Spatial-Temporal Analysis of Pedestrian Flow and Environmental Pollutants in Public Areas of Apartment Buildings

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Abstract. To optimize the living environment for health and sustainability, a deep understanding of the interactions between pedestrian dynamics and environmental parameters is crucial. This study conducts spatial-temporal analysis of key locations in the public areas of an apartment building, revealing the spatial-temporal characteristics and correlations between pedestrian flow and environmental pollutants. The study found that there are two peak periods of human flow in the morning and evening, accounting for about 24% of the total daily pedestrian flow. There is a clear preference for using ascending elevators, resulting in a typically lower daily average downward load compared to the upward load. Additionally, the study found varying correlations between pedestrian flow and environmental pollutants: $PM_{2.5}$ and PM_{10} show weaker correlations, while noise, TVOC, formaldehyde, and ozone are more strongly correlated with human activity. The choice of time granularity is critical for analyzing these correlations. The research also indicates that the particulate matter and ozone levels are higher in the 7th floor elevator area, with high levels of ozone and noise on the ground floor, posing a double risk of ozone exposure for residents on the 7th floor. This study clearly identifies health risks in the apartment's public areas and their causes, providing vital insights for the design and management of apartment buildings.

Keywords: Apartment buildings; Public areas; Pedestrian flow; Environmental pollutants; Correlation; Health risk.

1 Introduction

Amidst the accelerating pace of urbanization, the increasing density of urban populations has spurred the extensive construction of high-density apartment buildings. This transformation not only reshapes urban skylines but also potentially impacts the environmental welfare of residents within these buildings [1-3]. Most of the time residents spend in these apartments is within their own homes, where numerous studies have focused on assessing and controlling the quality of the indoor

© The Author(s) 2025
W. Guo et al. (eds.), *Proceedings of the 3rd International Conference on Green Building, Civil Engineering and Smart City (GBCESC 2024)*, Advances in Engineering Research 264,
https://doi.org/10.2991/978-94-6463-728-1_46

environment [4-6].

However, recent studies increasingly indicate that short-term exposure to environmental pollution has a significant impact on residents' health that cannot be overlooked [7-10]. Thus, the issue of environmental pollution in the public areas between residential spaces and the outside of apartment buildings—areas through which residents pass briefly but frequently—is particularly critical. In apartments, due to the regularity of residents' routines and the concentrated distribution of pedestrian flow, the risk of environmental pollution exposure may vary across different areas.

Given the critical importance of identifying the risks of environmental pollution exposure in the public areas of apartments, this study, through the analysis of actual measurement data, aims to clarify the spatial-temporal distribution characteristics of pedestrian flow and common environmental pollutants in typical public areas within apartment buildings, as well as their interrelations, to define the environmental pollution exposure risks faced by residents. This research will provide theoretical support for improving the operational level and environmental quality of apartments.

2 Materials and Methods

In our study, we utilized an air quality sensor (PR-3001-MG111-4G, Prsens, Shandong, China) to gather environmental pollutants at different locations. Common indoor pollutants measured include $PM_{2.5}$ (0-1000 ug/m^3, ±3% FS), PM_{10} (0-1000 ug/m^3, ±3% FS), noise (30-130 dB, ±0.5 dB), TVOC (0-200 mg/m^3, ±8% FS), formaldehyde (0-10 mg/m^3, ±5% FS), ozone (0-20 mg/m^3, ±6% FS), and carbon monoxide (0-800 mg/m^3, ±10%), and the data collection interval is one minute. All pollutants, once calibrated, fell within an acceptable accuracy range. This study used a pedestrian flow counter (UDTK, Dongqia Technology, Zhejiang, China), which can collect pedestrian flow data and entry and exit directions at designated locations in real time.

This study selects high-rise corridor-style apartment buildings as the research object and further explores the characteristics of this type of apartment buildings. We found that these apartment buildings usually have a regular shape and are generally composed of single or multi-sided panel structures. In order to improve the represent-activeness of the research results, we selected a board-type high-rise corridor-style apartment building located in a university in Dalian to collect data on pedestrian flow and environmental pollutants. The apartment building has 14 floors and a total permanent population of 623. The data collection locations are located at the entrance of the apartment building and the elevator rooms on the 1st, 7th, and 14th floors. Since there are no physical partitions on the same floor, the internal environmental quality of the corridor is closely related to the living habits of the residents on that floor, so it is not considered in this study for the time being

According to the results of a week-long preliminary experiment, the distribution of pedestrian flow at the apartment entrance indicates that pedestrian flow from 01:00 to 05:00 only accounts for 0.32% of the daily total. Consequently, this study designates 01:00 to 05:00 as the static monitoring period, and 05:00 to the following 01:00 as the

dynamic monitoring period. In this research, real-time monitoring of pedestrian flow was conducted for 13 days at the apartment entrance and the elevator room entrances on the 1st, 7th, and 14th floors, including two weekends to ensure coverage of both weekdays and weekends (from 2023-06-07 to 2023-06-19).

To ascertain the correlation between pedestrian flow and environmental pollutants, environmental parameters were collected when there was no pedestrian movement, during pedestrian movement, and after pedestrian movement, thus clarifying environmental conditions under different scenarios. The experiment was divided into two parts: static monitoring, which was conducted for 8 hours across two consecutive days from 01:00 to 05:00, and dynamic monitoring, which lasted from 05:00 to 01:00 the next day, totaling 20 hours (form 2023-06-07 to 2023-06-08). The measurement locations of environmental pollutants are located at the entrance of the apartment and the center of the elevator room on each floor to improve the representativeness of the sampling results. Since the environment is an indoor environment, there are no significant differences in other pollutants between summer and winter except for differences in temperature and humidity.

In this study, we initially formatted and merged data on pedestrian flow and environmental pollutants from various locations and times. Then, we conduct a comprehensive analysis of the spatial-temporal distribution characteristics of pedestrian flow and environmental pollutants. Given that the relationships among environmental parameters may not be entirely linear and their distribution does not conform to the normal distribution assumption, coupled with the potential presence of outliers in the collected data, this research employed the Spearman rank correlation coefficient instead of the Pearson correlation coefficient in the analysis of correlations. Furthermore, the research delved into the potential relationships between pedestrian flow within apartments and environmental parameters, based on various time granularities including 1 minute, 10 minutes, 30 minutes, and 1 hour.

3 Results

3.1 Spatial-temporal characteristics of the pedestrian flow

The distribution of pedestrian flow at the apartment entrance is shown in Fig. 1. The data indicates that the daily peak ingress and egress periods (08:00-09:00 and 22:00-23:00) account for 24.13% of the total daily movements, with a standard deviation of 3.63%. This signifies that these two hours comprise nearly a quarter of the total daily flow, with a relatively small fluctuation in the proportion of flow during peak periods, suggesting a consistent pattern of resident movement daily. Additionally, the weekends of 06-10, 06-11, 06-17, and 06-18 show a distinctly different distribution compared to other dates. Calculations reveal that the standard deviations for "In" flow during these four days are 39.21, "Out" flow 35.45, and total flow 55.8, compared to 47.94, 49.59, and 69.82 on weekdays, indicating more stable pedestrian flow at the apartment entrance during these days compared to other dates, which show greater variability.

The distribution of pedestrian flow at the 1st floor elevator room is illustrated in Fig. 2. Similar to the apartment entrance, the 1st floor elevator room exhibits distinct morning and evening peaks, although the numbers are slightly lower than at the entrance. Further analysis indicates that the flow of people ascending via the elevator generally exceeds those descending, with an average daily difference of about 137 people. This suggests that compared to descending, a greater number of residents prefer to use the stairwell, particularly as ascending and descending are more convenient on lower floors.

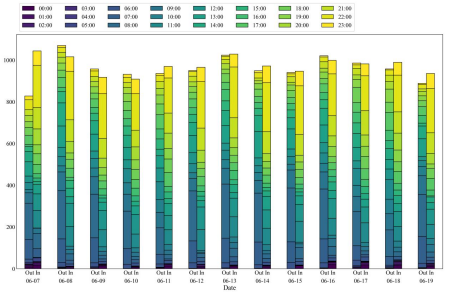

Fig. 1. The pedestrian flow at apartment entrance

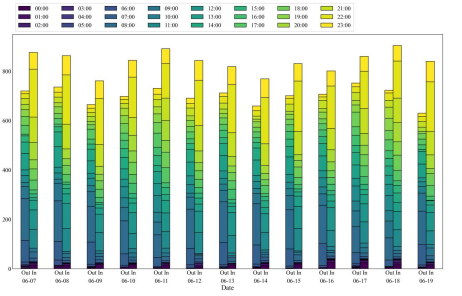

Fig. 2. The pedestrian flow at 1st floor elevator room

Analysis of pedestrian flow at the elevator entrances on the 7th and 14th floors reveals that the volume of people ascending to these floors is significantly lower than those descending. The investigation identifies two main reasons for this phenomenon: firstly, property management staff, during routine patrols and cleaning, prefer to ascend via the stairwell and descend via elevator, integrating work tasks with physical exercise. Secondly, some residents opt to use the stairs for exercise, customarily ascending by stairwell and descending by elevator. Further calculations show that the total pedestrian flow for elevators on the 14th floor is 1.88 times that of the 7th floor, likely related to residents' habits and the height of the floor. On the 14th floor, the pedestrian flow leaving by elevator accounts for 45.2% of the total flow, while on the 7th floor, the proportion is 39.2%, indicating that lower floors reduce the frequency of elevator use for descending. Notably, regardless of whether it is the 7th or 14th floor, the probability of leaving a floor via elevator is lower than that of entering, demonstrating that the daily elevator down-load generally is less than the up-load, providing crucial data for the efficient operation of elevators.

3.2 Correlation analysis between pedestrian flow and environmental pollutants

Given the distinct regularity in pedestrian flow within the apartment complex and considering the environment as a semi-enclosed space with stable human activity patterns, environmental parameters exhibit cyclical variations daily. Therefore, this study primarily focuses on the correlation changes between environmental parameters and pedestrian flow during two different phases: static and dynamic monitoring. During the dynamic monitoring phase, the highest concentration of carbon monoxide

reached 1 mg/m³, significantly lower than the 10 mg/m³ standard set by the "Indoor Air Quality Standard" GB/T18883-2022. Consequently, carbon monoxide will not be considered further in subsequent studies. This research utilizes the Spearman rank correlation coefficient (r) to analyze the correlation between pedestrian flow and environmental pollutants across four different time granularities: 1 minute, 10 minutes, 30 minutes, and 1 hour, as shown in Fig. 3. The results show that the 1-hour granularity accounts for 72.5% of instances, suggesting that larger time granularities are more likely to reveal the maximum correlation between pedestrian flow and environmental pollutants. However, other time granularities also account for nearly 30%, indicating the necessity of selecting different time granularities during the analysis. Throughout the various phases, the correlation between $PM_{2.5}$ and PM_{10} with pedestrian flow in terms of entries, exits, and total is weak ($r < 0.3$), indicating that the concentrations of these particulate matters are essentially unaffected by changes in pedestrian flow. In contrast, noise, TVOC, formaldehyde, and ozone show stronger correlations with pedestrian flow at least one measurement point ($r > 0.3$), particularly noise, which has a significantly higher correlation with pedestrian flow, thus confirming that residents are the primary source of noise within the apartment complex. Further, this study will analyze changes in environmental pollutants based on the strength of the correlations.

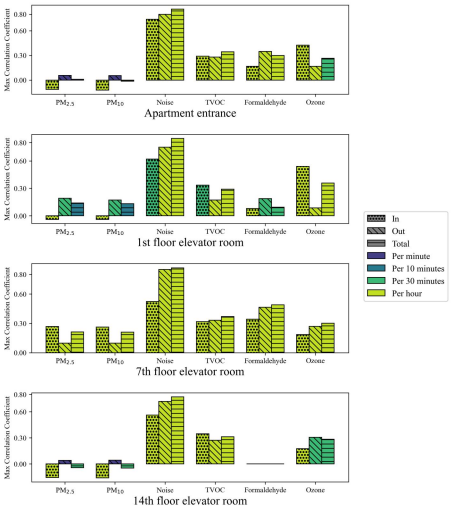

Fig. 3. Max Spearman correlation at different locations

3.3 Spatial-temporal characteristics of the environmental pollutants

Fig. 4 displays the temporal variations of $PM_{2.5}$ and PM_{10} across different locations. The concentrations of particulate matter at all monitored sites show almost identical trends. When calculating the Spearman's rank correlation coefficient between $PM_{2.5}$ and PM_{10}, we found a very high correlation of 0.99, indicating a highly consistent pattern in their variations. The figure also clearly shows that, compared to other

floors, the particulate matter levels in the elevator room of the 7th floor are consistently higher, sometimes even surpassing the concentrations at the apartment entrance. This is caused by the altitude of the location: there are certain differences in the concentration of particulate matter at different altitudes in the external environment.

Analysis of formaldehyde concentration data reveals that during the static monitoring period (01:00-05:00), all measurement points registered zero formaldehyde concentration. During the dynamic monitoring from 5:00 AM to 1:00 AM the next day, formaldehyde was detected for a total of 9 hours, accounting for only 5.4% of the total monitoring duration. The highest average hourly concentration recorded was 0.035 mg/m^3 in the 7th floor elevator room, which is only half of the limit of 0.07 mg/m^3 specified by the "Standard for Indoor Air Quality" (GB/T 18883-2002). Further analysis, in conjunction with pedestrian flow characteristics, indicates that the intervals with increased formaldehyde concentration typically correspond to higher pedestrian flow. Therefore, it is recommended to enhance ventilation in high-flow areas such as elevator rooms to prevent exceeding formaldehyde limits.

Fig. 5 illustrates noise level variations at different locations during the dynamic phase (05:00-01:00 next day). The noise levels at the apartment entrance and the 1st floor elevator room were significantly higher than at other locations, with average noise levels of 49.84dB and 48.09dB, respectively. These conditions arise because (1) the apartment entrance serves as a common passageway for all residents; (2) the 1st floor elevator room is frequently traversed by non-ground-floor residents; (3) continuous noise-emitting devices such as washing machines and vending machines are located on the 1st floor. Although these levels do not exceed the daytime standards of the "Environmental Noise Quality Standard" (GB 3096-2008) — 55dB from 07:00 to 22:00 — they surpass the nighttime standard of 45dB from 22:00 to 07:00. Measures are recommended to reduce noise to minimize the disparity in living experience between residents on the 1st floor and those on other floors.

Fig. 6 illustrates the variations in TVOC concentrations at different locations. Notably, the TVOC concentration in the elevator room on the 14th floor is significantly higher than in other areas, with a maximum recorded concentration of 0.79 mg/m^3. Despite the considerably lower pedestrian flow in the 14th floor's elevator room compared to the apartment entrance and elevator room on the 1st floor, the total volatile organic compounds (TVOC) concentration is generally higher than other places on the 14th floor. Given the strong correlation between TVOC and pedestrian flow, it can be inferred that specific behaviors in the 14th floor elevator room may have led to a substantial increase in TVOC pollution. Further onsite investigations revealed that property maintenance staff frequently park cleaning carts and supplies in the 14th floor elevator room after hours (after 17:00) to facilitate the next day's work. This behavior has resulted in TVOC concentrations exceeding the limit of 0.6 mg/m^3 set by the "Indoor Air Quality Standard" (GB/T 18883-2002). Therefore, it is essential to focus on the locations of TVOC sources and implement appropriate measures, such as standardizing property cleaning procedures.

Fig. 7 illustrates the variations in ozone concentrations at different locations. The data show that the ozone concentration at the apartment entrance is lower compared to

other locations, likely due to better ventilation at this site. During the static monitoring period (01:00-05:00), the ozone concentrations at nearly all monitoring points were close to zero, with some fluctuations in the 1st floor elevator room, but these also tended towards zero before sunrise, indicating a reduction in indoor ozone pollution overnight. Calculations of average ozone concentrations revealed a decreasing trend from the 1st floor elevator room to the 7th, 14th floor elevator rooms, and the apartment entrance.

It is notable that the hourly average ozone concentrations in the elevator rooms on the 1st and 7th floors often exceed the limit of 0.16 mg/m³ set by the "Indoor Air Quality Standards" (GB/T 18883-2002), posing a risk of short-term ozone exposure to residents passing through during these periods. Particularly, the 1st floor elevator room recorded the highest average hourly concentration at 0.38 mg/m³, indicating the greatest risk of short-term ozone exposure. Given that the 1st floor elevator room is a transit point for most residents moving between floors, this suggests a potential short-term ozone exposure risk during certain periods. Additionally, the ozone concentration in the elevator room on the 7th floor exhibits significant fluctuations, with a peak value of 0.36 mg/m³. This indicates that residents on the 7th floor may face a dual risk of ozone exposure from both the 1st and 7th floor elevator rooms. The reason for this is the same as for particulate matter, which is caused by altitude.

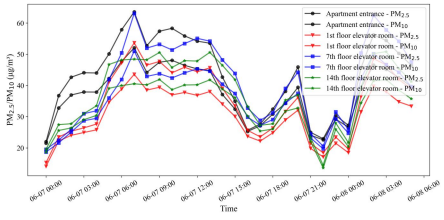

Fig. 4. Distribution of $PM_{2.5}$ and PM_{10}

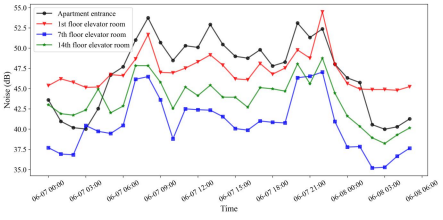

Fig. 5. Distribution of noise

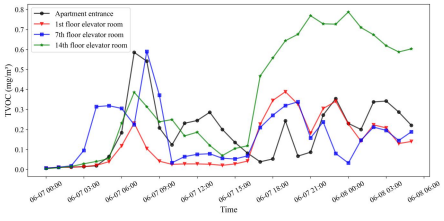

Fig. 6. Distribution of TVOC

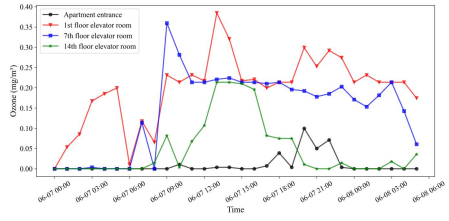

Fig. 7. Distribution of ozone

4 Conclusions

This study explores the relationship between pedestrian flow and environmental pollutants in an apartment building by monitoring and analyzing data. Key findings include: peak pedestrian flow at the apartment entrance occurs between 08:00-09:00

and 22:00-23:00, with more even distribution on weekends. Lower floors correlate with less frequent use of elevators to descend, resulting in the average daily downward load of the elevator being generally lower than the upward load. Environmental analysis shows a weak correlation between fine particulates ($PM_{2.5}$ and PM_{10}) and pedestrian flow, whereas noise, TVOC, formaldehyde, and ozone demonstrate stronger correlations, with time granularity playing a crucial role in calculating these correlations. The general conclusions drawn are: elevated levels of particulate matter and ozone in the 7th floor elevator room, with a potential dual ozone exposure risk due to high ozone levels in the 1st floor elevator room; elevated noise levels at the apartment entrance and 1st floor elevator room; and TVOC pollution resulting from the storage of cleaning products in the elevator areas. Recommendations include enhancing ventilation in high-flow areas to mitigate potential exceedances of pollutant thresholds.

Acknowledgement

This work was supported by the National Key R&D Program of China (Grant No.2022YFC3803200), the Fundamental Research Funds for the Central Universities (No.DUT21JC22), and the National Natural Science Foundation of China (Grant No.52370194).

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