

A Multi-Dimensional Quantitative Assessment Framework for Digital Integration in Sustainable Environmental Design of Residential Complexes (Al-Sultan Residential Complex in Najaf Al-Ashraf as a Case Study)

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Abstract:

The present study is concerned with creating a comprehensive evaluation framework consisting of multiple dimensions of quantitative indicators for measuring digital integration levels in the context of sustainable environmental design for residential complexes. The framework has been created based on the information provided about the Al-Sultan Residential Complex in Al-Najaf Al-Ashraf, Iraq.

In response to the absence of a clear quantitative mechanism for assessing digital integration in sustainable environmental design, the proposed framework suggests that the use of digital technology to measure environmental indicators enhances the process of assessing performance, including energy efficiency, thermal comfort, and internal environmental quality. The research methodology was both analytic and evaluative and used quantitative indicators across five major areas; digital connection, digital environmental monitoring, energy use efficiency, environmental integration with vegetation, safety and security. All of these indicators were compared against benchmarks using international standards.

Digital simulation, according to the obtained results, can be implemented across all areas of design to achieve energy savings and improved thermal comfort, as well as to ensure adequate indoor air quality through monitoring systems. On the other hand, the results revealed that there was no net-zero energy performance because buildings are still utilizing traditional forms of electricity; further, there is little green space even though the pedestrian network has been designed properly and is up to code with the amount of native plants; and finally, the ratings for safety were moderate.

According to the research, in order for home complexes to develop environmentally sustainable practices, they need to utilize a complete planning technique that integrates growing the amount of green space, utilizing renewable energy resources, and improving the quality of

urban areas so as to change the concept of sustainability from a descriptive one into an ability to do a measurable assessment of sustainability.

Keywords: Digital Integration, Sustainable Environmental Design, Quantitative Environmental Indicators, Sustainable Environmental Performance Assessment of Residential Complexes, Digital Environmental Simulation, Al-Sultan Residential Complex

1. Introduction

The architecture/construction industry has experienced significant changes during the last several decades because increased environmental issues (globalisation), population increases in cities and increased consumption of energy. In fact, as buildings make up about 34% of the total energy consumed worldwide and are responsible for around 37% of carbon emissions related to energy consumption, improving the environmental performance of buildings should be a primary goal for creating sustainable development goals. [1]

As a result, Sustainable Environmental Design has now become a core component of modern architectural design. Through implementing sustainable features in buildings, the negative environmental impact can be reduced by improving energy conservation, using resources wisely, and providing better indoor environmental quality through coordinating and harmonizing environmental, financial and social factors [2]

Digital technology continues to rapidly advance, and as a result, Building Information Modeling (BIM) and energy simulation systems are now being used together in what may be considered a standard method for enabling designers to see and test their design decisions before making them permanent. Recent studies have shown that using digital technologies such as these has produced measurable improvements in the areas of energy efficiency and advancements towards sustainability in the environment [3] [4]

Extensive research has been conducted on the relationship between using digital tools and how buildings perform environmentally. Multiple authors have traced the development of BIM, as a framework for supporting design decisions throughout the building lifecycle; integrated simulations with BIM platforms and improved energy efficiency, thereby reducing carbon footprint; and demonstrated a strong correlation between the design strategies used with energy and how well a building performs environmentally (inside), specifically CO₂ levels and thermal comfort. The contemporary literature appears to provide opportunities for developing quantitative indicator-based models as a means of objectively measuring and comparing sustainability levels as a result of digitization.

Nevertheless, many of the current studies focus on a single building and rely on descriptive research methods without a strong quantitative component that allows for measuring digital integration across multiple dimensions in a rigorous way. This is an especially prominent

issue in the built environment of Arab/Iraqi regions, where there are no field studies that employ integrated quantifiable indicators to measure residential complexes. Because of this gap in knowledge, there is an increased need for a multi-dimensional assessment framework to determine integrated digital integration, environmental monitoring, energy efficiency, and safety in relation to each other in accordance with the aforementioned requirements of the research.

1-1 Research Problem

Accordingly, the research problem lies in the absence of a comprehensive quantitative framework capable of measuring digital integration and evaluating sustainable environmental performance in residential complexes through multiple interconnected dimensions.

1-2 Research Objective

This research proposes a framework for measuring the digital integration of residential housing through a quantitative assessment of five different axes: digital integration, environmental monitoring, energy efficiency, environmental integration with nature, and safety and security. The research will apply these measures to the Al-Sultan Residential Complex in Najaf Al-Ashraf, Iraq.

1-3 Digital Integration

Digital integration within sustainable architectural design involves the progressive use of computer software/programs/equipment to analyses and assess buildings' ecological performance through the many stages of the design process. Digital integration also extends beyond individual buildings to urban-scale modelling and simulation, where computational tools can be employed to analyses urban growth patterns, transportation systems, and environmental interactions. Such approaches support more informed planning decisions and enhance the sustainability performance of the built environment through predictive modelling and scenario evaluation [5]. These approaches include digitally simulating designs, analyzing environmental data and creating computation modelling, allowing designers to foresee the effects on the ecological performance of buildings, as a result of their decisions, before any construction takes place.

The integration of these elements enhances and supports design decision-making by providing quantitative data on energy efficiency, thermal comfort, and indoor environmental quality that enables monitoring of the relationship between buildings and their context. Current research shows how the combination of digital analysis and sustainable design principles provides an opportunity to develop quantitative indicator-based assessment models for use in sustainable design, thus allowing for the objective and comparable measurement of sustainability levels in various projects, and increasing the capacity of designers to improve environmental performance. [6]

1-4 Sustainable Environmental Design

Through a combination of energy-efficient design and indoor environmental quality, sustainable environmental design is an encompassing strategy for minimizing the effects of built-up warehousing on our planet. By embedding environmental concerns throughout the entire design and planning processes of any built project, sustainable environmental design can create buildings that are more efficient in the way they consume energy/produce emissions or can increase thermal comfort and use natural resources, including daylighting and ventilation, to their fullest capacity.

There are many studies that prove the benefits of using sustainable building techniques to improve the environment, use fewer resources, and provide healthier living and working conditions for occupants. For this reason, sustainable environmental design has grown in importance to the overall progress of the construction industry as it relates to reaching the UN's sustainable development goals and minimizing the negative impacts associated with urban living. [7] [8]

1-5 Environmental Sustainability Indicators

Quantitative Environmental Indicators, analytical tools used to assess the environmental performance of buildings quantitatively and comparatively, convert into numerical values the environmental aspects of projects and provide a means for making an objective assessment of the efficiency of urban development projects. This method will enable the creation of a database of quantitative data identifying the relationship between urban elements and the impact these elements have on sustainability.

In modern literature, quantitative measures represent a scientifically useful tool for evaluating how well the environment performs; they allow for accurate measurements of levels of effectiveness, provide opportunities to compare projects to each other, and increase the quality of decision-making processes in design (10) (11).

The relationships and environmental performance factors affect multiple components within an urban environment; therefore, quantitative indicators are particularly important when evaluating residential complexes. This research will establish a set of quantitative indicator measures of the dimensions of digital integration of sustainable environmental design and include the following categories: digital integration, environmental monitoring systems, energy efficiency, environmental integration with nature and safety/security. This will allow for the creation of a holistic assessment framework of the environmental performance of residential complexes while identifying strengths and weaknesses of the study area.

1-6 Environmental Monitoring System

Environmental monitoring systems consist of several digital technologies and tools that are used to monitor the environment within buildings and in urban areas. These systems mainly use advanced sensing devices and digital technologies to gather various types of data from the environment and convert it into information that can be analyzed or interpreted. This may

include data on indoor air quality, the concentration of gases, and levels of pollutants, as well as thermal variables related to buildings' indoor climates. The use of these systems will provide an accurate picture of the actual environmental conditions in architectural features, and help people understand how the characteristics of buildings are related to the environmental conditions around them.

Contemporary literature on this topic supports that environmental monitoring systems are a foundational pillar of sustainable building management systems as they provide continual monitoring of the indoor environment and allow for the collection of data that can be used to evaluate the environmentally sound performance of the building and improve the operational efficiency of the building. The function of environmental monitoring systems is also increased in smart buildings and modern residential developments, as the data collected provides inputs into environmental analyses that help make decisions regarding energy efficiency improvements and increasing indoor environmental quality [6] [9]

2- Methodology

2-1 Research Methodology

The research applies a quantitative analytical method to measure how well residential projects have performed environmentally in terms of sustainability and to assess how well digital technologies are helping to create sustainable environments from design through construction and operation by evaluating each aspect of an environment's sustainability with a quantitative environmental indicator (i.e., the characteristics of an environment that determine its environmental sustainability) that supports each aspect of its sustainability by providing a numerical value to facilitate comparison and analysis with quantitative analytics, standards, and benchmarks derived from both scientific studies and applicable international standards.

The research method focuses on the relationship between digital integration and the environmental performance of urban areas, specifically, the assessment of a collection of indicators related to environmental monitoring systems; indoor air quality; energy efficiency; integration of nature into the built environment; and safety/security features. Additionally, this provides a consistent methodological framework for determining the environmental performance of a residential complex in a rigorous and scientific way. Furthermore, this will enable a meaningful comparison of a residential complex's environmental performance against reference values from existing international literature and standards. Furthermore, GIS-based spatial analysis has been widely recognized as an effective approach for environmental assessment, spatial suitability analysis, and sustainable planning decision-making, allowing the integration of multiple environmental variables within a comprehensive analytical framework. [10]

2-2 Research Design

This research design is based on developing a quantitative evaluation system to measure how well residential buildings are performing based upon how environmentally sustainable they are. The evaluation will use constructed quantitative indicators associated with the idea of digital integration in the design of sustainable buildings throughout the evaluation process. The analysis of a number of critical dimensions will be used to evaluate the performance of residential buildings, which will be organized into five basic areas, including: the amount of digital

integration during the design process and the ability to model the building's environmental impact before it is built; the presence of systems which monitor the building's impact upon indoor air quality; the buildings' ability and efficiency of operation when using energy; the building's ability to integrate with nature and have sufficient vegetation around it; and lastly, the building's ability to provide a safe and secure environment for its occupants and the surrounding community.

Using these axes as an analytical framework, the environmental performance of a residential development can be evaluated, converting each axis in to measurable quantitative indicators via equations and benchmark references established in academic sources and international standards relative to environmental sustainability assessment for buildings and residential developments. The design will also provide the basis for a complete analytical methodology for assessing the environmental performance of the residential development and will help define a methodical and scientific basis of evaluating the residential development's environmental performance by comparing the actual measured values of the environmental indicators with the appropriate reference values from published international literature and standards.

To ensure the reliability and objectivity of the proposed assessment framework, the selected indicators were evaluated against internationally recognized reference systems and standards. ASHRAE standards were adopted for indicators related to indoor environmental quality, thermal comfort, ventilation, and energy performance. LEED criteria were used to evaluate sustainability-related aspects such as environmental integration and site performance. In addition, ISD indicators were utilized as a reference framework for assessing broader sustainability dimensions. These reference systems provide benchmark values that enable the comparison and interpretation of the measured performance indicators.

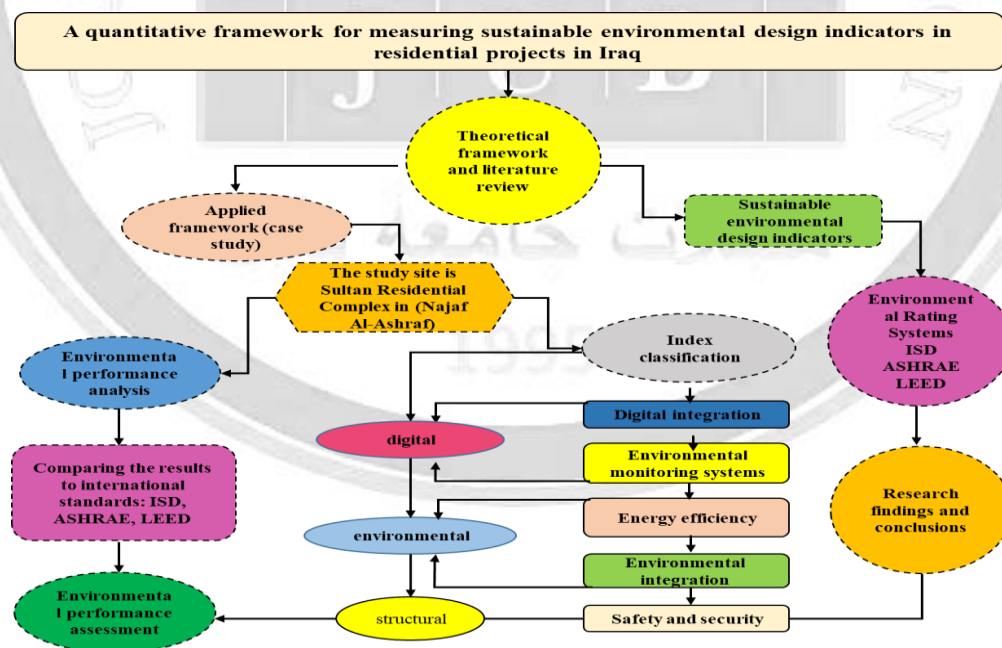


Figure (1) illustrates the methodology used in the study

2-3 Indicator Extraction and Classification

The purpose of this study is to develop a system of quantitative indicators that can be used to assess the environmental performance of buildings and sustainable residences based on academic research. These indicators have been chosen based on specific criteria that support compatibility with the concept of digital integration into sustainable environmental design. Using these indicators will provide more consistent, measurable and comparable ways to evaluate the environmental performance of residential buildings and complexes.

A set of axes were established for the purposes of organizing and managing the analytical process and to guide the development of environmental indicators adopted in this study, including: a) Digital Integration; b) Environmental Monitoring Systems; c) Energy Efficiency d) Environmental Integration with Nature; e) Safety and Security within the Built Environment. Based on each of the five axes, the environmental indicators were translated and developed into quantified indicators by means of analytical equations and by developing reference benchmarks from the scientific literature and international standards that pertain to environmental sustainability assessment of buildings.

2-4 Measurement Tools, Quantitative Equations, and Measurement Procedures

To evaluate residential complexes' sustainable environmental performance, this research uses specialized analytical tools and quantitative equations. The researchers selected measurement tools and reference benchmarks established by the scientific community and based on internationally accepted standards for assessing environmental sustainability in the construction of buildings. Indicators will be used to measure the incorporation of digital technologies into sustainable environmental design, the use of environmental monitoring systems, the energy efficiency of the buildings, and the degree to which the building interacts with nature. The researchers will also use indicators that measure how safe and secure the buildings are.

Quantitative equations were employed to rigorously and systematically measure the specified indicators, thereby allowing for the identification of numerous different environmental types and the corresponding conversion of those environmental types into numerical values, which could then be analyzed and compared. As a part of this process, measures of digital integration in design and environmental simulation processes, thermal comfort improvement in buildings, and indoor environmental quality (IEQ) through gas concentrations in indoor air were included as indicators. Various international reference standards, such as ASHRAE, LEED, and IEA, were utilized to compare of measured values against established thresholds or benchmark values in building environmental assessments.

The quantitative environmental indicators were calculated using field measurements collected from the residential complex, including indoor environmental quality and thermal performance data. These measurements were then integrated with digital analysis outputs obtained from GIS spatial analysis, ENVI-met environmental simulations, and digital monitoring systems. The link between these data sources was established by converting all collected and simulated results into standardized quantitative indicators, which were subsequently compared

with international benchmark values. This integrated approach enabled a comprehensive assessment of the sustainable environmental performance of the residential complex.

3 -Case Study: Al-Sultan Residential Complex in Najaf Al-Ashraf

3-1 Introduction

Najaf Al-Ashraf is located within an arid and semi-arid climatic zone characterized by elevated summer temperatures, scarce precipitation, and intense solar radiation — conditions that directly influence buildings' energy efficiency and thermal comfort requirements, making sustainable design a fundamental challenge in urban planning [11] [12]

Al-Sultan Residential Complex is a planned residential development within Najaf Al-Ashraf's urban fabric, comprising residential units of consistent architectural character alongside an internal street network and essential services

3-2 Geographic Location

The complex is situated in the northeastern part of Najaf Al-Ashraf within the Al-Nida district, near Airport Street and Al-Kafeel University Road. Its boundaries are defined by the main complex road to the north, agricultural land to the south, investment developments to the east, and modern residential clusters to the west — positioned within the city's urban expansion

zone with connectivity to the urban fabric.

3-3 Architectural and Urban Planning Layout

The complex adopts a grid distribution system with rectangular residential masses of 10×20 meters arranged in parallel rows, with appropriate setbacks creating semi-public spaces that enhance privacy and natural ventilation. Units are oriented along north-south and northeast-southwest axes in response to local climatic conditions, while the circulation system branches from a primary axis into secondary streets and dedicated pedestrian pathways.

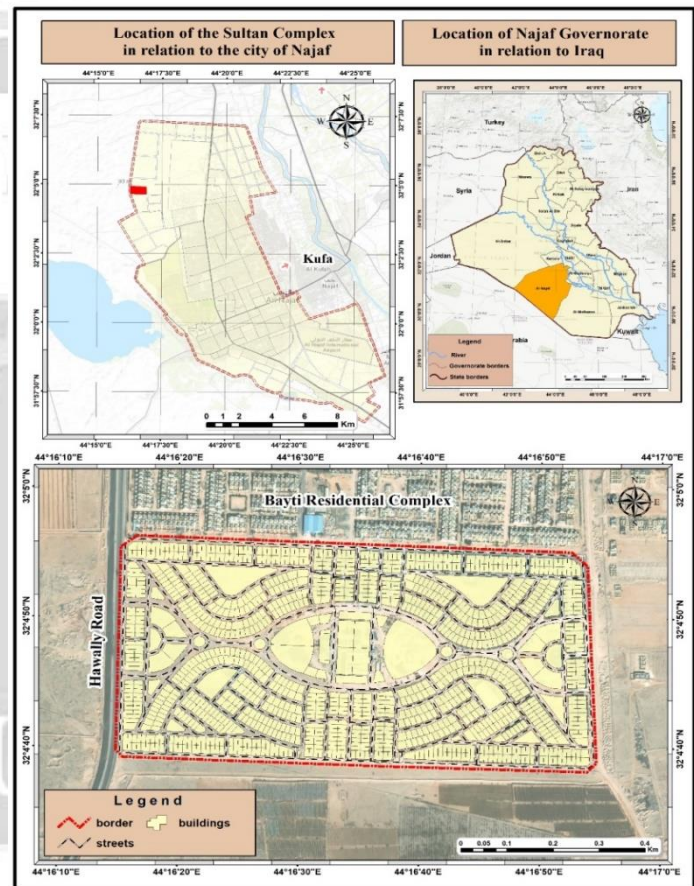


Figure (3) is a diagram showing the location of [13].the Sultan residential complex

Al-Sultan was selected as the case study due to its representation of contemporary residential complexes in Najaf Al-Ashraf, availability of architectural plans, and the feasibility of field measurements. Its repetitive typological character provides an appropriate environment for systematic quantitative analysis generalizable across the entire complex [13] [14].



3-3 Complex Characteristics

The complex extends across approximately 211 dunams (21.1 hectares), accommodating 1,168 residential units ranging between 175–200 square meters. Insulating Concrete Formwork (ICF) technology was employed to achieve high thermal efficiency and minimize noise transmission. Service facilities include schools, a mosque, a commercial center, and municipal installations, alongside distributed green spaces. Established in 2011 under the supervision of investor Dhargham Karim Saleh in coordination with the Najaf Investment Commission, the complex adopts reinforced concrete as its primary structural system, with infrastructure encompassing road networks, water pumping stations, telecommunications, electricity, and sewage systems. [13] [14]

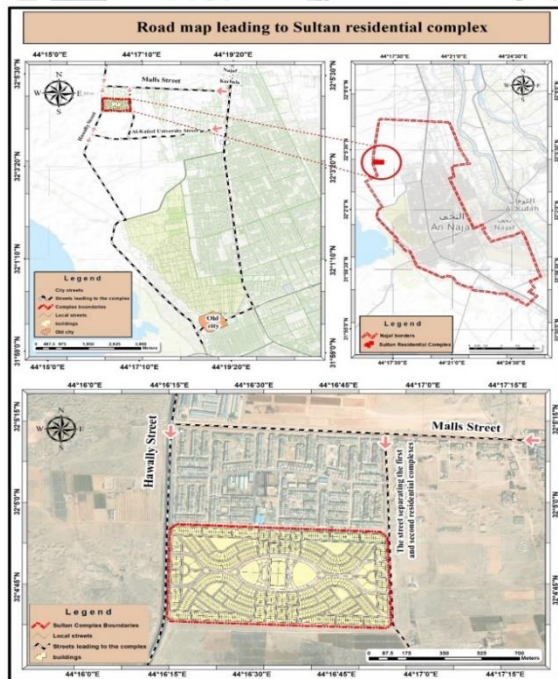


Figure (4) is a diagram showing the access routes and possibilities to the Sultan residential complex [13].



Figure (5) shows the land use plan for the Sultan residential complex [13].

3-4 Sampling Procedure

The Al-Sultan Residential Complex consists of 1,168 residential units. To ensure that the selected measurement unit was representative of the overall residential stock, a GIS-based spatial analysis was first conducted to classify and quantify the different housing types within the complex and identify the dominant residential category. Subsequently, field observations and preliminary measurements were performed on a group of residential units belonging to the dominant category. As the measured environmental characteristics showed only minor variations among these units, a representative residential unit was selected for detailed monitoring and experimental measurements. Furthermore, GIS analysis and environmental simulations were employed to extend and interpret the findings at the scale of the entire residential complex rather than limiting the assessment to a single dwelling unit.

4- Results

This section presents the results of applying the quantitative environmental indicators adopted in the study to the Sultan Residential Complex in Najaf, with the aim of evaluating its level of sustainable environmental performance. The calculated indicators included the dimensions of digital integration in design processes and environmental simulation, indoor air quality monitoring systems, as well as energy efficiency indicators, integration with the natural environment, and environmental safety and security.

The evaluation process was based on comparing the measured values of these indicators with reference values derived from international standards and specialized scientific literature, in order to determine the performance level of each indicator and its consistency with the standards adopted in evaluating the environmental sustainability of buildings and residential complexes.

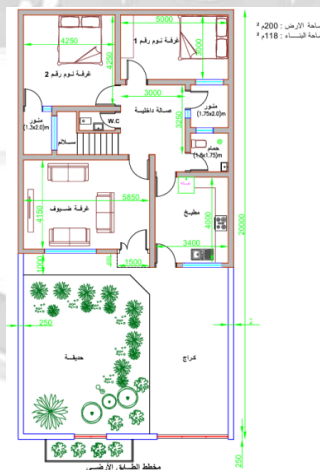


Figure (7) shows the model of the residential unit that was adopted in the measurement, representing the majority category in the complex.

Table (1) presents the results of calculating these quantitative environmental indicators for the complex, including the measured values for each indicator alongside the adopted reference values, with an interpretation of the level of environmental performance for each based on the results of comparing the two values.

Table (1) The table shows the measured environmental indicators and their comparison with the reference values

Main Indicator	Sub- Indicator	Measured Value	Benchmark Comparison	Interpretation	Result	
Digital integration	Integration of digital simulation of the design process	The ratio of integration between simulation and design	Simulation Integration%= 100%	%80–40)Attia 2012	Indicates full reliance on digital simulation in the design process, enhancing design decision-making accuracy.	High
		Energy savings resulting from integrating simulation into the design process.	Energy_Saving %=62.42%	%50–20)Nguyen 2014.	Energy savings are high as a result of improved thermal envelope and environmental strategies	High
		Thermal comfort level improved due to the simulation	Thermal_Comfort_Improvement% = 58.3%	PPD <10% according to ASHRAE 55 (2017)	Reduced thermal dissatisfaction and improved indoor environmental quality	High
Digital environmental monitoring systems for gases (CO ₂ and CO)	Monitoring gas concentrations using digital sensors (CO ₂ and CO)	Calculating the average CO ₂ concentration over a specific period	CO ₂ _avg = 720 ppm (After optimization) CO ₂ _avg = 950 ppm)Before optimization(CO ₂ ≤ 1000 ppm according to ASHRAE 62.1(2022) standard	A decrease in the average carbon dioxide concentration to 720 ppm indicates that indoor air quality is within acceptable limits according to international standards, reflecting improved ventilation efficiency in the indoor space after the implementation of .optimization measures	Compliant
		Calculating the rate of exceeding the standard limit	ETR = 12.5%	According to < %20 indoor air quality studies (Daisey et al., (2003	The low exceedance rate of 12.5% indicates that the majority of readings recorded during the measurement period remained within acceptable limits, reflecting relative stability in indoor air .quality	low

		Analysis of) concentration reduction based on hourly monitoring (data	RE = 24.2%) %40–15Persily & de Jonge, 2017	This result reflects the capacity of natural ventilation improvement measures to reduce carbon dioxide concentrations within interior spaces, thereby contributing to enhanced indoor air quality and reduced pollutant .accumulation	Medium
Energy efficiency	Zero energy	Annual energy balance equation	Net_Energy = A negative value indicates network dependency	Zero-energy buildings achieve Net Energy ≈ 0 ((IEA, 2013	A negative value indicates that the building relies on the conventional electricity grid and does not produce renewable energy on-site, meaning the building is far from achieving the concept .of net-zero energy	Compliant
		Zero Energy Access (%) Index	NetZero_Index = 0%	Zero-energy buildings achieve 100% (IEA, 2013	The result reflects the lack of renewable energy production within the building, placing the project outside the scope of net-zero energy .buildings	Non-compliant
	Efficiency of the electrical lighting system	Lighting Efficacy	Lighting-Efficacy_system = 83.3 lm/w	≥ 80 lm/W U.S. Department of Energy, 2022	The calculated value indicates that the lighting system used has acceptable efficiency within the approved range for LED lamps, thus contributing to reduced electricity .consumption	Medium
		Energy density used in lighting	LPD = 4 w/m ²	Depending on usage, typically $\leq 8-12$ W/m ² According to ASHRAE 90.1 (2019)	The low luminous power density value indicates a good level of energy efficiency in the lighting system compared to the standard permissible .limits	Compliant
Environmental Integration	Pedestrian walkways and green spaces	Ratio of green spaces to total area	GRA = 2.70%	10%-30% According to Gill et al., 2007	The value is below the recommended limit and indicates a lack of green spaces within .the site	low
		density of pedestrian walkway	WPD = 0.136m ²	There is no fixed numerical standard, however, higher	The calculated value indicates a relatively acceptable internal	Medium

		network		pedestrian density is associated with increased walkability in residential complexes according to the principles of New Urbanism and .Walkability Indicators	circulation network that supports walkability within the complex and can be further developed as green corridors or shaded pedestrian .paths	
	Using native plants, transforming the site into a nursery serving the city, and linking it to the environment and community through environmental education.	Percentage of native plants	LPR=60%	≥ 50% According to LEED Sustainable Sites	The high proportion of native plants indicates good compatibility with local climatic conditions, which contributes to reducing irrigation and maintenance needs and enhancing the environmental sustainability of the .site	Compliant
		Nursery area ratio	NRS=0.21%	There is no fixed standard, however, increasing the areas allocated for plant production promotes support for urban afforestation in accordance with FAO Urban Forestry .recommendations	The low value indicates the limited role of the nursery in supporting the future expansion of vegetation cover within the complex, necessitating an increase in the areas allocated for plant production to promote .afforestation	low
Safety and security	Structural safety		SSI%=93.1%	≥ 80% Reflects a high level of safety according to structural safety assessments.	The values indicate a high level of structural safety stability, with the potential to improve certain organizational aspects such as raising the level of supervision and enhancing full compliance with the .executive codes	High
	Environmental safety		ESR%=40%	acceptable %80-%40 environmental safety level (according to UN-Habitat, 2020; World Green Building (Council, 2020	An index value of 40% indicates that the level of environmental protection at the site is moderate, with some protective elements such as green spaces or waste management available, but other environmental elements such as soil protection, surface water management, or biodiversity support .are still limited	Medium

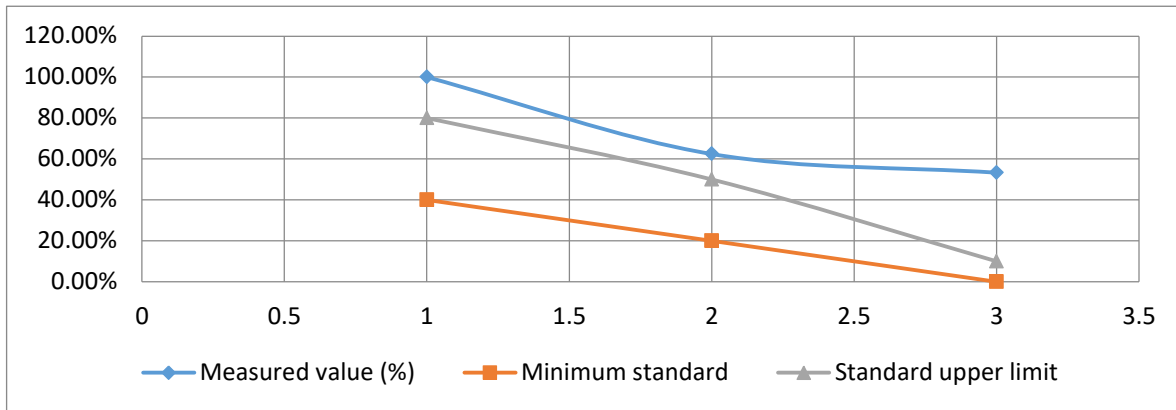


Figure (6) is a diagram illustrating the difference between the measured value and the reference value of the digital integrity standard.

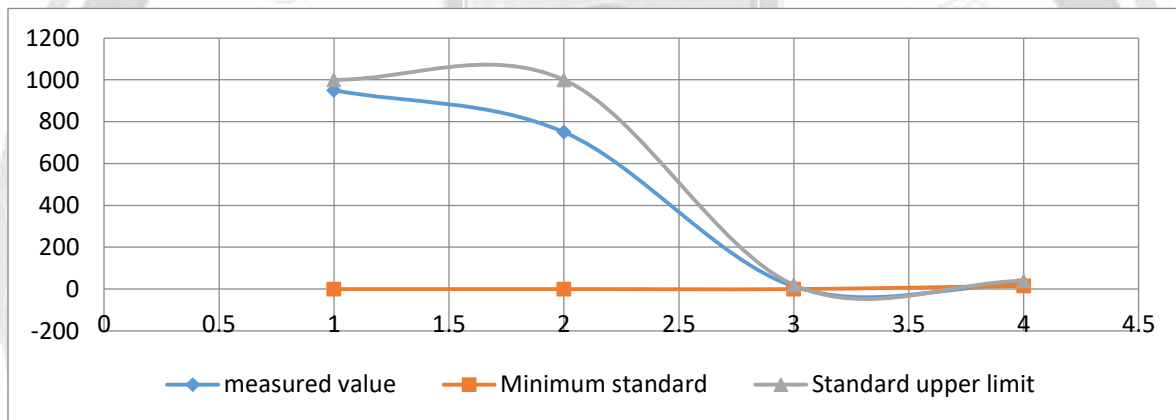


Figure (7) The diagram illustrates the difference between the measured value and the reference value for the Environmental Monitoring Systems Standard

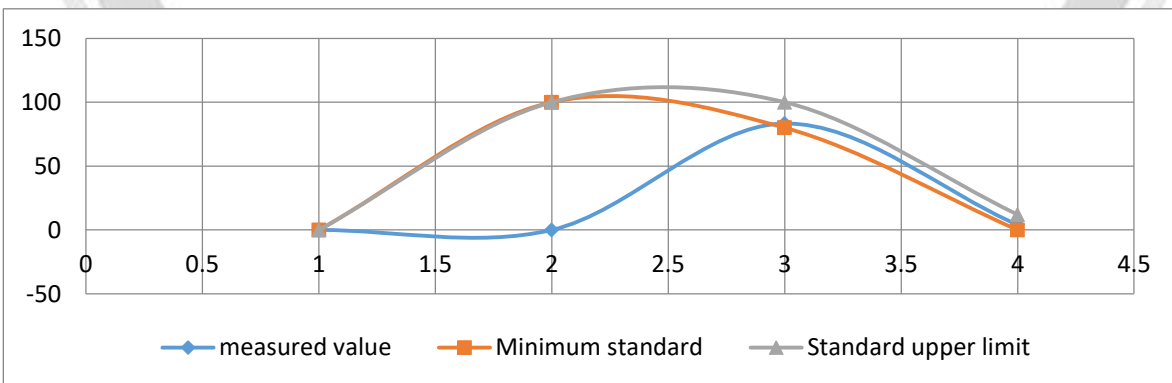


Figure (8) The diagram illustrates the difference between the measured value and the reference value for the energy efficiency standard

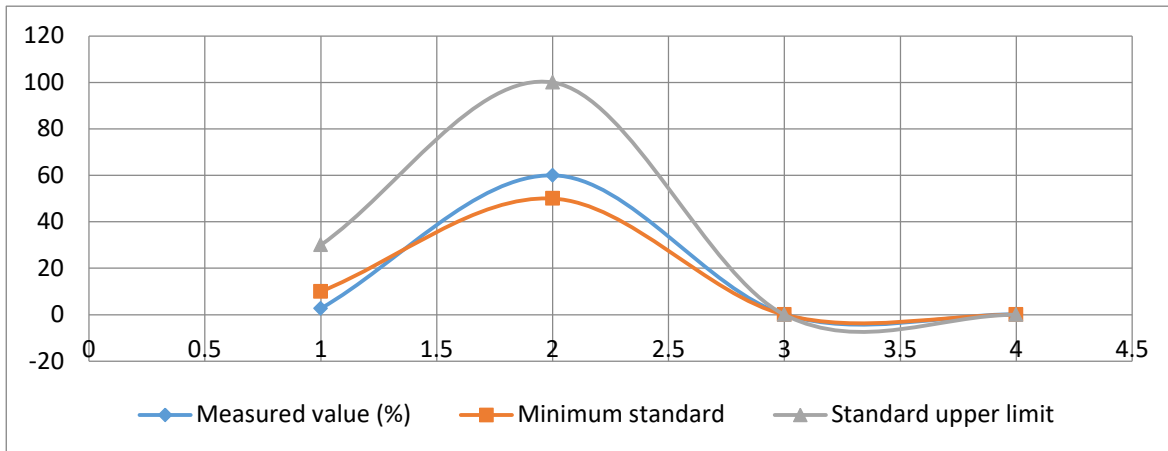


Figure (9) The diagram illustrates the difference between the measured value and the standard value of the environmental integration standard

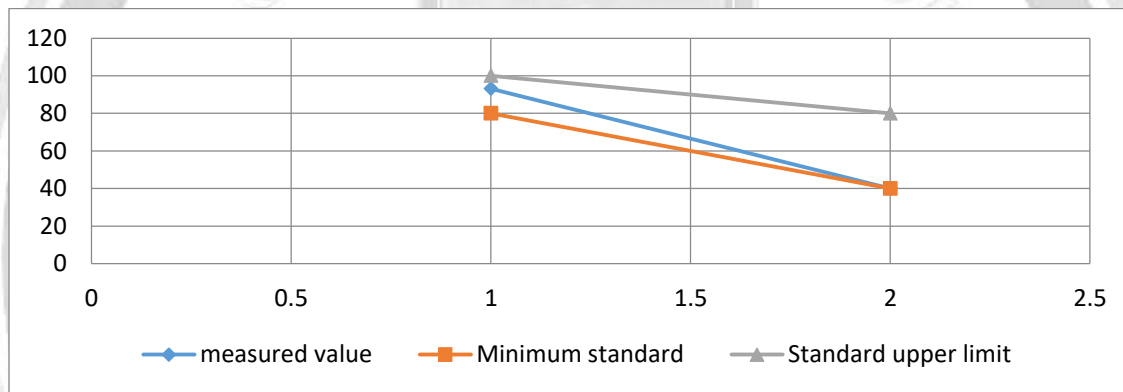


Figure (10) The diagram illustrates the difference between the measured value and the reference value for the safety and security standard.

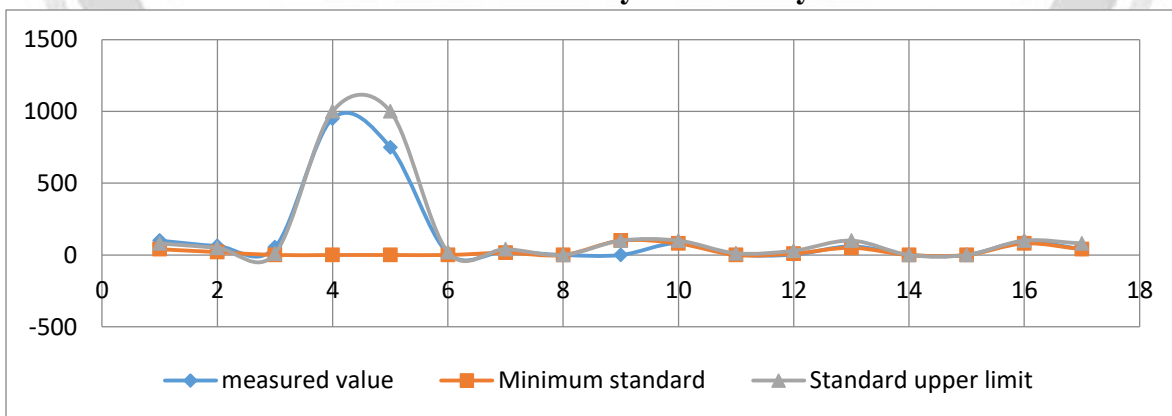


Figure (11) The diagram illustrates the difference between the measured value and the reference value for the sustainable environmental design indicators

4- discussion

The findings of the quantitative analysis of environmental performance indicators at Al-Sultan Residential Complex revealed considerable variation in the degree to which digital integration principles were realized within the sustainable environmental design framework. Indicators pertaining to the incorporation of digital simulation tools into the design process ranked highest among the high-performing indicators, with the Simulation Integration ratio reaching 100% — a figure reflecting comprehensive deployment of digital analysis tools in evaluating design alternatives prior to the adoption of the final solution. This outcome aligns with the well-established conviction in contemporary scientific literature regarding the importance of embedding environmental simulation tools in the early design phases, as a foundational element for advancing the environmental performance of buildings and residential complexes .[15]

In the same vein, the Energy Saving Indicator revealed a potential reduction in consumption rates of approximately 62.42% relative to the reference baseline, a substantial figure that reflects the effectiveness of digital analysis in optimizing building envelope performance, regulating aperture orientation, and controlling solar heat gain. This finding exceeds the 20–50% reduction range reported in numerous studies on digital environmental simulation, suggesting that advanced integration between simulation tools and design decision-making can yield energy savings beyond conventional thresholds [16]

Regarding thermal comfort, the results yielded a potential improvement of approximately 58.3%, manifested in a reduction of PPD from 24% in the reference baseline to approximately 10% following design enhancements, indicating that digital analysis can contribute to elevating thermal conditions within architectural spaces in alignment with ASHRAE 55 (2017) .[17]

Environmental monitoring indicators showed indoor CO₂ concentrations declining from 950 ppm to 750 ppm following improvement measures, falling within ASHRAE 62.1 (2022) [18] acceptable limits of 1000 ppm reflecting a tangible advancement in indoor air quality.

Concerning energy indicators, the Net-Zero Index recorded zero, confirming full reliance on conventional energy sources in the absence of sufficient renewable energy production systems. However, lighting efficacy reached 83.3 lm/W reflecting the adoption of LED technology, while Lighting Power Density recorded a low value of 4 W/ m²; both fall within acceptable efficiency thresholds stipulated by DOE (2022) and ASHRAE 90.1 (2019) [19] [20] , indicating sound energy efficiency in the lighting system.

Regarding environmental integration, the Green Area Ratio reached only 2.7% significantly below the recommended 10–30% range in sustainable urban planning literature, exposing a clear deficiency in the integration between urban design and natural elements, and necessitating a reconsideration of greening strategies in future development plans [21] [22]

LEED assessment systems similarly emphasize vegetative cover as a fundamental pillar for enhancing environmental performance and achieving urban sustainability [23] Pedestrian movement indicators showed a Walkway Path Density of 0.136 m/m², reflecting a relatively acceptable internal circulation network while simultaneously pointing to potential for further enhancement through expanded dedicated pathways and stronger connectivity with open spaces. [24] demonstrated that pedestrian movement patterns and spatial suitability analysis can play a significant role in supporting sustainability objectives and improving the performance of urban environments through the optimization of pedestrian infrastructure and mobility systems

Safety indicators demonstrated strong structural performance, with the Structural Safety Index reaching 93.1% confirming that the complex's structural characteristics conform to engineering safety requirements and adopted design standards. By contrast, the Environmental Safety Ratio (ESR) registered a value of merely approximately 40%, reflecting a moderate level of environmental safety elements within the site. The literature pertaining to urban sustainability indicates that the creation of safe and sustainable urban environments necessitates the adoption of integrated strategies for environmental risk management, the enhancement of built environment quality, and sustained attention to the health and wellbeing of occupants within urban spaces. [25]

The overall findings of the study indicate that the incorporation of digital analysis and simulation tools into the design process contributes meaningfully to the improvement of a range of environmental performance indicators, particularly those associated with energy efficiency, thermal comfort, and indoor environmental quality. Conversely, the results exposed evident deficiencies in certain dimensions of the urban environmental fabric, most notably green spaces and renewable energy production deficiencies that signal a pressing need to adopt more comprehensive and integrated design strategies capable of accommodating both digital and environmental dimensions within a single cohesive framework, with the overarching objective of advancing sustainability levels in the planning of residential complexes .

6. Conclusions

According to the results of the research, using digital analytical and simulation tools in the design phase is an effective way to enhance the environmental performance of apartment buildings and to promote the principles of sustainability in the built environment. The integration of digital tools demonstrated increased levels of digital simulation used in the design phases which in turn provided quantifiable benefits to the environmental performance of buildings, particularly with significant reductions in energy consumption and improved thermal comfort within the space. Additionally, there were also indicators of improvements in the quality of indoor air with decreasing levels of CO₂, which are consistent with internationally acceptable levels, and thereby providing support for the value of environmentally based design practices enhanced by the use of digital tools.

On the other hand, there were several measurements of the Urban Environmental Fabric that indicated areas needing additional focus, most notably the amount of green space available in the complex was well below what is suggested in the urban sustainability literature; secondly, the net zero energy goal was not met due to continued reliance on traditional sources of energy. The urban mobility and environmental safety indicators also recorded moderate results, but if pedestrian networks and safety features in urban environments are developed further, these indicators could increase.

Overall, the results of this study support the contention that true integration between digital tools and sustainable environmental design principles will be an important means for enhancing overall environmental performance efficiency within residential complexes. In order to achieve this increased level of sustainability, it will also require that there is a greater focus on planning methodologies such as creating additional green spaces, creating renewable energy systems, and improving the quality of the urban environment. All of these elements must work together to create a harmonious balance between both the digital component of the design as well as the environmental component when planning and developing residential complexes sustainably.

7- Recommendations

Drawing upon the findings of the study, a set of recommendations may be formulated aimed at strengthening the integration between digital tools and sustainable environmental design principles in the planning and development of residential complexes. Foremost among these recommendations is

- the importance of broadening the adoption of digital environmental simulation tools in the early design phases, given their pivotal role in improving energy efficiency and advancing levels of thermal comfort and indoor environmental quality.
- The study further recommends enhancing natural elements within residential complexes through increasing the proportion of green spaces and developing green infrastructure, thereby contributing to the moderation of the urban climate and the mitigation of urban heat island effects.
- Added to this is the necessity of supporting the transition toward renewable energy sources, particularly solar energy, in pursuit of realizing the concept of net-zero energy buildings and complexes.
- The study also calls for the development of pedestrian movement networks within residential complexes and the strengthening of their connectivity with open spaces and surrounding environmental elements, thereby promoting walkability and elevating the quality of the urban environment.
- Future studies may expand the proposed framework by integrating social and economic sustainability indicators to achieve a more comprehensive sustainability assessment model.

- Finally, the study proposes expanding the horizons of future research to encompass a greater number of residential complexes, alongside the application of more advanced digital assessment models, with the objective of constructing a comprehensive and integrated framework for environmental sustainability evaluation in urban environments.

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إطار تقييمي متعدد الأبعاد للتكامل الرقمي في التصميم البيئي المستدام للمجمعات السكنية (دراسة حالة مجمع السلطان السكني في النجف الأشرف)

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الخلاصة

تهدف هذه الدراسة إلى بناء إطار تقييمي شامل متعدد الأبعاد يعتمد على مجموعة من المؤشرات الكمية لقياس مستويات التكامل الرقمي في سياق التصميم البيئي المستدام للمجمعات السكنية. وقد تم تطوير هذا الإطار بالاستناد إلى البيانات الخاصة بمجمع السلطان السكني في مدينة النجف الأشرف، العراق.

وانطلاقاً من غياب آلية كمية واضحة لتقييم التكامل الرقمي في التصميم البيئي المستدام، يقترح الإطار التقييمي توظيف التقنيات الرقمية في قياس المؤشرات البيئية بما يعزز من كفاءة عملية تقييم الأداء البيئي، بما في ذلك كفاءة الطاقة، والراحة الحرارية، وجودة البيئة الداخلية. واعتمد البحث منهجاً تحليلياً وتقييمياً استند إلى مجموعة من المؤشرات الكمية ضمن خمسة مجالات رئيسية هي: الاتصال الرقمي، والمراقبة البيئية الرقمية، وكفاءة استخدام الطاقة، والتكامل البيئي مع الغطاء النباتي، والسلامة والأمان. وقد جرى تقييم هذه المؤشرات ومقارنتها بالمعايير الدولية المرجعية المعتمدة.

وأظهرت النتائج أن تطبيق تقنيات المحاكاة الرقمية يمكن أن يسهم في مختلف جوانب التصميم من خلال تحقيق وفورات في استهلاك الطاقة، وتحسين مستويات الراحة الحرارية، وضمان جودة الهواء الداخلي عبر أنظمة المراقبة البيئية. وفي المقابل، كشفت النتائج عن عدم تحقيق مستوى الطاقة الصفرية الصافية ((Net-Zero Energy)، نتيجة استمرار اعتماد المباني على مصادر الكهرباء التقليدية. كما أظهرت محدودية المساحات الخضراء رغم كفاءة تصميم شبكة المشاة وتوافقها مع المعايير التخطيطية، إضافةً إلى أن مؤشرات السلامة والأمان جاءت ضمن المستوى المتوسط.

وتستنتج الدراسة أن تعزيز الاستدامة البيئية في المجمعات السكنية يتطلب تبني منهج تخطيطي متكامل يجمع بين زيادة المساحات الخضراء، وتوسيع استخدام مصادر الطاقة المتجددة، وتحسين جودة الفضاءات الحضرية، بما يسهم في تحويل مفهوم الاستدامة من إطار وصفي إلى إطار قابل للقياس والتقييم الكمي.

الكلمات الدالة: التكامل الرقمي، التصميم البيئي المستدام، المؤشرات البيئية الكمية، تقييم الأداء البيئي المستدام للمجمعات السكنية، المحاكاة البيئية الرقمية، مجمع السلطان الس