.165 W/m·K. This low conductivity, combined with its moderate density and high specific heat capacity, enables B15 to act as an excellent thermal buffer, minimizing heat loss during colder months and delaying heat penetration in warmer periods. Overall, the lower thermal conductivity observed in plastic bricks compared to traditional Turkish hollow bricks suggests that these innovative materials can significantly improve insulation performance, contributing to reduced energy consumption for heating and cooling in residential buildings.

4.1.3 Specific heat capacity

The Turkish hollow brick exhibits a specific heat capacity of 840 J/kg·K, [30], which reflects its moderate ability to store thermal energy. This capacity influences how the brick responds to temperature changes, affecting the indoor thermal environment by absorbing and releasing heat at a certain rate. In contrast, plastic bricks generally demonstrate significantly higher specific heat capacities, with values ranging from approximately 900 J/kg·K to as high as 2300 J/kg·K, as exemplified by Brick 12. This elevated specific heat capacity in plastic bricks indicates a superior capability to store thermal energy, enabling these materials to absorb more heat during warmer periods and release it slowly when temperatures drop. Such thermal storage capacity is crucial for moderating indoor temperature fluctuations, as it helps maintain a more stable and comfortable indoor climate by reducing rapid temperature swings. Consequently, buildings constructed with plastic bricks benefit from enhanced thermal inertia, which can lead to reduced reliance on mechanical heating and cooling systems, improving overall energy efficiency and occupant comfort. This distinction in specific heat capacity between traditional Turkish hollow bricks and innovative plastic bricks underscores the potential of plastic composites to deliver improved thermal performance in residential construction.

4.1.4 Moisture resistance

The Turkish hollow brick demonstrates a relatively high moisture absorption rate of 15–20% by weight, which indicates a moderate susceptibility to moisture infiltration [30]. This level of water uptake can lead to potential issues such as material degradation, reduced durability, and compromised thermal performance over time, especially in environments with significant humidity. In contrast, plastic bricks generally exhibit substantially lower water absorption rates, often falling below 1%. For instance, B7 reports an exceptionally low water absorption value of just 0.04%, and some plastic bricks even approach near-zero moisture uptake. This pronounced moisture resistance inherent in plastic bricks is particularly beneficial in humid climates like Istanbul’s, where elevated ambient moisture levels can otherwise accelerate deterioration in conventional masonry materials. By minimizing moisture ingress, plastic bricks help maintain their structural integrity and thermal insulation properties, thereby ensuring more consistent and reliable energy performance in residential buildings subjected to such climatic conditions. This advantage underscores the suitability of plastic bricks as a durable and energy-efficient alternative to traditional clay bricks in regions characterized by mild-humid weather patterns.

4.1.5 Fire resistance

The Turkish hollow brick is recognized for its robust fire resistance, being classified as non-combustible under the A1 fire class, with an ability to withstand fire exposure for a duration ranging between 2 to 4 hours [31]. This high level of fire resistance is a significant safety feature, making it a reliable choice in construction where fire safety standards are stringent. In contrast, plastic bricks exhibit a wide range of fire resistance characteristics that are largely dependent on the type of polymer used and the specific composition of the brick. For instance, bricks incorporating polypropylene (PP) demonstrate melting points in the range of approximately 130°C to 220°C. Despite this relatively low melting temperature, some PP-based plastic bricks have ignition points that are considerably higher, with documented values reaching up to 590°C, indicating a capacity to endure elevated temperatures before combustion initiates. Additionally, certain plastic bricks have been tested to withstand temperatures as high as 700°C for short periods, showcasing some resilience under extreme thermal conditions. Nevertheless, it is important to note that, overall, plastic bricks tend to have lower fire resistance compared to traditional clay bricks. This disparity in fire performance is a critical factor to consider in terms of safety and compliance with building codes, as the reduced fire resistance of plastic bricks may limit their applicability in scenarios where stringent fire safety regulations are enforced. These considerations underscore the need for careful evaluation of material properties in the selection of masonry units for construction projects, balancing thermal performance benefits with essential fire safety requirements.

Overall, this comprehensive comparison underscores the potential of plastic bricks to outperform traditional hollow clay bricks in key thermal and moisture-related properties. These improvements are especially relevant for energy-efficient building envelopes in Istanbul's mild-humid climate, where balancing insulation, thermal mass, and moisture control is essential for reducing operational energy consumption and enhancing occupant comfort. The findings suggest that with appropriate formulation and integration, plastic bricks can serve as a viable, sustainable alternative to conventional masonry materials in residential construction. Table 5 below states in detail the energy simulation results for all bricks tested, the table shows in detail the annual energy consumption of all the plastic bricks in relation to the regular how clay brick and a regular burnt clay brick.

Table 5. Energy simulation results by brick type

Material	**Total Elec (kWh)**	**Δ vs BB (kWh)**	**% Δ Elec**	**Heating Load (kWh)**	**Δ Heating vs BB**	**% Δ Elec**	**Cooling Load (kWh)**	**Δ Cooling vs BB**	**% Δ Elec**	**Total % Δ Elec**
Burned brick (BB)	956062.69	0.00	0.00%	549107.62	0.00	0.00%	131495.52	0.00	0.00%	
Turkish Hollow brick	897573.44	-58489.25	-6.12%	485957.49	-63150.13	-11.50%	134695.45	3199.93	2.43%	-15.18%
Brick 1	856649.14	-99413.55	-10.40%	441903.77	-107203.84	-19.52%	136765.26	5269.74	4.01%	-25.91%
Brick 2	861322.90	-94739.79	-9.91%	447980.93	-101126.69	-18.42%	135361.84	3866.31	2.94%	-25.39%
Brick 3	902169.12	-53893.57	-5.64%	494307.38	-54800.24	-9.98%	130333.74	-1161.79	-0.88%	-16.50%
Brick 4	888100.26	-67962.43	-7.11%	476712.32	-72395.30	-13.18%	133859.89	2364.37	1.80%	-18.49%
Brick 5	979975.56	23912.87	2.50%	585106.53	35998.91	6.56%	124378.22	-7117.30	-5.41%	3.64%
Brick 6	921454.76	-34607.93	-3.62%	516537.39	-32570.23	-5.93%	130548.92	-946.60	-0.72%	-10.27%
Brick 7	885173.21	-70889.48	-7.41%	479994.84	-69112.78	-12.59%	130475.26	-1020.27	-0.78%	-20.78%
Brick 8	847622.81	-108439.88	-11.34%	433599.25	-115508.36	-21.04%	135352.02	3856.50	2.93%	-29.45%
Brick 9	889830.66	-66232.03	-6.93%	472984.17	-76123.44	-13.86%	132910.38	1414.86	1.08%	-19.71%
Brick 10	937700.71	-18361.98	-1.92%	525228.39	-23879.23	-4.35%	131361.26	-134.26	-0.10%	-6.37%
Brick 11	844709.09	-111353.60	-11.65%	430659.40	-118448.22	-21.57%	136069.61	4574.09	3.48%	-29.74%
Brick 12	900371.95	-55690.74	-5.83%	491933.67	-57173.95	-10.41%	131259.94	-235.58	-0.18%	-16.42%
Brick 13	921151.02	-34911.67	-3.65%	507075.51	-42032.11	-7.65%	131705.06	209.54	0.16%	-11.15%
Brick 14	880014.14	-76048.55	-7.95%	459388.92	-89718.69	-16.34%	137164.28	5668.76	4.31%	-19.98%

Brick 15	823261.34	-132801.35	-13.89%	405024.19	-144083.43	-26.24%	137126.15	5630.63	4.28%	-35.85%
Brick 16	894959.56	-61103.13	-6.39%	487905.10	-61202.52	-11.15%	129927.86	-1567.66	-1.19%	-18.73%
Brick 17	944586.67	-11476.02	-1.20%	535512.96	-13594.65	-2.48%	131373.17	-122.35	-0.09%	-3.77%

5. DISCUSSION

5.1 Energy performance by brick material

The energy simulation results presented in the table provide a comprehensive comparison of the annual energy performance of 17 plastic brick types against the traditional Turkish hollow clay brick and burned clay brick benchmarks. The analysis reveals significant variations in total electricity consumption, heating load, and cooling load across the different materials, underscoring the potential of plastic bricks as superior alternatives for energy-efficient residential construction in Istanbul's mild-humid climate. The discussion below is organized into thematic sections to elucidate the performance trends and highlight the best-performing plastic bricks [32].

The burned clay brick (BB) serves as the baseline with total electricity consumption of 956,062.69 kWh annually. The Turkish hollow brick, widely used in Turkey, shows a 15.18% reduction in total energy use compared to BB, primarily driven by an 11.50% decrease in heating load, though with a slight 2.43% increase in cooling demand. This confirms the moderate improvement offered by traditional hollow bricks but also highlights their limitations in thermal insulation and energy savings. In contrast, several plastic bricks demonstrate markedly better performance, with total energy savings ranging from modest to substantial. Notably, nine plastic bricks outperform both Turkish hollow and burned bricks, indicating the promising potential of engineered plastic composites in reducing operational energy consumption in residential buildings.

5.2. Identification of the best-performing plastic brick: b15

B15 emerges as the most energy-efficient material, achieving a 13.89% reduction in total electricity consumption relative to the burned brick benchmark. This is the largest energy saving among all tested bricks. The heating load reduction is particularly impressive at 26.24%, which significantly outweighs the modest 4.28% increase in cooling load. This trade-off is favorable in Istanbul's climate, where heating demand dominates annually. The superior performance of B15 is attributed to its exceptionally low thermal conductivity (0.165 W/m·K), moderate density (1420 kg/m^3), and high specific heat capacity (1900 J/kg·K). These properties enable it to act as an effective thermal buffer, minimizing heat loss in winter and delaying heat gain in summer, thus stabilizing indoor temperatures and reducing reliance on mechanical heating systems [33].

Table 6 below is a comparison between high-performing plastic bricks with significant energy savings and low performance bricks; this comparison is derived from careful observation and comparison of simulation results of all the bricks performance.

Table 6. Comparison of High-Performing (Group 1) and Moderate/Low-Performing (Group 2) Plastic Bricks

Criteria	**Group 1: High-Performing Plastic Bricks**	**Group 2: Moderate–Low-Performing Plastic Bricks**
Included Bricks	B1, B2, B4, B7, B8, B9, B11, B14, B15	All remaining bricks not included in Group 1
Total Energy Savings	6%–12%, with B15 reaching 13.89%	Marginal savings or no improvement; some underperform vs. Turkish clay brick
Heating Load Reduction	Often >20%, especially B8 and B11	Typically low; sometimes minimal or inconsistent
Cooling Demand Behavior	Slight increase or stable cooling loads	Frequently higher cooling demand, indicating poor insulation
Thermal Conductivity	Low: 0.20-0.28 W/m·K	High: >0.30 W/m·K
Specific Heat Capacity	Moderate-High: 1500–2100 J/kg·K	Lower or unstable, depending on porosity/mixing
Density / Mass	Moderate–high → strong thermal inertia	Low–moderate → weak thermal inertia
Material Composition	Recycled HDPE, LDPE, PET, PP + sand/fly ash/quarry dust	Poorer polymer mixing; higher porosity; less optimized fillers
Thermal Behavior	Absorbs & releases heat slowly → stable indoor temperatures	Fast heat transfer → greater temperature swings
Overall Performance Level	Consistently high; strong candidate materials	Moderate to weak; require formulation improvement

The comparison in Table 6 demonstrates a clear distinction between the two performance groups. Group 1 plastic bricks exhibit substantially higher energy efficiency due to their low thermal conductivity, moderate-to-high specific heat capacity, and optimized composite formulations involving recycled thermoplastics and stabilizing fillers. These properties enhance thermal inertia, enabling buildings to maintain more stable indoor temperatures and significantly reduce heating loads often by more than 20%. In contrast, Group 2 bricks deliver only marginal or inconsistent improvements, primarily due to higher thermal conductivity, lower density, and suboptimal polymer mixing, which collectively weaken insulation performance and sometimes increase cooling demand. Overall, the table highlights that only well-engineered plastic composites achieve meaningful energy savings, underscoring the importance of material optimization in the development of alternative masonry units.

5.3 Performance of traditional Turkish bricks

The Turkish hollow clay brick and burned clay brick performed weaker than most plastic bricks in terms of energy efficiency. Their relatively high thermal conductivity (exceeding 0.50 W/m·K) [30] leads to rapid heat loss in winter and heat gain in summer. Additionally, their high density combined with low specific heat capacity limits their ability to buffer indoor temperature fluctuations. Consequently, these traditional bricks result in higher operational energy consumption, with total energy demands nearly 14% greater than the best-performing plastic brick (Brick 15). This performance gap underscores the urgent need for material innovation in Turkish residential construction to meet modern energy efficiency standards.

6. CONCLUSION

This study has rigorously investigated the thermal performance and energy efficiency implications of various plastic brick materials in the context of residential building construction in Istanbul's mild-humid climate. By integrating long-term climatic data sourced from the Turkish State Meteorological Service with advanced energy simulation tools (DesignBuilder/Energy Plus), the research has provided a comprehensive comparative analysis of seventeen plastic brick formulations against traditional Turkish hollow clay bricks and burned clay bricks. The U-shaped building typology, identified as the most energy-efficient form due to its favorable passive design characteristics, served as a consistent architectural model to isolate and evaluate the influence of walling materials on annual heating, cooling, and total energy demands.

The findings demonstrate that several plastic bricks, particularly those incorporating recycled thermoplastics such as PET, HDPE, and PP combined with stabilizing fillers like sand, fly ash, and quarry dust, significantly outperform conventional masonry materials in reducing operational energy consumption. B15 emerged as the most thermally efficient material, achieving a remarkable 13.89% reduction in total energy use relative to the burned brick benchmark, primarily through a 26.24% decrease in heating load. This superior performance is attributed to its optimal balance of low thermal conductivity, moderate density, and high specific heat capacity, which collectively enhance thermal buffering and indoor temperature stability. Other high-performing bricks shared similar material traits, underscoring the critical role of polymer type, composite ratios, and thermal inertia in driving energy savings. Conversely, bricks with higher thermal conductivity, lower density, or incomplete polymer integration exhibited limited or marginal energy benefits, highlighting the importance of precise material engineering to optimize thermal performance. Traditional clay bricks, despite their widespread use, were shown to be the least energy-efficient, reinforcing the urgent need for innovation in building materials to meet contemporary energy and environmental standards.

The implications of this study extend beyond material science into the domains of architectural design, construction practice, and policy formulation. The demonstrated energy savings achievable through the adoption of thermally optimized plastic bricks suggest a paradigm shift in residential building envelope design, particularly in climates with significant heating demands like Istanbul. Architects and engineers should prioritize materials with low thermal conductivity and high heat capacity to enhance passive thermal regulation, reduce reliance on mechanical heating systems, and improve occupant comfort. The U-shaped building form, validated here as an energy-efficient typology, further complements material innovations by facilitating natural ventilation and solar control.

From a policy perspective, these results advocate for the integration of recycled plastic bricks into national building codes and energy efficiency standards. Incentivizing the use of such sustainable materials can reduce the environmental footprint of the construction sector, lower household energy costs, and contribute to circular economy goals by valorizing plastic waste streams. Moreover, targeted subsidies, research funding, and public awareness campaigns could accelerate market adoption and stimulate local manufacturing capabilities, fostering economic and environmental resilience. In conclusion, this research substantiates that intelligently engineered recycled plastic bricks represent a viable and superior alternative to traditional masonry materials in residential construction. Their adoption promises substantial energy savings, enhanced thermal comfort, and alignment with sustainable development objectives. Future work should explore lifecycle assessments, long-term durability, and scalability to fully realize the transformative potential of these innovative building materials in Turkey and comparable climatic regions.

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Modupe ODEMAKIN

Modupe Odemkain is a PhD student at Istanbul Okan University, she completed her B.Arch. and M. Arch at Eastern Mediterranean University, North Cyprus. Her PhD research focusses on housing affordability via energy efficiency.

Seyhan YARDIMLI, Assoc. Prof. Dr.

Dr. Seyhan YARDIMLI is a faculty member in the Department of Architecture at Istanbul Okan University at the position of Assoc. Prof. Dr. After completing her undergraduate education at Mimar Sinan University, she completed her Master's and Doctoral programs at Trakya University. Her field of study is building structure, materials, and sustainability. She has patents, articles, presentations, and various field studies in these areas. She is married and has one child.

Melody Safarkhani, Asst. Prof. Dr.

Dr. Melody Safarkhani is a faculty member in the Department of Architecture at Istanbul Okan University at the position of Asst. Prof. Dr. She holds a Ph.D. in Landscape Architecture from ITU, an M.Sc. in Architecture from METU, and a B.Sc. from PNU. She serves as Deputy Head of Department and Erasmus Coordinator and teaches at both undergraduate and graduate levels, with additional teaching experience at Özyeğin and Yeditepe Universities. Her research focuses on sustainability, environmental performance, and human comfort, with particular emphasis on the relationship between spatial qualities, sensory perception, and human experience and behavior.

Research Article

Evaluation Of Healthy Buildings And Well Building Standards Within The Architectural Framework

Pelin KARAÇAR
Istanbul, Türkiye
İstanbul Medipol University, Faculty of Fine Arts, Design and Architecture*, Istanbul, Türkiye*
Department of Architecture
pkaracar@medipol.edu.tr
https://orcid.org/0000-0002-9469-3711
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Abstract: *Globally, with the rapid changes occurring in daily lifestyles, the built environment has become a significant factor for human health and well-being. Although physiological and psychological functions have been dependent on nature throughout evolution, approximately 90% of human life is spent indoors. Today, largely due to urbanization, people have become disconnected from nature. As this disconnection from nature has become more pronounced, architecture has gained significant importance in recent years in creating healing environments that support human health and well-being by aiming to establish a relationship between nature and humans. In architecture, biomimicry and biophilic design are approaches that aim to improve health and well-being by protecting human health and offering healthy design solutions. Healthy buildings are part of the green building concept. A healthy building is also created with sustainable design features. In this context, sustainable buildings are a holistic approach that encompasses the concepts of biophilic design, green buildings, and healthy buildings. Healthy building practices are regulated by various more targeted certification programs that provide specific, science-based standards to guide implementation. The WELL Building Standard, approved by the Green Building Certification Institute, is one such program. The WELL building standard is a new and unique performance-based rating system focused on the health and well-being of building occupants. The WELL Building Standard (WELL) is a set of standards developed for the well-being of all building types in terms of sustainability. This standard is a performance-based system that certifies features affecting human health through seven key areas: air, water, nutrition, light, fitness, comfort, and mind. It is based on medical research that examines the built environment where people live and work and its impact on the health or well-being of the users of these environments. The study uses a descriptive and conceptual synthesis model for qualitative literature review. This study was selected to reveal the evolution, definitions, and interconnections of fundamental concepts such as "healthy building" and "WELL Building Standard" and to synthesize information from various disciplines within a consistent framework. Healthy building design concepts were examined using the comprehensive framework of the WELL Building Standard, which brings together evidence from the disciplines of architecture, public health, and environmental psychology. The aim of the study is to evaluate the feasibility of using health-focused criteria within an architectural framework by presenting and evaluating comparative analyses of health and well-being-focused building design standards, healthy building standards, and the design criteria in the WELL Building Standard.*
Keywords: *Health, WELL Building standard, Well-being, Biophilic Design, Sustainable Building, Green Building, Healthy Building.*

Mimari Çerçevede Sağlıklı Binaların ve WELL Bina Standartlarının Değerlendirilmesi

Özet: *Dünya genelinde, günlük yaşam tarzlarında meydana gelen hızlı değişimlerle birlikte, inşa edilmiş çevre insan sağlığı ve refahı için önemli bir faktör haline gelmiştir. Fizyolojik ve psikolojik işlevler evrim boyunca doğaya bağımlı olsa da insan yaşamının yaklaşık %90'ı iç mekanlarda geçmektedir. Günümüzde, büyük ölçüde kentleşme nedeniyle insanlar doğadan kopmuştur. Doğadan kopukluk daha da belirginleştikçe, Mimarlıkta, doğa ve insan arasında ilişki kurmayı amaçlayan insan sağlığını ve refahını destekleyen iyileştirici ortamlar yaratmada mimarlığın rolü son yıllarda büyük önem kazanmıştır. Mimarlıkta, biyomimikri ve biyofilik tasarım, sağlık ve refahı iyileştirmeyi amaçlayan insan sağlığını koruyan ve tasarımda sağlıklı tasarım çözümleri sunan yaklaşımlardır. Sağlıklı binalar yeşil bina anlayışının bir parçasıdır. Sağlıklı bir bina aynı zamanda sürdürülebilir tasarım özellikleriyle oluşturulmaktadır. Sürdürülebilir binalar bu bağlamda, biyofilik tasarım, yeşil binalar ve sağlıklı binalar kavramlarını kapsayan bütüncül bir yaklaşımdır. Sağlıklı bina uygulamaları, uygulamaya rehberlik edecek spesifik,*

bilimsel temelli standartlar sunan çeşitli daha hedefli sertifikasyon programları tarafından düzenlenmektedir. Yeşil İşletme Sertifikasyon Enstitüsü tarafından onaylanan WELL Bina Standardı da bunlardan biridir. WELL bina standardı bina sakinlerinin sağlığı ve refahına odaklanan yeni ve benzersiz bir performans tabanlı derecelendirme sistemidir. Sağlıklı binaların sürdürülebilirlik açısından WELL Bina Standardı (WELL), tüm bina türlerinin refahı için oluşturulmuş standartlardır. Bu standart, hava, su, beslenme, ışık, zindelik, konfor ve zihin olmak üzere yedi temel alan aracılığıyla insan sağlığını etkileyen özellikleri onaylayan performansa dayalı bir sistemdir. İnsanların yaşadığı ve çalıştığı inşa edilmiş çevre ile bu çevrelerin kullanıcılarının sağlığı veya refahı üzerindeki etkisini inceleyen tıbbi araştırmalara dayanmaktadır. Çalışma, niteliksel literatür incelemesi için tanımlayıcı ve kavramsal bir sentez modeli kullanmaktadır. Bu çalışma, "sağlıklı bina" ve "WELL Bina Standardı" gibi temel kavramların evrimini, tanımlarını ve birbirleriyle olan bağlantılarını ortaya koymak ve çeşitli disiplinlerden elde edilen bilgileri tutarlı bir çerçeve içinde sentezlemek amacıyla seçilmiştir. Mimarlık disiplini ile, halk sağlığı ve çevre psikolojisinden elde edilen kanıtları bir araya getiren WELL Bina Standardı'nın kapsamlı çerçevesini kullanarak sağlıklı bina tasarımı kavramları incelenmiştir. Çalışmanın amacı, sağlık odaklı kriterlerin mimari çerçevede kullanılabileceğine dair, sağlıklı ve refah odaklı bina tasarım standartları ile sağlıklı bina standartları ve WELL Bina Standardı'ndaki tasarım ölçütlerinin karşılaştırmalı analizlerinin ile ortaya konularak değerlendirilmesidir.
Anahtar kelimeler: *Mimarlık, WELL Bina standardı, Refah, Biyofilik tasarım, Sürdürülebilir Bina, Yeşil Bina, Sağlıklı Bina.*

1.INTRODUCTION

Recent research indicates that most of society's life is spent indoors, averaging 16 hours per day on weekdays and 17 hours per day on weekends. It has been found that the time spent at home by young and elderly individuals has increased significantly. For children and the elderly, the time spent indoors is even higher, ranging from 19 to 20 hours per day [1].

Buildings play a vital role in human health due to their energy systems and changing climate conditions. This leads us to question how different architectural designs for buildings psychologically impact their occupants. In the 1990s, it was estimated that people in more than forty percent of indoor spaces suffered from health, comfort, and safety-related complaints and illnesses [2]. Fisk [3] identified only twenty percent of existing buildings as healthy.

Research has demonstrated that light exerts a significant influence on various physiological systems, impacting not only physical but also psychological and physiological functions. Insufficient lighting has been shown to disrupt sleep patterns, alter daily hormonal secretion, and affect body temperature, among other effects [4]. The general consensus is that well-being (also written as prosperity or well-being) is simply synonymous with health, happiness, and quality of life, and is also associated with comfort and health [5].

The terms biomimicry and biophilic design are approaches often used in regenerative architectural design aimed at improving health and well-being. While biophilia is more directly related to architectural and urban design, as well as interior design, biomimicry is relevant to technology and product development. These concepts address nature in different ways; biophilic design recognizes the health and well-being benefits of connecting with nature, while biomimicry recognizes the innovative potential of natural solutions [6]. Biophilic design is the design of buildings that reduce stress and increase occupant productivity and engagement by incorporating nature into their design. The idea behind biophilic design is to provide people with much-needed interaction with nature by incorporating natural features and systems into the built environment [7]. The concept of architecture biomimicry can be defined as a design approach that uses nature to solve human problems. The utilisation of the subject in question is twofold: firstly, in the context of health concerns, and secondly, in the context of the production of healthy buildings. (Figure 1), [8].

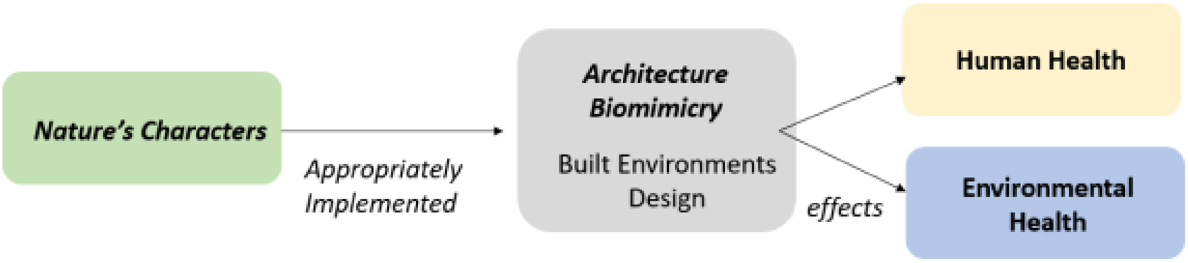

***Figure 1**. The Concept of Healthy Buildings in Architecture and its Relationship with Biomimicry [8]*

The literature widely discusses biomimicry architecture, which can create a healthy and sustainable environment for healthy building criteria. Biomimicry architecture is also a subfield of sustainability, and the principle of sustainability supports the creation of healthy buildings for people and the environment. [8].

The frequent use of indoor spaces in society is a concerning trend for human health; one is the evidence that time spent outdoors is associated with better health and well-being; the other is that time spent indoors is negatively associated with several health problems [9]. The architectural profession faces many challenges in building healthier buildings. The primary concern pertains to a dearth of knowledge, underscoring the necessity for augmented research endeavours to elucidate the intricate interplay between built environmental factors and their repercussions on human health. The second is the lack of emphasis currently placed on learning about human health as part of the compulsory education curriculum for the architectural profession [10]. The concept of biophilia, has also gained widespread acceptance in architectural design, with architectural designs that promote daylight and views, access to outdoor spaces, and the integration of place-based natural and cultural spaces within the built environment gaining prominence. These designs spurred the "good building" movement in the mid-2000s [11].

Buildings that incorporate natural elements in their surroundings, developed with biophilic design, have helped provide people with a better place to think and work, because the “green” areas around them make them feel comfortable and at peace in the atmosphere they are in. In the context of the built environment, there is increasing interest among stakeholders in architecture in design approaches that promote healthy environments and support well-being. In architecture, the design of buildings is not limited to material selection, design, and implementation: architecture must provide a healthy environment for users by considering comfort and requirements, addressing health needs as a whole, including physical environmental factors, psychological comfort, and social well-being [12]. In recent years, studies that finally draw attention to healthy buildings and an increasing number of examples in architectural structures have brought the topic of healthy design to the forefront. The concept of healthy building design in architecture is crucial for enhancing the well-being of building occupants by focusing on the physical, psychological, and social aspects of health. Research in this field has demonstrated that the physical environment, including indoor air quality (IAQ), thermal comfort, and acoustics, plays a significant role in the physical health of people living or working in these spaces. These studies have shown that the physical environment, including indoor air quality (IAQ), thermal comfort, and acoustics, plays a significant role in the physical health of people living or working in these areas. In addition to physical needs, factors such as lighting, color scheme, and views are also priorities for users' psychological well-being [12].

Architecture plays an important role in ensuring the healthiness of buildings and preventing sick building syndrome for the well-being of users. The frequent use of indoor spaces in society is a concerning trend for human health; one is the evidence that time spent outdoors is associated with better health and well-being;

the other is that time spent indoors is negatively associated with a number of health problems [9]. The architectural profession faces many challenges in building healthier buildings. The primary concern pertains to a dearth of knowledge, underscoring the necessity for augmented research endeavors to elucidate the intricate interplay between built environment factors and their repercussions on human health. The second issue pertains to the absence of a discernible emphasis on the subject of human health within the prevailing compulsory education curriculum for the architectural profession. [10].

Sustainable buildings are holistic, encompassing the concepts of green buildings and healthy buildings, along with other social and economic responsibilities. The term "healthy building," dating back to the 1980s, is the result of major movements aimed at ensuring health and good conditions, representing a new principle or element of sustainability. Healthy buildings are the next step in green buildings and sustainable buildings.

When a healthy building is constructed, it can be said that a green and sustainable building has been constructed. A green building is a subset of sustainability and contributes to improving the well-being of users through its design features. A healthy building is created through green and sustainable design features [13].

Table 1. Brief of the comparison between the three concepts [13]

GREEN BUILDING	SUSTAINABLE BUILDING	HEALTHY BUILDING
Minimizes the environment impact due to the design procedures.	Look at a building's whole life cycle from crib to grave (including demolition or disassembly)	Look at a building's whole life cycle from crib to grave (including demolition or disassembly)
Hard to achieve suitable emphasis on human health	Hard to achieve suitable emphasis on human health	Support and protect health ethos for better wellbeing.
Focused on the current state	Focused on the distant future for the building and its components	Focused on the distant future for the building and its and occupants
Term used mostly for process or product that has little impact on the environment	In addition to the environmental strives to at least acknowledge the social and economic ramifications Sustainable is still focused on the environment instead of the building occupant	Term used mostly for process or product that has no negative impact on the environment and buildings occupants
Green isn't always sustainable	Sustainable is more than green design it is a higher degree So sustainable is always green	Healthy buildings are the next chapter of green and sustainable buildings It is the introduction of health and well-being as another element of green and sustainability
Green is a subset of sustainable	Sustainable includes green	Healthy is a green and sustainable building as well as it contributes to improving the mental state of its occupants through its design characteristics.

Sustainable green building methods focus on making buildings more energy efficient, but they do not directly improve the physical and mental health of the people who use them. There exists a considerable knowledge deficit concerning the practical integration of health-oriented tools, such as the WELL Building Standard, into the conventional architectural design process and the potential for this integration to enhance health outcomes. This study offers a tangible, evidence-based framework for action, addressing the essential gap between health evidence and design choices, and prioritizing human well-being within the built environment.

This study aims to contribute to the literature on healthy building design concepts and health-focused criteria by utilizing the comprehensive framework of the WELL Building Standard, which integrates evidence from the disciplines of architecture, public health, and environmental psychology.

2. LITERATURE REVIEW

2.1.Well being and Healthy Building

Well-being has become a significant area of interest for researchers and professionals across a range of disciplines in the built environment. The interactions between individuals, building features, and the relational dynamics within the context of the environment and the wider community are important in assessing well-being.

The definition of well-being is generally understood as a state characterized by a high quality of life encompassing physical, mental, emotional, social and, in some contexts, spiritual and self-actualization dimensions [14]. Well-being is defined as a concept encompassing "thinking, feeling, and functioning," while at the environmental level, well-being relates to the quality of the individual's physical and social environment [15].

The term "healthy building" emerged in the 1980s and was not widely adopted for a decade. Initially, it was considered the opposite of the concepts of sick building, problematic building, or building prone to complaints. The widely accepted definition describes a situation where there is no evidence that buildings cause illness, and therefore no reason for people to become ill [16]. The International Conference on Healthy Architecture, held in the millennium, defined a healthy building as the way of experiencing the building's interior environment, including physical elements such as temperature, humidity, noise, light, and air quality, as well as subjective psychological elements such as spatial arrangement, color, and materials used [17]. The necessary components for healthy, high-performance buildings designed to provide high-quality air, temperature control, light, ergonomics, privacy, and interaction, as well as access to the natural environment. Health has been linked to [18]:

- Sustainable Air;
- Sustainable Temperature Control;
- Sustainable Light;
- Workplace Ergonomics And Environmental Quality;
- Access To The Natural Environment;
- Land Use And Transportation

A healthy building is defined as a building that safeguards its own health, protects the health of its surroundings, and places greater emphasis on the physical and mental health of builders and users throughout the building's life cycle [19]. The concept of a healthy building should be considered throughout the entire life cycle of the building design and in the post-use phase of the building [20]. This type of building is a new type of building that develops and evolves based on the entire life cycle of traditional buildings, encompassing many dimensions such as comfort and health, living space, energy saving, environmental protection and ecological environment [18].

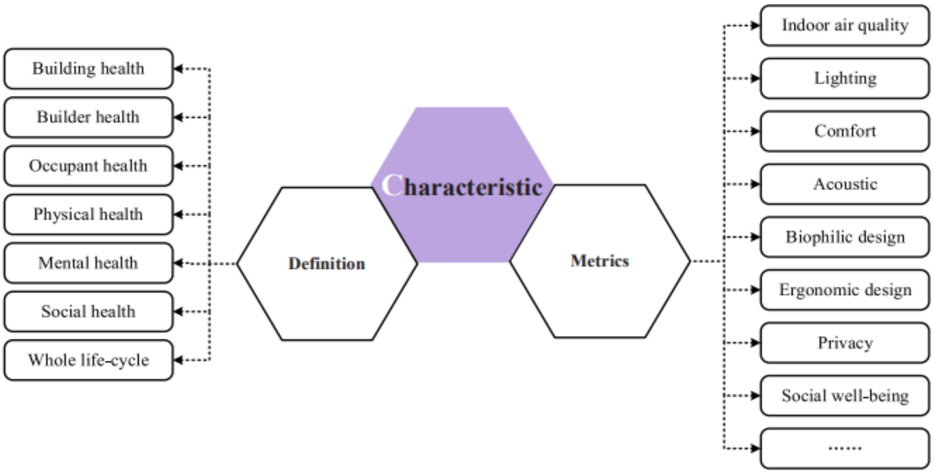

***Figure 2**. Characteristic of healthy building [9]*

The concept of healthy building, encompassing green building and sustainable building concepts, connects factors related to human health throughout the building's life cycle, including its interior and exterior environments, integrates various social resources, and is associated with the design, construction, and use phases. Modeling healthy building characteristics demonstrates what a healthy building is and the criteria it encompasses (Figure 2) [9].

Besides healthy building metrics, healthy buildings also have other indoor environmental issues such as biophilic design and ergonomic design [21]. Healthy buildings are meticulously designed and constructed with a focus on optimizing the health and well-being of their occupants [22].

A key aspect of healthy buildings is maintaining excellent indoor air quality (IAQ) through proper ventilation systems, effective filtration of pollutants, and management of volatile organic compounds [23]. Additionally, maximizing exposure to natural light while minimizing glare and providing balanced lighting levels is essential to enhance occupant well-being and support natural daily rhythms. Thermal comfort is achieved by maintaining optimal temperature levels throughout the building and reducing thermal fluctuations, which increases both comfort and productivity [22,23]. Effective sound insulation and noise control measures create quieter environments that increase concentration and reduce stress.

Healthy building is often measured by improvements in occupant health metrics. This can include reduced absenteeism due to fewer health issues, increased productivity and cognitive function, and enhanced overall well-being. Surveys and health studies are commonly used to assess these outcomes, providing evidence of the positive impacts of healthy building design on occupants [9]. Triggers represent the stimuli that drive the development of healthy buildings, including external and internal factors (Figure 3).

-Triggers for health problems

Many studies have shown that environmental problems such as global air, water and noise pollution lead to various health problems [23].

-Triggers for government

Regulations and policies are important drivers that require stakeholders to promote healthy building [24].

-Triggers for occupant

It is stated that a healthy building should prioritize the health needs of its occupants, thus meeting the physical, psychological and multi-level social needs of life [19].

-Triggers for building

Building-related health problems and sick building syndrome frequently arise, posing a concern for developers and residents. Indoor air quality, thermal comfort, lighting, and noise are considered important criteria in green buildings. Healthy buildings are recommended as a suitable complement to green buildings [25].

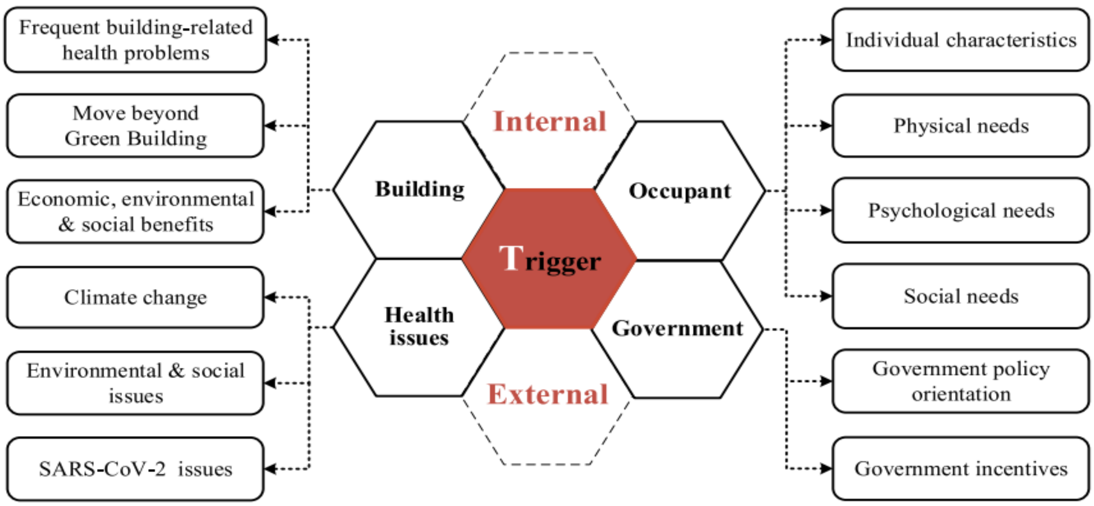

Figure 3. Triggers of the development of healthy buildings [9].

Healthy buildings can be achieved by taking precautions during the construction design and building process. For a healthy building, sound design and construction are essential for its technical functioning, mechanical stability and the basic safety of its occupants.

2.2.Well Building Stardard

Healthy buildings can be achieved through measures taken after the design, construction, and occupancy stages. Although "healthy building" is a new concept from the 2000s, it is implemented under the guidance of scientifically derived standards by certification programs such as WELL Building Standard.

The WELL Building Standard was launched in 2014 following a comprehensive expert peer review by the International WELL Building Institute (IWBI) and certified by the Green Business Certification Institute. WELL Building Standard is a new and unique performance-based rating system that focuses primarily on the health and well-being of building occupants. It aims to improve and protect the health and well-being of building occupants through on-site measurement, certification and monitoring of the built environment [25].

Although it will always be preferable to design a new healthy building from the 'ground up', these principles can be readily applied as retrofits to existing buildings. 9 Foundations, which are explored in detail (Figure 4) [26].

1. Air quality: Air quality requires the use of low-emission building materials and maintaining humidity levels between 30-60%.

2. Dust and pest control: Use vacuum cleaners with high-efficiency filters and antibacterial cleaning of surfaces.

3. Lighting and landscape use: Use lighting that provides as much daylight as possible and is enriched with blue light.

4. Moisture Control: Prevent moisture or mold growth by regularly inspecting roofs, plumbing, ceilings, and HVAC equipment.

5. Noise Control: Take measures to protect against outdoor noise and control indoor noise with mechanical equipment.

6. Ensuring safety and security: Ensuring safety and carbon monoxide standards and developing an emergency response plan.

7. Thermal health balance: Ensuring minimum thermal comfort standards for temperature and humidity.

8. Ventilation Quality: Ensuring that occupants meet or exceed local guidelines for building air quality.

9. Water Quality: Meeting relevant national standards and establishing an effective water treatment system.

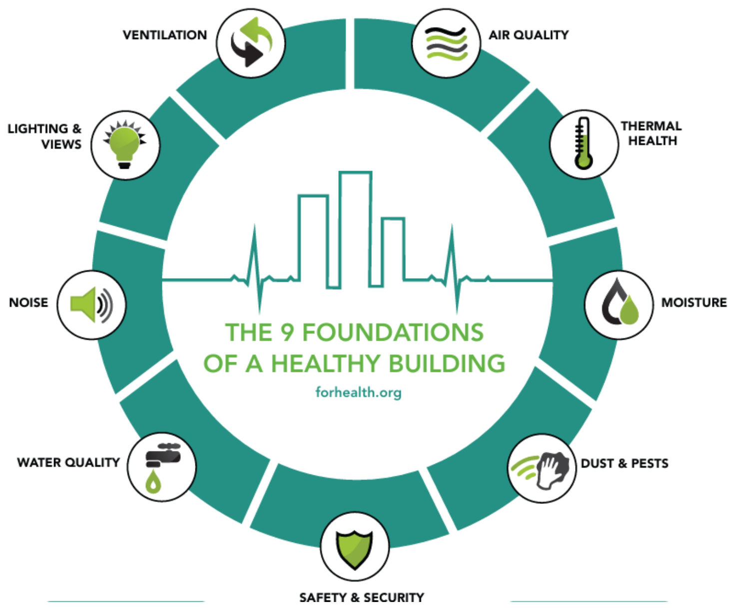

***Figure 4**. Healthy building from the 'ground up', these 9 principles [26].*

Healthy buildings emphasise occupant health and well-being, prioritising design features that enhance air quality, natural lighting, and overall comfort. Sustainable buildings on the other hand adopt a holistic approach, integrating environmental, social, and economic considerations to ensure long-term viability and resilience [27].

One of the many standards for evaluating healthy buildings is the WELL Building Standard (WELL) is an up and coming green building certification explicitly embracing comfort, health and well-being in the built environment. The standard covers seven over-arching topics for which the indoor environment is evaluated by; Air, Water, Nourishment, Light, Fitness, Comfort, and Mind. Compared to well-established Green Building Certifications [28].

The WELL Building Standard is a performance-based system for measuring, certifying, and monitoring improved environmental features that affect human health and well-being, investigating how to optimize the design, operation, and behavior of places where people live and work [9]. The standard WELL is an environmental evaluating program to measure and observe the interior environment features which effect on well-being and health of human [29].

It is an integrated system re-inventing environment which built on its users, and transfer places lived by people who work and learn to create systems which aim to reinforce and improve well-being and human health. The standard relies on a group of medical research which discovers the relation between buildings and health affections on their users. This will help to establish built environments that work on improve nutrition, fitness, mood, and sleeping pattern [30].

Indoor air quality, temperature, humidity, and lighting are just some of the many criteria that contribute to a healthy building. Understanding these criteria will help ensure that buildings do not negatively impact occupants, employees, or the environment. The WELL Building Standard, developed by the International WELL Building Institute, comprises some of the more commonly cited criteria. (IWBI) [31].

The seven concepts of the WELL Building Standard are: Air, Water, Nourishment, Light, Fitness, Comfort, Mind. These concepts cover aspects like air and water quality, access to healthy foods, adequate lighting and views, opportunities for physical activity, thermal and acoustic comfort, and support for mental and emotional health. Another seven criteria for healthy buildings are also based on the WELL criteria that are compared below. (1) Good Air Conditioning Systems, (2) Material Health Control, (3) Lighting and Views, (4) Noise Control, (5) Good Building Plan, (6) Water Quality, and (7) Environmental Sustainability Contributes. [8].

The design process for healthy buildings is guided by concepts outlined in standards such as WELL. Table 2 shows the 11 concepts in the WELL Building standard [20].

Table 2. Eleven concepts in the WELL building standard [20].

1. Air	Promote clean air, and minimize human exposure to harmful contaminants
2. Water	Increase rate of adequate hydration in building users, reduce health risks due to contaminated water and excessive moisture, and provide adequate sanitation
3. Nourishment	Encourage healthy and sustainable eating patterns
4. Light	Promote exposure to light, and create lighting environments that improve sleep quality and positively impact mood and productivity
5. Movement	Encourage physical activity in everyday life by ensuring that movement opportunities are integrated into the fabric of the culture, buildings, and communities
6. Thermal comfort	Improve human productivity and provide a maximum level of thermal comfort among all building users
7. Sound	Bolster health and well-being by identifying and calibrating acoustical comfort parameters that shape the sound-scape of the built environment
8. Materials	Reduce human exposure, whether direct or through environmental contamination, to chemicals that may affect health during the construction, remodeling, furnishing, and operation of buildings
9. Mind	Promote mental health through policies, programs, and design strategies to address the diverse factors that influ-ence cognitive and emotional well-being
10. Community	Support access to fundamental healthcare, build a culture of health that accommodates diverse population needs, and establish an inclusive, engaged occupant community
11. Innovation	Include other strategies to create healthier environments, such as green building certification and carbon disclosure/ reduction

2.3. A Comparative Framework: Healthy Building Design with WELL Building Standards in Architecture

Architecture, acting as a "third skin," fundamentally influences human experience through physical and cognitive stimuli. A design paradigm focused on human health produces considerable social, economic, and environmental advantages [9]. The main challenge is to go from designing simple shelters to creating spaces that actively promote the well-being of their occupants. Well-being is a multidimensional state that includes a high quality of life in physical, mental, emotional, and social areas [14]. People often use the terms "healthy building design" and "well-being building design" interchangeably, but a closer look shows that they focus on different things and employ distinct evaluative frameworks.

Traditional healthy building standards mainly focus on reducing health risks and making sure people are comfortable. They often start because of specific problems, like Sick Building Syndrome (SBS), and their main goal is to stop people from getting sick or complaining [14].

The basic principles, like those described by Allen and Macomber [26], stress important operational and environmental factors: controlling sources of pollution and providing good ventilation to improve indoor air quality (IAQ), keeping mold and pests away, providing enough light, thermal comfort, and safe water quality. Most of the metrics are objective and environmental, like VOC levels in $\mu g/m^3$, lux levels, and temperature ranges. The main goal is to make the workplace safe so that people don't get sick or miss work [9,19]. This method is based on reducing risks and setting a neutral baseline for the health of the people who live there.

In contrast, standards that focus on well-being, like the WELL Building Standard, take a more proactive and holistic approach. They are based on medical and psychological research that aims not only to avoid harm but also to improve human potential [20, 26, 28]. They include all the necessary parts of a healthy building, but they also go far beyond that to include things that help people thrive. The WELL Building Standard's ideas about Mind, Nourishment, Fitness, and Light (with a focus on circadian rhythm) show how this change is happening [20, 28, 31]. These ideas are meant to help people feel better mentally and emotionally, lower their stress levels, encourage healthy behaviors, and support their mental and emotional health [20, 7, 15]. Metrics usually have both performance-based standards (like daylight simulation thresholds) and policy-based features (like making mental health support resources available and building accessible staircases to encourage movement). The goal is to move beyond a neutral state and have a positive effect on mood, cognitive function, productivity, and overall quality of life [9,20, 22] (Table 3).

Table 3. Comparison of Healthy and Well-Being Building Design Standards

Comparison Criteria	Health-Focused (Healthy) Building Design Standards	Well-Being-Focused Building Design Standards (e.g., WELL)	References
Core Philosophy & Goal	Prevention of illness, reduction of complaints, maintaining neutral/baseline health. "Do no harm" principle.	Enhancement of existing health, development of psychological and physical capacity, promotion of user "thriving."	[9, 14,16, 19,28, 22]
Primary Focus	**Physical environment & hazards:** Air quality, temperature, humidity, noise, lighting (for visual task), water quality.	**User experience & behavior:** Physical environment + Mental health, nourishment, physical activity, social connection, circadian rhythm, cognitive performance.	[15, 18, 26, 28, 31]
Design Approach	Control and mitigation of hazards (e.g., low-VOC materials, filtration). Reactive (response to problems).	Creation of opportunities for healthy behavior and positive experiences (e.g., attractive staircases, restorative spaces). Proactive (focus on potential).	[7, 19, 26, 28, 31]
Metrics & Measurement	Primarily **quantitative, objective, and environmental:** µg/m³ VOC, dB(A) noise levels, lux, temperature °C, bacterial count.	**Quantitative + qualitative and performance-based:** Daylight autonomy (sDA), circadian lighting design, accessible physical activity amenities, mental health support policies, and user satisfaction surveys.	[4, 15, 18, 23, 28, 31]
Timeframe & Impact	**Short-Medium Term:** Reduction of acute symptoms (headaches, allergies), decreased absenteeism.	**Long Term:** Reduction of chronic stress, increased life satisfaction and sense of belonging, sustained improvement in cognitive function and productivity.	[7, 9, 15, 16, 22]
Relationship with Nature (Biophilia)	Often indirect or at a basic level (e.g., ventilation for fresh air).	**Integrated as a core design principle.** Promotes direct and indirect connection through natural views, plants, water features, natural materials and patterns.	[7, 10, 18, 28]
Example Standards / Frameworks	Local building and health codes, ASHRAE Standards, WHO indoor environment guidelines.	**WELL Building Standard,** Fitwel, Living Building Challenge's "Health & Happiness" petal.	[4, 16, 19, 28, 31]

This relationship is both hierarchical and synergistic. To achieve better health outcomes, it is necessary to understand healthy building principles well. People cannot feel better in a place with poor air quality or excessive noise. However, excellent IAQ does not mean that people living there will feel better mentally or be more socially connected. The fundamental difference lies in the design goal and how results are measured. Healthy building standards ask, “Is this building safe and free from hazards?” Well-being standards ask, “Does this building actively help its occupants thrive, learn, heal, and connect?” To meet the latter, one needs to be more knowledgeable about behavioral science, biophilic design principles that address the human need to connect with nature [7, 11], and the commitment to meeting both physiological and psychological needs. Table 4 below shows how these two related but different paradigms compare in a structured way.

Table 4. Design Metrics Comparison in Healthy Building Standards and WELL Building Standard

Design Dimension/Criterion	Traditional Healthy Building Standards	WELL Building Standard	Architectural Design Response and Key Metrics
Air Quality (Air)	1. Use of low-emission building materials. 2. Humidity control maintained between 30-60% [26].	**Principles:** 1 (Air Quality) & 8 (Ventilation). 1. Source elimination and material health optimization. 2. Enhanced ventilation rates (exceeding prescribed minimums) 3. Advanced filtration (e.g., MERV 13+).	**Design Integration:** Specification of low-VOC, health product-declared materials; integrated design for cross-ventilation and dedicated outdoor air systems (DOAS); selection of high-efficiency HVAC filters. **Key Metrics:** VOC, PM2.5, and CO_2 levels (µg/m³); Air Changes per Hour (ACH).

Water Quality (Water)	Compliance with relevant national water quality standards [26].	**Principle:** 9 (Water Quality). 1. Integration of point-of-use or central filtration/purification systems 2. Regular water quality testing and monitoring protocols.	**Design Integration:** Provisioning filtration systems at building water mains or specific use points (kitchens, drinking fountains) in early-stage MEP planning. **Key Metrics:** Maximum contaminant levels for specific pollutants (e.g., lead, Legionella, total coliforms).
Lighting Design (Light)	Provision of ample daylight and/or high-intensity, blue-enriched lighting [26].	**Principle:** 3 (Lighting and Views). 1. Circadian lighting design supporting melatonin suppression and circadian entrainment. 2. Daylight autonomy (sDA) and visual connection to the outdoors. 3. Glare control strategies.	**Design Integration:** Building massing, orientation, and fenestration design optimized via daylight simulation (sDA, ASE); specification of tunable-white LED systems; integration of glare-control devices (louvers, fritting). **Key Metrics:** Spatial Daylight Autonomy (sDA300,50%); Equivalent Melanopic Lux (EML); Unified Glare Rating (UGR).
Thermal Comfort (Comfort)	Meeting minimum thermal comfort standards for temperature and humidity [26].	**Principle:** 7 (Thermal Health). 1. Provision for individual thermal controllability (local thermostats, operable windows). 2. Control of radiant temperature asymmetrical and draft risk.	**Design Integration:** Zoning strategies for HVAC controls; design for operable fenestration within façade systems; use of thermal mass and insulation to mitigate surface temperature fluctuations. **Key Metrics:** Predicted Mean Vote (PMV) / Predicted Percentage Dissatisfied (PPD) index; operative temperature range; local air speed.
Acoustic Performance (Comfort)	Protection from outdoor noise and control of indoor noise from mechanical equipment [26].	1. Maximum background noise levels (NC/RC curves) and reverberation time (RT) criteria 2. Sound transmission performance requirements for partitions.	**Design Integration:** Spatial programming for noise buffer zones; specification of sound-absorbing finishes (NRC); structural design for flanking noise control (STC ratings). **Key Metrics:** Background noise levels in dB(A); Reverberation Time (RT60); Sound Transmission Class (STC).
Physical Activity & Nourishment (Fitness & Nourishment)	Access to the natural environment [18].	1. Design of attractive, centrally located, and well-lit staircases to promote incidental activity. 2. Provision of infrastructure for healthy food preparation and storage (refrigeration, pantries) 3. Interior circulation design encouraging movement.	**Design Integration:** "Stairs-before-elevators" circulation hierarchy; dedicated spaces for food storage/prep in floor plans; design of internal active pathways. **Key Metrics:** Accessibility to primary staircases; availability and quality of spaces supporting healthy eating behaviors.
Mental & Emotional Well-being (Mind)	Access to views and green spaces [18].	1. Comprehensive integration of biophilic design patterns [7, 11]. 2. Dedicated restorative spaces and retreat areas. 3. Design features that reduce stress and foster a sense of community and place.	**Design Integration:** Application of direct (plants, water features, vistas) and indirect (natural materials, fractal geometries, dynamic light) biophilic elements; programming of contemplative niches and social hubs. **Key Metrics:** Diversity and intensity of biophilic design elements; accessibility and quality of designated restorative spaces.
Core Design Philosophy	**Reactive & Protective:** Mitigating existing health hazards to establish a neutral baseline. Focus on "do no harm." [16, 26]	**Proactive & Enhancing:** Augmenting physical and cognitive potential, promoting salutogenic behaviors. Focus on "enable thriving." [12, 28]	**Architectural Implication:** Traditional approaches provide a *prescriptive framework* for meeting minimum code requirements. WELL, offers a *performance-based guide and certification roadmap* that dictates targeted outcomes and user experiences, deeply informing design decisions [9, 31]

The WELL Building Standard, on the other hand, tells the architect "what performance outcome and user experience they need to achieve" (for example, a certain light level that supports circadian health and a spatial quality that encourages rest). Traditional standards tell the architect "what they need to provide" (for example, low VOC). This makes the architectural design process more than just choosing materials and systems. It also connects it to the quality of the space, the psychology of the user, and the behavioral sciences.

3. METHODOLOGY

This study employs a qualitative research design focusing on a comprehensive and critical literature review to evaluate the characteristics of healthy buildings within the context of the WELL Building Standard. The WELL Building Standard is a voluntary rating system developed in recent years to support, protect, and promote the health and well-being of building occupants. While studies on the application of WELL in buildings have been increasing, the system has not yet been fully adopted. This study aims to provide an overview of the current state and trends in the literature, the scope of the effectiveness of WELL use in buildings, and further information about this new standard. Articles examining healthy buildings from the perspective of sustainable green buildings and biophilic design were researched, reviewed, and examined in detail, and a comparative analysis was conducted. The main goal is to bring together what we currently know about architecture, public health, environmental psychology, and building science to create a clear, evidence-based picture of how health-focused criteria can be used in architectural design and to show how the WELL Building Standard fits into this picture.

3.1.Research Design: Qualitative Literature Synthesis

The study employs a descriptive and conceptual synthesis model for qualitative literature review [4, 14]. This design is selected to delineate the evolution, definitions, and interconnections of fundamental concepts such as "healthy building" and the "WELL Building Standard," while synthesizing insights from various disciplines into a cohesive framework [20]. The process is not intended to produce new primary data; rather, it focuses on organizing, assessing, and interpreting the existing corpus of academic and professional knowledge to establish conceptual clarity and a foundational evaluative framework for the discipline [9, 20,22].

3.2.Data Collection: A systematic search strategy and selection criteria

Data collection adhered to a structured protocol founded on established systematic search and selection criteria to guarantee transparency and replicability. A systematic search was performed across multidisciplinary databases such as Scopus, Web of Science, PubMed, and the Avery Index to Architectural Periodicals. This search was also conducted at the official resource library of the International WELL Building Institute (IWBI). The study was used keyword combinations like: ("healthy building" OR "well building standard") AND ("architecture" OR "design"); ("biophilic design" OR "salutogenic design") AND ("health" OR "well-being"); and ("indoor environmental quality" OR "IAQ") AND ("productivity" OR "cognitive function") [20].

The search primarily concentrated on literature published between 2000 and 2024 to encompass contemporary advancements, while seminal theoretical works essential to the field's foundation [8, 16] were included regardless of publication date.

The review included peer-reviewed journal articles, scholarly books, reputable industry reports, and standard documentation (for example, the WELL guidebook). Sources were chosen because they were directly related to:1) defining or assessing healthy buildings or the WELL Building Standard) talking about biophilic design principles and how they affect health; 3) showing research on how the built environment affects the physical or mental health of people who live there (for example, [7, 15, 16].

Studies that concentrate exclusively on energy efficiency without considering occupant health, publications situated outside architectural contexts, commentaries based solely on opinion lacking empirical or theoretical support, and sources unavailable in English or Turkish were omitted.

3.3. Data Analysis: Thematic and Comparative Content Analysis

The fundamental concepts of the WELL Building Standard (Air, Water, Nutrition, Light, Fitness, Comfort, Mind) and core cross-themes such as Biophilic Design and Definitions of Healthy Buildings. A comparative content analysis was conducted simultaneously [4]. Key documents, particularly the WELL Building Standard, general healthy building principles [18, 26], and literature discussing alternative green building certification systems referenced in the literature were reviewed. The aim was to conduct a structured comparative analysis that would directly compare the criteria and metrics of the WELL Building Standard with the broader healthy building characteristics found in the literature [14, 19]. This method allowed for an objective assessment of the Standard's scope, focus, and unique contributions.

3.4.Putting things together and mapping out the framework

The last step was to combine the results from both analytical methods. The thematic analysis identified characteristics, strategies, and metrics that were explicitly aligned with the structured concepts of the WELL Building Standard under the overarching "Healthy Building Concept" theme. This synthesis and mapping exercise constituted the principal method for assessing the comprehensiveness and specificity of the WELL Building Standard in relation to the complex dimensions of occupant health as delineated by current research [28, 31]. The result is a unified, analytical framework that emphasizes synergies and clarifies the role of the WELL Building Standard within the wider context of health-promoting architectural design.

3.4. Limitations of Methodology

This study is inherently constrained by the scope, quality, and accessibility of existing published research, given its literature-based review nature. It lacks primary data collection via case studies, post-occupancy evaluations, or surveys, which could provide additional empirical validation and contextual depth. Nonetheless, this methodological approach yields an essential and rigorous foundational synthesis, creating a distinct, evidence-based conceptual framework for subsequent empirical and applied research [9, 22].

4. CONCLUSION AND RECOMMENDATIONS

This study has assessed the concept of healthy building design using the extensive framework of the WELL Building Standard, integrating evidence from architecture, public health, and environmental psychology. The analysis produces three principal findings. First one is the WELL Building Standard which puts into action a mandate for holistic health. The WELL Building Standard offers a framework that includes approximately more health-focused criteria than basic green building standards; it provides improvements not only in energy efficiency and hazard reduction, but also in mental health, nutrition, fitness and cognitive support, by controlling adverse effects [20,28, 31]. To fully utilize the principles of the WELL Building Standard, they need to be integrated into the architectural design process from the very beginning, starting with programming and schematic design, through specifications and post-occupancy evaluation [24]. Evidence shows that buildings constructed according to these standards can increase occupant productivity and reduce absenteeism related to sick building syndrome [9, 20,22].

This study adds to the theoretical conversation by suggesting a Health-First Design Framework. This framework places occupant health not as a subordinate advantage of sustainable design, but as the principal aim and foundational principle. It further advances an integrated model that lets you compare how different standards deal with all aspects of human health. Finally, it offers an Evidence-Based Design Decision Matrix that helps architects choose the changes that will have the biggest effect on well-being [9, 14].

This study translates its findings into actionable tools for the profession to bridge the gap between theory and practice. It suggests a toolkit for architectural field for practical contribution. A checklist for a Health Impact Assessment (HIA) is a step-by-step guide for architects to use at each stage of a project to check their design choices against important WELL Building Standard ideas. A Template for Client Education and Involvement is a structured presentation that explains the value of healthy buildings by connecting design features to real health and financial benefits. Specification Guidelines for Healthy Materials is a carefully chosen list of materials that are low in emissions and have been verified by standards like Declare Labels and Cradle to Cradle certification to make it easier to choose materials.

This research recognizes specific constraints. It has a global reach in terms of geography and culture, so WELL Building Standard strategies need to be adapted to fit the specific weather, laws, and social situations in each area. The conclusions are limited by the present availability of longitudinal data; additional long-term studies are required to accurately quantify the lifetime health benefits. Moreover, the inconsistency in industry adoption rates and the perception of upfront costs continue to pose substantial obstacles to widespread implementation, which this research can illuminate but not completely rectify.

Based on this investigation, important points for future research include strengthening the evidence base, conduct longitudinal (5–10 year) health impact studies in WELL-certified buildings. Also, creating more detailed cost-benefit analysis models for different types of buildings, like schools, hospitals, and offices. Looking into how digital twins can be used to model and predict health performance outcomes during the design phase. Looking into AI-assisted design optimization tools that can automatically suggest changes to designs to improve health metrics.

Healthy buildings are still in the work. They are not as well-developed as established green building movements in terms of policy, technical systems, and market maturity. But as health problems around the world get worse, the proof is clear: architecture is a key factor in health [16, 18]. The ongoing absence of compulsory health and well-being emphasis in architectural education and regulation signifies a significant knowledge deficiency [10].

The shift from stopping sick buildings to promoting health is a necessary change in the way architecture works. This study gives us both the proof and the tools we need to make this change possible. It makes the case for a future where space design is naturally measurable, restorative, and thriving, meeting the needs of everyone who lives there. To make this vision a reality, public health professionals, architects, and urban planners will have to work together in ways that have never been done before. By taking this integrated, health-first approach, architects can firmly establish their role as an important part of public health in the built environment. They can design not only shelters, but also things that make people feel better. The WELL Building Standard appears to be an innovative and user-centric framework that closely aligns with the fundamental characteristics of healthy buildings outlined in the existing literature, particularly those related to the physical and psychological well-being of users.

This study was obtained by conducting a literature review and making conceptual comparisons. It concludes that healthy buildings are an extension of green buildings. The future of green building development is about adopting and adapting the features of healthy building standards, and this will determine the future direction of architecture. In the event of widespread adoption, healthy buildings with smart technologies are expected to draw greater attention to ecological and ecosystem services, becoming the defining criterion for health.

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Pelin KARAÇAR, Assist. Prof. Dr.

Karacar received her B.A. in 1995 from İstanbul Technical University's Department of Architecture and went on to complete her M.A. in the field of Building Construction management and Economics in 2000 and Ph.D. in the field of Construction at Yıldız Technical university in 2010. She has carried out academic studies on Construction Technology, Technological innovations in construction products, Nano technological materials and sustainability, Timber building technology, Ecology and Project Management. She worked as a research assistant at Yeditepe University, Faculty of Fine Arts, Architecture and Design, Department of Architecture between 2002-2011 and as a doctoral faculty member in the Department of Interior Architecture between 2011-2015. In 2015, She became a founding member of the Faculty of Fine Arts, Design and Architecture of Istanbul Medipol University as a doctoral faculty member in 2015, and served as the Head of the Interior Architecture Department of the Interior Architecture and Environmental Design Turkish and English programs between 2015-2021. Since 2021, she has been continuing her academic studies and coordinator of Construction Technologies courses as a doctoral faculty member in the Department of Architecture.

Assessing Urban Morphological Complexity Through Fractal Geometry: Evidence From Turkish Cities



Dr. Mustafa Raşit ŞAHİN[1], Dr. Sıla ÖZDEMİR[2], Prof. Dr. Emine YETİŞKUL[3]
Middle East Technical University, Faculty of Architecture, *Department of City and Regional Planning, Ankara, Türkiye* [1, 2, 3]
mustafarasit@gmail.com[1,] sila1299@gmail.com[2,]
yetiskul@metu.edu.tr[3]
https://orcid.org/ 0009-0001-4809-3950[1]
https://orcid.org/ 0000-0002-6382-1311[2]
https://orcid.org/ 0000-0003-0829-1562[3]
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Abstract: *Complexity science examines the emergence of structure in self-organising open systems, where interactions among individual components give rise to dynamic and adaptive patterns. Within this paradigm, cities are conceptualised as complex systems characterised by adaptability, self-organisation and sensitivity to initial conditions, reshaping how urban environments are understood. Urban planning literature increasingly adopts this perspective, recognising that cities evolve through non-linear processes and often exhibit self-similar spatial configurations. Fractal geometry, introduced by Mandelbrot, provides a powerful analytical framework in this context, enabling the identification and measurement of structural complexity in urban systems by means of the fractal dimension [Fd]. This study synthesises the theoretical background of fractal structures in cities and outlines the main methods of fractal analysis, with a particular focus on their relevance for urban morphology and planning. It discusses key approaches such as multi-scale, self-affine and multi-fractal analyses, explaining how these methods capture density, continuity, fragmentation and boundary complexity in urban form. Drawing on empirical studies, especially those conducted in Turkish cities, the paper examines spatial patterns of Fd values from city centres to peripheral zones and explores the relationships between fractal dimension, urban sprawl, road network hierarchy and planning decisions. The findings demonstrate that fractal geometry offers a robust quantitative framework for assessing spatial heterogeneity, evaluating urban compactness and monitoring fragmentation processes. In doing so, fractal approaches strengthen the role of quantitative methods in contemporary urban planning by providing tools to guide sustainable and resilient urban growth.*
Keywords: *Fractal dimension, Road network analysis, Urban sprawl, Morphology, Fractal analysis of Turkish cities.*

Kentsel Morfolojik Karmaşıklığın Fraktal Geometri Yoluyla Değerlendirilmesi: Türkiye Kentlerinden Bulgular

Özet: *Karmaşıklık bilimi, bireysel bileşenler arasındaki etkileşimlerin dinamik ve uyarlanabilir örüntüler ürettiği, öz-düzenleyici açık sistemlerde yapının ortaya çıkışını inceleyen bir yaklaşımdır. Bu paradigma, kentleri uyarlanabilirlik, öz-düzenleme ve başlangıç koşullarına duyarlılık gibi özelliklerle tanımlanan karmaşık sistemler olarak ele alarak kentsel çevreyi anlama biçimimizi dönüştürmüştür. Kentsel planlama literatürü giderek artan biçimde bu bakış açısını benimsemekte ve kentlerin doğrusal olmayan süreçler aracılığıyla evrildiğini, çoğu zaman öz-benzerlik sergileyen mekânsal yapılara sahip olduğunu kabul etmektedir. Mandelbrot tarafından ortaya konan fraktal geometri, özellikle fraktal boyut [Fd] kavramı aracılığıyla kentsel sistemlerdeki yapısal karmaşıklığın tanımlanması ve ölçülmesine imkân tanımaktadır. Bu çalışma, kentlerde fraktal yapılara ilişkin kuramsal çerçeveyi derleyerek fraktal analiz yöntemlerinin temel ilkelerini ortaya koymakta ve fraktal analizlerin kent morfolojisi ile planlama pratiklerine yönelik sunduğu içgörüleri tartışmaktadır. Çok ölçekli, öz-afin [self-affine] ve çok-fraktal yaklaşımlar dâhil olmak üzere fraktal analiz türleri incelenmekte; bu yöntemlerin kentsel dokunun yoğunluk, süreklilik, parçalanma ve sınır karmaşıklığı gibi boyutlarını nasıl yakaladığı açıklanmaktadır. Özellikle Türkiye kentleri için gerçekleştirilen ampirik çalışmalar üzerinden Fd değerlerinin kent merkezlerinden çevreye doğru mekânsal farklılaşma örüntüleri ele alınmakta; fraktal boyut ile kentsel yayılma, yol ağı hiyerarşisi ve planlama kararları arasındaki ilişkiler tartışılmaktadır. Bulgular, fraktal geometrinin mekânsal heterojenliği nicelleştirme, kentsel sıkılığı [kompaktlığı] değerlendirme ve parçalanma süreçlerini izleme açısından güçlü bir analitik çerçeve sunduğunu göstermektedir.*

Böylece fraktal yaklaşımlar, sürdürülebilir ve dirençli kentsel büyümeyi yönlendirecek nicel yöntemler sağlayarak çağdaş kentsel planlamada güçlü bir araç olarak konumlanmaktadır.
Anahtar Kelimeler: *Fraktal boyut, Yol ağı analizi, Kentsel saçaklanma, Türkiye kentlerinin fraktal analizi.*

1.INTRODUCTION

Complexity science is defined as the study of emergence in self-organizing open systems. These systems, characterized by rules and structures, are inherently dynamic and evolve through numerous synergistic interactions rather than through predetermined plans or complete external control. Urban environments exemplify complexity through their non-linear interactions, emergent spatial patterns, and dynamic adaptability. Traditional deterministic urban planning methods often fall short in addressing this intrinsic complexity effectively. This limitation has led to a shift away from conventional, rigid classifications of cities and regions towards more adaptive and flexible frameworks influenced by evolving epistemological and ontological perspectives in both the physical and social sciences. Complexity science provides alternative frameworks— such as fractal geometry, dissipative structures, cellular automata, and agent-based models—to better understand and manage urban systems, with the cited studies serving as foundational and representative reviews of complexity-based urban approaches [1-6].

Among these, fractal geometry has emerged as particularly useful for interpreting urban morphology, spatial patterns, and development dynamics by identifying and measuring self-similarity across multiple scale self-similarity as reflected in a broad body of foundational studies [7-13].

Building on this perspective, the study offers an extensive overview of fractal analyses conducted on Turkish cities, emphasizing key findings, methodological diversity, and planning-relevant implications. The reviewed evidence is organized comparatively (Table 1) to clarify what fractal measures capture in urban contexts and to consolidate insights for urban planning practices and policies.

2. MATERIAL AND METHOD

This study adopts a synthetic approach to fractal analysis in urban morphology by examining how fractal geometry has been used to conceptualize cities as complex systems and to measure morphological complexity in Turkish cities. Rather than producing new empirical measurements, the paper systematically reviews and synthesizes existing studies, focusing on the analytical purpose of fractal metrics, their interpretation in planning-related discussions, and their application across different urban contexts in Türkiye. The reviewed literature is comparatively organized according to city, fractal analysis technique, and key findings, as summarized in Table 1, which provides a consolidated overview of methodological diversity and empirical insights reported in previous research.

3.DEFINITION OF FRACTALS

In physics, the primary factors defining objects, spaces, or masses are typically space and time. Chaotic structures can be represented in space through non-linear dynamics, where complex spatial patterns emerge from simple interaction rules [14]. In such systems, chaos is not limited to spatial configurations but also manifests over time, as dynamic processes continuously modify system states. A defining characteristic of these dynamics is sensitivity to initial conditions, meaning that small variations at the outset may lead to substantially different trajectories over time. This inherent sensitivity renders chaotic systems resistant to traditional deterministic or reductionist analytical approaches. In this context, the emergence of fractal structures can be understood as the outcome of sustained interactions between temporal and spatial chaos within complex systems [15]. Complex systems differ from chaotic systems despite sharing certain characteristics. Specifically, complex systems are characterized by strong interdependencies among their components, such that the behavior of the whole cannot be reduced to the simple sum of its parts. These systems exhibit hierarchical structures that extend across multiple scales, with similar organizing principles observable at different levels of resolution. Moreover, emergent behavior in complex systems arises from global, self-organized interactions among components, producing scale-dependent patterns that are not imposed externally but generated through the dynamics of the system itself.

The term "fractal" was introduced by Benoît B. Mandelbrot in 1967 [16] to describe shapes characterized by intrinsic asymmetry, scale invariance, and self-similarity. Fractal geometry acts as a spatial representation of chaos theory, reflecting interactions between chaotic and orderly elements across multiple scales in complex systems. Jean-Pierre Baranger [15] emphasizes that fractals maintain their complexity at every scale, resisting simplification upon closer examination**.** Lewis Fry Richardson's work on measuring the length of coastlines and national boundaries [17] prompted Benoît B. Mandelbrot to further develop this idea through shoreline analysis in his paper *"How Long Is the Coast of Britain?"* [16]. Fractal objects are characterized by non-integer (Euclidean) dimensions between 1 and 2, being longer than a straight line yet shorter than a plane. Unlike the classical Euclidean framework that utilizes whole-number dimensions of 0 (point), 1 (line), 2 (plane), and 3 (cube), fractal analysis introduces fractional dimension (Fd). The top row in Figure 1 shows basic geometric forms while the bottom illustrates how complexity evolves with dimensionality: isolated points (0D), a branching fractal (~1.2D), and nested cubes (~2.3D). This progression demonstrates how increasing dimensions enable greater structural complexity, especially in fractal and spatial systems.

The key principles underlying fractal geometry include [7]:

- Self-similarity, wherein fractals exhibit consistent irregularity across different scales,
- Hierarchical order of self-similar elements such as trees, roads, and settlements,
- Non-differentiability, indicating fractals cannot be precisely defined by standard calculus methods.

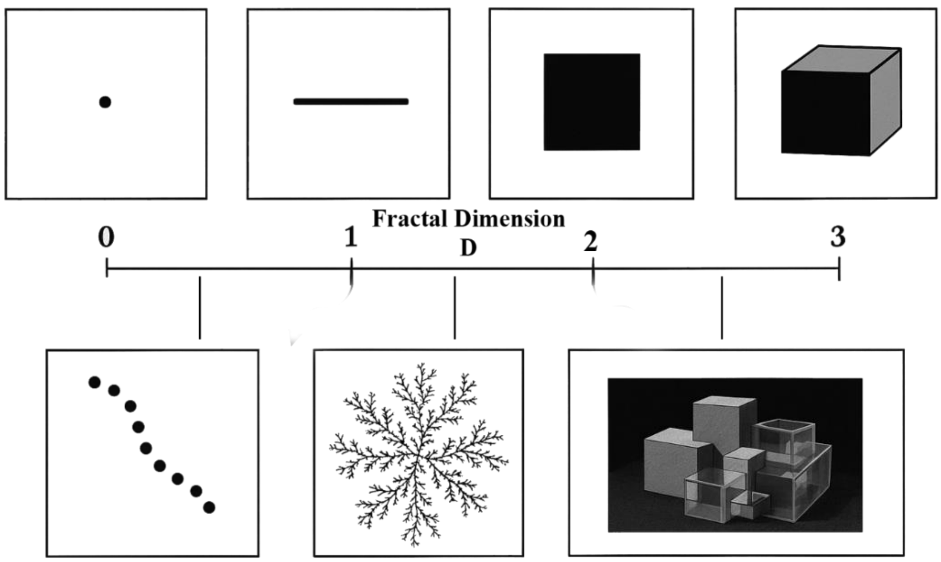

Figure 1*. Dimensionality, Structural Complexity and Fractal Dimensions. Reproduced from [7].*

Fractals can also be generated artificially using iterative processes involving three main elements [18, 19]: (i) base material or concept, (ii) an initiator or initial shape, (iii) a generator, defining the repetitive transformation process.

To illustrate how fractal geometry translates abstract complexity principles into concrete geometric constructions, classical theoretical fractals are often used as explanatory models. The Koch Curve illustrates this concept effectively. It starts with a simple initiator [straight line] and repeatedly applies a generator (dividing the line into three segments and replacing the middle segment with two segments forming an equilateral triangle). Continuous iterations lead to increasingly complex yet self-similar patterns. Figure 2 illustrates the Koch curve generated by recursively applying a generator of 4 segments to an initial straight line (initiator). Each segment is scaled by a ratio r=1/3, resulting in a fractal with dimension D=log(4)/log(3)≈1.2618. At each iteration, every segment is replaced by the generator, increasing geometric complexity. The cascade tree on the right represents the recursive structure, where each node splits into 4 new branches per level. Other theoretical fractals include the Sierpinski Carpet, Dragon Curve, and the 'C' Curve, each having distinct fractal dimensions, such as "1.585" for the Sierpinski Carpet. These artificially created fractals find extensive applications, particularly in computer graphics and simulations, simplifying repetitive tasks and accurately modeling complex, self-similar structures.

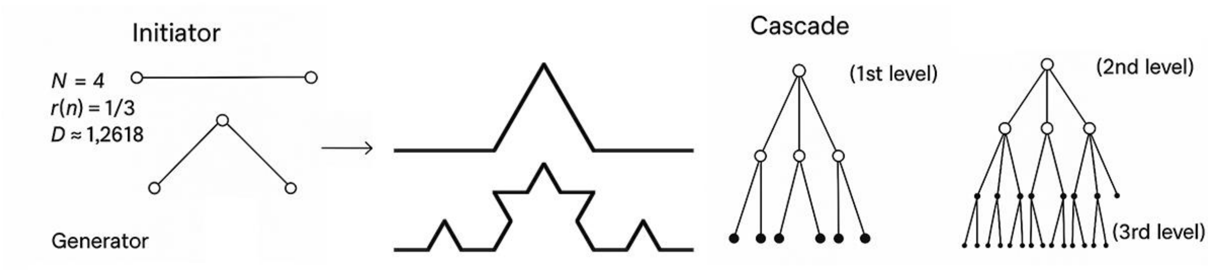

***Figure 2**. Koch Curve Construction and Recursive Tree. Reproduced from [7].*

4.SUBJECTS OF FRACTAL ANALYSIS

The literature on fractal analysis is extensive, offering diverse methodologies applicable across various disciplines. Multi-scale fractal structures, self-affine fractal structures, and multi-fractal structures are key fractal analysis techniques for modelling urban complexity.

Multi-Scale Fractal Structures

Multi-scale fractal structures demonstrate self-similarity across various scales of magnification. This means that the same spatial pattern repeats with increasing detail at finer levels, though the specific scaling behavior may vary. In practice, this is observed in urban development patterns where dense urban cores gradually transition into more fragmented suburban zones. In the seminal work of Frankhauser [9] more than 20 metropoles were analyzed, and the values of the scaling exponent remained at a constant level between 1.8 and 1.9 in central zones while in transient zones the scaling exponent dropped. For European agglomerations this decrease occurs within a rather restricted range of distances, whereas for the more homogeneous patterns of American cities the decrease of the scaling exponent extends to a wide range. These urban patterns are visualized using double-log plots, where breaks or changes in slope indicate varying fractal dimensions (Fd_s) across spatial regimes, each revealing different organizational principles.

Self-Affine Fractal Structures

Self-affine fractal structures exhibit self-similarity but with varying scale factors in different directions, leading to an anisotropic or directionally dependent pattern [18, 20]. Such fractals are commonly observed in natural phenomena like coastlines, mountains, and river networks, finding applications in geomorphology and image processing [21]. This is also particularly relevant in analyzing urban skylines or transportation corridors, where spatial features expand at varying rates horizontally and vertically.

Exploring self-affinity becomes pertinent when delving into three-dimensional fractals. While perfect self-similarity would yield a predictably monotonous complexity, real-world fractals often display statistical self-similarity, revealing layers of complexity. Natural occurrences exhibit multifaceted fractal behaviors that introduce additional intricacies. Figure 3 demonstrates the self-affine structure of the Barnsley Fern, generated using an iterated function system (IFS). The fern is composed of multiple copies of itself, each created by an affine transformation of the initial form.

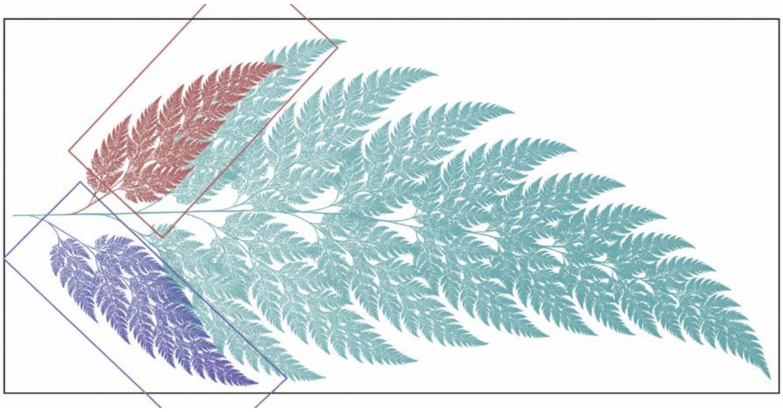

Figure 3. *Affine Self-Similarity in the Barnsley Fern.*

Multi-Fractal Structures

Unlike single-dimension fractals, multi-fractals consist of a range of Fractal Dimensions (Fd_s), capturing complex spatial variability and heterogeneity. This approach is ideal for analyzing uneven distributions of population density, land use intensity, or infrastructure. Cornelis J. G. Evertsz and Benoît B. Mandelbrot [22] define multi-fractality as the coexistence of multiple scaling behaviors within a single system. A practical urban application comes from Yanguang Chen and Jinfeng Wang [23], who used multi-fractal analysis to examine the distribution of urban built-up areas in Beijing. If various zones at the same level of an urban hierarchy have equal chances to develop, the city will have self-similarity; otherwise, it may have a multifractal structure. Their findings revealed that more developed districts showed higher Fractal Dimensions (Fd_s), while less developed peripheries displayed wider variation, pointing to unequal development patterns. This method enables planners to identify spatial imbalances, assess fragmentation, and guide equitable infrastructure investments.

5.FRACTAL GEOMETRY APPLICATIONS IN URBAN STUDIES

Fractal geometry, developed by Benoît Mandelbrot [24], provides quantitative tools to analyze complex spatial patterns that traditional Euclidean geometry cannot adequately describe. Fractals exhibit a different kind of regularity. However, at first glance, this may not be visible to the observer. Fractal geometry captures the intricacies of irregular, self-replicating forms across multiple scales, offering new insights into the spatial and functional organization of urban landscapes. Urban environments are complex mosaics integrating architectural designs, infrastructural networks, and human activities. Traditional analytical methods frequently overlook the nuanced and intricate processes that shape urban evolution. Benoît B. Mandelbrot's pioneering research on fractal patterns in coastlines laid the foundation for extensive urban applications, significantly advancing urban planning methodologies.

Fractal geometry offers an analytical framework for examining the spatial complexity of urban systems. It enables researchers and planners to uncover patterns of spatial organization, morphological change, and functional structure that are often obscured by traditional Euclidean models. Applications of fractal geometry in urban studies include:

Urban spatial analysis enablesplanners to examine the spatial arrangement of urban areas in order to detect patterns in the distribution of buildings, roadways, and other structural elements. Through such analyses, it becomes possible to map urban connectedness, distinguishing areas with high accessibility to services and facilities from more secluded or poorly connected locations. This perspective also supports the assessment of infrastructural resilience by identifying urban regions that may be more susceptible to disruptions, such as those caused by natural disasters. Furthermore, spatial analysis can be used to optimize transportation network structures—including bus and subway systems—by enhancing accessibility and reducing travel times, while also providing a basis for estimating broader impacts on urban performance and functionality. Fractal geometry supports the interpretation of hierarchical spatial structures, spatial thresholds, and multifractal properties in urban patterns [13]. Effective spatial planning recognizes urban forms as multi-scalar systems composed of nested hierarchies—such as central business districts, sub-centers, and peripheral zones—distributed across space [9, 25]. As cities expand, particularly under unregulated or uneven development, spatial fragmentation increases. Fractal analysis quantifies this complexity, allowing comparative evaluations of different urban morphologies.

The work of central place studies was not only involved with the scaling laws of complexity theory but also self-similarity, and self-organization are also properties, related to the complexity. A central place system can be seen as both a hierarchy with cascade structure and a network with self-similar properties. Hierarchical structure is a very significant notion for us to understand urban fractals [1, 7, 9]. Empirical studies have confirmed fractal properties in central place systems, such as the hierarchy of southern German cities [25], while theoretical work by Sandra L. Arlinghaus [26] and work with William C. Arlinghaus [27] articulated the fractal texture of central place networks. Expanding this approach, Guoqiang Shen [12] demonstrated that urbanized areas exhibit fractal properties with respect to scale-dependent changes in occupancy, land-use intensity, and density gradients. Similarly, Yang Chen [28] distinguished between the structural and textural fractality of central place systems, arguing that urban settlements display intermittent, fractal-like spatial arrangements governed by scaling laws.

The core body of research on the spatial variation of fractal dimension values shows that these values are generally highest in central business districts and decrease toward the outer suburbs [7, 10, 29]. Moreover, the rise in central Fractal Dimensions (Fd_s) combined with a decline in peripheral values is associated with compact, well-structured development, whereas the opposite trend indicates urban sprawl. In addition to centrality, the relationship between urban form regularity and Fractal Dimensions (Fd_s) has also been discussed in urban morphology literature. Regular, grid-like urban layouts typically exhibit lower Fractal Dimensions (Fd_s), reflecting their geometric simplicity and lack of complexity across scales. In contrast, irregular, organically evolved urban forms display higher Fractal Dimensions (Fd_s), indicating greater spatial complexity and self-similarity [7, 30, 26, 31, 32].

Urban sprawl, characterized by outward expansion, low density, fragmented land use, and poor spatial continuity, has been extensively analyzed through fractal methods. Batty and Longley [7] were among the first to systematically demonstrate that urban sprawl exhibits lower Fractal Dimensions (Fd_s) compared to more compact urban forms, highlighting its fragmented and inefficient spatial structure. Frenkel and Ashkenazi [33] employed Fractal Dimensions (Fd_s) as indicators to quantify urban sprawl, effectively capturing the degree of fragmentation and further developed an integrated sprawl index combining various metrics of urban configuration and composition, demonstrating that lower Fractal Dimensions (Fd_s) are indicative of more sprawling and inefficient urban patterns. Similarly, De Keersmaecker et al. [30] explored the relationship between urban density and Fractal Dimensions (Fd_s) in the peripheral areas of Brussels, emphasizing the complex interplay between compactness and fragmentation. Generally, higher fractal values correlate with more compact and space-filling urban structures (yellow color boxes in Figure 4), whereas lower dimensions typically signal increasing sprawl and peripheral dispersion (blue color boxes in Figure 4).

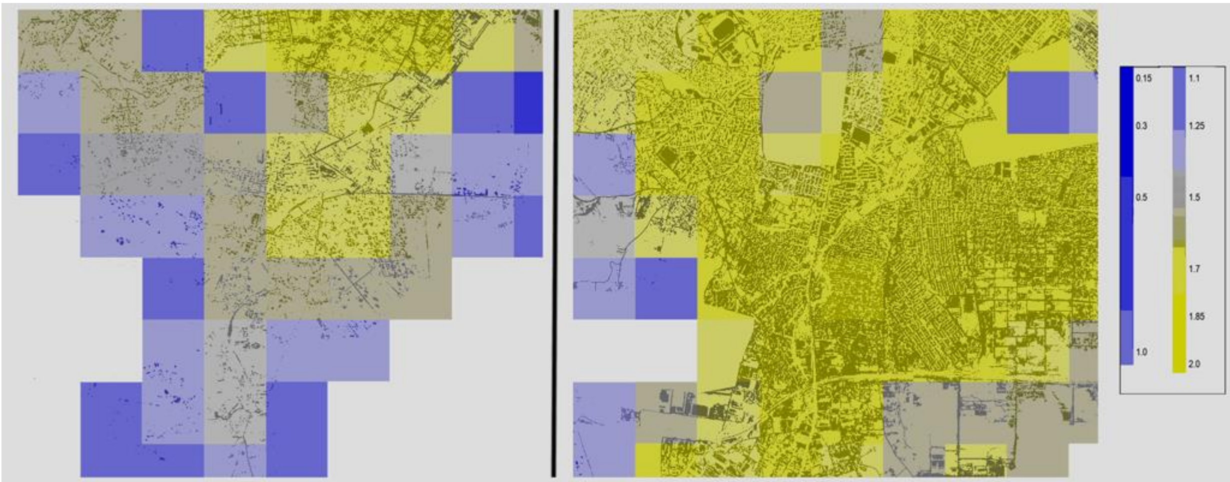

***Figure 4**. The color scale represents variations in fractal dimension (D) values. Lower fractal dimension values (blue tones) indicate more fragmented and less space-filling urban patterns, whereas higher values (yellow tones) correspond to denser, more space-filling and morphologically complex urban structures. Intermediate colors reflect transitional levels of urban complexity across the analyzed spatial grid. [34].*

Fractal Dimensions (Fd_s) have also informed urban morphology measurements. Thomas Frankhauser [25] employed Fractal Dimensions (Fd_s) analysis to examine the structure of European urban outskirts, aiming to classify urban agglomerations based on their spatial complexity. Similarly, Shen [12] compared the morphology of 20 urban areas in the United States, highlighting how variations in urban size and form are reflected in differences in Fds. In the context of longitudinal studies, Benguigui et al. [35] analyzed the built-up patterns of Tel Aviv, concluding that the Fractal Dimensions (Fd_s) of the metropolitan area tends to increase over time as urban growth progresses. This trend was later analyzed by Benguigui et al. [35], who further explored the leapfrog development of Tel Aviv's periphery through fractal and scaling relationships such as area-perimeter analysis and rank-size distributions.

6.METHODS OF FRACTAL ANALYSIS IN CITIES

Two primary criteria commonly determine whether spatial forms exhibit fractal characteristics: power-law distributions and scale-free organization [7, 9]. A power-law distribution implies urban elements, such as building sizes or street lengths, exhibit disproportionate structures, where a few large elements coexist with numerous smaller ones, maintaining consistent scaling across multiple levels. Scale-free organization, by contrast, indicates the absence of characteristic lengths, meaning spatial patterns retain similar properties across different scales, Fractal Dimensions (Fd_s) quantify these spatial complexities using various techniques. The box-counting method is prevalent in urban morphology, overlaying grids onto urban forms and counting occupied cells at varying scales, thereby capturing the hierarchical arrangement of built environments [29, 9]. Alternatively, the mass-radius [area-radius] method calculates the number of urban elements within expanding radii from a central point, providing insights into urban density and scaling behaviors [11].

Fractal analysis techniques examine diverse urban structures, including macro-scale urban forms, road networks, and built environment patterns. There are three primary application methods, depending on urban analysis objectives:

Macro-form Analysis: Fractal analysis of urban macro-forms [12, 25] helps track city evolution, identify trends, and predict future growth. This approach also investigates urban compactness by assessing urban development levels and vacant spaces, linking directly to sustainable urban development. Understanding the compactness of cities is crucial for evaluating environmental sustainability and resource efficiency. By examining the fractal characteristics of urban macro form, researchers can identify factors contributing to compactness. Understanding urban macro-form characteristics provides a useful context for debates on compactness and sustainable urban development, particularly in relation to land-use, transportation, and zoning policies[36, 37]. Incorporating fractal principles into planning enables more coherent and adaptable spatial strategies, effectively managing urban heterogeneity, self-organization, and growth issues. Decision-makers can better address urbanization's complex challenges and opportunities

Road Network Analysis: Urban Road networks frequently exhibit fractal geometry, characterized by self-similarity across scales and non-integer dimensions ranging between 1 (linear) and 2 (planar). As cities expand and become more densely filled, the Fractal Dimensions (Fd_s) of their road networks typically increases. Practically, a higher Fd signifies enhanced connectivity and accessibility due to increased routing options and loops, particularly noticeable in central urban areas [10, 35]. An example of its application can be observed in Figure 5. It illustrates this approach, highlighting how road network fractal analysis enables observation of dynamic urban changes over time, revealing patterns of development direction, areas of urban growth, and spatial transformation. Increasing fractal dimension values indicate a transition toward more space-filling, continuous, and structurally complex urban patterns over time. [9, 10].

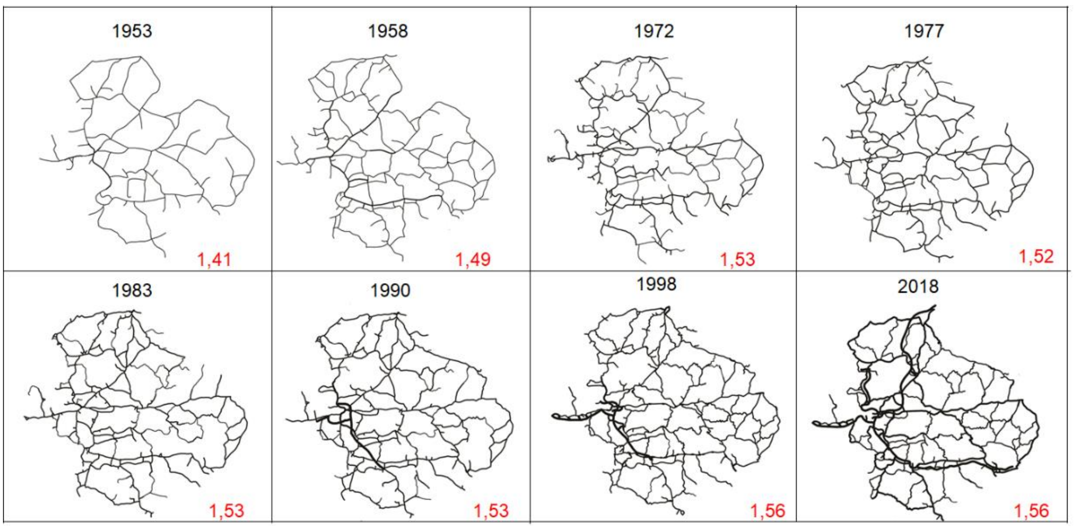

***Figure 5**. emporal evolution of fractal dimension values in the İzmir regional hinterland (1953–2018), indicating changes in urban morphological complexity [46]*

Analysis of Built Environment Structure: Fractal analysis is also applicable to specific components within the built environment (Figure 6). Beyond merely computing Fractal Dimensions (Fd_s), the concept of lacunarity is employed to evaluate the texture and spatial organization of urban forms, particularly regarding void distribution within built-up areas. This approach builds upon foundational research in statistical fractal geometry, notably Benoît B. Mandelbrot's [38] conceptualization of gaps or lacunae within fractal structures, later adapted to ecological and urban studies to characterize clustering patterns and spatial voids. Lagarias [34] utilized lacunarity to examine urban compactness, demonstrating that fragmented urban development patterns typically exhibit lower Fractal Dimensions (Fd_s) and higher lacunarity, indicative of spatial inefficiencies.

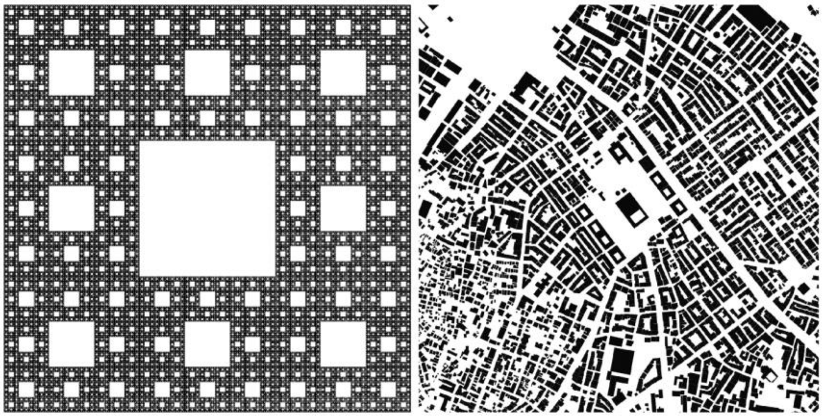

Figure 6*. Theoretical Fractal of Sierpinski Carpet and İstanbul's Fractal Urban Pattern, [39].*

In analyzing road systems, fractal methods typically involve box-counting and mass-radius (sandbox) techniques. The box-counting method involves overlaying grids at various scales and counting occupied cells, plotting results on a log-log graph to derive the Fractal Dimensions (Fd_s). In contrast, mass-radius approaches measure how the cumulative length or density of roads increases outward from a central point, highlighting scale-invariant growth patterns. Frankhauser [10] and Shen [12] have effectively employed these techniques to assess densification and spatial expansion. Additional methodologies, including network-based box-covering and ruler (divider) techniques, provide alternative perimeter-focused and topological perspectives. Urban roadway networks, land-use patterns, and the distribution of city elements have been consistently shown to be hierarchical, self-similar, and diverse [40]. Their fractal characteristics enable simplified quantification through Fractal Dimensions (Fd_s), reflecting their spatial occupation capacity and distributional efficiency within urban spaces.

7.FRACTAL STUDIES CONDUCTED FOR CITIES IN TÜRKİYE

In Türkiye, a growing body of research has emerged, adapting fractal methods to local urban systems. These studies have aimed to measure, visualize, and model urban development patterns by calculating Fractal Dimensions (Fd_s), employing methods such as box-counting, lacunarity, and space syntax. As cities increasingly confront challenges related to sprawl, densification, and infrastructural reconfiguration, fractal analysis has proven to be a valuable tool for assessing spatial efficiency, urban form, and the impact of planning interventions across different scales. Mehmet Ali Yüzer's PhD thesis [41] constitutes one of the earliest systematic studies on fractal analysis in Turkish urban research. The primary objective of the study was to forecast urban development patterns based on the fractal structure of the metropolitan area, utilizing a cellular automata model. Emphasizing fractal analysis as a complementary tool for predicting macroform development and land-use changes, Mehmet Ali Yüzer calculated the Fractal Dimension (Fd) of Bursa's built-up area, comparing the urban form corresponding to a population of 1.066.559 in 1997 with projections for a population of 2.813.394 by the year 2020.

Using the box-counting method applied over a 1-hectare grid, observed in Figure 7, the Fractal Dimension (Fd) of Bursa's metropolitan area in 1995 was determined to be approximately 1.60, whereas the projected urban form for 2020 exhibited a Fractal Dimensions (Fd_s) of 1.89. The simulation framework, built on cellular automata principles, grounded the urban growth rate between 1995 and 2020 on the differences in Fractal Dimension Fds. Notably, this research was conducted without the use of specialized fractal analysis software, making it one of the pioneering studies in Türkiye to systematically link urban growth modeling with fractal geometry. Another significant contribution to the fractal literature in Türkiye is H. Serdar Kaya's Msc thesis [42], which approaches urban space through the theoretical frameworks of complexity and chaos, incorporating fractal measurement methods across various scales, from the city level down to building facades. Employing the box-counting method applied to road networks via HarFA software, the study calculated the Fractal Dimensions (Fd_s) of traditional urban fabrics in several cities, as listed in Table 1, finding values between 1.49 and 1.89.

***Figure 7**. The Fractal Structure of Bursa's Built-up Area in 1995 [65]*

In addition, H. Serdar Kaya [42] undertook a detailed analysis of two neighborhoods in İstanbul, examining their road networks, boundaries, blocks, silhouettes, and building facades. The results demonstrated that the neighborhood located within the historical peninsula exhibited a higher Fractal Dimensions (Fd_s) highlighting the multi-fractal structure of İstanbul. Specifically, the Fd of the road network in Cerrahpaşa was calculated as 1.72, compared to 1.40 for Marmara Evleri, a modern residential area characterized by grid-planned apartment blocks. Building on these findings, H. Serdar Kaya and Fulin Bölen [43] articulated two critical observations: (i) the modernist planning approach, with its emphasis on ordered geometries, has resulted in open spaces becoming undefined and underutilized, disrupting the continuity of intricate urban systems by producing enclosed and isolated areas; and (ii) the absence of a hierarchical structure within the transportation network, combined with a high degree of geometric regularity, has diminished the potential for interaction and connectivity among urban elements.

Following Mehmet Ali Yüzer's [41] pioneering work, Gizem Erdoğan and K. Mert Çubukçu [44] investigated changes in Bursa's fractal dimension values to evaluate the efficiency of space utilization. Utilizing remote sensing data and applying the box-counting method through Fractalyse software, they determined that Bursa's fractal dimension values increased from 1.68 in 2002 to 1.71 in 2012. This finding aligns with theoretical predictions by Micheal Batty and Paul Longley [7], and Micheal Batty and Yichun

Xie [45], who argued that Fractal Dimensions (Fd_s) typically rise over time due to population growth and the spatial densification associated with planned urban development. Moreover, they attribute part of this positive trend to the enactment of the 2004 Metropolitan Municipality Law (Law No. 5216), which centralized planning authority, promoted a more structured and measurable growth trajectory for Bursa's metropolitan area. In contrast, Fatih Terzi and H. Serdar Kaya [46] reveal a different dynamic in İstanbul's urban evolution. Their fractal analysis identifies a 'concentrated urban form' between 1975 and 1995, followed by the emergence of a more 'dispersed and semi-linear form' between 1995 and 2005.

As the population of the mega city continued to increase and its boundaries approached environmental thresholds, multi-centered development strategies through master plans encouraged further outward expansion. This expansion led to a decline in İstanbul's Fractal Dimensions (Fd_s) values, indicating increasing spatial fragmentation. These findings of Fatih Terzi and H. Serdar Kaya [46] underscore a negative correlation between Fractal Dimensions (Fd_s) and urban sprawl. Another significant study examining the long-term evolution of space-filling efficiency in urban form was conducted by Gizem Erdoğan and K. Mert Çubukçu [47]. Using aerial photographs and satellite imagery of the metropolitan area of İzmir, they calculated the Fractal Dimensions (Fd_s) of the urban macroform boundaries for the years 1951, 1963, 1987, 1996, and 2000. Their findings, as seen in Figure 8, the progressive increase in fractal dimension (D) values over time, indicating a transition from more fragmented and less space-filling urban patterns toward increasingly compact, continuous, and morphologically complex urban form. Higher D values reflect intensified spatial occupation and structural integration of the metropolitan area. Notably, the decrease in Fractal Dimensions (Fd_s) observed in the second period is attributed to the first major wave of urban spillover triggered by rural-to-urban migration during the 1950s.

A comparable pattern was identified in Bursa by Ceyda İlhan and Özgür M. Ediz [48], where the Fractal Dimensions (Fd_s) sharply declined from 1.82 to 1.57 between 1939 and 1958, coinciding with the onset of industrial development, the establishment of the Bursa Organized Industrial Zone, and the expansion of surrounding villages. Lacunarity analysis further corroborates this shift, with an increase in porosity value during the same period, reflecting a more fragmented and perforated urban structure. In subsequent decades, an increase in the Fractal Dimensions (Fd_s) and a concurrent decrease in lacunarity indicated that the urban fabric gradually became more continuous and homogeneous. This evolution toward greater compactness can be attributed to infill development along main transport corridors and the closure of spatial gaps between previously isolated settlements. Neşe Aydın [49] identified a similar trajectory in the city of Isparta, where satellite image analysis at two-year intervals between 2003 and 2015 revealed a steady trend toward urban compactness, characterized by a reduction in void spaces relative to built-up areas.

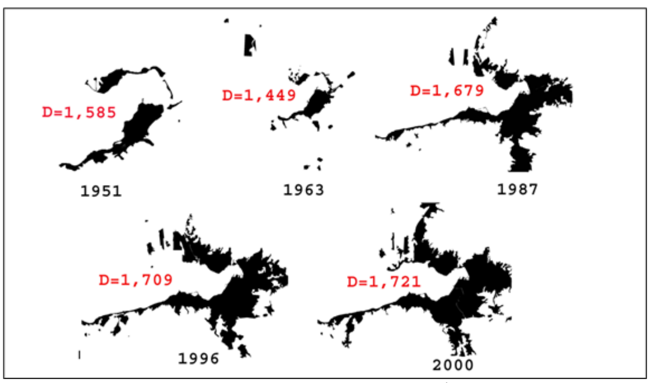

Figure 8*. Temporal change in fractal dimension values of the İzmir Metropolitan Area between 1951 and 2000 [47].*

Another historical analysis of urban Fd change is provided by Beyza Köprülü and Mehmet Topçu [50], who calculated fractal dimension values across six different periods between 1946 and 2020 in the evolution of Konya’s urban texture. Their findings demonstrate a rapid increase in the fractal values beginning in 1999, particularly in the last three periods, reflecting the intensification of urbanization and corresponding rise in the complexity. Moreover, by analyzing several neighborhoods characterized by different urban textures the study revealed that the transition from traditional, organically evolved forms to modernist urban construction was associated with a noticeable decrease in Fractal Dimensions (Fd_s). On the other hand, Atabeyoğlu and Bulut [51] conducted a fractal analysis for the city of Ordu using Harfa 5.3 software, aiming to explore the relationship between Fd and various spatial parameters. A quantitative evaluation was carried out by analyzing fifteen neighborhood-level spatial factors, including aesthetic, historical, and touristic values, as well as green area density.

One of the major findings of Ömer Atabeyoğlu and Yahya Bulut [51] was that Ordu's overall Fd, calculated at 1.49, was significantly lower than the values typically observed for other Turkish cities, such as İstanbul, where Fractal Dimensions (Fd_s) in 2006 ranged from approximately 1.70 to 1.80, comparable to those observed in major European metropolitan areas [19]. However, while the average Fd for the city of Ordu was relatively low, individual neighborhoods exhibited Fractal Dimensions (Fd_s) closer to 1.7. This suggests that although individual districts possessed sufficient spatial complexity, the city as a whole appeared simpler, more uniform, and aesthetically less rich when considered as a unified system. Furthermore, the study highlighted that the distribution of green areas across Ordu was highly uneven. Although certain parts of the city exhibited dense "green tissues," other zones suffered from a marked deficiency of green spaces, as reflected in the lower average fractal values for green areas.

H. Serdar Kaya and Fulin Bölen [52] conducted a comprehensive analysis of İstanbul’s urban structure by jointly examining geometrical, topological, use- and perception-related, and complexity parameters as complementary dimensions. Their study focused on the multi-Fd of İstanbul by considering scaling relationships, developing an integrated model to provide a deeper understanding of the city's urban character. This model synthesizes multiple morphological parameters—fractal analysis, lacunarity, and space syntax—to map urban patterns from the building scale to the citywide level. The model conceptualizes the "DNA" of urban form, highlighting that İstanbul does not follow a consistent pattern of densification from the center toward the periphery. Instead, the level of spatial complexity tends to increase in relation to the age of the urban pattern, with historic areas. A broader national study was conducted by Ceyda İlhan and Necmi Gürsakal [53], who employed the open-source software ImageJ and its FracLac plugin to perform fractal analysis across all 81 provincial centers in Türkiye. Their findings, subsequently subjected to hierarchical cluster analysis, revealed that smaller-sized cities tend to exhibit more morphological similarities.

One notable contribution is the identification of a statistically significant positive correlation [$p<0.01$] between Fractal Dimensions (Fd_s) and socio-economic indicators such as population size and GDP per capita at the provincial level. Complementing these findings, Rana İbrahim Abid and Ahmet Tortum [54] performed a nationwide analysis of Türkiye’s provincial centers, focusing specifically on transportation networks. Using BENOIT software, they analyzed merged railway and road network systems based on OpenStreetMap data, cropped according to visualized urban boundaries. Their study examined the correlations between Fractal Dimensions (Fd_s) and variables such as the number and total length of network lines, urbanized area, and population. The results indicate positive correlations across all variables, with the number of transportation lines showing the strongest relationship to Fractal Dimensions (Fd_s). This suggests that a more mature city is likely to possess a denser, more intricate transport network system than a less mature one. In contrast, a moderate correlation was observed with population, leading to the conclusion that further population growth does not necessarily translate into increased spatial complexity. The spatio-temporal evolution of the urban fabric across 17 districts of Samsun province was analyzed by Derya Öztürk Engin and Uğur Gündüz [55] through the integration of GIS and fractal analysis, using CORINE Level-2 land use/cover data for the years 1990 and 2012. Areal transformations were identified via superimposition and cross-tabulation techniques, while fractal analysis was employed to assess patterns of urban sprawl and spatial heterogeneity. In a related study, Sıla Özdemir [56] investigated regional complexity in the İzmir by analyzing an extended territorial scale encompassing major connecting corridors of adjacent provinces, including Manisa and Aydın (Figure 9). The study focused primarily on temporal changes in the structure of 1:25,000-scale road networks from the 1950s to the present, segmented into four distinct time periods. By correlating population data with road network-derived Fractal Dimensions (Fd_s), the research identified a statistically significant positive relationship [$p<0.01$]; however, continuous population growth did not always correspond with increased spatial complexity. Instead, the extended region displayed alternating periods of stability and transformation, a dynamic consistent with chaos theory [56].

As Micheal Batty [1] and Peter M. Allen [57] note, cities often exhibit chaotic behavior over the long term, wherein steady states or slow processes are punctuated by rapid changes and turbulence in the short run. In addition to the extended regional analysis, Sıla Özdemir [56] calculated the Fractal Dimensions (Fd_s) of 30 districts within İzmir province, analyzing both individual components and the provincial system as a whole. Interestingly, non-urban peripheral settlements exhibited relatively high Fractal Dimensions (Fd_s) during the earlier periods, which the study attributes to the complex spatial patterns of rural and agricultural land use. These findings suggest that spatial isolation can itself embody a degree of intrinsic complexity. Moreover, the study identified spatial clustering tendencies among İzmir's districts, allowing for the delineation of sub-regions based on similarities and differences in their Fractal Dimensions (Fd_s). The findings emphasized that network complexity is not solely determined by centrality; traditional rural settlements such as Ödemiş consistently exhibited high Fractal Dimensions (Fd_s) values, suggesting that spatial complexity can also emerge in peripheral and historically evolved areas.

Sıla Özdemir [56] further advanced its analytical framework by integrating space syntax metrics to examine the internal dynamics of spatial complexity. Sub-regions were defined endogenously, based on functional and morphological relationships, rather than constrained by official administrative boundaries. This approach revealed the changing spatial linkages between the central city and sub-centers, as well as between the broader metropolitan region and its hinterland. Building on this foundation, Şahin [58] employed the same road network dataset for İzmir, covering the period from the 1950s to the present. In this study, road patterns were segmented according to master plan boundaries corresponding to each historical planning phase, enabling the assessment of metropolitan-scale spatial complexity. Şahin investigated the relationship between metropolitan-level land use planning decisions and temporal changes in Fractal Dimensions (Fd_s) values, placing particular emphasis on the interplay between unplanned urban development and the self-adaptive capacities of the metropolitan system. The findings conclude that spatial planning interventions—including master plans—actively shape and trigger morphological transformations, both within the designated planning areas and in their surrounding contexts through spatial interaction and diffusion effects.

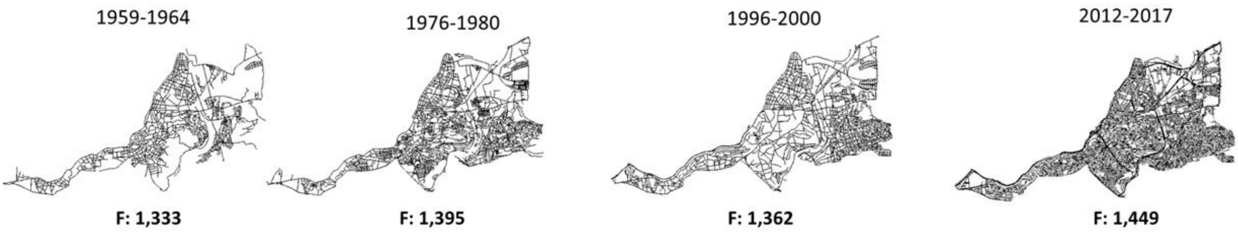

Figure 9. *Fractal Dimension Changes of Konak District [46]*

This section provides a comprehensive review of empirical studies conducted in Türkiye that apply fractal geometry to urban form, macrostructure, transportation networks, and land use patterns. From early foundational work by Mehmet Ali Yüzer [41] and H. Serdar Kaya [42] to more recent integrative approaches by Sıla Özdemir [56] and Mustafa Raşit Şahin [58], this literature reflects the methodological evolution and thematic diversification of fractal analysis within the Turkish urban context. In addition, the list of studies is given in Table 1. Almost all uses box-counting methods. These contributions not only validate the relevance of fractal methods for measuring space-filling efficiency and spatial heterogeneity but also demonstrate their capacity to uncover long-term urban dynamics, regional complexity, and the differentiated impacts of planning practices in metropolitan and peripheral settings. The reviewed body of research illustrates the increasing methodological sophistication and empirical richness of fractal studies conducted in Türkiye's urban environments. From Bursa and İstanbul to İzmir, Konya, and Ordu, Fractal Dimensions (Fd_s) have been used to assess urban compactness, sprawl, and morphological transitions across both historical and contemporary time frames. These analyses reveal that fractal geometry is not merely a descriptive tool, but a diagnostic and predictive framework capable of capturing the non-linear, multi-scalar, and often chaotic behavior of urban systems.

Table 1. A Literature Review of Fractal Dimension Analysis of Turkish Cities

Reference	Case City/ Region	Analysis Method	Main Findings
[65]	Bursa	Grid based box-counting; Urban macroform	Fd of the metropolitan area is calculated as 1.60 for 1995 and forecasted as 1.89 for the projection year of 2020.
[34]	Çorum, Erzurum, Giresun, İzmit, K.Maraş, Mardin, Siirt, Sivas, Trabzon & two neighborhoods of İstanbul	Box-counting; Urban macroform, road network, blocks, street silhouette & facades	Fds of road networks across different cities are ranging from 1.49 to 1.89. Fd in Cerrahpaşa is calculated as 1.718, compared to 1.402 for Marmara Evleri.
[35]	İstanbul	Not mentioned; Blocks	Fds of İstanbul, generally between 1.7 and 1.8 in 2006 are comparable to those of other cities in Europe and the developing world. Fractal values around 1.7 and lower reflect modern layout.
[45]	İstanbul	Box-counting; Urban macroform	Fds between 1975-1995 are gradually increased from 1.58 to 1.70. Fractal value decreases to 1.57 in 2005.
[58]	İzmir	Box-counting; Urban macroform	Fds are increasing from 1.59 in 1951 to 1.72 in 2000. Decrease in 1963 can be explained by rural immigration during the 1950s.
[21]	Bursa	Box-counting;	Fd increased from 1.68 in 2002 to 1.71 in 2012.

		Urban macroform	
[22]	Ordu	Box-counting; Aerial photographs and street scenes	Fd of the city as a whole is 1.49. However, individual neighborhoods exhibit Fds closer to 1.70.
[5]	Isparta	Box-counting; Urban macroform	Fds are increasing from 1.36 in 2003 to 1.43 in 2015.
[6]	İstanbul	Box-counting; Urban blocks	Highest Fds, 1.80 in the European and 1.77 in the Anatolian side, are seen in the historical core. It reduces to 1.40 in the newly developed periphery.
[27]	Bursa	Box-counting; Urban macroform	Fractality and lacunarity values in 1939 are 1.82 and 0.14. The city has compacted from 1.57 and 0.62 in 1958 to 1.80 and 0.21 in 2019.
[28]	81 provincial centers of Türkiye	Box-counting; Road network	Highest Fds are 1.77 of Ankara, 1.74 of Kocaeli and 1.73 of Antalya while lowest Fds are 1.34 of Bitlis, 1.39 of Çankırı and 1.42 of Bilecik. Lowest lacunarity values are 0.45 of Kocaeli, 0.46 of Zonguldak and 0.55 of Düzce while highest values are 1.09 of Kırşehir, 1.05 of Hakkari and 1.04 of Çanakkale.
[50]	Samsun	Box-counting; Corine data	Fds increase in 9 of 17 districts of Samsun between 1990-2012, and lacunarity index also increase in 6 of them.
[1]	81 provincial centers of Türkiye	Box-counting; Road and railway network	Fds are between 1.438 and 1.795. Strongest positive correlation is with the log of number of transport lines. Moderate positive correlations are found with the logs of both urbanized area and population.
[46]	Extended region of İzmir, province & 30 districts of İzmir	Box-counting; Road network	Fd of extended region of İzmir is steadily increasing from 1.41 in 1953 to 1.56 in 2018. Fds of province are 1.50 in 1958-1964, 1.58 in 1976-1980, 1.82 in 1996-2000, and 1.72 in 2012-2018. Fds of Konak among districts are 1.33, 1.40, 1.36 and 1.45 from mid 1950s to late 2010s.
[39]	Konya	Box-counting; Urban macroform	Fd in 1941 increases from 1.62 to 1.67 in 1964, then decreases to 1.61 in 1982. Fds are increasing from 1.60 in 1999 to 1.68 in 2020.
[56]	Metropolitan area of İzmir	Box-counting; Road network	Fds in 1950s are increasing from 1.49 to 1.58 in 2020s within the boundary of Aru Master Plan. Fds are increasing from 1.37 to 1.48 within the boundary of IMM Plan for 1973-78. Fds are increasing from 1.41 to 1.59 within the boundary of IMM Plan for 1989. Fds are increasing from 1.28 to 1.41 within the boundary of IMM Plan for 2012.

8.CONCLUSION AND RECOMMENDATIONS

The integration of fractal geometry into urban planning has not only enriched our theoretical understanding of spatial complexity but also expanded the practical tools available for analyzing and guiding urban development. Cities should be viewed as self-organizing systems whose forms emerge from bottom-up processes rather than top-down designs [1, 2, 3, 5]. This perspective challenges conventional planning paradigms by recognizing the dynamic, adaptive, and often non-linear nature of urban growth. Fractal geometry offers a quantitative framework to represent these complex dynamics, capturing the irregularity, scale dependence, and self-similarity observed in urban structures. This study has examined the multifaceted applications of fractal analysis in urban contexts, revealing underlying order within the apparent chaos of cities.

Fractal geometry introduces a dynamic dimension to urban studies, allowing for the anticipation of development trends and the formulation of responsive planning strategies. Multi-scale fractal structures have enriched our understanding of urban form by revealing hidden systems across various levels of magnification, helping planners detect patterns often overlooked by traditional methods. This layered complexity supports urban designs that align aesthetic, functional, and environmental dimensions. Likewise, self-affine fractal structures underscore the inherent adaptability of cities, reflecting their capacity to adjust to evolving demands and environments —a foundational principle in promoting urban resilience. The investigation of multi-fractal structures further captures the hierarchical and heterogeneous nature of urban complexity, providing a holistic understanding that supports optimized spatial organization and resource distribution.

By applying fractal geometry to urban morphology, insights into the distribution of built forms, public spaces, and architectural features have been harnessed to foster designs that resonate with aesthetic appeal and functional efficiency. Numerous studies have demonstrated that urban formation and spatial distribution adhere to fractal principles. Essential findings from these studies indicate that Fractal Dimensions (Fd_s) typically increase as cities expand and infill, shifting to denser, more space-filling urban forms. Benguigui et al. [8], for instance, illustrated how Tel Aviv's street network evolved from a fractal configuration concentrated in its core towards a comprehensive, city-wide fractal structure following substantial peripheral development. Similarly, Guangjiyan Shen [12] documented Baltimore's fractal growth over two centuries, or for Antwrep [59] by using road system as a fractal structure, noting a consistent rise in spatial complexity. These empirical examples show that fractal metrics can reflect shifting urban patterns, offering planners a quantitative basis for assessing spatial efficiency and fragmentation.

In Türkiye, extensive empirical research has validated the utility of fractal geometry in assessing urban morphological changes and guiding sustainable urban development policies. City-specific and nationwide studies conducted in Turkish cities reveal significant findings regarding the current complexity dynamics of cities and the impact of urban development and sprawl on urban complexity and efficiency. The consistent use of fractal methodologies across diverse urban settings underscores their versatility and robustness. Future urban planning approaches, leveraging fractal analysis, can more precisely address the nuanced dynamics of urban growth, promoting resilient, adaptive, and coherent urban spatial strategies. Despite its promise, the challenge remains in translating fractal-based insights into actionable planning policies. Translating fractal insights into regulatory frameworks, zoning policies, or design guidelines requires further methodological refinement and institutional adaptation.

As De Roo et al. [60] and Emine Yetişkul [6, 61] discuss, planners must navigate between order and complexity, embedding flexibility within planning systems while maintaining regulatory coherence. This requires a shift in planning practice—away from rigid, deterministic approaches toward adaptive frameworks that acknowledge and work with the inherent complexity of urban systems. Fractal geometry offers a powerful paradigm for interpreting and shaping urban systems. It bridges analytical rigor with creative vision, equipping planners and researchers with the tools to understand urban complexity in ways that traditional models cannot. In conclusion, fractal geometry emerges not simply as a descriptive technique but as a foundational component of a new urban science—one that understands cities as evolving, complex systems and equips us to design them more effectively in a rapidly changing world.

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Mustafa Raşit ŞAHİN, Dr.,
An expert at the Financial Services Department of Altındağ Municipality and a part-time lecturer in the Department of City and Regional Planning at Middle East Technical University, Ankara, Türkiye.

SILA ÖZDEMİR, Dr.,
City planner in the General Directorate for Protection of Natural Assets at the Ministry of Environment, Urbanization and Climate Change and a part-time lecturer in the Department of City and Regional Planning at Middle East Technical University, Ankara, Türkiye.

Emine YETİŞKUL, Prof. Dr.,
Professor in the Department of City and Regional Planning at Middle East Technical University, Ankara, Türkiye.

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