**Challenges in Sustainability**
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# Integrating Geospatial Technologies and Multi-Criteria Decision Analysis for Sustainable and Resilient Urban Planning

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**Received:** 12-23-2024 **Revised:** 03-05-2025 **Accepted:** 03-13-2025

**Citation:** Chaoui, G., Yaagoubi, R., & Mastere, M. (2025). Integrating geospatial technologies and multi-criteria decision analysis for sustainable and resilient urban planning. *Chall. Sustain.*, *13*(1), 122–134. https://doi.org/10.56578/cis130109.



**Abstract:** The increasing pace of urbanization has heightened the need for urban systems that are both sustainable and resilient. While extensive research has been conducted on these two concepts, the interplay between them remains insufficiently explored. In particular, sustainability is often associated with efficiency—maximizing resource utilization—whereas resilience emphasizes redundancy, ensuring the presence of backup systems to mitigate risks. To address this critical gap, a comprehensive framework is proposed that integrates these dual objectives within urban land-use planning. Geospatial technologies and multi-criteria decision analysis are employed to systematically assess the balance between efficiency and redundancy in urban environments. A machine learning (ML)-based classification of land use and built-up area changes, combined with demographic and infrastructural data, is utilized to quantify these factors. The proposed approach provides urban planners and policymakers with an adaptable decision-making tool, enabling context-specific prioritization of efficiency or redundancy based on local requirements. In high-density urban areas experiencing rapid expansion, efficiency is emphasized to optimize land and resource use, whereas in regions vulnerable to environmental hazards, redundancy is strategically incorporated to enhance resilience without undermining overall urban functionality. The flexibility of this method offers a significant advantage over rigid, predefined planning policies that may not be suited to specific urban contexts. By facilitating informed decision-making, the framework enhances risk management, optimizes resource allocation, and supports the development of customized urban strategies, ultimately improving long-term urban performance under diverse developmental scenarios.

**Keywords:** Machine learning (ML); Geospatial analysis; Urban resilience; Urban sustainability; Land-use planning; Multi-criteria decision analysis

## 1. Introduction

In recent decades, unprecedented global urbanization has occurred, accompanied by the concurrent expansion of urban land and the migration of floating populations driving this trend. By 2050, the global urbanization rate is projected to reach 68% (Sulemana et al., 2019), further exacerbating the strain on cities resulting from this surge in urbanization. Even though urbanization significant economic, social, and cultural benefits (Angelidou & Mora, 2019; Carling & Collins, 2018; Cohen, 2006), the acceleration of urbanization poses significant challenges for cities as they grapple with complex issues. The uncontrolled expansion of built-up areas affects the efficiency of land use as well as sustainable urban development, leading to negative consequences that are detrimental to sustainable urban development (Diksha & Kumar, 2017).

Conversely, urban resilience is equally crucial in highly urbanized systems. Municipalities and government institutions that adopt coherent land use plans and risk reduction strategies are better equipped to create urban areas resistant to natural disasters (Burby et al., 2000). These approaches not only allow for rapid recovery after disruptive events but also enable long-term adaptation with limited financial impact. As a result, effective urban planning integrating both sustainability and resilience is essential for addressing these diverse challenges.

Sustainability and resilience are valuable strategies for enhancing the urban planning process and addressing potential threats (Pirlone et al., 2020). Urban sustainability aims to balance social equity, economic prosperity, and environmental quality within cities, while minimizing negative impacts and ensuring fair resource distribution across generations (Nagendra et al., 2018; Wu, 2010). Complementing this, urban resilience refers to an urban area's capacity to sustain its functions and structures despite disruptions and crises. It is the ability to absorb shocks, adapt, and transform in order to recover swiftly from disturbances, while considering the natural, economic, social, institutional, and physical dimensions of the urban environment (Ribeiro & Pena Jardim Gonçalves, 2019; Büyüközkan et al., 2022).

Urban planning, with its emphasis on spatial dimensions, plays a crucial role in effectively integrating these concepts into cities. Strategic land use management must not only improve urban efficiency but also should offer considerable potential for promoting both sustainability and resilience (Dempsey et al., 2008).

However, despite their importance, sustainability and resilience are often used interchangeably in the urban context. Policy-makers and academics tend to confuse these concepts, which are often poorly defined, making them difficult to put into practice (Elmqvist et al., 2017). While achieving both sustainability and resilience can mutually reinforce each other, their goals can also lead to trade-offs in urban planning and development (Marchese et al., 2018). This complexity highlights the need for an integrated approach that acknowledges potential conflicts. The implications of these challenges vary across different urban contexts, particularly in rapidly urbanizing regions. In Moroccan cities, for instance, rapid urbanization and rural exodus have led to extensive urban sprawl. The 2024 population and habitat census confirms that urban expansion is primarily occurring on city outskirts, resulting in significant pressure on natural land (Haut Commissariat au Plan HCP, 2024). This expansion, estimated to require 7,000 hectares per year by 2030 (Mondiale, 2018), raises major environmental concerns (Luan & Li, 2021). In response, Morocco has implemented several initiatives to promote sustainable urban development, including the 2014 Framework Law for the Environment and Sustainable Development (Ministère délégué auprès du Ministre de l'Énergie-des Mines-de l'Eau et de l'Environnement, 2014) and the National Sustainable Development Strategy (Ministère de la Transition Énergétique et du Développement Durable, 2017). Despite these efforts, managing urban growth effectively remains a crucial challenge, necessitating a comprehensive approach that balances urban resilience and sustainability.

Although numerous studies have explored the relationship between urban sustainability and urban resilience, highlighting their interconnectedness (Zeng et al., 2022), a comprehensive approach that effectively integrates both concepts into planning practice remains scarce. Prior research has primarily focused on either sustainability metrics or resilience indicators separately. For instance, Huang et al. (2015) and Yigitcanlar & Kamruzzaman (2015) developed extensive frameworks for measuring urban sustainability, placing a strong focus on sustainability metrics, while placing less emphasis on resilience aspects. Conversely, Meerow et al. (2016) and Sharifi & Yamagata (2016) concentrated on resilience indicators and principles without explicitly addressing their intersections with sustainability.

Similarly, Rezvani et al. (2023) developed a GIS-based decision-making tool tailored for urban resilience, particularly in disaster recovery, yet their approach did not fully integrate broader sustainability concerns. Zeng et al. (2022) highlighted theoretical overlaps between sustainability and resilience, but their study focused primarily on conceptual discussions rather than offering actionable urban planning frameworks.

In addition, Elmqvist et al. (2019) proposed theoretical models linking sustainability and resilience in urban transformation, contributing valuable insights into their interdependencies. However, their work did not provide operational tools for practical implementation. Romero-Lankao et al. (2016) examined the transition from research to practice, specifically focusing on the transfer of knowledge related to urban sustainability and resilience. However, their study did not explore the inherent trade-offs between efficiency (sustainability) and redundancy (resilience) in land use management.

Finally, Xie (2023) contributed to the development of sustainability indicators, complementing existing research on urban sustainability. However, like previous studies, this work did not fully integrate resilience planning into decision-making frameworks, leaving room for further exploration in practical urban management strategies.

This lack of procedures and operational tools to assess the potential sustainability and resilience of an urban system represents a significant gap in research. This omission can lead to the implementation of ineffective solutions, the reinforcement of undesirable resilience, and missed opportunities for transformation of cities (Elmqvist et al., 2019). These flaws in city planning can harm both the long-term sustainability and resilience of urban areas. Therefore, developing approaches that enable the evaluation of both resilience and sustainability potential simultaneously, without compromising either objective, is imperative.

In this article, we strive to fill the noted research gap by presenting an integrated approach aimed at modelling the intricate relationship between urban sustainability and resilience. Central to our proposal is the recognition of the critical role that land use management plays in effectively implementing both sustainability and resilience measures. In this paper we focus on land use management, which is a crucial concept of urban planning. By strategically regulating how land is utilized, cities can foster sustainable growth and improve the quality of life for residents. Effective land use policies ensure the efficient use of resources, reduce environmental impact, and promote social equity. Ultimately, land use management is key to building resilient, adaptable urban areas that can thrive in the face of future challenges. This integrated approach offers a comprehensive framework for operationalizing the assessment of urban resilience and sustainability. Furthermore, it provides actionable insights for urban planners and policymakers, enabling them to navigate the complexities inherent in the relationship between these two concepts.

## 2. Conflicting Objectives of Sustainability and Resilience in Land Use Management

The literature reveals ongoing challenges in integrating sustainability and resilience within urban land use management. One significant issue is the conceptual tension between efficiency and redundancy. In urban planning, efficiency is often regarded as a cornerstone of sustainability, ensuring optimal resource allocation, reducing environmental impact, and enhancing economic viability (Romero-Lankao et al., 2016). However, it can sometimes conflict with redundancy, a key characteristic of resilient urban systems, as highly efficient, resource-conserving systems may lack the flexibility needed to absorb shocks and disturbances (Spaans & Waterhout, 2017; Dennis & James, 2018).

These trade-offs are particularly evident in urban contexts, where compact and efficient development—widely promoted as a sustainability strategy—can limit the diversity and adaptability necessary for resilience. Meerow & Newell (2019) emphasize that existing planning tools remain insufficient for addressing the complex relationship between sustainability and resilience. Similarly, Marchese et al. (2018) identify different approaches to integrate these two concepts, often treating one as a subset of the other. However, such models remain largely theoretical and offer limited methodological guidance for urban planners seeking to balance these priorities effectively. The absence of a clear approach raises concerns about whether existing tools can manage both dimensions simultaneously.

Indeed, methodological limitations further complicate the integration of sustainability and resilience. Feleki et al. (2018) developed a sustainability framework that struggles to incorporate resilience metrics, highlighting the difficulty of designing comprehensive planning tools that address both aspects. Likewise, Rus et al. (2018) point to the lack of integrated approaches capable of simultaneously evaluating sustainability and resilience in urban environments. These gaps fuel ongoing debates about whether trade-offs between efficiency and redundancy are inevitable or if synergies can be achieved through innovative design. On one hand, Béné et al. (2018) argue that efficiency and redundancy are inherently contradictory, making trade-offs unavoidable in urban development strategies. Conversely, Chelleri et al. (2015) suggest that synergies between these concepts are possible, though empirical evidence remains scarce. Wardekker et al. (2020) further explore this issue, noting that resilience-oriented approaches tend to emphasize redundancy but rarely address efficiency, reinforcing the need for empirical validation to resolve these theoretical debates.

Finally, the lack of spatially explicit tools that effectively capture the dynamics of efficiency and redundancy in urban systems remains a critical gap. Traditional methodologies often separate sustainability and resilience, failing to recognize their interconnections (Feleki et al., 2018). However, integrating spatial data, as suggested by Wardekker et al. (2020), could provide valuable insights into the interactions between different urban land uses and help reconcile the trade-offs between efficiency and redundancy.

Given these challenges, we propose an approach that examines the complex interplay between sustainability and resilience in urban land use management. Our methodology integrates qualitative and quantitative spatial indicators, which are essential for developing land use strategies and assessing the sustainability and resilience of current urban land management practices. By capturing the complexity of spatial dynamics, these indicators provide valuable insights that support informed decision-making in urban planning.

To further this goal, we establish a theoretical framework that defines spatial indicators for evaluating the balance between efficiency and redundancy. This model acknowledges inherent trade-offs while identifying potential synergies, fostering a more holistic approach to urban land use management. Through this spatially explicit approach, we bridge gaps in existing research and provide a practical solution for reconciling sustainability and resilience in urban planning.

## 3. Framework for Assessing Urban Land Use Balance

This section presents a comprehensive framework for assessing the balance in urban land use, focusing on indicators of efficiency and redundancy. We introduce a set of spatial indicators that capture these two crucial aspects of urban land management, demonstrating their impact on urban sustainability and resilience. The framework is divided into two subsections: the first addresses indicators affecting efficiency, while the second focuses on indicators related to redundancy in urban systems.

### 3.1 Efficiency in Land Use Planning

Land use efficiency in urban planning involves coordinating socioeconomic production and environmental conservation (Wang et al., 2018). Embracing efficient land use practices is essential for fostering sustainability across urban areas by optimizing land use, thereby enhancing environmental quality, promoting social equity, and bolstering economic prosperity.

Indicators for assessing land use efficiency encompass various factors that contribute to the effective utilization of land within urban areas. Mixed land use is a key variable associated with high land use efficiency (Storch & Schmidt, 2008). Furthermore, the UN Habitat indices, which focus on annual land consumption, population growth rate, and built-up area densification, provide valuable tools for assessing and monitoring the efficiency of land use in urban environments.

In the following, the main indicators used for land use efficiency are presented.

3.1.1 Land-use mix

Mixed land use integrates economic vitality, social equity, and environmental factors, making it a cornerstone of urban sustainability (Grant, 2002). In their comparative study on land use mix and urban sustainability, Iannillo & Fasolino (2021) compared various indicators to assess land-use mix in urban environments. Their findings highlighted the Entropy Index (Eq. (1)) as a particularly effective tool for capturing the diversity and distribution of land uses.

$$\text{Entropy Index} = (-1) \times \sum_{j}^{n} Pj \frac{Pj \ \times \ln(Pj)}{\ln J} \tag{1}$$

where, $Pj$ is the ratio of a type of land use's area to the total area; $J$ is a region's total number of land uses.

3.1.2 Population density and land consumption rate

Concentrating development intensity on the most suitable available land is emphasized as a means to achieve sustainability (Stevens et al., 2010). Compact development fosters non-hazardous land use and infrastructure systems, enhances access to diverse resources and services, and optimizes land use efficiency (Chang & Shinozuka, 2004).

To assess land use efficiency, the UN-Habitat (2018) introduced the indicator SDG 11.3.1, known as the Land Consumption Rate Per capita Growth Rate (LCRPGR) (Eq. (2)). This indicator compares the Land Consumption Rate (LCR) to Population Growth Rate (PGR) to identify efficient urban expansion strategies (Wang et al., 2020).

A value of $0 \leq \text{LCRPGR} \leq 1$ signifies efficient land use where population growth exceeds land consumption, indicating densification. Conversely, $1 < \text{LCRPGR} < 2$ indicates inefficient land use, with land consumption surpassing population growth, suggesting low density. $\text{LCRPGR} > 2$ signifies highly inefficient land use, where land consumption is at least twice the rate of population growth.

$$\text{LCRPGR} = \frac{\text{land consumption rate (LCR)}}{\text{population growth rate (PGR)}} \tag{2}$$

3.1.3 Total change in urban infill

The swift pace of urbanization often results in the excessive depletion of land resources (Diksha & Kumar, 2017). To address this issue, promoting the densification of existing urban structures is widely recognized as crucial, as it enhances land use efficiency and helps mitigate urban sprawl (Behnisch et al., 2022). Additionally, urban densification, measured through infill development, serves as an important indicator of land use efficiency. It quantifies the extent of development within a city's built-up area, with higher densification suggesting the presence of significant vacant land within the given area.

This approach to urban development is considered essential in promoting city sustainability by enabling more efficient land use, reducing urban sprawl, and minimizing the consumption of valuable ecological land (Schorcht et al., 2023). The computation of the percentage change in urban infill, a measure of densification, involves assessing the alteration in density within pre-existing urban areas between two specific times ($t1$ and $t2$). The specific formula for calculating this is presented in the following equation (Eq. (3)) (Koroso et al., 2020).

$$\text{Urban Densification} = \frac{\begin{array}{c}\text{Total built up area in } t2 \text{ within } t1 \\ \text{urban boundaries} - \text{Total built up area in } t1\end{array}}{\begin{array}{c}\text{Total built up area in } t1 \text{ within} \\ \text{urban boundaries}\end{array}} \tag{3}$$

### 3.2 Redundancy in Land Use Planning

Redundancy is a key factor in building urban resilience through spatial planning (Fleischhauer, 2008). It refers to having multiple components or systems that can fulfill similar functions (Cimellaro et al., 2010). In urban contexts, this translates to designing with multiple nodes or areas for critical services and infrastructure (Wardekker, 2017). This ensures that if one element fails, the entire system doesn't collapse (Cruz et al., 2013). As Anderies (2014) suggested, redundancy allows the system to absorb disruptions by having substitutes readily available.

In the following sections, the main criteria used to assess resiliency in urban landscapes are discussed.

3.2.1 Reserve areas

Reserve areas play a crucial role in promoting redundancy in the context of urban planning (Maru & Worku, 2022), by providing buffer space for disasters, effectively limiting their spread, and reducing hazards to other area (Jayakody et al., 2018).

We can determine the percentage of land designated for reserve purposes within a city by taking the total reserved land area and dividing it by the total city land area (Eq. (4)).

$$\text{Ratio of reserved land} = \frac{\text{Total reserved land area}}{\text{Total urban bondaries land area}} \times 100 \tag{4}$$

However, determining optimal ratios for different types of reserved lands and balancing competing urban space demands remain significant challenges for limited urban space. Additionally, political considerations and stakeholder interests can influence decision-making processes related to land allocation (Jayakody et al., 2018).

3.2.2 Open Public Space (OPS)

OPSs, which are often overlooked, holds immense potential in promoting redundancy within urban environments. By virtue of their inherent multifunctionality, these spaces go beyond their primary recreational purpose. They offer a range of benefits that significantly contribute to urban resilience. These benefits include facilitating emergency evacuation, serving as multi-functional spaces for assembly, and providing temporary shelter and basic life support after disasters (Jayakody et al., 2018; Koren & Rus, 2019).

The sustainable development goal indicator 11.7.1 in the UN 2030 Agenda measures the average share of the built-up area of cities that is open space for public use for all. This indicator supports the broader target 11.7, which aims to provide secure, inclusive, and accessible green and public spaces for all, ensuring equitable access, reducing privatization and exclusion, and enhancing urban livability through improved environmental conditions (Chen et al., 2020).

By incorporating more OPS into urban design, cities can enhance their resilience in several ways: improved emergency evacuation routes, increased capacity for disaster response activities, and the provision of essential services during disruptions.

$$P_{POPS} = \frac{S_{streets} + S_{ops}}{S_{urban\ boundaries}} \times 100\%$$

where, $S_{streets}$: Total Area Occupied by Streets (km²); $S_{OPS}$: Total Area Occupied by OPS (km²); $S_{urban\ bondaries}$: Sum of Areas of All Localities (km²).

However, ensuring an equitable distribution of accessible OPS within a 400-meter walking distance along the street network is crucial (Han et al., 2022). This approach, measured by the share of the urban population with convenient access, guarantees everyone has vital resources nearby in times of crisis (Eq. (5)).

$$\text{Access} = \frac{\text{Total population withn 400m walking buffers to OPSs}}{\text{Total urban population}} \times 100 \tag{5}$$

3.2.3 Land use planning for multiple centers

One manifestation of redundancy in urban structures is the development of polycentric cities, characterized by multiple centres of activity and resource distribution (Fleischhauer, 2008). Polycentric cities stand in contrast to monocentric cities, where a single dominant centre concentrates population, functions, and infrastructure. This concentration creates a single point of failure, making the city more vulnerable to disruptions. In contrast, polycentric cities distribute these elements across multiple sub-centres, fostering redundancy and reducing the impact of localized disruptions.

The benefits of polycentricity in enhancing urban resilience are manifold. By spreading out population and resources, polycentric cities reduce the potential for widespread damage in the event of a disaster. Additionally, the modularity of polycentric structures allows for more efficient recovery efforts, as sub-centres can support each other in the aftermath of a disruption. Moran's I Index (Eq. (6)) is a spatial autocorrelation statistic (Dale & Fortin,

2014) that can be employed to evaluate the polycentricity of cities.

$$\text{Moran's I} = \frac{N}{W} \times \frac{\sum_i \sum_j (X_i - \bar{X})(X_j - \bar{X})}{\sum_i (X_i - \bar{X})^2} 100\% \tag{6}$$

where, $N$: the total number of spatial units (sub-centres); $W$: the sum of all spatial weights $w_{ij}$; $w_{ij}$: the spatial weight between units $i$ and $j$; $x_i$: the value of the variable of interest (population) in unit $i$; $x_j$: the value of the variable of interest in unit $j$; $\bar{x}$: the mean of the variable of interest for all units.

By analysing the spatial distribution of land-use types, it can reveal the concentration or dispersion of activity centres and residential areas. A high Moran's I value suggests a monocentric structure with a dominant centre, while a low value indicates a polycentric structure with multiple dispersed centres.

While redundancy is essential for enhancing urban resilience, it can sometimes conflict with land use efficiency goals. For instance, reserve areas play a crucial role in mitigating environmental risks and providing flexibility in urban planning, but they also occupy valuable land that could be used for residential or economic development, thereby reducing land use efficiency. Similarly, OPS is vital for ensuring a healthy living environment and improving resilience to crises, yet their excessive expansion can limit urban densification and compromise land optimization.

The polycentric approach, which aims to distribute activities and infrastructure across multiple centers to enhance redundancy, can also pose challenges to urban efficiency. Poorly managed polycentric development may lead to high infrastructure and transportation costs, making urban planning less efficient and increasing daily commuting times. The Moran's I Index, used to assess polycentricity, helps determine whether the distribution of urban centers effectively balances resilience and efficiency or, conversely, causes excessive fragmentation.

Therefore, it is crucial to adopt an integrated approach that balances efficiency and redundancy, considering various urban planning indicators to ensure both sustainable and resilient urban development.

## 4. Balancing Land Use for Urban Sustainability and Resilience

Achieving a balance between resilience and sustainability is crucial for guiding urban systems onto desirable trajectories (Elmqvist et al., 2019). Sustainable land management generally aims to avoid inefficiencies by optimizing existing infrastructure and adapting institutions. However, this approach can overlook a key feature of resilient systems, redundancy. Moreover, maximizing efficiency in land use can reduce the necessary redundancy to absorb shocks and recover from disruptions, thereby compromising urban systems' ability to withstand and adapt to crises (Folke, 2016). Therefore, it is essential to find a balance between efficiency and redundancy to develop urban systems that are both sustainable and resilient, capable of progressing on desirable long-term trajectories.

Our study proposes a comprehensive framework for urban land-use planning that integrates both sustainability and resilience concepts. This framework is built upon two key pillars: A spatial data-driven approach that leverages geospatial information for precise calculation of indicators, and a strategy for balancing land use for urban sustainability and resilience that aims to optimize urban development.

### 4.1 Spatial Data-Driven Approach

Spatial planning, as defined by (Okeke, 2015), plays a critical role in fostering resilience and sustainability. This role is further emphasized through four key approaches that influence urban development: avoiding developments in hazard-prone areas, making differentiated land-use decisions, establishing legally binding land-use regulations, and incorporating adaptability into spatial plans (Sutanta et al., 2010). By adopting these frameworks and translating them into practical implementation strategies, cities can enhance their resilience and sustainability (Fleischhauer, 2008).

Building upon the crucial role of spatial planning in promoting resilient and sustainable cities, geospatial information serves as an indispensable tool for quantifying indicators and informing decision-making. Spatial data, including satellite imagery, land use maps, and infrastructure datasets, provides a rich source of information for quantifying all aspects of our new integrated approach (Figure 1), which considers both sustainability and resilience factors. We employ two key techniques derived from satellite imagery analysis: land cover classification to calculate changes in built-up areas, and land use classification to determine specific class areas. These techniques are fundamental to mapping indicators of efficiency and redundancy, enabling a more comprehensive and nuanced understanding of urban dynamics. By strategically integrating these elements, our approach represents a significant advancement in urban planning, offering planners and policymakers a powerful framework for creating more sustainable and resilient cities.

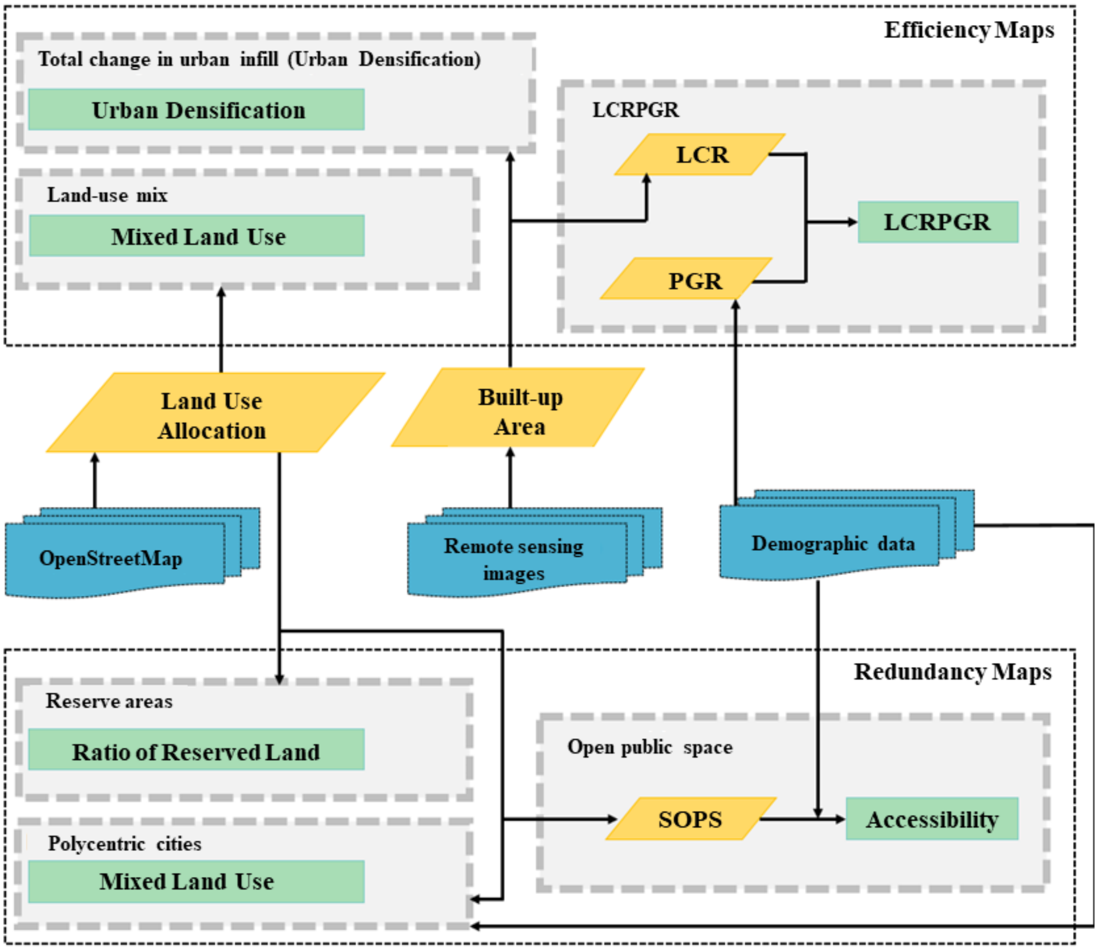


**Figure 1.** Workflow for efficiency and redundancy indicators assessment in urban systems

4.1.1 ML models for urban resilience and efficiency indicators from satellite images

The convergence of advanced remote sensing technologies and artificial intelligence (AI) has revolutionized urban analysis. This synergy provides an abundance of high-quality data with unprecedented spatial and temporal resolution (Cao et al., 2019), enhancing our ability to understand, map, and quantify urban systems across diverse scales. The resulting wealth of information offers new opportunities for assessing indicators of urban resilience and efficiency.

Furthermore, the integration of remote sensing data and AI has become a powerful tool for supporting land use planning efforts. ML has emerged as a key technique, offering exceptional performance processing massive datasets with high accuracy (Chaturvedi & De Vries, 2021). Our approach leverages this potential through the strategic application of ML models for land cover classification.

Three ML models form the foundation of our classification methodology (Figure 2): Random Forest, Support Vector Machines (SVM), and Minimum Distance. Each model offers distinct advantages in the context of land cover classification:

- Random Forest: An ensemble learning method that combines multiple decision trees, Random Forest excels in classification accuracy without requiring prior knowledge of data distribution (Breiman, 2001). Its robustness to overfitting and ability to handle high-dimensional data make it particularly suitable for complex urban landscapes (Slagter et al., 2020).
- SVM: SVM utilizes kernel functions to map multispectral remotely sensed data into higher-dimensional spaces, improving class separation. This characteristic renders SVM especially powerful for classifying intricate urban land use patterns (Lee & Yang, 2023).
- Minimum Distance: This algorithm classifies pixels based on their proximity to class centroids. While conceptually straightforward, Minimum Distance demonstrates remarkable efficiency in handling large datasets, providing a balance of simplicity and accuracy crucial for extensive urban areas (Gound & Thepade, 2021; Okeke, 2015).

The assessment of these models allows for a comparative classification approach that evaluates their individual strengths. By testing Random Forest's accuracy, SVM's robustness, and Minimum Distance's simplicity separately, we can determine the most effective method for land use classification, which is crucial for quantifying urban indicators. This assessment aims to identify the best-performing model for classifying remote sensing images.

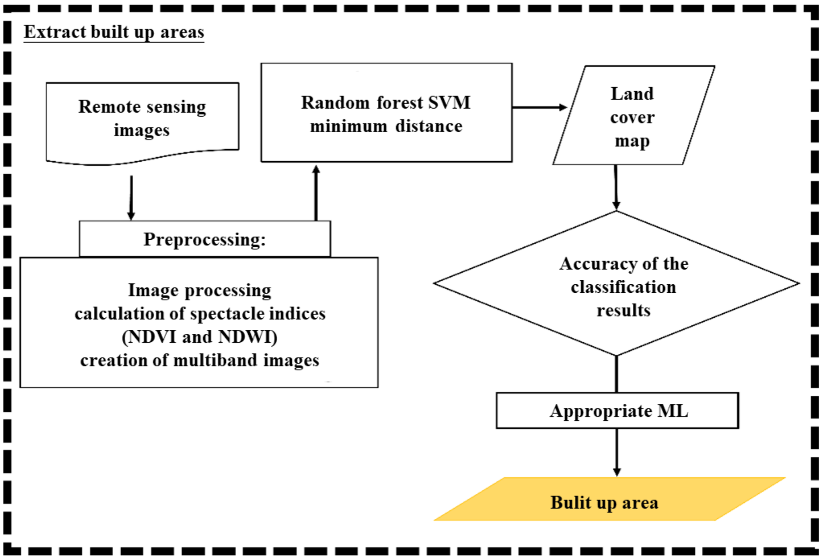


**Figure 2.** ML for built-up extent mapping via remote sensing

A key strength of our methodology lies in its adaptability to diverse geographical contexts and temporal variations. This flexibility enables consistent application across varied urban environments, facilitating comparative analyses and long-term studies of urban resilience and efficiency. Our approach, designed for universal applicability, provides valuable insights regardless of the specific urban context or scale of analysis a crucial feature given the diversity of urban forms and development patterns.

By leveraging this ML classification approach, we accurately map and quantify critical urban indicators. The ML models play a vital role in the precise classification of built-up areas, a fundamental step in calculating the total change in urban infill indicator. Furthermore, integrating demographic data with classified built-up areas allows us to compute the Land Consumption Rate to Population Growth Rate (LCRPGR) indicator.

4.1.2 Urban resilience and efficiency indicators with OpenStreetMap data

Our approach relies on precise land use classification to calculate key indicators for our methodology. Land use classification involves categorizing land areas into distinct classes based on human activities (Anderson et al., 1976). To ensure our approach is applicable to all study areas, even in the absence of official land use data, we propose using OpenStreetMap (OSM) data available online (accessed on 21 July 2024): https://www.openstreetmap.org/. OSM is one of the most widely used Volunteered Geographic Information (VGI) platforms, offering an extensive range of data on road networks, buildings, and land cover (Vargas-Munoz et al., 2021).

OSM provides a detailed representation of land use and land cover (LULC). While OSM is a highly valuable resource for collecting reference data in land cover mapping (Schultz et al., 2017), it is important to note that the completeness and accuracy of OSM data may vary significantly across regions. The data quality can be influenced by factors such as the density of local contributions, the level of community engagement, and the extent of authoritative data integration in different areas. In regions with limited local mapping activity or in rural areas, the OSM data may be sparse or less accurate, potentially affecting the reliability of the land use classifications and indicators derived from it. Despite these challenges, the crowdsourced nature of OSM also offers significant advantages, including the ability to capture fine-grained features, such as medium-sized buildings and intricate road networks, which may not be represented in official datasets. However, to address the potential limitations in data quality, we recommend validating OSM data with other reliable sources where possible. This could include remote sensing data or authoritative land use data from local governments or other official bodies, especially in regions where OSM coverage may be incomplete.

We utilize OSM data to calculate the areas of different land use classes, which is a crucial element for computing the land-use mix index. By integrating demographic data, we can also measure the polycentric cities index.

The quality of OSM data, while heterogeneous due to its crowdsourced nature and partial integration of authoritative sources, offers fine granularity, extending to the representation of medium-sized buildings in urban areas. This precision allows us to use OSM as a reference data source for mapping road networks (Wu et al., 2019) and urban open spaces (Cramwinckel, 2019). These data enable us to calculate both the Reserve Areas index and the OPS index, with the latter also incorporating demographic data.

By leveraging OSM data in conjunction with our ML-based classification approach, we enhance the robustness and accuracy of our urban analyses. This integration provides a solid foundation for evaluating and optimizing sustainable urban development strategies, even in areas where official land use data may be limited or inaccessible.

### 4.2 Striking a Balance: Efficiency and Redundancy in Urban Planning

This article proposes an approach for integrating sustainability and resilience concepts in urban land-use planning. Our method relies on a rigorous selection of previously identified relevant indicators to assess both aspects in urban systems. Efficiency as a key characteristic of sustainability can be measured using parameters such as land-use mix, which promotes walkability and reduces dependence on cars. Additionally, population density and urban densification rates serve as indicators of compact development, minimizing land consumption. However, redundancy, a fundamental feature of resilience within a polycentric structure, is equally important.

Strategically planned reserve areas near existing centers offer flexibility for future growth, while OPS not only fosters community connections and healthy urban environments but also serves as crucial evacuation zones during catastrophes. Hence, land-use planning faces the critical challenge of balancing efficient development with strategic redundancy, ensuring optimal resource utilization while maintaining necessary reserves.

These seemingly conflicting goals are crucial for creating sustainable and resilient cities. Achieving the right balance requires a complex decision-making process, demanding a comprehensive evaluation tailored to each city's unique priorities. Therefore, this objective necessitates a multi-criteria evaluation framework capable of assessing both efficiency and redundancy. This framework analyzes the relevant criteria previously identified in our approach while assessing their relative importance to a given urban area. By systematically prioritizing these criteria based on the unique objectives and challenges of each city, this process highlights the importance of developing flexible urban frameworks adapted to a variety of urban environments (Lee & Yang, 2023).

## 5. Discussion

In the scientific literature addressing urban development, the concept of efficiency has gained prominence due to growing concerns about urban sustainability. While redundancy is recognized as an important aspect of urban resilience, efficiency, particularly in urban land use, has been the subject of numerous studies aimed at developing quantitative measures and analytical frameworks. This emphasis on efficiency aligns with the increasing need for sustainable urban planning and resource management amid rapid urbanization and environmental challenges.

Some researchers have proposed measuring urban land use efficiency by calculating the ratio of urban land consumption to population growth rate, an approach that aligns with the United Nations' Sustainable Development Goal 11.3.1 (Estoque et al., 2021). Others have developed more comprehensive approaches that account for the complex interplay of various factors affecting land use efficiency, including economic and demographic dynamics (Han et al., 2020; Wang et al., 2023).

Alongside efficiency, urban resilience has emerged as a critical focus. This growing interest is driven by an increasing awareness of urban societies' vulnerability to diverse risks (De Ruiter et al., 2020). Several studies have explored theoretical frameworks, practical implementations, and the resilience of urban public spaces, as well as comprehensive assessment methodologies in the context of urban resilience (Dianat et al., 2022; Silva et al., 2022).

However, despite this growing body of research, urban resilience still lacks a standardized framework for quantification (Wu et al., 2022). This limitation extends to the concept of redundancy in land use management. While redundancy is recognized as a fundamental component of resilience, the literature has not yet established a comprehensive approach for calculating or quantifying redundancy specifically in land use management scenarios.

Recognizing the limitations of approaches that prioritize efficiency at the expense of resilience, this article proposes a holistic framework that balances both imperatives in urban development. By incorporating redundancy into land use management strategies, we aim to bridge the gap between optimized resource utilization and the need for adaptable, robust urban systems. This balanced approach ensures that urban areas maintain the necessary redundancy to absorb and recover from disruptions while also acknowledging the importance of efficient land use.

Building on this need for balance, we propose a comprehensive methodological framework for evaluating sustainability and resilience indices. Our approach employs a global method derived from a single data source, facilitating its implementation across different urban contexts. By incorporating a weighting system for these indices, we provide decision-makers with a flexible tool that can be tailored to the specific characteristics of each urban area. This methodology allows for a nuanced assessment of both efficiency and redundancy, enabling urban planners to make informed decisions that support sustainable development.

Our framework thus offers a practical solution to the balancing of competing priorities in urban land use management, offering a practical solution to balancing competing priorities in urban land use management. Through this integrated perspective, we advance methodologies that promote both efficient resource management and long-term urban resilience.

## 6. Conclusion

Our research has made significant strides in exploring the complex relationship between sustainability and resilience in urban planning. By focusing on two essential yet opposing concepts—efficiency and redundancy—we have highlighted how these aspects interact within urban systems. While efficiency prioritizes optimizing land use and minimizing waste, redundancy plays a crucial role in ensuring urban resilience against environmental and social shocks. Moreover, other parameters or components of resilience and sustainability may also present tensions between achieving sustainability and resilience goals, which provide deeper insights into the challenges urban planners face, as discussed in previous studies.

The strength of our proposed framework lies in its ability to integrate these complementary yet conflicting goals into a cohesive urban planning process. By adopting a multi-criteria evaluation approach, our framework enables the incorporation of diverse perspectives from various stakeholders—including government planners, local communities, and experts—thus fostering a more balanced and informed decision-making process. This collaborative approach can guide the development of urban spaces that are both sustainable and resilient, offering a clearer strategy for addressing the challenges posed by rapid urbanization.

The broader implications of these findings are particularly relevant for rapidly urbanizing regions, especially in developing countries. As cities in these areas expand at an unprecedented rate, the challenge of balancing economic development with environmental protection and resilience becomes increasingly critical. The proposed framework helps to develop a practical tool to support policymakers in understanding how urban systems can be optimized for long-term sustainability and resilience. It provides key insights for managing urban growth in a way that simultaneously addresses the immediate needs of a growing population while preparing for long-term challenges such as climate change, resource scarcity, and social inequalities.

To the best of our knowledge, this research presents a unique framework that integrates sustainability and resilience for urban planning. However, we acknowledge at this stage, it remains the theoretical foundation. In future research, we will focus on implementing the proposed framework using appropriate Multi-Criteria Decision Analysis (MCDA). Additionally, a case study will be conducted to demonstrate the relevancy of selected spatial indicators in achieving a balance between sustainability and resilience in urban planning applications.


### Data Availability

The data used to support the research findings are available from the corresponding author upon request

### Conflicts of Interest

The authors declare no conflict of interest


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