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Daylight, Thermal Comfort, and Energy Performance in High-End Pakistani Residences: An Integrated Post-Occupancy Evaluation Framework

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ABSTRACT

Enteric methane mitigation has moved from a narrow search for antimethanogenic compounds toward a systems problem involving ruminal hydrogen transfer, microbial ecology, animal variation, delivery technology and credible on-farm verification. This critical narrative review organizes current evidence around the rumen hydrogen network and evaluates whether interventions produce durable methane abatement without impairing intake, fiber digestion, productivity, product safety or whole-system environmental performance. Recent meta-analyses identify 3-nitrooxypropanol, nitrate, selected lipid sources and Asparagopsis-derived products as the most consistently effective nutritional interventions, but their responses are strongly conditioned by dose, basal diet, exposure duration and production system. Plant secondary compounds and probiotics can alter fermentation and microbial networks, yet pooled in vivo effects are generally smaller or less consistent than results from in vitro screening. Direct inhibition of methanogenesis also increases the need to account for the fate of excess hydrogen; failure to redirect reducing equivalents can limit energetic recovery and may explain why methane reduction does not consistently improve feed efficiency. Advances in metagenomics, metatranscriptomics and microbial network analysis indicate that functional guilds and interspecies hydrogen transfer are more informative than methanogen abundance alone. Precision feeding, sensor-derived phenotypes, mechanistic models and machine learning offer a pathway to match interventions to responsive animals, maintain effective exposure and verify outcomes under commercial conditions. We propose a mechanism-to-deployment framework in which mitigation options are compared using seven linked criteria: methane production and yield, hydrogen fate, rumen function, animal performance, persistence, safety and farm deliverability. Future progress will depend on long-duration, adequately powered studies that report harmonized methane metrics, hydrogen emissions, productivity, microbial function, economics and life-cycle consequences. Effective low-methane production will therefore require coordinated management of diet, microbiome and measurement rather than reliance on a single additive.

Introduction

Residential building performance is now known to be a multi-faceted solution to the design of buildings, their building envelope, indoor environment, energy systems, and occupant behaviour. While modern today residential architecture has a tendency to focus on: aesthetic quality, spatial openness, natural lightning and high standards of comfort on the inside, it does not mean that all of these design objectives are necessary to insure the effective action of the building. An architecturally significant house can have lots of glazing, two story rooms, open layout, and high-quality artificial lights and still have a very poor distribution of daylight, too much solar heat gain, thermal discomfort and an increased electricity bill. Therefore, the assessment of the performance of residential buildings must be done taking in account different aspects such as environmental quality or satisfaction of the user, as well as operational energy demand, as interdependent components.

Considerations are especially relevant to high quality residential structures, in which the architectural expression and the luxury expectations may be essentially responsible for the use of large/expansive windows, large internal volumes, broad glazed facades and mechanical cooling systems that run at high intensities. Environmental performance of this feature depends on a range of features such as orientation and geometry of the building, window to wall ratio, window glass properties, external shading, envelope thermal performance, room geometry and operational control of lighting and cooling. Thus, the interplay between these factors will either inhibit or manifest the architectural design concepts into a comfortable and energy efficient occupied environment.

Daylight is also one of the most important components for the quality of residential environment, and enables visual tasks to be completed, can connect with the natural outdoors, and can help to reduce the use of electric light during certain times of day. However, the ability of the item to perform during daylight is not always quantifiable. Excessive direct light, glare, excessive luminance contrast or high level of light irregularity may affect the visual comfort of the occupants and result in the closing of blinds or curtains. This response can then add to less daylighting and more artificial light. So, the quantity of daylight coupled with the quality of daylight available and the amount of visual discomfort to be expected in daylighted spaces must be part of daylighting assessment.

Thermal Comfort is also an essential aspect of performance of buildings in the residence. It depends on the air temp, mean radiant temp, rel. humidity, air velocity, clothing insulation, metabolic activity and on the adaptative responses of the occupants. The thermal environment of a space inside a house is also affected by building orientation, solar exposure, envelope characteristics, opportunities for ventilation and mechanical cooling strategies. ASHRAE (2023) give well-documented methods in Standard 55-2023 for assessing the thermal environmental condition in terms of human occupancy. In a certain particular geographical climate, internationally recognized assessment methods should be subjected to a cultural practice when it comes to building use and climate.

One of these is how energy is performed when the machine is in use. Cooling an air-conditioned house for a longer period in order to ensure comfortable indoor temperature and conditions may result in raising the electricity consumption and its related environmental impacts. On the other hand, reduction on mechanical cooling can lead to hot conditions inside the room during hot days and can save energy. These rival effects demonstrate the need to consider energy efficiency in a complementary way with the comfort of the occupants. Instead, it must be considered together with the architectural and operational consideration which impact both.

Seasonality in outdoor temperature, solar exposure, humidity and atmospheric conditions is an important aspect to consider when examining these relationships in Lahore, Pakistan. Average performances in a family's house can vary from summer to winter and shoulder season. In addition, there are differences in indoor EVQ and electricity usage that can be attributed to things like the direction of the front facade, shading solutions, window types, resident occupancy and the set-point of their air conditioning unit, as well as the ways in which residents operate their windows. This study is relevant in the context of high-end residences because the architectural ambition and expectations for indoor thermal comfort in these dwellings may lead to unique interactions and outcomes between architectural features and environmental performance.

Post-Occupancy Evaluation (POE) is a method of reviewing building performance after completion and occupancy. Prescribed specifications, or design intentions or predicted performances, are different in that POE looks at building performance during its actual use. The combination of environmental measurements, architectural documentation, occupant surveys, behavioral observations and records of energy-consumption allows discrepancies between intended and observed performance to be detected. If implemented within a comprehensive approach, POE can also be used to describe the interaction between daylighting, thermal conditions and occupants' luminance and/or their energy demand in residential built environments.

Therefore, this study plans an integrated PoE for daylighting performance, thermal comfort and operational energy consumption in selected high-end residential buildings of Lahore. The study looks at the combined dimensions in a common

empirical context, aimed at producing evidence of fit in the context of sustainable residential design and the matching of architectural quality, wellbeing and energy performance.

Aim, Objectives, and Research Questions

An overall objective would be to establish a clear and repeatable POE method to collectively evaluate daylight performance, thermal comfort and electricity use during occupancy in high-end dwellings in Lahore. The protocol is formulated for later use in empirical field applications and not complete field measurements are reported here.

The specific objectives are to:

1. For a multi-case residential POE, identify facilitated streams of data related to building space, occupants, energy and the environment.
2. Identify rules for daylight, thermal comfort and electricity-use indicators for measurement, seasonality coverage, data quality and reporting.
3. Educate and develop an analysis and integration model that can facilitate comparisons of evidence across cases, without getting into a confusion between “association” and “causation,” and without collapsing the results down to an “average score.”
4. Before empirical application, determine the boundary conditions, feasibility requirements and limitations of the protocol.

The study is guided by four research questions:

- **RQ1.** What does it take to combine architectural features, daylight measures, thermal metrics, people's reactions and electricity meters in one reproducible residential POE package?
- **RQ2.** What rules are necessary to differentiate a point in time measurement from an annual sunlight or energy indicator?
- **RQ3.** How can the protocol compare performance trade-offs across cases whilst taking into account occupancy, operating practices, data quality and uncertainty?
- **RQ4.** What is feasible; what are the "interpretive limits" that need to be negotiated before the protocol can be adopted in high-end residences in Lahore?

The following questions relate to the design and applications need of a protocol. These are not put forward as "hypotheses about measured performance, since the proposed fieldwork has not yet been conducted.

Literature Review

Post-Occupancy Evaluation in Residential Buildings

Post-occupancy evaluation (POE) is a systematic process of building performance evaluation after occupation. It takes an in-depth look at how well a building fulfills the desired purposes of function, environment, operation, and occupants. POE evaluates a building in use as opposed to design stage assessments that are based on assumptions, simulated conditions and predicted performance. It therefore provides a means of identifying design/operational mismatch detection. Li et al. (2018) gave an overview of current research and practice in POE, including existing POE framework and evaluation protocols, methodological differences and potential areas which can be evaluated more comprehensively for building performance. Consistently, Elsayed et al. (2023) found that methodologies, data collection methods, monitoring plans and analysis strategies employed during residential POE studies were inconsistent. Findings justify the use of well-defined and replicable assessment model. An effective home-based POTW will combine quantitative and qualitative evidence. The scientific assessment of the interior's conditions occurs with environmental monitoring, while surveys of the interior are conducted by the occupants assessing their degree of comfort and satisfaction, and the utility records provide information on the actual building use of energy. Both the combined sources can be utilized to see if performance targets are being achieved, but can also be used to determine and explain the outcomes that are observed, based on the attributes of the building and the practices of the Occupants (people). Roberts et al. (2019) also explored the evolution of POE research and the challenges of incorporating a building-performance evaluation approach in the context of facilities management. Residential POEs have also been the subject of recent reviews, with a lack of consensus regarding approaches across studies, and a need for a very clear protocolestablished (Elsayed et al., 2023; Zhao et al., 2024). In this study POE is being considered as building performance evaluation (BPE) and not just a

satisfaction survey. Time-dependent variables (such as people being in the room and temperature, window opening, blind operation, equipment use) will be separated from the relatively stable building characteristics (such as orientation, window glazing configuration, room dimensions). This separation is significant as variations in environmental conditions and energy used could be due to operation or architectural design.

Daylight Performance and Visual Comfort

Daylight performance relates to the quality, comfort and utilization of daylight in living areas. It depends on window area, direction of the sun, transmittance of the glazing, external shading, room depth, room surface reflectance, and shading configuration. But light availability should not be interpreted as visual comfort: high light levels might not correspond to high levels of visual comfort if there are high contrast in order to compensate for high glare. In 2001, Reinhart and Walkenhorst did a study examining the validity of dynamic Radiance daylight simulation in a test office with exterior blinds as a part of validation testing on computational approaches for assessing daylight conditions. Their study focused on an office space, but the methodology is also applicable to the review of daylighting distribution and shading performance in homes. The inadequacy of traditional daylighting metrics and the need to consider temporal and spatial variation in appraising daylighting performance were also raised by Mardaljevic et al. (2009). Climate based daylight modelling is more comprehensive than isolated illuminance measurements as it quantifies daylight performance under varying outdoor conditions over a representative meteorological year. The Illuminating Engineering Society (2023) provides a procedure for spatial daylight autonomy (sDA) and annual sunlight exposure (ASE) evaluations in ANSI/IES LM-83-23. These indicators can be used to examine the amount of useful daylight and any excessively high amount of direct sunlight exposure.

For the present study, daylight assessment will combine:

- Horizontal illuminance measurements in lux.
- Lighting coverage of typical illuminated space.
- Window to wall ratio, orientation, window characteristics, shade.
- Daylight Simulation based on weather conditions using a suitable weather file for Lahore.
- Occupant reported glare, daylighting sufficiency, and use of curtains/blinds.

Spatial daylight autonomy and annual sunlight exposure will be calculated if sufficient building geometry, material properties, weather data and appropriate simulation software is available. These annual measurements will not be judged by single point measurements. Daylighting will be separated from visual comfort and analyzed based on measures or simulation as well as on subjective assessment made by the occupants.

Thermal Comfort in Residential Environments

Thermal comfort is defined as when occupants feel content with regard to their thermal environment. It depends upon the air temperature, mean radiant temperature, air velocity, relative humidity, clothing insulation, and individual's metabolic rate. Comfort in residential settings can similarly be influenced by the expectation, adaptive opportunities and control of occupants with the indoor environment.

Fanger (1970) proposed a basic analytical method of thermal comfort based on the connection between human thermal balance and subjective thermal comfort response. Later de Dear and Brager (1998) proved the adaptive thermal comfort models to be important, as these models can account for the fact that thermal comfort levels may change depending upon the type of climatic conditions outside the building, and the possibilities of self-regulatory choices. Nicol and Humphreys (2002) also explored the adaptive comfort-sustainable thermal environment link.

Adaptive comfort plays an important role in considering houses in warm climates. Marginal interventions consist of adapting the clothing, using fans, opening windows, changing the thermostat setting or moving from one room to another as indoor conditions change. These behaviours can impact both thermal satisfaction and energy use. However, those methods of calculation for adaptive comfort must not be used in situations where the environmental conditions and functioning of a building do not satisfy the applicability conditions in the standard.

Thermal environmental conditions are addressed in Section No. 3 of ASHRAE 2023 for evaluating the conditions with applicable analytical and adaptive procedures. In this study, the environmental air temperature and RH will be measured continuously or at an appropriate sampling time interval. Measuring air speed and mean radiant temperature also will be done where

equipment and access allows. Thermal sensation will be recorded in the occupant survey as will thermal acceptability and preference for warmer or cooler conditions.

The applicable ASHRAE method will be used to measure the thermal comfort which will be justified on the basis of building use. Merely meeting a "comfortable" set zone temperature range cannot ensure that a space is comfortable. Measured conditions will be interpreted along with occupant responses and appropriate means of adaptive opportunities instead.

Residential Energy Performance

The characteristics of the building envelope, mechanical systems efficiency, lighting, household appliances, building occupancy and preferences affect the energy consumption during operation of residential buildings. The use of electricity is especially of importance in residential buildings where air-conditioning makes a significant impact on the cooling load during hot periodsNevertheless, the energy use in households where electricity is used for cooling alone does not define the cooling efficiency. Variations between homes can be attributed to varying floor area, occupancy, ownership of appliances, amount of time the appliances run, thermostat settings, and amount of conditioned space. It's important to do energy comparison, therefore one has to have consistent measurements of periods and relevant background information.

Zhang et al. (2018) covered how building occupants' behaviour can affect building energy performance and the need to take occupants' behaviours with windows and lighting controls, as well as their heating and cooling practices, into account when addressing energy-use differences. Their review suggests that occupant behaviour should be used as an explanatory variable, instead of assuming that the consumption they have observed is a direct consequence of the quality of the buildings' design.

This study will break out cooling and lighting usage from the total household electric use if there is a record available or if an approximation was provided in the Submetering Report. The bottom line will be calculated in kWh/m2/year (Annual consumption) and in kWh/m2/month (Monthly consumption) with a well-defined and clearly agreed denominator, floor-area. Wherever possible, conditioned floor area, appliance usage, AC system usage and thermostat settings will be recorded.

Household disparities are not eliminated, although floor-area normalisation will improve the comparability. For this reason, the energy uses will be analysed in conjunction with the indoor environment measurements, together with the building properties and the information gathered regarding the practices of building use. This integrated approach decreases the risk of considering low energy usage as indication of efficiency, while it could as well, or even primarily, be due to limited utilization of cooling or insufficient satisfaction of cooling demand.

Interactions Between Daylight, Thermal Comfort, and Energy

Daylight, thermal comfort and operational energy use are interrelated building-performance system. The daylighting configuration also has implications on the solar heat gain contribution, in addition to daylighting. Glazing can minimise direct solar exposure and glare, at the expense of daylight penetration. Likewise, thermal conditions may affect the window blinds/AC operation length and intensity, and window reduction/blinds qualities may affect daylight, ventilation, cooling demand.

Mardaljevic et al. (2009) pointed out the necessity of daylight measurement parameters that more closely reflect the temporal variation and link daylight provision to occupant comfort and energy-related effects. Similarly, Zhang et al (2018) paved the way for the importance of occupant behaviour in the building energy performance understanding. These studies combined indicate the importance of assessing architectural and operational variables together in view of the interdependency between the different variables rather than the three variables: daylight, comfort and energy as separate products.

The relationships need not be linear. It is possible that as window area is increased there is a greater amount of daylight available in some locations and an increase in glare and/or

overheating in others. The effectiveness of external shading depends on its orientation, geometry and climatic conditions; it may improve the visual/thermal balance. Likewise, decreasing electricity use can signify using efficient design, decreasing building occupancy, limiting cooling, and/or poor thermal comfort.

Within this context, the study will be undertaken concentrating on areas where more than one outcome comes into play as opposed to simply each architectural element contributing to all outcomes. Given the nature of the observation based experimental design, the connections between building elements, daylighting design parameters, thermal comfort, human response and building operation energy consumption will be discussed.

Recent reviews reaffirm that explicit reporting is important and that a single method of POE is not universally applicable. Inconsistencies in residential POE practices, in terms of methods, monitoring, and reporting have been reviewed by Elsayed et al. (2023), as well as differences in approaches to thermal comfort and energy efficiency in residential regions as per Zhao et

al. (2024). The current study builds on Boissonneault and Peters' (2023) analysis of the portrayal of the concept of performance in the POE literature. The reviews provide a rationale for the evidence streams and decision rules of the protocol; however, they do not validate the recommended process toward developing a Lahore framework.

Research Gap and Distinction from Existing POE Methods

While there are well-known methodologies to integrate technical building-performance data with occupants' feedback in existing POE studies, significant variability in data collection, monitoring period, evaluation tools, and reporting was observed. This variation is detrimental to the replication and comparisons in residential research (Li et al., 2018; Elsayed et al., 2023; Zhao et al., 2024). Other strands of research offer a way to evaluate daylighting and thermal-comfort performance dynamically, and to analyze how occupants affect energy use (Reinhart & Walkenhorst, 2001; ASHRAE, 2023; Zhang et al., 2018). There is hence no lack of methods for each particular domain.

The specific gap focused on this paper is procedural and contextual: there is a need for a transparent protocol to coordinate these evidence streams in the context of occupied high end-residences in Lahore, while at the same time preserving the distinction between (a) roomconditions measured in buildings, (b) occupants' reports of values, (c) annual daylight indicators from climate-based simulation, and (d) household electricity records. These are the different types of data which fail to be the same at temporal and spatial levels.

These four components are proposed as follows: a linked case-level data structure, which brings different components of the case together so that architectural, climatic, behavioural, daylight, thermal and energy variables are all reported together; explicit rules to communicate when annual daylight metrics and annual energy-use intensity are reported, as well as rules to report when this is not possible; quality-assurance and data-boundary rules for missing, uncertain or not-comparable data records; and an integrated case matrix where dimension-specific outcomes can be reported without arbitrary weighting. It does not have to be just a sustainability survey: it is a “protocol” which incorporates energy records and technical measurement as well as responses from its building occupants.

This is a thought-out methodological design, not a research discovery or an instrument. Its feasibility, reliability and usefulness will be checked in an application to a pilot district and fieldwork. The study does not state that this particular combination has not been put together in other places, but rather tells how and how to coordinate the components and how to report them for the specific housing context.

Conceptual Framework

An integrated building-environment-occupant conceptual approach has been used to examine the relationship between architectural parameters, outdoor environment, occupant's behaviour, daylight performance in terms of daylight illuminance, thermal comfort, and operational electric energy consumption in high-end residences of Lahore, Pakistan.

The framework incorporates lessons learned from POE research that has highlighted the benefits of combining technical building-performance data with feedback from building occupants, as well as research that has identified occupant behaviour as a key consideration in energy analysis (Li et al., 2018; Elsayed et al., 2023; Zhang et al., 2018).

Three principal groups of explanatory factors are identified:

- Architectural characteristics: Orientation of the building, ratio of glazed area to wall area, glazing characteristics, external shading, room geometry, envelope construction and natural-ventilation provisions.
- Outdoor environmental conditions: Ambient temperature, solar radiation, relative humidity and other climatic parameters of interest.
- Occupant behaviour: Window and blind operation, artificial lighting, thermostat setting, air-conditioning schedules, occupancy pattern and individual comfort preferences.

The effects of these factors for three key outcomes of building performance will be examined: daylight performance, internal thermal performance, operational electricity consumption. The daylight will be judged based on the illuminance measurement and distribution, simulation (where possible), and perceived visual comfort by the occupants. Thermal conditions and their impacts on the occupants will be measured and will take into account environmental conditions. Based on electricity-use records, energy will be discussed, in particular electricity-use for cooling and electricity-use for lighting at the time, if available.

The model also recognizes that there can be some changes to the relationship between the architectural features and the observed performance due to changes in the occupant responses. A location where, for example, blinds can be drawn to block

out glare - which may result in more man-made light. Similarly, when the solar heat gain is higher the greater number of air conditioners are operated. These pathways will be considered possible relationships, not necessarily cause and effect.

The connections may be uncovered in the methodological layout of the incorporated POE process. Issues relating to performance will be uncovered, and some differences between intended and measured performance will be determined, using architectural inspection, environmental monitoring (including survey questionnaires), behavioural data and energy data from the building users. Consequently, recommendations for contemporary high-end residential buildings for an enhancement of daylighting quality and thermal comfort, energy efficiency and reduction will be drawn from the assessment by the application of evidence.As such, the framework is set as the foundation of the study's research questions, variable selection, data collection and data analysis. As the research is observational, the interpretations of the results will be treated as relationships as opposed to evidence of causation.

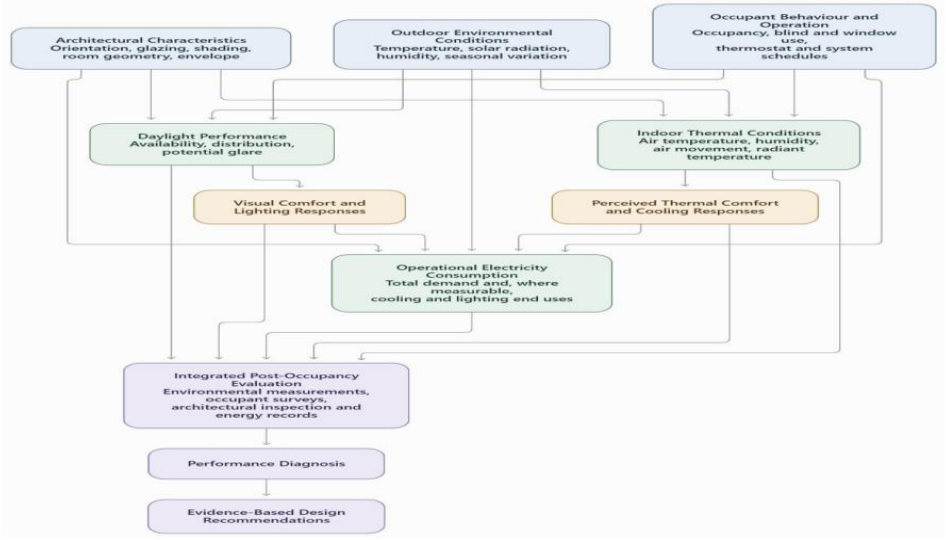


Figure No 1: Overall POE process and concept of relationship between proposed architectural and environmental factors, occupant behavior, residential performance indicators, and overall POE process.

Variable classification

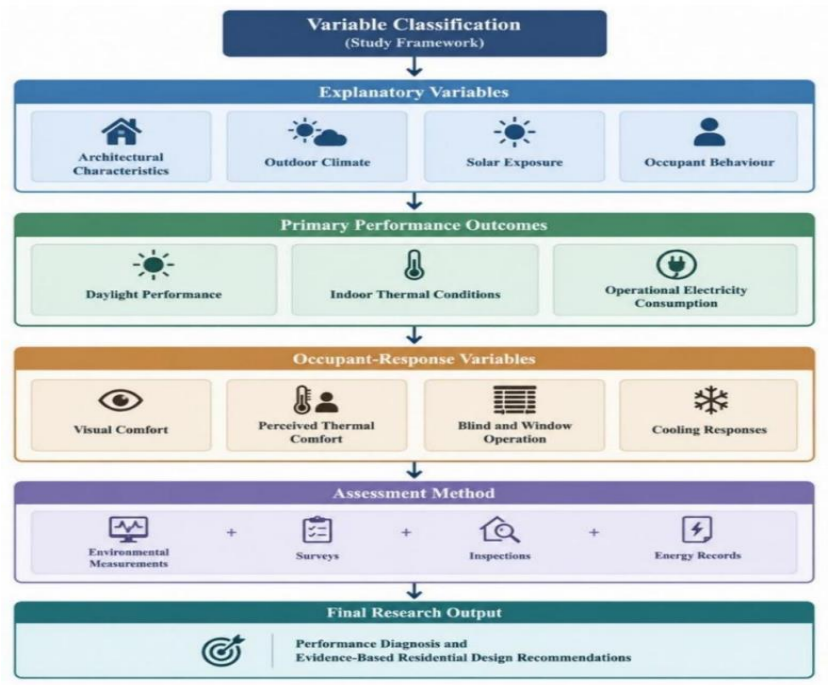


Figure No 2: Explanatory variable, performance, occupant response, assessment methods and intended outputs.

This is the sequence of the flowchart:

- **Explanatory Variables:** Some architectural aspects, exterior climate conditions, solar exposure and the behaviour of the users.
- **Primary Performance Outcomes:** Daylight performance, indoor thermal conditions and operational energy use.
- **Occupant-Response Variables:** Visual comfort, perceived thermal comfort, blind and window operation and cooling responses.
- **Assessment Method:** Environmental measurements, surveys, inspections and energy records.
- **Final Research Output:** Recommendations and design of homes based on performance diagnosis, with evidence.

Research Methodology

Research Design and Methodological Approach

The objective of this study is to investigate integral daylight performance, indoor thermal comfort and energy performance during the operational phase of the high-end residential buildings of Lahore city within an integrated post-occupancy evaluation (POE) methodology, as it is idiosyncratic and belongs to the framework development class of research. In the methodological approach building characteristic assessment, monitoring of the surrounding environment, response of the occupants and energy performance analysis are coordinated in an integrated structure of an assessment.

An overall framework is conceived to overcome the drawbacks associated with a one-indicator approach to the environments' performance in dwellings. There is an interrelationship between daylighting, indoor thermal conditions, occupant behaviour, and energy consumption as part of the building performance in residential buildings. The total evaluation of them can give a more complete knowledge of how architecture design decisions, operating conditions, environment and occupant experiences are correlated.

The proposed approach is organized within five inter-dependent elements:

1. Characterization of building and architecture.
2. Indoor environmental monitoring.
3. Occupant assessment.
4. Operational energy assessment.
5. Integrated performance diagnosis.

These components are designed to facilitate systematic comparisons for the selected residences and evidence-based architectural and interior design recommendations.

This is a study intended as a framework-development paper and not as results of field measurement or empirical validation. For future uses of the framework, the processes outlined below for data collection and analysis should be applied.

Framework Development and Variable Selection

The proposed integrated post-occupancy evaluation framework will be presented by structured synthesizing the literature related to an integrated approach addressing the performance of residential buildings including daylight assessment, indoor thermal comfort, occupant behaviour and operational energy consumption. The aim of this process is to determine main domains of assessment, variables of each domain and make a logical relationship between the domains and relate architectural features to indoor environment and occupant response to energy performance.

The framework-development process will consist of 4 stages. First, specific conceptual and methodological literature will be reviewed to locate existing assessment methods and the drawbacks of attempting to assess the residential environment using single indicators. Secondly, the approaches identified will be overlaid on the goals and contextual needs of high-end residential buildings in Lahore. Third, variables will be grouped into: building, environment, occupants and energy; their operational definitions, data needs, and suggested protocols for assessment will be summarized in a matrix of measurements. Fourth, the evaluation system will be sequential; that is, the building characterization and environmental monitoring will be linked to the

occupant assessment, energy analysis, and performance diagnosis will be linked with the others.Variables will be selected based on: relevance to research goals, ease of measurability under residential conditions, availability of adequate data sources, and usefulness to architect/designer decision making in architectural and interior design. If there is a variable that needs certain equipment and/or documentation it will be designated as a conditional variable and if access is limited and resources are required the variable will not be listed as a mandatory measurement.

The resulting framework is designed to give a clear and concise methodical structure for integrated residential performance assessment. However, its development using literature synthesis sets the conceptual and procedural groundwork for the proposed approach, and it will need to be applied or peer-reviewed as an expert-reviewed process in order to be validated and assessed for implementation reliability.

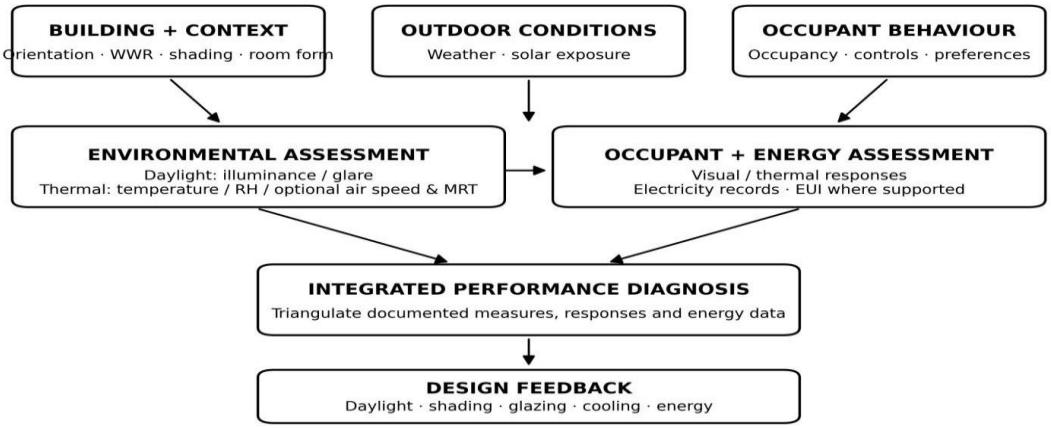


Figure No 3: Proposed integrated residential POE framework

Study Area and Scope

Proposed geographical scope: Lahore in the province of Punjab, Pakistan. The subject has been discussed in the context of high-end residences in Lahore, where the defined urban context is taken into account along with climatic, architectural and operational conditions.

The focus of the study is on existing high-end residential buildings from which relevant architectural data, representative indoor spaces, environmental monitoring sites and energy records from households can be acquired. The residential focus is to be able to address the interplay between building configuration, glazing, solar exposure, interior spatial characteristics, cooling behaviors and building users' responses.

Any future application of the results should be seen in the context of the buildings and geography of this study. The findings obtained from Lahore study results cannot be automatically assumed to be applicable to the other cities or climatic regions in the country Pakistan.

Proposed Sampling Strategy

It is recommended that the residences be selected through a purposive sampling approach that will yield a sample of approximately 15–20 residences (although access, data completeness, and monitoring resources may limit the sample size to 12–20 residences). Variations of architectural and operating characteristics such as building orientation, window-wall ratio, shading facilities, room functions, characteristics of the glazing and cooling systems, and occupancy patterns will be maximized as appropriate.

The unit of analysis will be the individual residence and will include about 2 – 4 representative occupied rooms within the selected residence. Wherever possible room selection will be considered with regard to differences in orientation, daylight exposure, room use, and the cooling conditions. Multiple measurements from the same homes will be considered as nested observations, not as different residential measurements.

Table 1: Proposed Sampling Strategy and Case Selection Specifications

Sampling Parameter	Proposed Specification
Minimum sample	12 residences
Target sample	15 residences
Maximum sample	20 residences
Sampling technique	Purposive maximum-variation sampling
Unit of analysis	Individual residence
Rooms per residence	2–4 representative occupied rooms
Minimum room observations	24 rooms (12 × 2)
Target room observations	30–60 rooms (15 × 2–4)
Maximum room observations	80 rooms (20 × 4)
Geographic scope	Lahore, Punjab, Pakistan
Case selection criteria	Architectural characteristics, daylight exposure, cooling systems, occupancy patterns, and data accessibility

Note. The proposed sampling strategy adopts purposive maximum-variation sampling to capture differences in residential characteristics, architectural configurations, daylight conditions, cooling systems, and occupancy patterns. The individual residence serves as the primary unit of analysis, while representative occupied rooms constitute the room-level observation units. The target sample of 15 residences, with 2–4 rooms per residence, is intended to support exploratory comparative case-study analysis.

Table No 2: The sampling scenarios and room counts proposed for post occupancy evaluation for high-end residences in Lahore, Pakistan.

Scenario	Residences	Rooms per residence	Total room observations
Minimum feasible sample	12	2	24
Target sample	15	2	30
Target sample	15	3	45
Target sample	15	4	60
Maximum feasible sample	20	4	80

Inclusion criteria

A residence will be considered eligible when it:

- It is an occupied High End residential building in Lahore.
- Allows for the proposed environmental monitoring and building inspection.
- Provides adequate architectural information to describe related design variables.
- Consents to adult occupants for questionnaire proffer if assessment is made by occupant.
- Gives information about electricity use or a way to find information about energy use.
- Allows monitoring in documented operating conditions in representative occupied rooms.

Exclusion criteria

A dwelling may not be considered if there are legal restrictions on access, the architectural features are not comprehensible, the environment is inadequate for functioning monitoring or energy data for analysis are not feasible. If a dwelling does not have a specific data category but is eligible for other types of assessment it can be kept for the specific assessments, but missing information is noted.

The sample is proposed in the aim of exploratory, comparative, analysis at the level of the case-study, and methodological demonstration. Is not claimed to be a statistically representative sample of all the high-end properties in Lahore or Pakistan.

Building and Architectural Characterization

The information on each home that participates will be collected using a structured building-assessment sheet to record architectural and operations characteristics. The information will be gathered by site investigation, through the use of drawings available, and/or through photographic documentation (where allowed) and/or through occupant interviews or the building owner.

The key variables will be:

- The orientation of the building and the related façade orientation.
- Floor area in which space-conditioning is provided (conditioned floor area).
- Room function, size, floor and relevant spatial communication.
- Window size, window type and Window to Wall Ratio (WWR).
- Externally provided shading, solar adjacent obstructions and other solar control features relevant to the project.
- Interior surface finishes and visible-light-reflectance characteristics, measurable or documented.
- Type of cooling system, rated capacity (if available), thermostat settings and schedules of operation.
- Daylight-control practices (e.g. blind or curtain operation).
- Occupancy patterns and other operating features relevant to the environmental performance.

The total window area will be divided by the gross exterior wall area of the relevant façade and expressed as a percentage, window to wall ratio:

$$\text{WWR (\%)} = (\text{Total window area} / \text{Gross exterior wall area}) \times 100$$

Measurement boundaries and treatment of window frames, doors and glazed openings will be well defined before data collection. Drawings or specifications, if missing, will be determined, and estimates will be marked as such when compared to directly measured or documented quantities.

Daylight Performance Assessment

The daylight part will focus on how natural light is available and how it is distributed in the chosen inhabited rooms and on how this is related to architectural features and response. Window orientation, glazing area, room depth, external obstruction, shading and interior surface characteristics will be evaluated as part of the proposed assessment. If possible, and equipment availability allows, the illumination within the building at various work plane locations documented will be measured with a calibrated lux meter.

The measurements will be made at a fixed height, and the position of the sensors, Date, Time, Sky conditions, status of electric-lighting, shading configuration, etc., will be also monitored to gain consistency and interpretability. The measurements won't be solely based on brightness but rather based on a predetermined spatial sample process used to measure brightness.

With additional light measurement variables including the geometry of the room, window properties and reported visual comfort, glare and daylight sufficiency will be assessed. When sufficient architectural model and material data are available, daylight simulation can be used as an additional evaluation. Simulation’s input and assumptions, weather data and calculation settings will be saved.

The annual daylight number simulated will not be considered as measured and the simulated result will not accompany the measured numbers. It will differentiate daylight availability and visual comfort within the framework. High illuminance might not necessarily be not glare-free, and low illuminance might be suitable for some tasks.

Therefore, daylight performance will be evaluated based on a number of indicators based on environmental observations and occupant response.

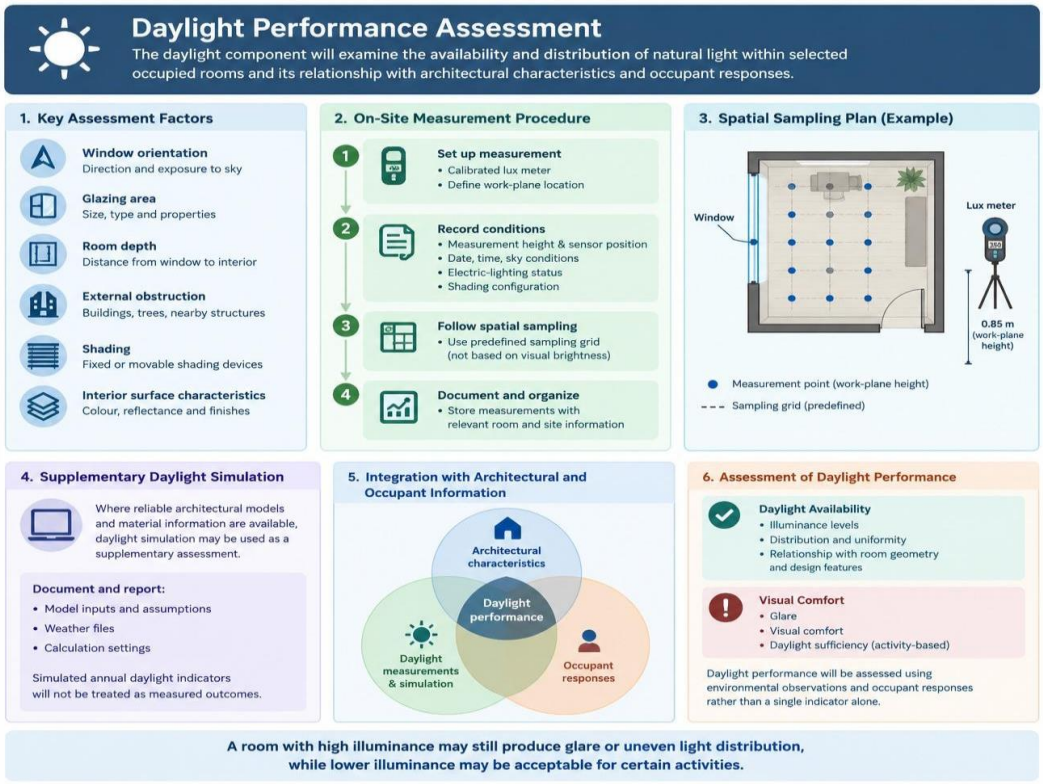


Figure No 4: An integrated daylight performance assessment framework consisting of key architectural variables, illuminance measurements on-site, spatial sampling of lighting levels, additional daylight simulation, and environmental measurement and occupants' response to assess daylight availability from both spaces and visual comfort.

Indoor Thermal Environment Assessment

The indoor thermal conditions will be measured using the environmental monitoring and occupant-response assessment. The proposed monitoring variables are: indoor air temperature (°C) and indoor air relative humidity (%RH). Where possible, equipment and resources to assess air speed (m/s) and mean radiant temperature °C will also be available.

Temperature and humidity loggers are to be placed in typical occupied locations, not in direct sunlight, or in the vicinity of supply-air outlets or other local effects that might affect the measurements. The location of sensors, measurement periods, period of monitoring, calibration, and operational conditions will be recorded.

Monitoring schedules to record relevant occupied periods and variations in cooling operations will be designed. Data on the outward temperature and humidity will be collected from an appropriate means at a local weather station or other source of representative weather data. The source and temporal and spatial relevance of the data measured outdoors will be reported. Indoor environmental measurements, as well as cooling-system operation, window and door opening, shading practices, occupancy, and occupant-reported thermal sensation and acceptability will all be included in the thermal assessmentmean radiant temperature (MRT) or air speed (V) cannot be measured, the study will explicitly indicate that the evaluation omits the measurement of some variables required to calculate thermal comfort. Where the assumptions of thermal-comfort standards are relevant and applicable to the residential setting, they can be used as interpretive references.

The appropriate method and necessary input variables will be explained for any assessment made against one of the standards. Air temperature will NOT be used to imply thermal acceptability.

Occupant Assessment

Occupant assessment is suggested as a way to determine the occupants' experience with daylight and thermal properties inside the building, as well as how their activities affect building performance. A structured survey will be conducted with consenting adult community members subject to ethical and access limitations of the study.

The questionnaire will cover:

- “Perceived Daylight Sufficiency” and “Visual Comfort”.
- Occurrence and severity of glare.
- Thermal sensation and thermal acceptability.
- The use of air-conditioning and other cooling measures.
- Operation of windows, blinds, and curtains.
- Relationship between indoor environment and electrical energy consumption.
- General occupation trends and environmental preferences pertinent to the study.

Clearly defined response scales will be used for thermal sensation and acceptability responses. If a known scale of thermal sensations is used, categories and scoring method to be used should be consistent. A set of questions will separate the notions of perceived brightness, daylight sufficiency and glare from a single and undifferentiated measure.

Each of the questionnaire answers will be correlated to residence and to the room and period of environmental monitoring, if available. Responses will be summarized descriptively and interpreted in conjunction with the physical measurements. Although subjective responses will not be used as substitutes for environmental measurements, these will instead be compared with them within the proposed framework.

Operational Energy Assessment

Using available electricity bills, meter readings, or smart-meter data or submetering records, operational energy performance will be considered. It is desirable that the assessment period be for a full 12 months to reflect changes in seasonal demand for cooling and for other household electricity consumption. When less detailed records are available the period will be noted, and the lack of seasonality interpretation will be noted.

Each assessment will capture electricity usage (in kilowatt-hours, kWh), the timeframe of the assessment, conditioned floor area, cooling-system details, household size, occupancy patterns, and other important operating factors. Where applicable, the presence of photovoltaic systems, batteries, electricity imports/exports will also be documented.

When a sufficiently complete annual electricity record is available, energy-use intensity (EUI) will be determined as follows:

EUI = Annual electricity consumption (kWh) / Conditioned floor area (m^2)

The resulting unit will be kWh/m^2/year. The energy numerator and the floor-area denominator will be applied uniformly for all residences. If electricity used for buildings is total household electricity, the indicator will be expressed as whole-household electricity EUI, as opposed to cooling-specific EUI. Where it is possible to measure or reliably separate cooling-specific consumption then only such consumption will be reported.

Data for electricity will be aggregated with cooling schedules, system characteristics, building occupancy and building design. The comparison of homes in column B will be based on such things as household size, appliance usage, PV generation and other operating factors. Unless the distinction is possible, no explanation or statement about architectural features or energy consumption will be made with regard to causality.

Integrated Analytical Framework

Table 1. Summary of Building, Daylight, Thermal, Occupant, Energy, and Environmental Variables: Measurement Methods and Analytical Considerations

Domain	Variable / Indicator	Proposed Source / Measurement Method	Unit / Output	Analytical Role / Methodological Considerations
Building	Orientation, room function, room dimensions, and conditioned floor area	Architectural drawings, site inspection, and structured assessment sheet	Orientation (direction); floor area (m^2); room descriptors	Provides building context and establishes a consistent boundary for floor-area measurements.
Building	Window-to-wall ratio (WWR)	Window and gross exterior façade measurements	%	Calculate as: WWR = (Window area / Gross exterior wall area) × 100. Document the measurement convention for window frames and openings.
Building	Glazing characteristics, shading devices, adjacent obstructions, and interior finishes	Site inspection, architectural drawings, and photographs (where permitted)	Categorical or documented descriptors	Supports interpretation of daylight availability and solar exposure. Clearly distinguish directly measured characteristics from estimated observations.
Daylight	Indoor illuminance	Calibrated lux meter at predefined work-plane measurement points	lux	Record sensor position, measurement height, time, sky conditions, electric lighting status, and shading conditions.
Daylight / Occupant	Glare, daylight sufficiency, and visual comfort	Structured occupant questionnaire using a predefined response scale	Defined response scale	Assess glare separately from perceived brightness and daylight sufficiency to maintain conceptual clarity.
Thermal	Indoor air temperature	Temperature data logger positioned in a representative occupied location	°C	Document monitoring intervals, sensor location, monitoring duration, calibration, and building-system operation.
Thermal	Relative humidity	Humidity data logger	%	Interpret relative humidity alongside indoor temperature and building operating conditions.
Thermal (Conditional)	Air speed and mean radiant temperature	Anemometer and globe thermometer or other validated measurement methods, where feasible	m/s; °C	If these parameters are not measured, explicitly acknowledge the limitation. Do not infer comprehensive thermal comfort indices from air temperature alone.
Occupant	Thermal sensation, thermal acceptability, and occupant control actions	Structured questionnaire and occupant interviews, where permitted	Defined response scale; categorical or narrative responses	Align occupant responses with the corresponding room and environmental monitoring period wherever possible.
Energy	Monthly or annual electricity consumption	Electricity bills, utility meters, smart meters, or submeters	kWh	Specify the reporting period and clarify whether the consumption represents the entire household/building or a specific end use.
Energy	Energy-use intensity (EUI)	Annual electricity consumption divided by conditioned floor area	kWh/m^2/year	Calculate only when annual electricity consumption and conditioned floor area are adequately documented. Household-level EUI should not be interpreted as cooling-specific energy consumption.

Context	Outdoor air temperature and relative humidity	Documented meteorological station or another representative weather-data source	°C; %	Report the data source, temporal resolution, and geographical and temporal relevance to the study site.

Note. WWR = Window-to-Wall Ratio; EUI = Energy-Use Intensity. All measurement procedures should be consistently documented to ensure methodological transparency, comparability, and reproducibility. Where direct measurements are unavailable, limitations should be explicitly acknowledged rather than replaced with unsupported estimates.

Table No 3: Operational variables, data sources and analytical use

The proposed framework is an integrated approach and involves a structured diagnostic process of the building, environment, occupant and energy data.

Stage 1: Building characterization

Identify architectural elements, space and material and operational characteristics of each house and selected rooms.

Stage 2: Environmental assessment

Note the date, time, room illumination and outdoor temperature and weather conditions.

Stage 3: Occupant assessment

Sort answers to the questionnaire according to residence and relevant room, and monitoring period to the question being asked.

Stage 4: Energy assessment

If data exists on the record or floor area, find data for electricity use.

Integrated diagnosis

Examine design features, environmental influences, human response and indicators of energy, and the convergence and divergence of such elements.

Stage 6: Design feedbackEngage in translation from the documented patterns to a contextualization recommendation for daylight, shade, glass, space, temperature, user engagement and energy management

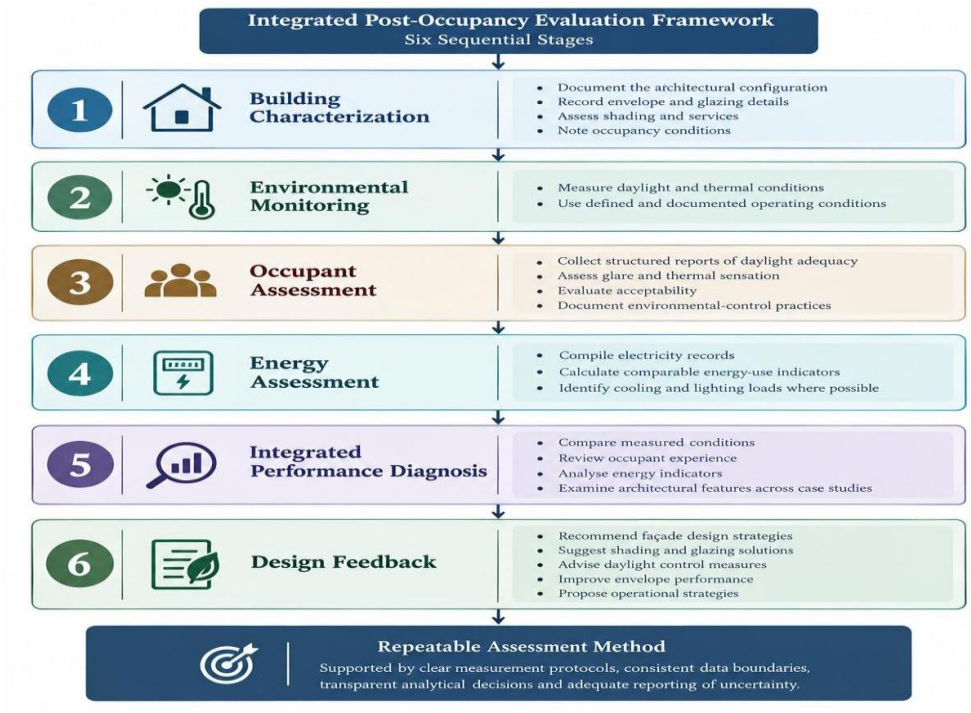


Figure No 5. Workflow for High end Residence Integrated Post occupancy evaluation (POE) Lahore in 6 stages

The structure of the framework is analytical:

Occupational responses + Indoor environmental conditions → Occupant behaviour + Outdoor climate + Architectural characteristics → Operational energy performanceIt is just a statement of the concept links that are in question and not meant to imply that a single factor would ensure that a particular event occurs. A relationship may be mutual but the meaning from the interpretation and what has been sampled will be influenced by the quality and quantity of what is being collected.

Data Management and Analysis

Data analysis will begin by completeness and consistency checks, measurement errors, no observation and a monitoring period difference. These data will be presented using summary statistics relevant to environmental data (including mean, median, range, time-series plots). The analysis of the daylight and thermal measurements will capture factors of measure time, room characteristics and operating condition, and daylight and thermal will be explained and interpreted.

The responses from the occupant questions will be summarized by using frequencies and other descriptive statistics as appropriate. Validation scales will be scored according to the instructions of the corresponding scale. Where appropriate, questionnaire results will be compared to the contemporary environmental observations.

These reviews will include checking for missing months, different billing periods, and different measurement boundaries on the energy records. The Eui will be calculated only if the annual consumption and conditioned floor area is properly documented. Incomplete records will be reported as such and not silently be annualized or treated as complete annual record.

The difference between a residence and a room will be compared based on case analysis with the same set of documented variables. If the number and quality of the observations allow, association of architectural features with environmental measurements and occupant responses with electricity consumption may be explored. For the proposed exploratory sample, it will notbe deemed to be appropriate to use complex multivariable modelling and population level inference.

The different variables, that is, variables measured directly, variables from questionnaires, characterized building features that were documented, indicators that were calculated, and values resulting from simulation, as well as the contextually interpreted results, will be separated using an evidence matrix. This separation will assist in avoiding unsupported causal inferences, and will clarify the analytical process.

Methodological Rigour and Quality Assurance

Operationally defined sensor placements, instrument calibration checklists, documented sensors, the recording of measurement conditions, and standardized data collection forms will all help support methodological rigour. Prior to administering the questionnaires, it will be reviewed for clarity with regard to the study objectives. Problems implementing monitoring and data collection protocol can be flagged, and conducted through a pilot test beforehand.

The findings from the various data sources will be compared using Data Triangulation and with an assumption that there is no need for certainty of the data. An occupant complaining of discomfort from heat is, for instance, given due consideration together with the indoor temperature and the manner that the cooling system is operating. In the same way, the use of electricity will be correlated with the occupancy and work activity conditions and not solely with the building design.

The first of these contributions in the framework is methodological, laying out a repeatable model to gather and analyze the various types of residential performance data. Predictions of reliability, feasibility or validity will need appropriate testing or application and not be described as an outcome if they lack supporting evidence.

Methodological Limitations

There are some anticipated limitations associated with the methodology proposed. Firstly, the sample size of 12-20 residences, using purposive sampling to select residences, will be limitingin terms of population level generalization. Second, environmental tests monitored over a short time span may not cover the range of seasonal and operating conditions. Third, the quantity of information available on architectural plans, electric records and appropriate monitoring devices may be different in various homes.

Fourth, whole-house electricity data may not differentiate energy use for cooling from that for lighting, appliances, and so on. Fifth, the response of occupants might be depending on their memories, expectations, and personal tastes of environments. Finally, the proposed design does not by itself provide causal inferences and provide an empirical validation.

The limitations will be addressed in an open way of reporting, meal measurement will be consistent and the resulting limited data points will be interpreted accordingly, as well as the general separation of the proposed procedures from completed assessments. Further empirical testing of the framework would need to be undertaken at other times of year in other further homes to evaluate the 'live' operation and practicality of the framework.

Framework Outputs and Research Contribution

This section describes what the analysis will uncover, and is not a statement of empirical results because data collection is still underway.

Intended Analytical Outputs

The outcome of the research is expected to be:

1. Daylighting profile with founding for some of the top-ticket residences.
2. Evaluation of thermal conditions and comfort inside measurements from seasonal point of view.
3. Similar patterns with regard to intensity of energy use in residential electricity.
4. Correlation of architectural elements, environmental components, occupants' activities and energy use.
5. A set of performance matrices, suggesting desirable cases and possible trade-offs, for the case study.
6. Annotation of the report by practical method of POE, which can be applied or adapted in further residential.

Theoretical Contribution

The study will help to broaden the body of knowledge relating to the performance of residential buildings since daylight, thermal comfort and operational energy will be considered as complimentary results instead of separate design requirements.

The conceptual gift is the fact that measurements of the physical conditions, the user experience and the operations record can all be woven into a common analytical structure.

Methodological Contribution

The method proposed integrates short term environmental monitoring, occupant surveys, building audits, analysis of energy recording, and daylight simulation models, which relies on climatic data. It will be methodologically valuable based on the clarity and repeatability of the completed assessment as well as its feasibility.

Practical Contribution

Studying the site may enable the architect and interior designer to have evidence obtained that will support decisions such as:

- Orientation-sensitive window design.
- Solar control glazing and external shading.
- Daylighting in large or open spaces.
- Thermal-envelope improvements.
- Lighting and cooling controls.
- Occupant-centred operational strategies.

Recommendations will be listed based on the observed evidence and feasibility and the type of identified performance problem.

Framework Rationale and Application

One of the strengths of the framework that has been proposed here is that it gives a clear pathway from evidence in the contexts of occupied buildings to feedback for design. It does not assume that better daylighting, better thermal comfort and the reduction of electricity consumption are always related. Additional glazing, for instance, can improve daylight penetration whilst adding exposure to the sun; shading, for example, can reduce glare and solar gain without the additional daylight penetration. They are hypotheses that may be explored following this paper, but were not substantiated by it.

One expected challenge will be where a successful result in one performance dimension can coincide with a less successful result in another dimension. For instance, bringing more daylight into the building can lead to more solar intensity or shading the charge for solar gain can result in shades or amount of natural light. These possibilities will be explored through measured and simulated evidence, as opposed to assuming a single direction of causation.

Energy consumption must be taken into account with conditioned floor area, occupancy, appliance load, cooling operation and the preferences of the occupant must be incorporated. Electrically using a comparatively small amount of electricity doesn't imply anything of the design's efficiency (or lack thereof), and the other way around is just as true. Measured conditions, reported satisfaction, simulated annual daylight conditions and energy-use indicators are proposed here for the application of individual reporting.

Where evidence is incomplete, mixed or uncertain case matrixes should be used. As an observational multiple-case design, the analysis presented here can only describe patterns and relationships and cannot determine causal effects, with confidence, as one can in a controlled intervention.

Lastly, the empirical paper will make both qualitative and quantitative distinctions between descriptive results and statistical associations and design interpretations.

Limitations

There are a number of drawbacks to take into account.Geographical scope:

The study is geographically limited to Lahore; therefore, extrapolation of its findings to other climatic regions, construction systems, and residential markets across Pakistan should be undertaken with caution. **Sample size:** The proposed sample size of 12–20 residences is appropriate for exploratory case-study comparisons; however, it may be insufficient for multivariable statistical modelling or broad population-level generalisation. **Monitoring duration:** Short-term monitoring may not capture seasonal variations in environmental and building performance. Therefore, annual daylight simulations and complete annual energy consumption records should be incorporated to support more reliable and defensible estimates of annual performance.

- **Access to energy data:** Household bills can contain several cooling loads, and if there is no Household Submetering, it might not be possible to know cooling specific consumption.
- **Occupant variability:** Thermal sensation, preference for daylight, planning and use of air-conditioning varies across individuals and households.
- **Measurement uncertainty:** Results may be affected by sensor placement, accuracy of instruments, undocumented materials, selection of weather files, and assumptions used in the simulations.
- **Selection bias:** Residents with detailed monitoring may not be the same as those who do not participate with monitoring.

The limitations of these will be addressed using clearly stated sampling parameters, documented procedures, quality assurance and careful analysis of results.



Figure No 6: Risks, limitations, and mitigation strategies for methodologies.

Conclusion

The aim of this paper is to outline a potential partial holistic post-occupancy assessment approach to analyse daylighting performance, thermal comfort and operational electrical energy use of high-end residential buildings in Lahore, Pakistan. The methodological core element is the structuring of different methods such as architectural audits, environmental monitoring, user feedback, electricity measurements and daylight simulation based on climate data in a transparent case study protocol. The protocol makes a distinction between measurement and reportage on experience and simulation of annual measurements, sets out the requirements with regard to the boundaries of the data set included in the measurement, implements quality assurance measures and does not resort to composite scores or unsupported causal statements.

The framework is designed to aid in subsequent evidence-based decisions regarding orientation, glazing, shading, envelope design, lighting controls and cooling strategies. At present, it is methodological and perspective, that is, the manuscript does not include finished fieldwork or empirical data.

The framework needs to be piloted and used for properties that are already occupied, before it can be used to make substantive design recommendations. The next steps involve instrument finalization, sampling criteria finalization, institutional (ethical) approval and a multi-period monitoring and data collection, to evaluate the feasibility of the integrated protocol and the extent of reproducibility. The conclusions that are drawn later on should be of an empirical type and confined to the data secured and the range of case samples.

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