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A multi-source and multi-perspective imagery method for assessing the physical appearance of gated communities

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Abstract

Traditional objective methods for assessing gated community (GC) environments rely primarily on on-site audits and street-view-based virtual audits. The former is costly and labour-intensive, while the latter faces limited spatial coverage and cannot capture temporally variable features. These constraints are especially problematic in enclosed residential forms like GCs, highlighting the need for a more scalable, data-driven assessment approach. This study proposes a multi-source and multi-perspective imagery framework that integrates aerial, external, and internal views to assess GC physical appearance. The framework is structured around a unified analysis model with tailored indicators, scoring rules, and integration criteria, enabling standardized measurement across perspectives. This work is methodology-based and is demonstrated through a gated-community case study in Xi'an District, Mudanjiang City, China. The case study shows the method's high agreement with on-site audits while substantially reducing time and labour requirements. Results show that although GCs perform well in security and privacy, they frequently lack adequate public resources and infrastructure. These findings underscore the need for systematic spatial monitoring to identify priority areas for improvement. The ability to incorporate both open-access and actively collected imagery enhances the framework's adaptability across diverse urban contexts. This approach provides a standardized, scalable tool for supporting data-driven decision-making in urban planning and residential management. Future extensions may include integrating socioeconomic indicators and applying the method in varied regulatory and geographic settings to further enhance its applicability.

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Data Availability Statement included at the end of the article.

Keywords
neighbourhood physical appearance, gated communities (GCs), street view imagery (SVI), remote sensing (RS), active sensing, virtual audit

Introduction

The physical appearance of a neighbourhood significantly influences residents' quality of life. Existing studies have confirmed strong associations between neighbourhood physical characteristics such as aesthetic quality, greenery, sidewalk amenities, physical disorder, and perceived safety, and a wide range of health and safety outcomes, a line of inquiry anchored in the seminal 'Broken Windows' hypothesis (Wilson and Kelling, 1982) and supported by recent syntheses (Mouratidis, 2021).

Traditional methods for measuring neighbourhood physical appearance primarily rely on on-site audits and resident surveys. On-site audits involve expert-based, objective documentation of visible conditions, while resident surveys capture subjective perceptions and may be influenced by personal bias. Although subjective surveys offer insights into perceived quality, they are often affected by same-source and social desirability biases (Sampson and Raudenbush, 1999; Sinha et al., 2017). In contrast, objective assessments provide a more actionable basis for urban planning decisions. However, on-site audits remain time-consuming, labour-intensive, and spatially constrained (Rundle et al., 2011).

With the rise of urban big data, Street View Imagery (SVI) has become a widely adopted alternative for urban assessments (Naik et al., 2016). Advances in computer vision (CV) have enabled automated assessments through both image rating and feature recognition approaches (Chen et al., 2023; Liu et al., 2017). Despite their feasibility in assessing general urban environmental conditions, SVI-based methods face limitations in spatial coverage, resolution, and the ability to capture temporally variable or semi-private environments (Clarke et al., 2010).

These limitations, particularly in data coverage and accessibility, systematically exclude privatized residential enclaves, such as gated communities (GCs), from mainstream environmental audits despite their growing influence on urban morphology. As enclosed neighbourhoods offering independent infrastructure and restricted access, GCs have become increasingly prevalent, particularly in China, Latin America, and other rapidly urbanizing regions (Dong et al., 2019; Ismail et al., 2019). While marketed as spatial solutions that enhance security, privacy, and quality of life, the lack of transparent environmental data poses challenges. Without accurate morphological assessments, it remains unclear whether these environments genuinely support residents' well-being or exacerbate spatial inequalities.

This study proposes a new method for assessing the physical appearance of GCs through a comprehensive index that integrates diverse spatial data sources, including aerial (remote sensing), external (street view), and internal (human perspective) imagery. Given the multi-layered spatial configuration of gated communities, where enclosed boundaries restrict street-level visibility, internal amenities and open spaces are typically located deep within the compound and inaccessible to public sensors, we leverage open data and active sensing inputs to achieve holistic coverage. Imagery from these perspectives is converted into quantifiable indicators using three scoring strategies: frequency-based (proportion of problematic images), compliance-based (alignment with standards), and binary existence (presence or absence of features). The scores are integrated into a unified output, providing a nuanced and objective evaluation of GCs' physical environments. Through an evaluation experiment conducted across 190 GCs in Mudanjiang City, China (Supplemental Figure S1), and comparisons with traditional on-site surveys in 8 communities, we demonstrate the method's feasibility, accuracy, and efficiency. We position this work as a methodology study, with the Mudanjiang application serving as a demonstrative case to illustrate the framework's feasibility and transferability. This approach offers a scalable solution for future large-scale urban environmental assessments.

Literature review

Neighbourhood physical appearance assessment

Foundational urban theorists such as Lynch (1960) and Jacobs (1961) emphasized the role of built form and legibility in shaping residents' safety, movement, and perception of urban spaces. More recently, the rapid transformation of urban areas and competition for resources globally have led to increasing interest in how physical environments relate to residents' well-being. Numerous studies have identified associations between neighbourhood characteristics and various social and health outcomes, including cardiovascular disease, self-rated health, obesity, lower-body functional limitations, conduct disorders, asthma, crime, and violence (Boehmer et al., 2007; Kim, 2008; Mouratidis, 2021; Sytsma et al., 2021; Wilson and Kelling, 1982).

In the selection of assessment indicators or audit attributes, some measurements are embedded in broader environmental assessment frameworks conducted by national surveys, such as the American Housing Survey, the English Housing Survey, and Chinese urban physical examination. Excluding housing unit components, common neighbourhood indicators typically fall into categories such as accessibility, safety, proximity to services, environmental quality, connectivity, and infrastructure provision (Ministry of Housing and Urban-Rural Development of China, 2024; UK Homes and Communities Agency, 2008; U.S. Department of Housing and Urban Development, 2013).

Other studies focus on specific aspects, selecting indicators to reflect particular dimensions. For instance, Bartzokas-Tsiompras et al. (2021) assessed walkability using street crossings, transit stops, and sidewalks. Chen et al. (2023) focused on disorder features like abandoned buildings and illegal ads. He et al. (2017) and Sytsma et al. (2021) examined crime-related environmental factors, albeit from different perspectives. Naik et al. (2016) developed an Urban Appearance Quality index focussing on safety perception by analyzing the relationship between 'ground', 'buildings', 'trees', and 'sky'. Liu et al. (2017) defined urban environment qualities using three indicators: building materials, industrial precision and craftsmanship, and maintenance. In gated community research, unique indicators such as residential density (Ismail et al., 2019), perimeter wall maintenance, and entrance traffic conditions have also been proposed (Zhao and Long, 2022).

Key assessment methods

Research on neighbourhood environments has primarily focused on two basic data sources and corresponding measurement methodologies: subjective and objective data. Traditional methods include questionnaires, interviews, resident surveys (Jackson and Archer, 2022), and on-site neighbourhood audits by experts (Sampson and Raudenbush, 1999). However, the inefficiency and high cost of traditional methods have spurred growing interest in alternative approaches to support urban data infrastructure (Thakuriah et al., 2016). The emergence of the internet has enabled the use of crowd-sourced data, such as VGI from social media (Kovacs-Györi et al., 2020), which effectively supplement resident surveys and reflect subjective environmental perceptions. However, self-reported neighbourhood data are prone to biases, particularly same-source and social desirability bias (Sampson and Raudenbush, 1999).

On the objective-data side, virtual audits have been introduced as an alternative to on-site surveys. These audits, based on the development of commercial street-view imagery (e.g. Google

Street View), use either manual audits or CV recognition. SVI has been employed to assess neighbourhood disorder, street quality, and public perception (Li et al., 2022). However, while general indicators often align with on-site audits, resolution and distance limitations reduce accuracy for fine-grained or time-sensitive features (Clarke et al., 2010). Imagery providers rarely cover semi-public areas, and property owners may request image removal, introducing data bias (Rundle et al., 2011). Horizontal coverage is also limited as SVI only penetrates 5–7 m into alleys (Grubesic et al., 2018), representing mostly outer appearances.

Beyond SVI, other sources include remote sensing for urban morphology (Patiño et al., 2014). Drones provide higher-resolution data to detect infrastructure issues (Grubesic et al., 2018), while surveillance systems offer continuous monitoring (Sytsma et al., 2021). These innovations signal a shift toward data-driven assessments, but the integration of multi-source imagery remains limited. Some scholars combined RS and photos (Ismail et al., 2019) or satellite imagery and SVI (Xing et al., 2023), yet few have proposed comprehensive, quantitative frameworks for physical appearance evaluation.

Physical appearance characteristics and challenges of gated communities

Gated communities are typically defined as walled or fenced housing developments that restrict public access. They are characterized by legal agreements binding residents to a common code of conduct and usually involve collective responsibility for management (Atkinson and Blandy, 2005). Blakely and Snyder (1997) categorized them into Lifestyle, Prestige, and Security Zone Communities, though this typology is less emphasized in recent evaluations. Emerging in the late 20th century, GCs rapidly became a global urban trend, appearing across North America, Europe, South Africa, and Australia (Gądecki and Smigiel, 2009; Hillier and Mcmanus, 1994; Jürgens and Landmann, 2006; Lewicka and Zaborska, 2007). Particularly in China and Latin America, they have become among the most prevalent urban forms (Dong et al., 2019; Silva De Araujo and Pereira De Queiroz, 2018).

The widespread popularity of GCs reflects residents' desire for an enhanced quality of life. Their expansion is often regarded as an effective response to concerns about crime, lifestyle aspirations, community awareness, social cohesion, and status differentiation (Roitman, 2013; Segura, 2023). Surveys of gated community residents indicate that they have higher expectations for the physical environment compared with those live in open communities (Wyczalkowska and Janda-Debek, 2015). Based on a review of existing research, the key concerns of GC residents and researchers can be effectively categorized into four primary dimensions: safety and privacy, public resources, maintenance, and infrastructure. This grouping is consistent with classic urban design theory, including Jacobs's account of everyday street life and Lynch's notions of imageability and legibility, together with the visible order tradition (e.g. 'broken windows'). Among these, safety and privacy represent the core motivations for choosing gated living (Lei and Zhang, 2018). The spatial form of GCs is designed to enhance security and often features walls, gates, and controlled access elements such as fences, guards, or entry systems (Bandauko et al., 2022; Blakely and Snyder, 1997; Owusu, 2021). Public resources are another defining physical characteristic of GCs, as these communities often include shared amenities and facilities such as recreational areas, landscaped greenery, private roads, and open spaces. Residents typically have higher expectations regarding the appearance and upkeep of these spaces compared to those in non-gated communities (Owusu, 2021; Wyczalkowska and Janda-Debek, 2015). Regarding maintenance, GC residents often worry that non-resident access may cause issues such as litter accumulation, illegal postings, disorderly parking, or damage to shared property (Lei and Zhang, 2018; Si et al., 2025). Infrastructure quality is a crucial aspect of neighbourhood assessments, including those of GCs. While well-maintained roads are a common expectation among residents, accessible infrastructure is especially important for vulnerable groups, including individuals with disabilities (Ministry of Housing and Urban-Rural Development of China, 2024; Zhao and Long, 2022).

Therefore, the distinctive characteristics of GCs warrant further consideration. However, the current state of some GCs often contradicts residents' expectations. Overcrowding is common, including excessive density, narrow roads, and lack of services or open space, all of which undermine environmental quality (Wyczalkowska and Janda-Debek, 2015). Insecurity: Gooblar (2002) argued that the walls of GCs prevent residents from having their 'eyes on the street', thereby reducing the safety of these communities. This not only impacts residents' living experience but also relates to spatial governance issues, such as how physical barriers influence the allocation of responsibilities for public service provision. For example, China's Property Management Regulations require private communities to assume some responsibilities for maintaining public facilities (State Council of the People's Republic of China, 2003), yet there is a lack of assessment standards and regulatory tools to enforce this.

Currently, assessments specifically addressing the unique characteristics of gated communities are relatively rare and typically small-scale. Notable examples include early qualitative studies in Istanbul (Geniş, 2007), comparative work in Poland (Wyczalkowska and Janda-Debek, 2015), and resident surveys in Ghana (Owusu, 2021). However, large-scale quantitative studies are still missing. There is a pressing need to establish a comprehensive framework for physical appearance evaluation specifically tailored to GCs.

Method

The framework of this study is illustrated in Figure 1. To enable a comprehensive spatial analysis, the system integrates imagery from three perspectives: aerial, external, and internal. Each perspective corresponds to both open data sources and active sensing methods. The evaluation process involves multiple stages, including data collection, preprocessing, feature extraction, and measurement using an analysis model. This model incorporates diverse indicators, data sources, scoring criteria, and integration rules to generate an overall score for the physical appearance of gated communities. To validate the accuracy of the results, conventional on-site audits are conducted in sample communities, where manual appearance scoring is used as the ground truth.

Assessment dimensions and indicators

The construction of our assessment framework follows a two-step, top-down logic: (1) establishing conceptual dimensions from foundational urban theory and (2) populating these dimensions with specific, operational indicators from contemporary audit literature. The structure and the concept-to-indicator correspondence are summarized in Table 1. The Attribute column in Table 1 specifies the operational definition of each indicator as an observable in imagery (Figure 2). These observables underpin the aforementioned feature extraction and scoring rules, with Table S1 providing the on-site audit scoring standards used as a common baseline for both calibration and validation.

Data acquisition and preprocessing

Data are obtained from three perspectives (aerial, external, and internal) to comprehensively assess all indicators (Figure 3). Open data is prioritized for its accessibility and serves as the primary source, while active sensing data is used when open data is outdated (older than four years) or lacks sufficient coverage. Detailed acquisition and preprocessing methods for each data type are outlined below. The most suitable data source for each perspective should be selected based on availability prior to assessment.

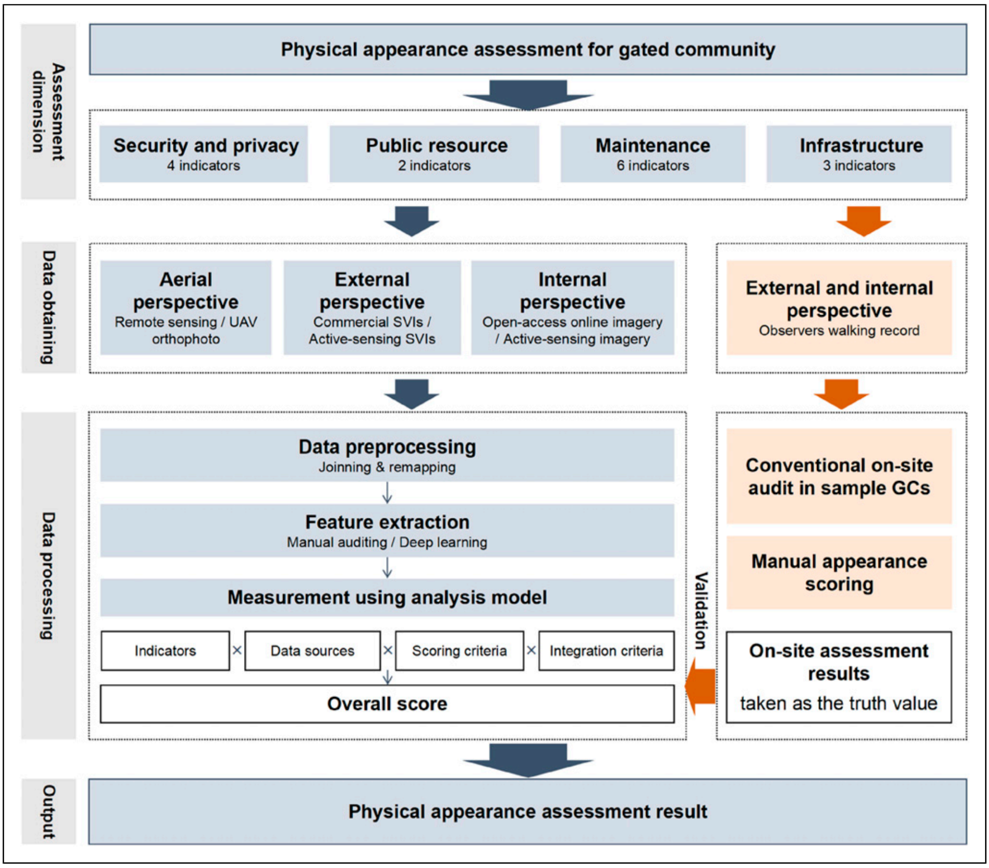

Figure 1. Framework of the study.

Aerial perspective. Satellite imagery is collected from sources such as WorldView-3 via Bigemap. Images are selected for high clarity (score ≥20), low cloud cover, and suitability for detailed interpretation.

UAVs with autonomous navigation (e.g. DJI PHANTOM 4 RTK and Mavic 3) are deployed to collect aerial imagery. The target area is defined, allowing the UAV to autonomously generate a flight path at a 90-degree downward angle, with Ground Sampling Distance (GSD) of no less than 2.4 cm and altitudes between 50 and 100 m. Flights are conducted in clear, calm conditions to optimize lighting and minimize distortion.

For data preprocessing, UAV-captured images are stitched into orthophotos using software such as DJI Terra. RS imagery preprocessing includes radiometric and geometric corrections, mosaicking, and enhancements such as contrast adjustment and noise reduction.

External perspective. SVI is acquired via APIs from platforms such as Baidu or Google. Images are downloaded using Python scripts at predefined intervals from two viewpoints along each road segment.

For mobile sensing, a camera-mounted vehicle is used to capture streetscape. Routes are planned using a simplified MCPP algorithm and imported into navigation apps. The vehicle drives at 20–40 km/h with GPS logging to ensure uniform lighting and coverage.

Table 1. Indicator system of the GC physical appearance assessment.

Dimension	Foundational concepts & core theoretical idea	Indicator	Attribute	Label	Reference
Security and privacy	Lynch (1960) legible edges and nodes: Boundary legibility supports perceived safety and access control	Fence/barrier	Broken or discontinuous fencing/walls	SP1	Wu et al. (2021); Zhao and Long (2022); Sytsma et al. (2021); He et al. (2017)
		Guard	Lack of security guard post/ personnel at entrance	SP2	Ismail et al. (2019); Si et al. (2025); Bromm et al. (2020)
		Building density	Overly dense building intervals	SP3	Ismail et al. (2019); Wyczalkowska and Janda-Debek (2015)
		Entrance condition	Non-existent/ broken/ obstructed door	SP4	Wu et al. (2021); Zhao and Long (2022); U.S. Department of Housing and Urban Development (2013)
Public resource	Jacobs (1961) everyday street life; Lynch (1960) imageability: Communal facilities and greenery enable everyday use and strengthen place imageability	Physical activity facilities	Missing or insufficient/ poorly maintained physical activity facility	PF1	Ismail et al. (2019); Wu et al. (2021); Owusu (2021); Wyczalkowska and Janda-Debek (2015); Zhao and Long (2022); Si et al. (2025)
		Greenery	Missing or insufficient/ poorly maintained greenery	PF2	Ismail et al. (2019); Owusu (2021); Wyczalkowska and Janda-Debek (2015); Sytsma et al. (2021); He et al. (2017); Chen et al. (2023)

(continued)

Table 1. (continued)

Dimension	Foundational concepts & core theoretical idea	Indicator	Attribute	Label	Reference
Maintenance	Wilson and Kelling (1982) "broken windows"; Lynch (1960) visual order/imageability: Visible order and facade care signal stewardship, reinforcing perceived safety and environmental image	Cleanliness	Stacked or discarded garbage	MT1	Ismail et al. (2019); Wu et al. (2021); Owusu (2021); Wyczalkowska and Janda-Debek (2015); Zhao and Long (2022); Si et al. (2025); Sytsma et al. (2021); Chen et al. (2023); Bromm et al. (2020)
		Facade maintenance	Cracked walls, peeled paint, unauthorized ads, etc.	MT2	Zhao and Long (2022); Ministry of Housing and Urban-Rural Development of China (2024); He et al. (2017); Chen et al. (2023); Liu et al. (2017); U.S. Department of Housing and Urban Development (2013)
		Structural regulatory compliance	Unauthorized protruding window fences, satellite dishes, garden expansions, etc.	MT3	Ministry of Housing and Urban-Rural Development of China (2024); Chen et al. (2023); Bromm et al. (2020); Liu et al. (2017)
		Window condition	Broken/missing windows	MT4	Zhao and Long (2022); Sytsma et al. (2021); He et al. (2017); Bromm et al. (2020); U.S. Department of Housing and Urban Development (2013)
		Parking management	Informal parking	MT5	Ismail et al. (2019); Wu et al. (2021); Wyczalkowska and Janda-Debek (2015); Zhao and Long (2022); Sytsma et al. (2021)
		Wiring/piping	Messy/loose wires, pipes, etc.	MT6	Ismail et al. (2019); Zhao and Long (2022); Chen et al. (2023); Liu et al. (2017); U.S. Department of Housing and Urban Development (2013)

(continued)

Table 1. (continued)

Dimension	Foundational concepts & core theoretical idea	Indicator	Attribute	Label	Reference
Infrastructure	Lynch (1960) paths and movement legibility: Path continuity, clear routing, and surface condition support movement legibility and everyday navigation	Barrier-free facility	Lacked or damaged curb ramps/ entrance slopes	IF1	Zhao and Long (2022); Ministry of Housing and Urban-Rural Development of China (2024); Bromm et al. (2020)
		Elevator	Missing or damaged elevator	IF2	Zhao and Long (2022); Ministry of Housing and Urban-Rural Development of China (2024); U.S. Department of Housing and Urban Development (2013)
		Road condition	Unhardened/ damaged road	IF3	Wyczalkowska and Janda-Debek (2015); Zhao and Long (2022); He et al. (2017); Chen et al. (2023)

For preprocessing, frames are extracted from video (1-second intervals), labelled with spatial coordinates, then mapped to 20 m-spaced points along GC boundaries to ensure even coverage (see Supplemental Figure S2).

Internal perspective. Open-access online imagery is sourced from real estate platforms and review platforms. Among real estate platforms, Anjuke in China provides community interior images and videos, while Zillow in the USA and Rightmove in the UK offer estate exterior photos and neighbourhood details. Review platforms include Dianping in China, Zigbang in Korea, Airbnb, and Google Maps reviews (Kweon and Lee, 2023; Wang et al., 2023).

For active-sensing internal data collection, a non-motorized vehicle is equipped with a motion camera, mount, batteries, storage, and a GPS device for internal data collection. Accessible GC roads are mapped, and bi-directional routes are planned. Routes are loaded into a navigation app, and GPS paths are recorded at a steady, safe speed. In restricted-access GCs, trained residents may collect data using a detailed manual, with quality ensured via validation procedures.

For preprocessing, frames are extracted from video (1-second intervals), labelled with spatial coordinates, then mapped to 10 m-spaced points along collection tracks to ensure even coverage.

Feature extraction

For each indicator, we calculate its proportion using only those images where the indicator is observable, with the denominators corresponding to the scoring rules illustrated in Figure 4. For street and internal view imagery, the detection pathway is chosen by dataset size. When annotated data are sufficient (targeting ≥1500 training images overall and, where feasible, ~10,000 labelled instances per class), deep learning (e.g. YOLOv8, Li et al., 2024) may be adopted; in such cases,

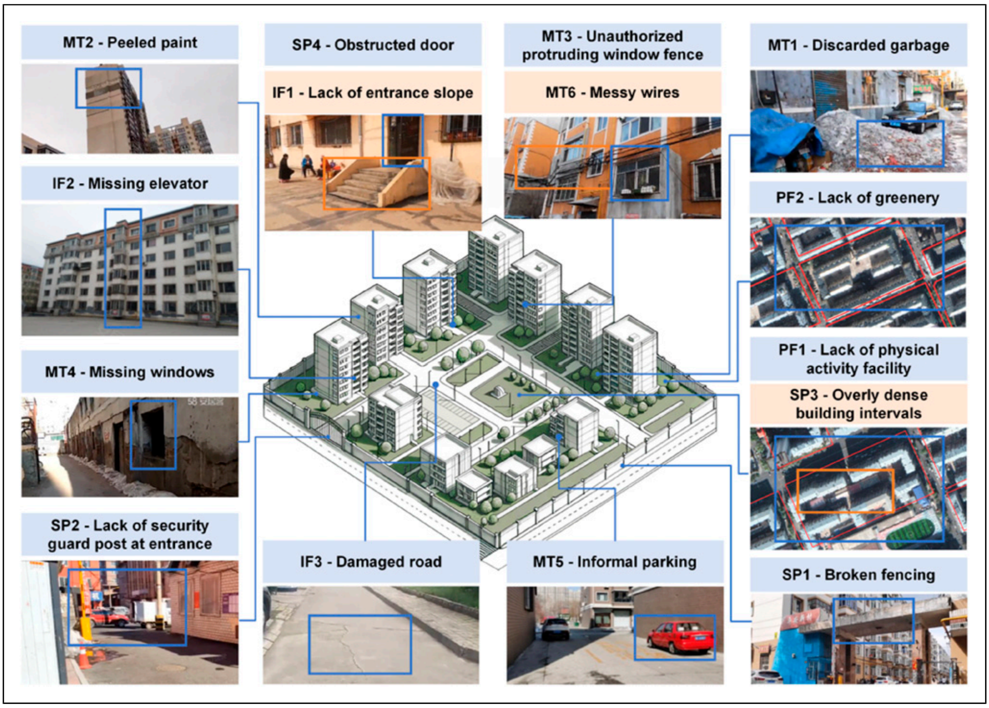

Figure 2. Examples of indicators and attributes.

training/validation/test splits, class counts, and precision, recall, F1/mAP should be reported. When data are insufficient, indicators are identified manually. Annotations are created in Labelbox with indicator-level labels for standardized export and analysis, and audit results are mapped to their respective GCs.

Measurement using analysis model

The extracted features are synthesized by the analysis model into 15 index scores, based on indicator-specific scoring criteria, data source selections, and integration methods, as illustrated in Figure 4.

Scores are assigned using three strategies: (i) existence/availability-based (presence/absence or level of provision of a feature; e.g. IF2 elevators present and functional vs missing/damaged; IF1 curb ramps), (ii) compliance-based (alignment with official thresholds; e.g. PF1/PF2 per Ministry of Housing and Urban-Rural Development of China, 2024), and (iii) frequency-based (proportion of images showing the issue; e.g. MT1).

All scores are normalized to 0 (best appearance) to 1 (worst appearance).

To integrate the scores from different data sources, four criteria are applied: (i) Merging two sources before calculation, where data sources are of the same type and thus combined at the beginning of the process. (ii) Using a single source for calculation, where only one perspective imagery captures the indicator. (iii) Choosing the maximum value among sources, where different data sources represent distinct attributes of the same indicator. (iv) Computing the mean value, where two types of data identify the issue differently but assess the same attribute.

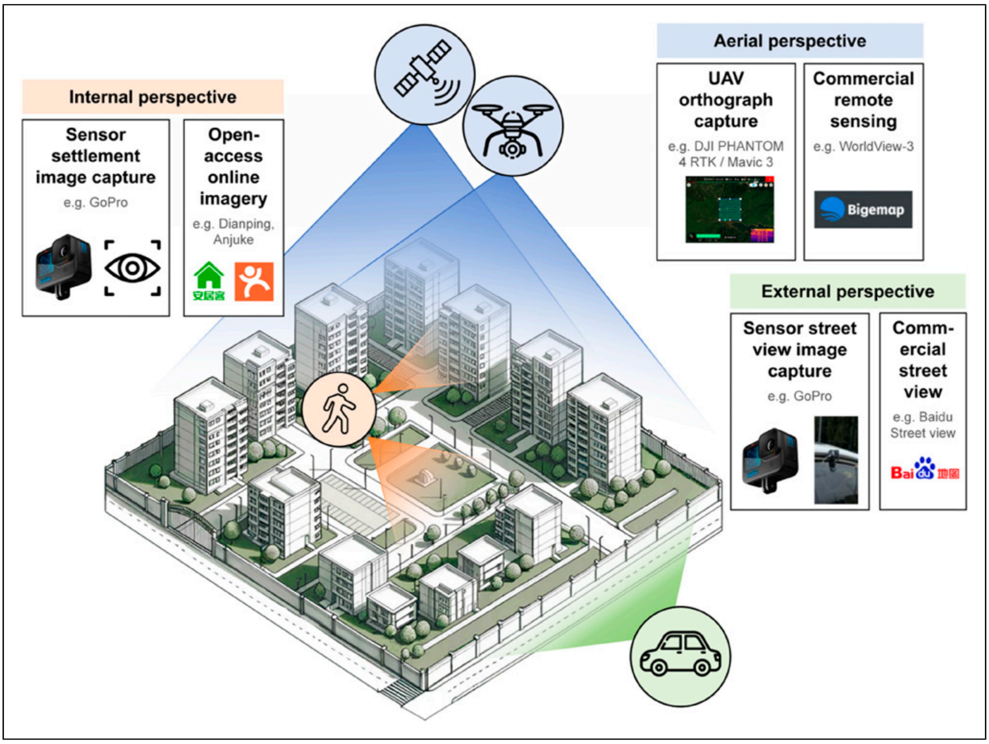

Figure 3. Three perspectives of GC space and data sources.

Validation

To validate the feasibility and accuracy of the proposed data sources and the method, we select eight GCs and apply a conventional on-site expert survey and audit to serve as the ground truth for comparison. To ensure a well-distributed sample that reflects diverse levels of spatial quality, we include GCs built across different years and located in various areas. We developed a scoring system based on typical official surveys, identifying the presence of issues. To further assess issue severity, we adopt a 5-point Likert scale based on previous housing quality surveys (Owusu, 2021). To reduce subjective scoring errors, two observers conduct the ratings following a unified scoring standard (Supplemental Table S1). To test the feasibility and accuracy of the new method, we use a confusion matrix and Root Mean Square Error (RMSE) as validation metrics.

Experiment

Study area

The proposed method was implemented in Xi'an District of Mudanjiang City, China, covering a built-up area of 13.90 km^2. This district represents a typical central urban area in China, characterized by a predominance of residential zones where GCs serve as the dominant housing form. The GCs in this area were developed between 1989 and 2024 and encompass both early socialist-era enclosed work-unit compounds from the pre-reform period and privately developed commercial residential estates that emerged following land reforms – a development pattern commonly observed in Chinese urban centres. We cross-verified the count and edges of GCs in the study area

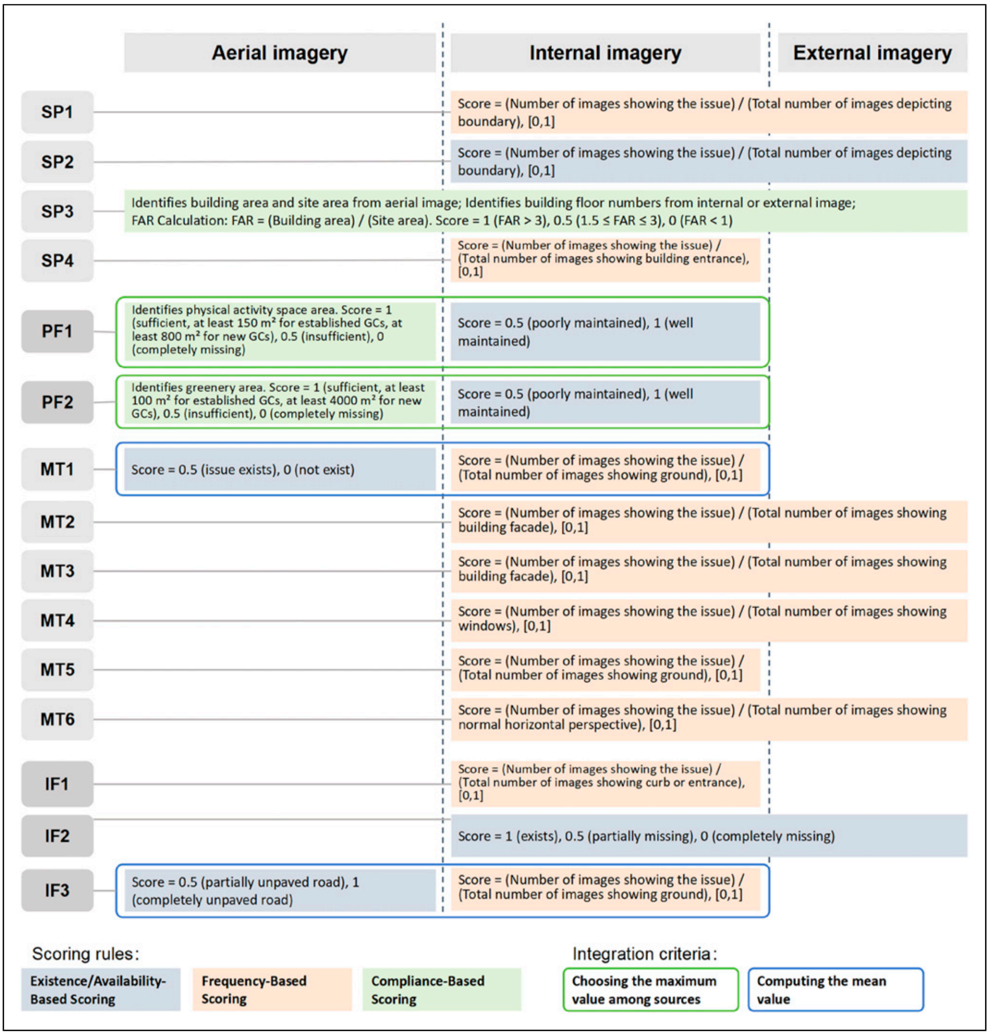

Figure 4. Framework of the analysis model: Indicators, data sources, scoring strategies, and integration criteria.

using land use data, real estate platform information, and online maps. Residential forms other than GCs, such as urban villages and apartment buildings, were excluded from this study. Ultimately, we obtained precise spatial information for all 190 gated communities (Supplemental Figure S1).

Data acquisition and processing

For aerial perspective data, due to UAV flight restrictions in Xi'an, we opted to use open data. The latest imagery, downloaded from Bigemap in October 2022, possesses a clarity level of 21 and a resolution of 0.138 m.

For internal perspective data, we downloaded 1775 videos and 525 photographs from Anjuke, and 158 photographs from Dianping, uploaded from 2020 to 2023, reflecting current spatial conditions in most GCs.

For external perspective data, as the outdated Baidu Street View imagery was last updated in 2016, and is therefore insufficient for assessing current spatial quality, we used active mobile sensing with GoPro11 cameras. Three observers alternated in pairs, conducting vehicle-based data collection from 8 AM to 3 PM to optimize winter lighting in Mudanjiang. Over 3 days, this method captured two-way street views on all accessible roads, covering 127.2 km (Supplemental Figure S2).

Data preprocessing involved spatial alignment using Python and QGIS. Remote sensing data covered all 190 GCs (Supplemental Table S2), while street-view imagery had partial gaps where GCs lack street frontage. To ensure assessment integrity, we computed each indicator from the available viewpoints and omitted it only when all supporting views were absent, with weights renormalized. Manual feature extraction was performed using Labelbox.

Assessment results

Overall, the physical appearance of GCs in Xi'an District, Mudanjiang City is illustrated in Figure 5(a). The average assessment score is 0.166, indicating a relatively good overall condition. Most GCs received scores between 0.1 and 0.2 (Figure 5(c)), suggesting that while some spatial issues exist, they are generally minor and confined to a limited number of indicators. However, seven GCs scored above 0.5, with the most problematic case being Laojiao Community, which received a score of 0.567. Built in 1991, this community exhibited severe and multidimensional spatial quality issues, with 10 out of 15 indicators scoring above 0.5.

The assessment results for the four dimensions are presented in Figure 5(b). Among these, the highest scores were observed in the 'Infrastructure' dimension. Specifically, most GCs lacked barrier-free facilities, and residential buildings under six stories were generally without elevators. The 'Public Resource' dimension also exhibited poor performance, primarily due to insufficient physical activity facilities and limited green space. The 'Security and Privacy' dimension had the lowest scores, indicating that the basic physical security features of GCs, such as fences and security guards, were generally well maintained. Other notably problematic indicators included 'Unauthorized external modifications' and 'Parking management', while the least problematic indicator was 'Window condition'.

From a temporal perspective, the analysis (Figure 5(d)) reveals a clear negative correlation between GC age and assessment score, indicating that newer communities tend to have better physical appearance, which aligns with general expectations. Spatially, GCs with poorer physical appearance tend to be concentrated near the city centre, whereas those in outlying areas generally perform better.

Accuracy validation

An on-site survey was conducted from 14 to 16 December 2023, by two professional observers in 8 randomly selected gated communities, serving as the ground truth. Accuracy was evaluated in two steps: (1) issue identification and (2) severity scoring.

For issue identification, we used a confusion matrix to compare predicted and actual binary results, calculating accuracy as:

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}} \times 100\%$$

Using the gated community as the evaluation unit, accuracy reached 84.4% for aerial, 93.2% for internal, and 98.0% for external perspective imagery, with an overall accuracy of 93.9%

Figure 5. Assessment results (a) spatial distribution; (b) results of 4 dimensions; (c) score distribution; (d) linear relationship between the scores and the year of construction of the gated communities.

(Supplemental Table S3). 14 out of 15 indicators exceeded 85% accuracy. The exception was 'Cleanliness' (56.3%), likely due to temporal variability and garbage clearance timing. Internal images, spanning longer time ranges than on-site surveys, may offer more representative observations.

To evaluate severity scoring, we compared model-generated scores with expert-assigned scores using RMSE:

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{n}} \times \sum (\text{combined score} - \text{true score})^2}$$

The RMSE for aerial, internal, and external perspectives were 0.075, 0.096, and 0.085, respectively, with an overall RMSE of 0.079 (Supplemental Table S4). All values were within 0.25, equivalent to one scoring degree, confirming the model's effectiveness in reflecting physical appearance severity.

Efficiency comparison

A comparison of efficiency between the proposed method and conventional approaches is presented in Table 2. In the experiment conducted across 190 GCs in Mudanjiang, data collection and processing required a total of 72 person-hours. For data sources in the Mudanjiang experiment that were not selected, the time required for data collection and processing was derived from our experiments conducted in other northern Chinese cities (Supplemental Table S5). For comparison, the conventional on-site audit method required two observers to spend 8 hours each assessing 8 sample GCs.

By averaging the person-hours per GC spent on each data category, we assessed the efficiency of each data source. Since our method involves selecting either open data or active-sensing data within each perspective, we calculated the overall efficiency range by summing the least and most efficient data sources across these perspectives, defining the efficiency range of the proposed method, allowing for a direct comparison with the conventional method.

In the Mudanjiang experiment, the average time required to assess each gated community was 0.38 person-hours per GC. Theoretical estimates suggest that the time cost of the proposed method ranges from a maximum of 0.99 person-hours per GC (when all data are obtained through self-sensing) to a minimum of 0.216 person-hours per GC (when all data are open-access). In contrast, the conventional method requires 2.25 person-hours per GC. These results clearly demonstrate the substantial efficiency gains achieved by the proposed method.

Discussion

In the field of neighbourhood physical appearance assessment, traditional on-site surveys are labour-intensive and costly, limiting large-scale application. As an alternative, virtual audit methods, which predominantly rely on street-view imagery, face significant limitations in enclosed spaces like gated communities (Grubesic et al., 2018; Rundle et al., 2011). Our approach addresses two major limitations of these methods.

First, street-view imagery has limited spatial and vertical coverage, especially in semi-enclosed spaces. To overcome this, we integrate multi-source data, supplementing aerial, external, and internal perspective imagery for comprehensive coverage. Second, by integrating multi-source data with different temporal characteristics, our approach introduces a form of random temporal sampling across an extended period, which helps mitigate bias caused by single-time-point imagery. Specifically, the dataset includes images collected between 2020 and 2024, covering various

Table 2. Efficiency comparison between new method and conventional method.

	Our method						Conventional method
	Aerial perspective		Internal perspective		External perspective		
Time cost	RS imagery	Active-sensing UAV imagery	Open-access online imagery	Active-sensing internal imagery	Baidu SV imagery	Active-sensing SV imagery	On-site assessment
Data collection (person-hour/GC)	1/190	2/8	6/190	10/30	2/200	32/190	16/8
Data processing (person-hour/GC)	1/190	0.5/8	12/190	2/30	20/200	20/190	2/8
Overall efficiency (person-hour/GC)	0.011 0.216-0.99	0.316	0.095	0.4	0.11	0.274	2.25

seasons and randomized times of day. This temporal dispersion is particularly valuable for indicators such as garbage accumulation or parking disorder, which exhibit high fluctuation across time. By enabling image-based assessments in previously inaccessible and temporally variable environments, this approach addresses key limitations of earlier virtual audit studies and expands their applicability to gated communities. Together, these adaptations enable image-based assessments in spatially restricted and temporally variable environments, thereby extending the applicability of virtual audit methods to gated communities.

The assessment in Mudanjiang shows a moderate overall GCs appearance (average score: 0.166). Major deficiencies are not widespread, yet issues related to infrastructure and public resources are common, whereas security and privacy perform best, which is consistent with the security-driven design of gated communities noted in prior work (Blakely and Snyder, 1997; Owusu, 2021). Read through the lens of street vitality and urban imageability/legibility, this pattern reflects a perimeter-led safety model that achieves risk reduction primarily via access control rather than eyes-on-the-street mechanisms; shortfalls in internal common spaces and upkeep dampen everyday social life and visible order signals, while gaps in internal circulation and barrier-free facilities erode path legibility and overall imageability. In practical terms, the findings suggest priorities that complement enclosure: expanding and maintaining internal common spaces, improving path and barrier-free accessibility, and enhancing entrance visibility and lighting, with older estates requiring targeted retrofits and stronger property oversight. The feasibility and pace of these adjustments will depend on local governance arrangements and market conditions.

The deliberate pairing of open-access imagery with targeted active sensing confers data agility on gated-community audits. Open-access sources supply economical baseline coverage, whereas self-captured data resolve spatial or temporal gaps and thus extend inspections into locations and moments that would otherwise remain unseen. Twelve of the fifteen indicators are informed by at least two viewpoints, which allows internal cross-validation and markedly lowers the risk of unobserved deficiencies arising from missing street-view coverage for GCs without street frontage or other indicator-specific missingness. Additionally, the framework provides a transparent, replicable baseline for oversight, supporting independent review and cross-community comparison alongside internal property inspections. Collectively, these features enable planning agencies to conduct routine, city-wide assessments of ageing gated estates without incurring the labour costs of full on-site surveys.

This study has certain limitations. First, in the Mudanjiang experiment we selected the four most suitable data sources with appropriate processing rather than testing all available options; accordingly, UAV imagery and on-site interior surveys were not applied, and we used manual recognition rather than training deep-learning models. Although both data types and DL-based detection have shown feasibility in prior studies, their absence here may limit a full assessment of the framework's robustness across all configurations. Second, the evaluation considers exclusively the physical appearance of gated communities and omits socioeconomic or cultural factors that may shape residents' experiences. Third, imagery for different indicators may come from different capture times; consequently, the scores reflect time-averaged prevalence over the sampling window rather than same-moment co-occurrence.

Conclusions

This study proposes a multi-source and multi-perspective framework for assessing the physical appearance of gated communities (GCs). By establishing a GC-specific indicator system with scoring rules and integration criteria, the method combines aerial, external and internal imagery to offer a scalable alternative to labour-intensive on-site audits. Validation against on-site surveys showed agreement above 90% while reducing effort to well under one person-hour per community.

Applied in Mudanjiang, the framework reveals a consistent pattern: strong performance on security and privacy alongside common shortfalls in internal public resources, accessibility and maintenance, indicating a perimeter-led safety model and a security-amenity trade-off typical of GC layouts. The framework provides transparent, replicable scores that enable regulators and property managers to identify deficiencies, prioritize interventions, and schedule retrofit cycles, thereby fostering data-driven governance and long-term spatial management.

Future research can further enhance this framework by incorporating socioeconomic and behavioural dimensions, adapting it to diverse geographic and policy contexts, and refining data acquisition strategies to address variations in image availability.

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Declaration of conflicting interests

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request. Self-collected raw imagery can be shared under a non-commercial data-use agreement. Platform-sourced imagery is subject to third-party licences and cannot be redistributed; acquisition instructions to re-obtain these data from the original providers are available on request.

Supplemental Material

Supplemental material for this article is available online.

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