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RESEARCH ARTICLE

# The Impact of Adaptive Micro-zoning on Students' Perception of Energy Efficiency and Comfort in Student Housing in Ghana

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**ABSTRACT**

Adaptive micro-zoning has attracted attention as a strategy to improve thermal comfort. However, there remains a gap in assessing the perceived energy efficiency of student housing in tropical regions. Consequently, this study examines how adaptive micro-zoning influences students' perceived thermal comfort and energy efficiency in on-campus student housing in Ghana. The study used a cross-sectional survey design, in which a total of 923 students were selected from two on-campus student housing units and two micro-zoned housing units in the southern and northern parts of Ghana. Mann-Whitney U test, Spearman's Rank Correlation, and ordinal logistic regression were used to assess group differences and identify predictors of perceived energy efficiency. The analysis revealed that students in micro-zoned housing reported considerably higher thermal comfort and more positive perceptions of energy efficiency, although the differences were moderate. Thermal comfort emerged as the strongest predictor of perceived energy efficiency, while zoning responsiveness and lighting quality contributed moderately. These results suggest that students do not perceive comfort solely through temperature control but also through environmental factors in multisensory, interactive ways. The study suggests that educating users, utilising adaptive lighting, accommodating temporal and cultural variations in occupancy behaviour, and simplifying the metering interface are significant factors for enhancing micro-zoning adaptation in tropical regions.

**Keywords:** Thermal comfort, Adaptive micro zoning, Adaptive lighting, Energy efficiency, Micro-zoning, Student housing

## 1.0 Introduction

The drive towards sustainable development is expanding to encompass broader aspects of a country's life, including higher education infrastructure. Universities and student housing providers are under pressure to implement energy-efficient strategies that promote environmental sustainability while maintaining high levels of comfort. In this context, it is essential to develop technologies that meet the demand for personalised comfort without incurring undue energy costs. One such innovation is adaptive micro-zoning, which is the localised, occupant-specific control of heating, cooling and ventilation systems in buildings. These systems not only increase comfort but also deliver substantial energy savings. Despite rising demand for adaptive micro-zoning as an approach to energy efficiency in buildings, there is limited empirical evidence of its effectiveness in student housing in developing countries. The challenge is compounded by the paucity of research on the effects of adaptive micro-zoning on energy efficiency and perceived thermal comfort compared with conventional housing in sub-Saharan Africa. This is critical given the high energy demand, changing energy-use behaviour and limited adoption of advanced environmental control systems in Ghana.

Traditional Heating, Ventilation and Air Conditioning (HVAC) systems often fail to account for individual variations in thermal preferences, resulting in uniform thermal conditions across spaces. As a result, such systems often fail to satisfy users and negatively impact energy efficiency, especially when rooms are conditioned even when unoccupied. Segmenting spaces into smaller, controllable zones that respond to occupancy and preferences counters this inefficiency through adaptive micro-zoning, providing an individualised environmental control system and efficient energy use in buildings. In this context, energy efficiency refers to reported cost savings in energy consumption attributed to the adoption of adaptive micro-zoning. In fact, the motivation for energy-efficient improvements in homes is mostly monetary and economic gains (Cole et al., 2018).

Although adaptive micro-zoning is an emerging system, scholars have not yet thoroughly examined its application to student housing, a unique context with distinct populations exhibiting diverse routines of living, studying and occupancy. Many studies on adaptive micro-zoning have focused on residential and commercial buildings (Arowoiya et al., 2024; Ghasaban et al., 2025; Jin et al., 2024). Energy and comfort perceptions among students, as well as the key factors influencing energy-use behaviours, are rarely examined in micro-zoned environments in tropical regions; as such, little attention has been paid to student housing in sub-Saharan Africa. In South Africa, technical issues, energy sources, ecological indicators and student behaviour influenced the implementation of revolutionary energy systems in higher education institutions (Almasri et al., 2024). In sub-Saharan Africa, the surge in student enrolment has led to increased energy consumption and waste, as well as a significant burden on university management in terms of energy costs (Oyedepo et al., 2021).

This situation is worsened by the limited use of adaptive micro-zoning, which can significantly reduce energy consumption in student housing. According to Mbazor (2021), these challenges affect higher education costs. In Ghana, challenges related to indoor environmental quality, financial issues and energy management techniques affect energy efficiency in student housing (Anugwo et al., 2025). Appau et al. (2024) and Attakora-Amaniampong (2024) have highlighted the need for improved energy management in university residences in Ghana. Anugwo et al. (2025) emphasised that student housing units often fail to adopt revolutionary design solutions, thereby affecting energy use and indoor environmental quality. The literature indicates a lack of, or limited use of, adaptive micro-zoning to reduce energy costs and to provide thermal comfort. This paper examines the use of adaptive micro-zoning in student housing by assessing students' perceptions of its energy-saving potential. Specifically, the paper answers the following questions: What is the extent of use of adaptive micro-zoning in student housing? What is the perception of students about the ability of adaptive micro-zoning to provide comfort in student housing? Adaptive micro-zoning offers a planned intervention in energy consumption that aligns with global sustainability targets while addressing the comfort needs of student residents.

Although adaptive micro-zoning offers substantial benefits, including energy savings and improved comfort, studies confirming these advantages are scarce, particularly in student housing. Thus, further research is needed to assess how lighting quality, room layout and zoning features affect overall comfort and energy efficiency in student housing. This study contributes to the subject by examining students' perceptions of comfort and energy efficiency in micro-zoned student housing. In assessing energy efficiency, the paper compares adaptive micro-zoned student housing with conventional student housing. To analyse survey data from students across various universities in Ghana, the study employs a robust statistical framework comprising the Mann-Whitney U Test, Spearman's rank correlation and ordinal logistic regression. This study is relevant in several ways. First, understanding the design optimisation needs through these relationships can influence occupant-centric behaviours in student housing. Second, the study is relevant to architects, facility managers and policymakers, as it provides evidence-based recommendations to enhance sustainability and liveability in student housing. Finally, the study advances knowledge in facilities and property management, behavioural energy research and sustainable buildings.

## 2.0 Literature Review

### 2.1 Adaptive Thermal Comfort Model

The Adaptive Thermal Comfort (ATC) model argues that individuals adapt through behavioural, physiological and psychological mechanisms. Proposed by Brager and De Dear (1998), the model emphasises that comfort is highly adaptive rather than relatively static. These adaptations enable occupants to remain comfortable across a broader range of temperatures than static models, which often allow users to adjust their clothing, open windows or modify their activity levels. In contrast with other traditional thermal comfort models that restrict standardised temperature ranges, this model views occupants as active agents who influence comfort conditions. The central tenet of the ATC model is personal control over systems (Brager & De Dear, 1998).

Individuals consistently report higher satisfaction when they have greater autonomy over their thermal environment, even when environmental conditions vary (Brager & De Dear, 1998). This principle has several important applications in building design, particularly in settings such as student housing, which are characterised by diverse occupants, fluctuating daily routines and varying thermal preferences and space-use patterns. This focus on personal control makes the Adaptive Thermal Comfort model significant for adaptive micro-zoning. This principle is enabled and localised through an individual environment adjustment model. Adaptive micro-zoning embodies this principle, allowing individuals to control the temperature, potentially enhancing comfort and energy efficiency. Aguilera et al. (2021) used this model and found that occupants in mixed-mode buildings with greater environmental control are more tolerant of wider temperature ranges. Thermal perception is further influenced by psychological adaptation, shaped by expectations and prior experience, especially among students (Zhuang et al., 2022). Despite these perceptions, little research has examined the relevance of the ATC model to student housing in tropical settings.

### 2.2 Occupant-Centric Control Strategies in Housing Adaptation

Occupant-Centric Control (OCC) marks a shift in building operations towards adaptive systems that respond to individual behaviours and preferences. This transformation is particularly relevant in student housing, where occupants' behaviour patterns often vary and thermal comfort needs are diverse. OCC is a system that collects data from occupants, the indoor environment and the outdoor environment to inform building control and improve comfort and energy efficiency. The literature shows that OCC holds much theoretical promise. While OCC systems are often recognised as very effective, their performance is more complex and sometimes inconsistent. For instance, Ouf et al. (2021) observed that OCC systems can be used to preserve thermal comfort and reduce energy use by up to 60%. However, there could be significant differences between observed and actual energy performance. The occupant-adaptive controls enhance energy efficiency and satisfaction when compared to conventional systems (Mazzone & Khosla, 2021; Loengbudnark et al., 2023; Tekler et al., 2023). However, these studies relied on users being continuously available and on sensor infrastructure being quite dense, assumptions that rarely hold in practice. This contrast between theoretical promise and practical limitations reveals a gap between the assumptions of Occupant-Centric Control design and actual energy-use behaviour.

In a study of German building operators, Hahn et al. (2022) found that occupancy sensors and BAS data are often underutilized or deactivated. The authors challenged earlier studies, emphasizing the importance of system responsiveness despite critical limits, particularly in the absence of real-time data integration. Occupant feedback plays a central role in OCC. Hahn et al. (2022) also reported that most feedback is anecdotal and reactive, typically occurring after comfort thresholds have been breached. Learning algorithms can use occupant interactions, although their subjectivity and irregularity impede optimisation, a finding consistent with Zhang et al. (2022). These problems are likely to be even more pronounced in student housing, where students exhibit irregular schedules, limited technical engagement and varying levels of awareness of building systems. OCC systems must interpret complex and variable occupant behaviours.

Gao et al. (2025) proposed an ontology for modelling these behaviours, enabling systems to map control logic to contextual patterns. However, such approaches do require significant computational resources. These resources, including data, are rarely available in the average student residence. Tsolkas et al. (2023) warned that context-insensitive systems fail to capture behavioural patterns, leading to suboptimal performance. On their part, O'Brien and Tahmasebi (2023) warned that interfaces with poor design or excessive complexity can alienate users, a concern validated by Hahn et al. (2022), who reported that operators sometimes turned off user-accessible features to prevent misuse, thereby undermining the core OCC principle of occupant agency. Satisfaction, coupled with productivity, correlates strongly with perceived environmental quality, which Liang et al. (2024) demonstrated is directly linked to thermal comfort. Similarly, comfort can directly affect academic performance in student housing. Notwithstanding the extensive research on Occupant-Centric Control in commercial and office buildings, there is limited empirical evidence on how these systems function in student housing in developing countries.

### 2.3 Energy-Use Behaviour in Student Housing

Energy-use behaviour among students in residential settings has been examined in studies on sustainability and building performance (Hou & Law, 2024). Students have irregular schedules, short-term occupancy, diverse cultural backgrounds and often limited financial resources (Appau et al., 2024; Fang & van Liempt, 2021). These exclusive features make student housing a highly dynamic environment where behavioural patterns play a critical role in shaping energy use. These factors together shape distinctive patterns of energy consumption. Understanding these patterns is essential when designing interventions, such as adaptive micro-zoning. For instance, Appau et al. (2024) found that student housing in Ghana has a higher Energy Use Intensity (EUI) than other residential building types owing to inefficient usage habits and often outdated building systems. Their study showed that daily habits contradicted expressed environmental values, e.g., leaving appliances on or maintaining HVAC settings at extreme levels. This phenomenon suggests that awareness campaigns alone fail to influence energy behaviour, as noted by Komendantova (2021). Thus, awareness alone is insufficient to determine energy-efficient behaviour, hence the need for energy systems that align comfort with efficiency and cost savings (Cole et al., 2018).

Perceptions of comfort and convenience are closely linked to students' energy-use behaviour. Studies show that students prioritize immediate comfort over long-term energy savings, citing academic stress, heavy workloads and social pressures as reasons for disregarding conservation behaviours (Hou & Law, 2024). In poorly designed housing where thermal comfort is not readily achievable, students may resort to inefficient practices such as using space heaters, blocking vents or manually overriding energy-saving settings (Hou, 2024).

These practices further contribute to energy waste. The physical characteristics of student accommodations also crucially shape behaviour. Buildings equipped with user-friendly energy-saving technologies encourage more responsible energy use among students (Roofigari-Esfahan & Morshedzadeh, 2025). No doubt, cultural factors shape student interaction with these systems. According to Cen et al. (2025) students from tropical or subtropical climates tend to have different expectations for thermal comfort. For example, students in Ghanaian contexts might tolerate warmer indoor conditions if air movement and ventilation are adequate. Therefore, micro-zoning should control temperature, ensure air quality and promote air circulation.

Another context is the influence of peers on energy consumption. According to Bae et al. (2025), students frequently adjust the thermostat for personal comfort, even when residents in the same HVAC zone share the same thermostat. This behaviour prompts others to use personal fans or heaters, leading to unintended energy conflicts. Adaptive micro-zoning can help reduce conflicts and offer more individualised control. According to Yu et al. (2024), the temporal dynamics of student life, including semester transitions, exam periods and holidays, influence occupancy patterns and energy demand. Buildings that lack operational adjustments for occupancy changes often show higher EUI.

## 3.0 Research Methodology

### 3.1 Research Design

This study employed a cross-sectional survey design to assess students' perceptions of energy efficiency and comfort in two distinct types of student housing: adaptive micro-zoned housing and conventional non-zoned housing. This design enabled the simultaneous collection of data from diverse student groups and the recording of variations in perceptions of thermal comfort and energy efficiency. In addition to the primary variables, other contextual factors, such as lighting quality and zoning features, were incorporated into the analysis due to their influence on energy efficiency.

### 3.2 Sampling Procedure and Mode of Data Collection

A stratified random sampling technique was used to select students living in purpose-built, micro-zoned student housing and in conventional student housing in Ghana. The selection procedure was based first on whether adaptive micro-zoning technologies were present in student housing. Second, only buildings less than five years old were selected to avoid older HVAC systems and sick buildings. Two purpose-built and two conventional on-campus student housing units were selected, one each from the southern and northern parts of Ghana. A total of 923 students were sampled across two categories of student housing: 609 from conventional housing and 314 from micro-zoned housing. This selection reflects the proportion of the general student population living in conventional student housing compared with micro-zoned student housing. To qualify for participation, students must have lived in the existing housing for at least one semester. Data were collected through a self-administered questionnaire structured into five sections: demographic information, housing type, perceptions of thermal comfort and energy-use efficiency, and an assessment of influencing factors such as lighting quality and zoning features. Perceptions were measured using a 5-point Likert scale, with "Strongly Disagree" (1), "Disagree" (2), "Neither Disagree nor Agree" (3), "Agree" (4) and "Strongly Agree" (5).

### 3.3 Variable Definition and Measurement

Energy efficiency, thermal comfort and micro-zoning features were each defined and operationalised using three primary variables. Based on the literature, students viewed energy efficiency as the extent to which they perceived their housing units to be effective. Four key indicators were measured for this variable. First, students agreed with statements such as "This housing helps me save electricity" to assess perceived energy savings. Second, the use of smart thermostats or LED lighting in their accommodation raised awareness of energy-saving technologies. Third, self-reported energy behaviour, such as how often students engaged in actions to conserve energy (e.g., switching off lights or unplugging devices), was assessed. Comparative energy use was measured by students' perceptions of energy use relative to their previous living conditions.

The Adaptive Thermal Comfort model defines thermal comfort as the degree to which an individual feels satisfied with their thermal environment. This definition accounts for psychological and behavioural adaptation, with the variable measured using four indicators. First, the rooms maintained a comfortable ambient temperature, with comfort reflected in satisfaction with the room's temperature. Second, thermal autonomy, or the ability to adjust HVAC settings, was taken to mean the capacity to control room temperature. Third, thermal adaptability was measured by how students responded to room temperature in their behaviour, either through the clothing they wore or by opening windows. Fourth, discomfort occurrences, such as feeling hot or cold, helped to measure the variability of comfort experiences.

Micro-zoning features were defined as architectural and technological systems that enable localised environmental control in individual student rooms. These features were treated as the primary independent variable, measured using four indicators, viz: the availability of zoning controls, such as individual thermostats or adjustable room vents; usage frequency, which gauges how often students interact with the systems to adjust their indoor environment; perceived responsiveness of the zoning system, measured by asking whether students believed the system adapted quickly to their inputs; satisfaction assessment, with users asked to assess their satisfaction with the zoning features, specifically how the system supported their individual comfort preferences.

### 3.4 Data Analysis

The analysis examined differences in students' perceptions of thermal comfort and perceived energy efficiency between adaptive micro-zoned student housing and conventional student housing. The Mann-Whitney U test was applied. Given the ordinal dependent variables, a nonparametric test was chosen, as the Kolmogorov-Smirnov test indicated that normality assumptions were violated.

The Mann-Whitney U test assesses whether two independent groups differ in their distributions of a variable, without assuming normality. The analysis procedure ranked all dependent variable values together from both groups. After that, the total rank sum was computed for each group. Furthermore, statistical significance at the 0.05 level was observed between groups, as indicated by a U value below the critical value. The relationship between students' perceived thermal comfort and perceived energy efficiency was assessed using Spearman's Rank Correlation.

Spearman's correlation is suitable for examining associations between variables. The study used it to measure the two variables on an ordinal scale. The scores for each respondent on both variables were first separately ranked to compute Spearman's correlation coefficient (ρ). Each individual's two ranks were used to calculate the square of their difference and to sum the results. At the 0.05 significance level, the correlation importance was determined. Perceived energy efficiency increased, as indicated by a positive, statistically significant ρ value, accompanied by increases in perceived thermal comfort. Finally, ordinal logistic regression was used to predict students' perceptions of energy efficiency using the following predictor variables: perceived thermal comfort, lighting quality, and zoning features. Before running the ordinal logistic regression, the study assessed the proportional odds assumption and the diagnosis-treatment interaction using the Test of Parallel Lines. The regression model is specified in the equation below:

$$\alpha_j - (\beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3) = Log\left(\frac{p(Y \leq j)}{p(Y > j)}\right)$$

This equation calculates the log-odds of a student's perceived energy efficiency. The variable Y represents perceived energy efficiency. Each $\alpha_j$ separates response categories above a threshold. The predictors, $X_1, X_2, and\ X_3$ represent thermal comfort, lighting quality and zoning features. Positive coefficients (β > 0) indicate that the likelihood of higher energy efficiency increases as the predictor increases (e.g., better thermal comfort). Negative coefficients could indicate lower-perception categories. This model helps identify aspects of student housing that most strongly drive sustainability perceptions. For each predictor, the model output included coefficient estimates along with odds ratios (exp(β)). The analysis shows that odds ratios greater than one mean that increases in the predictor increased the odds of a higher perceived energy efficiency category. Pseudo R-squared measures and Chi-square goodness-of-fit statistics were used to evaluate the overall model fit.

## 4.0 Research Findings

### 4.1 Descriptive Findings of Thermal Comfort and Energy Efficiency in Student Housing

The descriptive statistics provide an overview of residents' demographics and general perceptions of thermal comfort and energy efficiency in student housing. The gender distribution is nearly balanced, with 53.6% male and 46.4% female (see Table 1). The most represented age group was 25–30 years (49.4%), followed by 20–25 years (35.4%), with 31 and older at 15.2%, which aligns with the typical structure of student populations in tertiary institutions. Regarding housing type, as noted earlier, nearly 60% of students lived in conventional student housing, while 40% lived in micro-zoned student housing. Students reported moderately high thermal comfort (M = 3.81, SD = 0.78) and slightly lower energy efficiency (M = 3.57, SD = 0.86). The high standard deviation in energy efficiency suggests variation in how students interpreted and perceived it. These findings also imply that students have a positive perception of the general conditions of student housing.

**Table 1:** Descriptive Statistics of Participants and Key Variables

| Variable | Category | Frequency | Percentage | Mean (M) | Standard Deviation (SD) |
|---|---|---|---|---|---|
| Housing Type | Adaptive Micro-Zoned | | 40% | | |
| | Conventional Housing | | 60% | | |
| Gender | Male | 432 | 53.6% | | |
| | Female | 374 | 46.4% | | |
| Age Group | 20-25 years | 285 | 35.4% | | |
| | 25-30 years | 398 | 49.4% | | |
| | 31+ | 123 | 15.2% | | |
| Perceived Energy Efficiency Score | - | | | 3.57 | 0.8 |

***Source:*** Field data, 2025

### 4.2 Model Testing and Fit

The Cronbach's alpha of 0.82 (see Table 2) indicates strong internal consistency across survey items and supports the instrument's reliability. The Test of Parallel Lines ($p = 0.084$) was not significant, confirming that the proportional odds assumption was met and validating the ordinal logistic regression. The model fit is highly significant, as indicated by the model's chi-square ($\chi^2(3) = 32.51$, $p < 0.001$). The model explains a moderate proportion of the variance in perceived energy efficiency, as indicated by the Pseudo $R^2$ values (Cox & Snell = 0.133; Nagelkerke = 0.166). This implies that the "experiential factors meaningfully influence sustainability perceptions" in student housing.

**Table 2.** Model Treatment and Fit

| **Model Component** | **Result** |
|---|---|
| Cronbach | 0.82 |
| Test of Parallel Lines | $p = 0.084$ |
| Pseudo $R^2$ – Cox & Snell | 0.133 |
| Pseudo $R^2$ – Nagelkerke | 0.166 |
| Model Chi-Square | $\chi^2(3) = 32.51$, $p < 0.001$ |

***Source:*** Field data, 2025

### 4.3 The Influence of Adaptive Micro-Zoning on Energy Efficiency

The Mann-Whitney U Test results showed statistically meaningful differences in the type of student housing and relationship to perceptions of thermal comfort and energy efficiency. Table 3 shows that both students in conventional student housing and those in adaptive micro-zoned housing reported a higher level of satisfaction. For thermal comfort, micro-zoned housing had a mean rank of 426.32, while conventional housing had a mean rank of 414.23. For energy efficiency, residents in micro-zoned areas had a mean rank of 454.11, whereas those in conventional housing had a mean rank of 453.42. The statistical significance for both micro-zoned and conventional housing ($p = 0.041$ and $p = 0.042$, respectively) suggests that the variations are unlikely to be due to chance or that the impact in reality is minimal.

The indicators of thermal comfort were satisfaction with room temperature, perceived ability to adjust indoor conditions, and behavioural adaptability.

The findings show that students in micro-zoned housing experienced slightly greater control and fewer discomfort events (mean rank = 454.11). The energy efficiency indicators included perceived reductions in electricity use, students' awareness and use of energy-saving technologies, students' self-reported energy conservation and students' comparisons of their current housing experiences with their past experiences. Higher scores were recorded for micro-zoned student housing, suggesting that students felt the impact of energy-saving features in their housing, such as individual control systems or efficient lighting.

Assessing the impact of adaptive micro-zoning on students' lived experiences indicates a moderate effect relative to conventional housing. Table 2 indicates that micro-zoned student housing appears to have a greater influence on key indicators, including comfort, overall satisfaction, environmental quality and perceptions of sustainability in student housing. Spearman's Rank Correlation analysis revealed that perceived thermal comfort and energy efficiency among students were positively and statistically associated, with a correlation coefficient (ρ) of 0.43 and a p-value of 0.042. Students reporting greater satisfaction with thermal comfort were more likely to perceive their housing as energy-efficient. This indicates a moderate correlation, still reflecting a meaningful trend. Students who experience thermal comfort and adapt to their surroundings are more likely to use energy efficiently. Energy-saving features may be perceived or appreciated through this connection to subjective thermal satisfaction. These findings suggest that thermal comfort, primarily achieved through user-centric controls and adaptive zoning, may not only improve well-being but also reinforce a belief in energy-efficient and sustainable design, thereby enhancing satisfaction in student housing.

**Table 3:** Mann-Whitney U test and Spearman's rank correlation results

| Variable | Group | Mean Rank | U | p-value |
|---|---|---|---|---|
| **Mann-Whitney U Test** | | | | |
| Thermal Comfort | Micro-zoned Housing | 426.32 | 6234.5 | 0.041 |
| | Conventional Student Housing | 414.23 | | |
| Perceived Energy Efficiency | Micro-zoned Housing | 454.11 | 67310.1 | 0.042 |
| | Conventional Student Housing | 453.42 | | |
| **Spearman's ρ** | | p-value | | |
| Thermal Comfort and Energy Efficiency | 0.43 | 0.042 | | |

***Source:*** Field data, 2025

**4.4 Experiential Predictors of Perceived Energy Efficiency in Student Housing**

The ordinal logistic regression analysis revealed that three experiential factors — perceived thermal comfort, lighting quality, and zoning features — were statistically significant predictors of perceived energy efficiency among the students. Each variable influenced student evaluations, with p-values below 0.05 (see Table 4). Thermal comfort had the highest predictive value, with an odds ratio of 1.64. This implies that for every one-point increase in students' perception of comfort, perceived energy efficiency increased by 64%. Lighting quality also emerged as an important contributor, with an odds ratio of 1.50. This suggests that lighting quality, which supports visual comfort, might influence how students assess energy efficiency. That is, sufficient lighting might reduce the need for additional fixtures and modifications. Micro-zoning features had an odds ratio of 1.87; this indicates that such features, such as personalised control systems, almost double the likelihood that students perceive their environment as energy-efficient. These results suggest that user experience strongly influences perceived energy efficiency. They also indicate that the building structure itself is less influential on perceptions of energy efficiency than user experience.

**Table 4:** Predictors of perceived energy efficiency in student housing

| Predictor | Coefficient (β) | Standard Error | Odds Ratio (e^β) | p-value |
|---|---|---|---|---|
| Thermal Comfort | 0.45 | 0.16 | 1.64 | 0.046 |
| Lighting Quality | 0.36 | 0.10 | 1.50 | 0.049 |
| Zoning Features Presence | 0.58 | 0.11 | 1.87 | 0.047 |

***Source:*** Field data, 2025

## 5.0 Discussions

The study aimed to assess the contribution of micro-zoning to energy-use efficiency in student housing in Ghana. The findings align with the literature and theory, particularly those grounded in Occupant-Centric Control (OCC) frameworks and the Adaptive Thermal Comfort (ATC) model. For instance, Brager and De Dear (1998) observed a correlation between perceived thermal comfort and energy efficiency, affirming the proposition that when individuals have greater autonomy over their immediate environment, their satisfaction and perception of energy-use efficiency increases. This is supported by the positive predictive value of thermal comfort, as determined by the regression model in this study. Aguilera et al. (2021) echoed this point, emphasising that broader temperature tolerances and improved environmental control led to a greater perceived energy efficiency. They further observed that the adaptive comfort model allows for variations in temperature and energy use, provided occupants have greater control.

In this regard, the findings corroborate the value of adaptive micro-zoning in large-population environments, such as student housing. The findings further support the conclusions drawn by Zhuang et al. (2022) that psychological adaptation enabled occupants to cope with hot temperatures in summer and cold temperatures in winter, thereby influencing thermal comfort. That notwithstanding, this study departs significantly from the OCC implementation idealised in simulation-based works, such as Ouf et al. (2021), in which adaptive systems are expected to reduce energy use substantially. The findings suggest that although students in micro-zoned housing perceived improvements in energy efficiency, these perceptions did not necessarily translate into substantial differentiation or transformative experiences in actual energy savings. This divergence underscores how translating simulated efficiencies can limit perceptual and behavioural gains, as noted by Hahn et al. (2022).

Furthermore, the findings suggest that the effectiveness of micro-zoning adaptive systems is likely moderated by user engagement and technological literacy, although the study did not directly assess these factors. O'Brien and Tahmasebi (2023) have cautioned that participation in OCC requires intuitive interfaces, especially when students are unaware of or unable to use zoning technologies, thereby diminishing the anticipated benefits. Appau et al. (2024) have noted a persistent "value-action gap", that is, a mismatch between expressed environmental concern and actual energy behaviour among Ghanaian students.

The regression model identified zoning features as predictors of perceived energy efficiency. However, the odds ratio indicates influence rather than dominance. Roofigari-Esfahan and Morshedzadeh (2025) noted this harmony, stating that energy-efficient building designs must be human-centred to deliver benefits. In particular, lighting quality contributed meaningfully to this, suggesting a holistic perception of comfort that encompasses thermal, visual, and acoustic factors. This multidimensionality of comfort challenges the narrow focus on temperature control common in much of the OCC literature. Similarly, Liang et al. (2024) have advocated an integrated approach to environmental quality and comfort perception.

As this study found, Ghanaian students' expectations of comfort are significantly influenced by context. This supports the conclusion that students from tropical climates exhibit different tolerance thresholds and behavioural adaptations to thermal comfort (Cen et al., 2025). Therefore, thermal comfort models and technologies developed in temperate contexts may require localisation for other ecological zones. Energy efficiency and comfort are moderately correlated, indicating contextual specificity. Furthermore, students may perceive environmental adequacy based on their experiences and, therefore, interpret thermal satisfaction more flexibly, as they habitually adapt through ventilation and clothing behaviour.

The effect of these moderate findings is twofold. First, they suggest that comfort perception can be improved through adaptive micro-zoning, although students’ engagement with the supporting infrastructure will ultimately determine its full potential. Without intuitive interfaces and feedback mechanisms that reinforce responsible energy-use behaviour, micro-zoning risk becomes an underutilised technological asset. The findings further suggest that energy-saving actions in student housing should be supported by behavioural changes, education and culturally sensitive design modifications. It is hoped that perceptions of comfort and energy efficiency will become more positive as universities in the Global South adopt adaptive micro-zoning systems and students become familiar with these technologies. However, this will depend on institutions' willingness to invest in these technologies.

Looking to the future, it is reasonable to predict that the perceptual and actual gains in comfort and energy-use efficiency will be more pronounced when universities in the developing world fully adopt refined adaptive micro-zoning systems. These systems might be integrated with predictive algorithms and real-time occupancy feedback to optimise environmental controls, shifting them from an exception to the norm. The institutional willingness to invest in user education and system usability enhancements, rather than just devices, will have a significant impact on this evolution.

## 6.0 Theoretical and Practical Implications

This study has contributed to the discourse on smart buildings, property management and sustainable energy consumption. It has refined the Adaptive Thermal Comfort (ATC) model by showing that thermal autonomy does not uniformly translate into perceived energy efficiency or comfort across contexts. The ATC model posits that greater control over one's thermal environment improves satisfaction. However, it does not account for how structural, social and cultural traditions shape student housing in tropical regions. The study found that thermal comfort correlates moderately with energy efficiency, suggesting that user control must be accompanied by contextual relevance, usability and system responsiveness to yield impactful energy-efficiency outcomes. Therefore, the ATC model does not sufficiently address the psychosocial and infrastructural realities of non-commercial, multi-occupant settings. This study closes this gap by introducing a more context-sensitive adaptation for occupant-centric control. Thus, integrating variables such as lighting quality and perception of zoning systems strengthens the explanation of comfort-energy relationships.

In practice, user education and interface design enhancements can help students who lack awareness or confidence to engage meaningfully with zoning systems. This study found that lighting quality predicts perceived energy efficiency; therefore, new micro-zoning designs should consider visual, lighting and thermal comfort during development. This can be achieved by maximising daylighting layouts or implementing adaptive lighting systems. Moderate values in micro-zoned and conventional student housing suggest a need for flexible environmental systems that can dynamically adjust to usage patterns. Ventilation and air movement are crucial in tropical climates; however, control systems are often designed based on thermal expectations from temperate zones. Student housing designs must incorporate local comfort norms, including ventilation system design and control, tailored to the local environment. Finally, the study found that trust issues contributed to the moderate findings. To address this, the study proposes using energy dashboards or mobile apps to integrate real-time feedback mechanisms and encourage sustainable behaviours in student housing.

## 7.0 Conclusion

This study has provided insights into adaptive micro-zoning in student housing in Ghana. The findings indicate that students living in micro-zoned housing reported statistically meaningful but moderate improvements in comfort. There was also an improvement in perceived energy efficiency compared with those living in conventional student housing. While these improvements appear minimal in this study, they nonetheless affirm the relevance of occupant-centric control systems. The modest effect sizes suggest that perceptions will not change significantly solely through the implementation of technology. Thermal comfort correlates with energy efficiency, supporting the Adaptive Thermal Comfort model; however, adjustments are necessary when applying it across diverse environmental and sociocultural contexts. The study concludes that, in addition to thermal, visual and acoustic factors, lighting quality and zoning responses also predict environmental quality. These results call for a more integrated and user-centred approach to student housing design that goes beyond traditional temperature control.

This study has applied an occupant-centric control design theory to micro-zoned student housing in Ghana. The study affirms that behavioural patterns and localised designs remain important for realising the full potential of adaptive zoning technologies. However, it is worth noting that this study relied on students' self-reported perceptions of energy behaviour in student housing. While perceptual measures are critical in science, further studies could incorporate tracking of actual energy use in micro-zoned student housing.

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