Journal of Sustainable Development Indicators

http://www.sdewes.org/jsdi

Year 2025, Volume 1, Issue 1, 2020559

Original Research Article

An Interactive Decision Support Tool to Monitor and Measure Sustainable Development in Neighborhoods: A Data-driven Framework

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Cite as: Rasoulian, H., Eicker, U., Hachem-Vermette, C., An interactive decision support tool to monitor and measure sustainable development in neighborhoods: A data-driven framework, J. sustain. dev. indic., 1(1), 2020559, 2025, DOI: https://doi.org/10.13044/j.sdi.d2.0559

ABSTRACT

With more than half of the world's population living in urban areas, providing sustainable living conditions is highly important. Among sustainable development goals, established by the United Nations General Assembly in 2015, SDG 11 focuses on providing inclusive, safe, sustainable, and resilient cities for human settlement. Many sustainability assessment tools, rating systems and frameworks have been developed to benchmark and measure sustainability in urban areas. Most neighborhood sustainability assessment tools rely on simplified, static indicators that are not evenly distributed across the pillars of sustainable development. The primary objective of this research is to develop a framework for monitoring and measuring the progress toward urban sustainability development. The research employed a systematic approach to acquire, prepare, and standardize urban data for sustainability assessment. Then, the localized indicator sets were collected from three primary sources, i.e. SDGs, the new urban agenda, and the city prosperity initiative. The analysis was performed using two weighting approaches and normalization to derive a neighborhood sustainability score. The framework is then applied to nineteen neighborhood in Montreal, Quebec. Cluster analysis was employed to deepen the understanding of various variables. Results revealed that Verdun borough outperforms others, primarily due to its ample green space and accessible amenities, while Côte-des-Neiges ranks lower, reflecting deficiencies in green areas and basic services. An interactive decision-support tool visualizes these results. The implications of this research provide insights enabling policymakers and stakeholders to pinpoint improvement areas. By emphasizing transparent data handling and flexible indicator selection, this approach can be replicated in diverse urban contexts to measure, compare, and guide progress toward sustainable development goals at the neighborhood scale.

KEYWORDS

Sustainable development assessment, Neighborhood sustainability, Indicators, Sustainability score, Cluster analysis, Decision support tool.

INTRODUCTION

Currently, more than half of the world's population inhabits in urban areas, and this trend is projected to increase to 66% by 2050 [1]. Rapid urbanization leads to pollution of soils and water sources, temperature increase, negative effects on biodiversity, increasing traffic congestion, etc. [2], [3]. Many cities worldwide have begun to develop local regulations to overcome these challenges [4]. The introduction of Sustainable Development Goals (SDGs) in 2015 shed light on the importance of sustainable development and attracted the attention of countries [5]. The SDGs provide a blueprint for building a sustainable future for all through seventeen goals [5]. The SDGs have been the focus of extensive research; various frameworks have been developed to localize the targets of SDGs and evaluate the sustainability in cities neighborhoods, and buildings [6].

Sustainable development in urban areas has been traditionally recognized by social, environmental, and economic dimensions. Some resources have suggested the government and institutional as the fourth dimension of urban sustainability [8]. In sustainability evaluation, each dimension of sustainability is measured via a set of indicators, each measuring an aspect of sustainable development [9]. The quality of the measured indicator values highly depends on the quality of the input data [10]. Urban sustainability is a relatively new subject; the lack of standardized data formats, well-defined terminology, and application of methodologies increases the complexity [11].

A city is a complex system that includes various entities, for instance, humans, buildings, infrastructure, transportation, etc. [12]. Due to the interconnection between the entities, sustainability assessment on this scale faces many challenges; for example, current methods have limitations in providing accurate, reliable measures of sustainability [13]. One of the methods to reduce the uncertainties is simplifying the system by multiple assumptions, leading to biased results that mislead decision-makers [13]. On the other hand, neighborhoods and districts, as the core of the city [14], could offer a less complex system, which has been considered as the optimal scale that promotes the well-being and liveability aspects of sustainable development [15]. Neighborhood is considered the smallest scale to assess social, economic and environmental aspects of sustainability [16].

Objective of the research

The methods used to assess neighborhood sustainability are currently encountering a range of complex challenges [17]. One such challenge relates to the methodological assumptions made during the preliminary stages of the assessment process. These assumptions often involve setting goals and selecting indicators based on benchmark data and quantifying baselines [17]. If these steps are oversimplified, it can lead to biased results that can mislead stakeholders. Furthermore, challenges can arise in different stages of applying the assessment frameworks such as data collection, implementation, results analysis, and evaluation [17]. Therefore, there is a need for a generic approach that prevents manual calculations and applies the same method to different case studies. Despite these challenges, there is a growing need for effective neighborhood sustainability assessment approaches to overcome methodological shortcomings and promote a more sustainable and resilient future.

Among the three dimensions of urban sustainability, the social aspect has received the least attention [18]. One of the main reasons is the lack of clear conceptualized definitions, measurement methods, and analysis processes [19]. This paper aims to [20]:

- Develop a general NSA framework that is applicable to various case studies rather than focusing on a predefined location. The tool automates the calculation of indicators across different locations, reducing manual calculation and improving accuracy.
- Support decision makers by providing an interactive visualization tool that integrates sustainability indicators to demonstrate the real-world application of the sustainability assessment tools. This novel contribution helps policymakers identify areas requiring further attention to enhance sustainability.

The paper is structured as follows: A literature review of the neighborhood sustainability assessment approaches is conducted and presented in the remainder of this section. The materials and methods section present the methodology, and the selected indicators on the neighborhood scale. Three aspects of sustainability are considered while selecting the indicator sets. The indicators are weighted and normalized to report the neighborhood score.

Furthermore, the application of the method in the boroughs of Montreal, Canada, is explored. The results and an interactive web-based decision support tool are presented in the results and discussion section. Lastly, the conclusion is presented in the last part.

Literature review

Neighborhood context. Building sustainability assessment and its correlation with the city sustainability assessment revealed the missing piece of urban sustainability assessment, neighborhood scale [8]. While focusing in buildings provide valuable insights, the neighborhood is recognized as the minimum scale to deal with complex interactions between the buildings and other city entities [8]. Neighborhoods have particularly received considerable attention since they are small enough to effectively and efficiently experiment with innovative sustainable planning and design initiatives, and at the same time, large enough to take account of complex interactions between different urban components [15]. Such complexities are often not considered when the focus is only on smaller scales such as buildings and building blocks [21]. Sustainable neighborhoods can reduce transport costs, promote economic sustainability, and provide a common meeting place for residents to encourage social interaction [22]. Neighborhood scale enables community energy sharing and installing renewable energy sources, i.e. solar and wind [23]. These strategies improve resilience, mitigate power outage risks, and provide a more sustainable environment [24].

Sustainable development in a neighborhood context follows the three dimensions of sustainability. Environmental sustainability in the neighborhood refers to efforts to reduce the neighborhood's environmental impact [25]. Some of the common indicators to measure this dimension are energy efficiency, waste management, and green spaces [8], [25]. The significance of social sustainability within urban neighborhoods is gaining attention from both researchers and policymakers [20]. Urban social sustainability is a multidimensional concept that includes six main aspects: social interaction, sense of place, social participation, safety, social equity, and neighborhood satisfaction [19]. The third dimension of sustainable development in neighborhoods is the economic pillar. Some of the contributing aspects of economic sustainability in neighborhoods are the level of economic growth and development within the neighborhood; the affordability of housing and other essential services; the impact of neighborhood development on the local economy; the distribution of income within the neighborhood; the availability and accessibility of essential amenities and services such as healthcare and education; and the adoption of sustainable business practices within the neighborhood [25], [26], [27].

Sustainability assessment tools. Neighborhood sustainability is mainly assessed by utilizing key performance indicators covering various sustainability aspects. An indicator is a measure of executing best practices to different levels of achievement, and benchmarks represent target or reference values, i.e. the desired level of service, for sustainability indicators [9]. In sustainability assessment frameworks, indicator sets are used to factor in the sustainability dimensions, i.e., social, economic and environmental [9]. Indicators have been used in various approaches to measure the urban sustainability. United Nation has proposed categorised indicators in seventeen goal-oriented groups (sustainable development goals or SDGs) [28]. Among the seventeen SDGs, SDG 11 focuses on making cities and human settlements more resilient and sustainable [29]. To advocate neighborhood sustainability among various stakeholders, neighborhood sustainability assessment (NSA) tools have been developed which are operating based on indicators [21].

SDG 11 has fifteen indicators to address the ten targets related to inclusive, safe and resilient human settlement in cities [30]. 11 of 17 SDGs include targets that seek sustainable urban development. For example, SDG 1.4, ensures access to basic services for all; SDG 2.a, increasing investment in rural infrastructure; SDG 5.2, aims to eliminate all forms of violence against women and girls; etc. [30]. After the introduction of SDGs, various frameworks emphasizing urban sustainability were introduced, such as the New Urban Agenda (NUA) developed by the

United Nations. NUA relies on SDG 11 and other indicators from SDGs related to urban sustainability [29]. It also presents additional viewpoints that must be considered within this framework [29]. Another example is the City Prosperity Index (CPI) by UN-Habitat that is a versatile framework designed to facilitate the formulation, development, and monitoring strategies and measures aimed at enhancing the sustainability and prosperity of urban areas [31]. CPI has forty indicators across six domains: productivity, infrastructure for development, quality of life, equity, social inclusion, and environmental sustainability [31].

Sustainability assessment approaches in districts rely on Neighborhood Sustainability Assessment (NSA) tools. Some of the most well-known frameworks are introduced: LEED-ND [32] which stands for Leadership in Energy and Environmental Design for Neighborhood Development. It is a neighborhood sustainability assessment system developed by the United States Green Building Council. LEED- ND focuses on promoting sustainable and resilient neighborhoods through a credit-based rating system that addresses various aspects of sustainability such as transportation, site planning, social equity, and environmental considerations [32]. The second tool is BREEAM Communities developed for smart and sustainable urban design [33]. It focuses on assessing and promoting sustainability in the neighborhoods by evaluating various aspects of sustainable urban development, such as social adaptation, governance, community indicators, and climate change adaptation [33] Another example is EarthCraft Communities (ECC) a regional green building program in the Southeastern United States that promotes environmentally responsible, energy-efficient, and healthy communities through sustainable site planning, energy efficiency, water conservation, indoor air quality, and materials selection [34]. Lastly, HQE^{2}R is a European assessment tool aimed at promoting sustainable development and quality of life in urban neighborhoods [35].

Sustainability assessment tools and frameworks have played a significant role in promoting sustainable design and have contributed greatly to the increase in general awareness of sustainability principles [36]. The active participation in certification procedures has not only facilitated cooperation among developers but has also provided a platform for the exchange of experiences and knowledge-sharing [16]. A comprehensive analysis of the various NSA tools reveals that the projects that have been certified through these tools have effectively demonstrated improvements in key areas such as energy efficiency, reduction in Vehicle Miles Traveled (VMT), enhanced walkability, and an overall improvement in the quality of life and satisfaction levels of the residents [15]. Furthermore, the successful implementation of sustainability assessment tools has played a pivotal role in identifying priority development locations and highlighting areas requiring further improvements and enhancements [15].

In addition to the factors that contribute to the success of these tools, it is important to acknowledge the limitations of these frameworks. These tools are primarily designed to evaluate new projects through various rating methods. Notably, a subset of these tools follows a specific pattern that excludes regeneration projects from urban sustainability conversation [16]. Furthermore, it is important to recognize that the NSA tools are not applicable in assessing the sustainability of existing disadvantaged megacities [16].

Investigation into the various tools and frameworks used for assessing sustainability reveals that the environmental aspect of sustainability has received more attention compared to the other dimensions, namely social and economic considerations [25], [16], [15], [21]. One of the primary factors contributing to this disparity is the focus of many sustainability assessment tools on measuring the carbon footprint of urban areas [15]. Disregarding the socio-economic aspects of established communities can result in the proposal of unsuitable environmental interventions for these specific contexts [16]. Upon examining the indicators within a set of tools, namely LEED-ND, EarthCraft Communities (ECC), BREEAM Communities, CASBEE-UD, HQE2R, Ecocity, and SCR, it becomes evident that a significant number of NSA tools lack coverage in the areas of water, energy, affordable housing, and inclusive community criteria [21]. However, SDG 11 explicitly emphasizes inclusivity and affordable housing as key drivers in establishing sustainable communities.

Some NSA tools adopt a hierarchical approach that excludes input from local communities or stakeholders. The lack of transparency in the methodologies employed by NSA tools poses a challenge to users in comprehending the assessment process and the derivation of results [15]. Another drawback of these tools is their simplicity and limited usefulness in post-occupancy evaluation [16]. Additionally, these tools are restricted to a select few neighborhoods that are financially capable of covering the costs associated with consultation fees and data collection [16].

Many NSA tools have standardized criteria and indicators that may not adequately capture different neighborhoods' specific challenges and opportunities. Consequently, these tools fail to accurately depict the sustainability performance of a neighborhood, as they neglect to consider the unique social, economic, and environmental factors at play [15]. This drawback led to the development of frameworks to measure and monitor neighborhood sustainability. These frameworks aim to improve neighborhood sustainability by incorporating the project's special characteristics, i.e., density, population, and location, into the assessment process and valuing all the aspects of sustainable development [37].

One of the repetitive observed limitations of the local sustainability assessment tools is the lack of scalability and generalizability of the method. In [38], using weighting, normalization, aggregation, and Delphi study, the sustainability in the boroughs of Nagpur, India, is assessed. The indicators are selected to reflect the city’s needs, restricting the application to other locations. A framework to monitor and evaluate the progress towards sustainability, considering SDG 11, is developed in [39]. However, the paper lacks details on the application of the framework in different locations, particularly, regarding the data requirements for each indicator and mathematical operations involved to evaluate the sustainability progress.

MATERIALS AND METHODS

A sustainability assessment framework for urban neighborhoods was developed in this research. This framework is based on indicators in each dimension of sustainability and their relationship. The method is developed in a way that it could be applied to various cities. Dimensions of sustainability have equal weights and are assessed through a set of indicators. Considering the objectives, agenda, and data availability of cities, indicators could be added or eliminated. The UML diagram of the model is presented in Figure 1. The model relies on classes, sub-classes and their relationship. In this model, the variable’s data type is either qualitative, represented as a string (str), or quantitative, shown as an integer (int) and float.

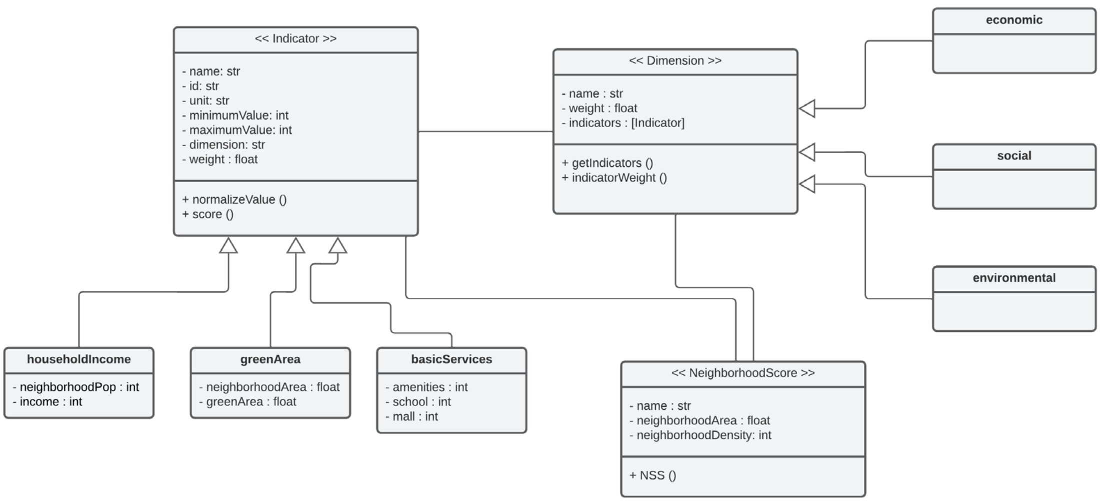

Figure 1. UML diagram of the developed framework with string (str), integer (int) and float values of the variables

The final purpose of the method is to report a Neighborhood Sustainability Score (NSS) computed by aggregating multiple indicators covering all the aspects of neighborhood sustainability. The steps followed in this process are: i) investigating the indicator sources and creating a pool of indicators; ii) selecting the indicators applicable to neighborhood; iii) searching for the data sources and formulas for each indicator; iv) weighting each sustainability dimension and indicators; v) normalizing the values; and vi) reporting the NSS. The step-by-step process is depicted in the framework in **Figure 2**.

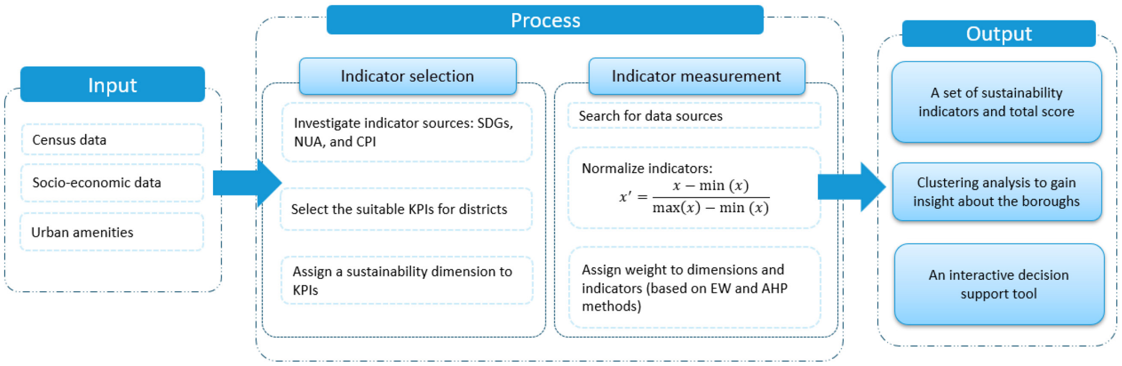

Figure 2. Input, process and outputs of the proposed framework

Investigating indicator sources

The SGD 11, NUA and CPI were selected as the sources for urban sustainability indicators. These frameworks focus on sustainable development related to urban areas, resilience enhancement, prosperity and social growth. The United Nations proposed a monitoring framework to measure the implementation of NUA with 77 indicators. The indicators are defined in terms of the three integrated dimensions of sustainable development **[31]**.

SDG 11 has 15 indicators to address the 10 targets related to inclusive, safe and resilient human settlement in cities **[40]**. Although 11 of 17 SDGs include targets that seek sustainable urban development. For example, SDG 1.4, ensures access to basic services for all; SDG 2.a, increasing investment in rural infrastructure; SDG 5.2, aims to eliminate all forms of violence against women and girls; etc. **[5]**. The CPI framework has 40 indicators across six domains: productivity, infrastructure for development, quality of life, equity, social inclusion, and environmental sustainability **[41]**. Therefore, a pool of 132 indicators was created from NUA, SDG 11 and CPI, and each was studied.

Indicators selection criteria

Each indicator in the pool was examined and selected for this framework based on the following criteria:

- The indicators should be unique. To avoid redundancy, the purpose of the indicators rather than the name was considered.
- The indicator should apply to the neighborhood scale. Although some indicators are related to the urban context, not all are helpful for measuring neighborhood sustainability.
- The indicators' purpose, unit, input data, and calculation method must be defined. The indicators with hypothetical values and unknown or unavailable data sources are not selected.
- Selected indicators should be measurable, and the values should benefit stakeholders.

Indicators were compiled in a spreadsheet and assessed based on their purpose. Since the focus of this study is on sustainability at a localized level, indicators that address the national and city-scale issues were excluded. Each indicator was evaluated for a clear definition, unit, methodology, and required input data. After refining the indicators using the criteria, 14 indicators were selected. Then, these indicators were categorized into three main dimensions of sustainability: social, economic, and environmental. Two publications have been considered as guidelines for assigning the dimensions to indicators. The first is a review paper [37] introducing and categorizing urban sustainability indicators. The second reference is published based on the outcomes of an experts-oriented workshop held in Montreal, Canada, to assess the relevant sustainability indicators in neighborhoods [42]. Selected indicators for this study and their sources are presented in Table 1.

Table 1. Selected indicators and their sources

Domain	Index	Indicator	Indicator full name	SDG	NUA	CPI
Society	1	Basic services	The proportion of the population living in households with access to basic services (for example, access to health centres, recreational, school, etc. within the 400 m)	1.4.1	yes	
	2	Access to public transport	The proportion of the population with convenient access (less than 500 m walking distance to a station) to public transport by sex, age and persons with disabilities.	11.2.1	yes	yes
	3	Population density	This is defined as the Gross density i.e. the total population divided by the total urban area in square kilometres.		yes	yes
	4	Gini coefficient	Measures the extent to which the distribution of income (or consumption expenditure) among individuals or households within an economy deviates from a perfectly equal distribution		yes	yes
Economic	5	Affordable housing	It is a measure of homeownership. The proportion of households that own the house to the total population.	11.1.1	yes	yes
	6	Use of Public transport	The proportion of trips made in Public Transport (PT) mode from the total number of motorized trips			yes
	7	Mean household income	Mean household income in the urban area			yes
Environment	8	Air quality	Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population-weighted)	11.6.2	yes	yes
	9	Access to Open Public Spaces	The average share of the built-up area of cities that is open space for public use for all, by sex, age and persons with disabilities	11.7.1	yes	yes
	10	Renewable energy share	Renewable energy shares in the total final energy consumption	7.2.1	yes	
	11	Green area per capita	Available green area per capita in urban areas	11.7.1	yes	yes
	12	Land use mix	The diversity of land use per square kilometre, within a city or urban area.		yes	yes
	13	Bike length availability	Percentage of road length that has dedicated bike lanes		yes	
	14	GHG emissions	Total greenhouse gas emissions per year/per capita	13.2.2	yes	yes

Data sources

Big data analysis and machine learning algorithms are crucial in enhancing city policies and urban issues, providing valuable support to inspire and develop data-driven sustainable solutions [43]. Big data analysis catalyzes the decision-making process and can influence the quality of the decisions [44]. However, reliable and clean data is essential to apply statistical analysis. Poor quality incomplete data sets lead to poor decisions and misleading assumptions [45]. Dealing with heterogeneous data sources and processing uncertain and inconsistent data are key challenges in incorporating big data in urban sustainability [46].

In this step, relevant data sources for each indicator were investigated. In many areas, data in the neighborhood level might not be collected. Depending on the objective of the indicator and data type, it might be possible to use the data with other levels of granularity to calculate the indicators on a neighborhood scale. Geospatial data has shown a promising capability on a neighborhood scale, providing valuable insights into the different domains [47].

Weighting

Weighting implies the significant level of each sustainability dimension [7]. In [38], the indicators' weights are distributed based on expert opinion surveys. Based on the indicator's importance, a number between one (low importance) and twenty (high importance) was given, and at the end, the weights were calculated based on the ranking results of thirty experts. In another study, equal weights were assigned to the neighborhood's sustainability goals [48]. Haider et al. assigned equal weights to the indicators to demonstrate their importance [49].

In this study, two types of weighting are implemented, as described below.

Method one: Equal Weights (EW). At first, equal weights have been given to each category. This implies the equal importance of urban sustainability dimensions. This is presented in eq. (1) where W_{S}, W_{En}, and W_{Ec} respectively are weights of social, environmental and economic dimensions:

$$W_{\mathrm{S}} = W_{\mathrm{En}} = W_{\mathrm{Ec}} = 0.333 \tag{1}$$

The weight of each indicator is determined by the number of indicators in each category, as formulated in eq. (2). It is assumed that indicators in each dimension contribute equally to the overall score.

$$w_i = 0.333 \times \frac{1}{n} \tag{2}$$

where w_i is the weight of indicators in a category and n is the number of indicators in a category.

Method two: Analytic Hierarchy Process (AHP) Method. In the second case, weights are distributed using the AHP method. This method addresses complex problems that lack objectivity and require the assignment of importance weightings to the elements involved in or related to the problem. The issue must be broken down into elements that are organized into a hierarchical structure (goal, criteria, and sub-criteria) to identify the interrelationships between them [50]. The AHP method applies to a wide range of disciplines. This method is valuable in neighborhood sustainability assessment as it breaks down complex problems into manageable parts, incorporates diverse expert knowledge, and adapts to various contexts [51]. It also provides a visual representation of results, facilitating clearer communication and decision-making [51].

The method involves making pairwise comparisons between the elements at each level of the structure, using a numerical scale from 1 to 9 points, as shown in **Table 2**, based on the contribution each element makes to the higher-level element or the overall objective [50]. The pairwise comparisons are represented in a square matrix where each element is compared with every other element at the same level of the hierarchy. The matrix A is constructed such that the element a_{ij} represents the comparison between element i and element j, using a scale mentioned in **Table 2**. Each comparison results in a ratio that reflects the relative importance of one element to the other. The reciprocal value is used for the opposite comparison, meaning $a_{ij} = 1/a_{ji}$.

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & 1 \end{bmatrix} \tag{3}$$

The pairwise comparison is used to determine the relative importance of various sustainability indicators. For example, in [52], a hierarchical model of indicators and sub-indicators is developed. Delphi study compared the importance of ecology and energy as factors in urban sustainability. Based on the outcome of the study, ecology was given more importance than energy, resulting in higher weight in the sustainability assessment [52].

Once the pairwise comparison matrix is constructed, the next step is to calculate the priority vector, which represents the relative weights of the elements. This is done by normalizing the matrix and averaging across the rows. The consistency of the comparisons is also evaluated using a Consistency Ratio (CR), which compares the Consistency Index (CI) of the matrix to the consistency of a randomly generated matrix. Based on [50], for CR < 0.1, the results are considered consistent.

Table 2. Fundamental scale of AHP weighting based on [50]

Scale	Degree of importance	Explanation
1	Equal importance	Two elements contribute equally to the objective.
3	Moderate Importance	One element is moderately more important.
5	Strong Importance	One element is strongly more important than the other.
7	Very strong importance.	One element is very dominant.
9	Extreme importance.	One element is extremely more important than the other.
2,4,6,8	Intermediate values between the two adjacent judgments.	Use for finer graduation of judgment.

Normalization

This framework aims to report a composite index as the sustainability level of neighborhoods. Indicators are measured in various units and have different ranges of values. Therefore, normalization is a crucial step that enables comparison among indicators with various measures [53]. In the literature, different normalization approaches have been used; for example, Bahadure *et al.* adopted a five-point system to represent the indicators on a uniform scale [38]. In [49], a linguistic scale in five stages (from very poor to very good) has been proposed and used for benchmarking indicators by looking at inputs from literature and experts' opinions. This is similar to categorical normalization implemented in [7] where the ranges of values (in percentage) are associated with a number between one to five.

This study relies on values found in literature and available data sources. Minimum and maximum values of indicators are determined, and using the internal normalization approach [53], these values are normalized. The min-max normalization approach scales and transforms data into a specified range, in this case, between 0 and 1. As presented in [53], the general formula for min-max normalization is:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \tag{4}$$

where x is the original value, x' is the normalized value, $\min(x)$ is the minimum value of the x and $\max(x)$ is the maximum value of the x.

Neighborhood sustainability score (*NSS*)

Having the weights and normalized values of the indicators, the Neighborhood Sustainability Score (*NSS*) is:

$$NSS = \sum_{i=1}^{i=n} w_i \times x'_i \tag{5}$$

where w_i is the weight of i^{th} indicator measured by either EW or AHP method and x'_i is the normalized value of the i^{th} indicator.

Clustering analysis

Clustering is the process of grouping together data points based on their similarities across various attributes to identify underlying patterns and structures in a dataset. The clustering is used in different domains; for example, in [54], clustering is employed to assess regional environmental quality by grouping regions with similar environmental characteristics, helping policymakers identify areas that require targeted interventions for sustainability improvements.

Common clustering methods include K-means, hierarchical clustering, and density-based clustering, each offering distinct advantages depending on the data distribution and the research objective. For the clustering analysis of the sustainability indicators and other parameters, K-means clustering is suggested. In [55], the complex relationship between national happiness and DGSs across 74 countries has been investigated. The K-means clustering is used to analyze economic, social, and environmental factors contributing to subjective well-being. The Davies-Bouldin Index (DBI) maximizes the inter-cluster distance and minimizes the distance between points in the cluster [56]. This DBI reports the optimum number of clusters. The cluster number that has the lower DB Index represents the optimum number of groups [56]. DBI is computed for different k values (number of clusters) to determine the optimal number of clusters.

Visualization tool development

An interactive decision support tool provides an interface for decision-makers to visualize, analyze, and gain insight into sustainability performance. Since the calculation is based on the neighborhoods performance, a map can best visualize the interested boroughs and illustrate various statistics. To serve this purpose, a GeoJSON file of the neighborhoods is needed. This file contains the latitude, longitude and other information of the boroughs. Calculated indicators and other characteristics of the locations are gathered following the UML diagram in **Figure 1**. A Python script was developed to process input data based on the UML diagram and output the interactive map. To create the application, the Streamlit library has been used, which is a Python library for creating interactive web applications. The **Figure 3** shows the process of creating the visualization tool.

One of the key features of this tool is the interactive map visualization that displays the boundaries and NSS of the boroughs. Colour-coding the neighborhoods based on the sustainability score could help to easily understand the performance of each area. For example, the scores could be reflected by colours ranging from red (lowest score) to green (highest score).

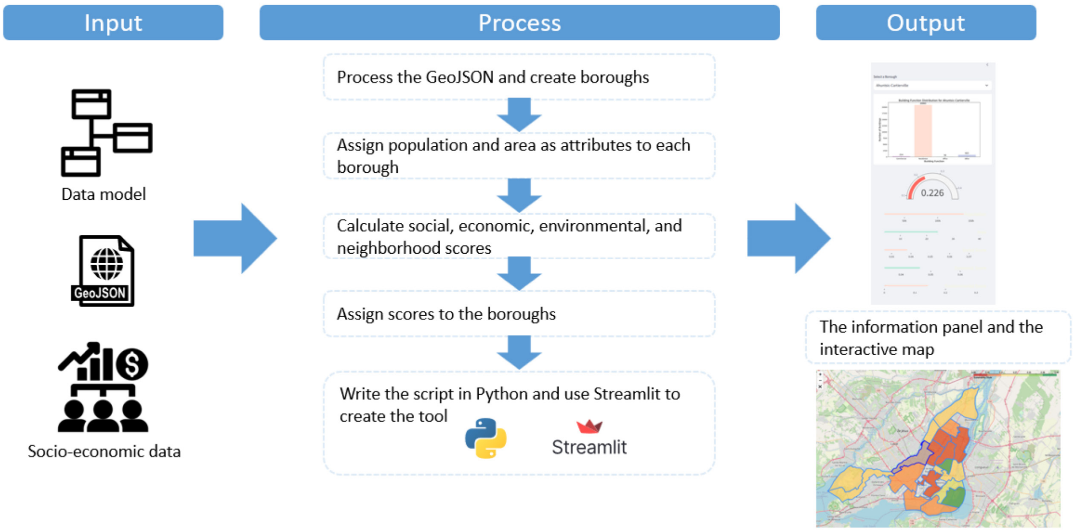

Figure 3.The process of developing the visualization tool

RESULTS AND DISCUSSION

Case study

As the second-largest municipality in Canada, Montreal has provided an action plan that includes goals, challenges, and requirements needed to become more sustainable [57]. The city's heritage preservation movement, initiated by Save Montreal in reaction to urban development pressures, reflects a commitment to community housing and public participation in planning [58]. Montreal's efforts in managing natural spaces highlight the importance of urban protected areas for biodiversity conservation amidst urban sprawl [58].

In the pathway toward sustainability and carbon mitigation goals, the city has three main sustainable development challenges, which are [57]:

- Reduction of GHG emissions by 80% (3,003 kilo tonnes of equivalent CO_2 eq.) by the year 2050 compared to the year 1990 baseline.
- Enhancing access to services and facilities among different neighborhoods in the city and ethical distribution of resources for every dwelling.
- Becoming an exemplary model for other cities by integrating sustainable plans into all aspects of the city.

Montreal has nineteen boroughs, each with a distinct character and socio-economic profile. Name, Population and total area of the boroughs are presented in **Table 4**. Assessing the city's current state in terms of sustainable development will help decision-makers better set future goals and develop strategies to overcome the three main sustainability challenges that the city faces. Six of the indicators from the proposed indicator list in **Table 1** have been chosen to address the challenges and measure the sustainability level at each borough. The indicators are i) green area per capita and bike path density for the environmental dimension, ii) population density and availability of basic services for the social dimension, and iii) mean household income and affordable housing for the economic dimension.

These indicators aim to assess inclusivity in terms of access to amenities, green spaces, and services. The results can help authorities identify neighborhoods with the least accessibility and take necessary steps. Two selected indicators, i.e., green area per capita and bike path density, represent the neighborhood's manifestation toward GHG reduction. Although these are not the only indicators to measure this issue, they were chosen based on data availability and methodological limitations. Implementation of this method in the city can inspire other municipalities to perform this analysis and move toward sustainability.

Details of the selected indicators are shown in Table 3. The units and formulas are extracted from the CPI [59] and NUA [31] frameworks. The Equal Weight column in Table 3 represents the first weighting method, where all the indicators in each category have the same priority. In this method, weights are distributed regarding the equal weight for dimensions (1/3) and the number of indicators in each dimension, as explained in the method section. However, the AHP Weight column (Table 3) represents the indicator weight measured by the AHP method. The criteria in the AHP method, which are the same as the sustainability dimensions in this study, are weighted equally (1/3). The sub-criteria matrix is developed for the indicators, and the weights are calculated and represented in Table 3. Data for the Montreal case study was sourced from multiple officials and publicly available datasets, including Statistics Canada and the City of Montreal open data portal. The total population and area of each borough are collected from the latest census population, which was done in 2021 [60]. Based on the boroughs' attributes, name, latitude and longitude, the population and total area were gathered. The official borough's boundaries were obtained from Statistics Canada [61]. The geospatial data is used for visualization purposes, as explained in the next steps. For bike path length, green spaces, available services, and household income, the data is reported based on geographical location, the borough, the type of service that it provides, etc. Therefore, after matching the names of the boroughs, the total number of each attribute per borough was calculated and used for the next steps.

The data collection process involved searching for the required dataset, direct extraction from government databases, and manual verification to ensure consistency across sources. One of the issues in working with various datasets was raised due to different naming conventions for the boroughs. After collecting all of the required datasets, Table 3, a list of borough names was collected. A program was developed to detect discrepancies and standardize them in a way that makes them unique in naming, which is presented in Table 4.

Table 3. Details of selected indicators for the Montreal boroughs

Index	Indicator	Unit	Equal Weight	AHP Weight	Formula	Data sources
EN1	Green area per capita	m^2/capita	(1/3) (1/2)	0.28	Total green area (m^2) / total population	[62]
EN2	Bike path density	1/m	(1/3) (1/2)	0.06	Bike path length(m) / area (m^2)	[63]
SO1	Population density	People/ km^2	(1/3) (1/2)	0.25	Population / area(m^2)	[60]
SO2	Basic services	Services/ capita	(1/3) (1/2)	0.08	Available services in the borough/population	[62]
EC1	Mean household income	USD/ household	(1/3) (1/2)	0.28	The mean income of the households	[64]
EC2	Core housing need	%	(1/3) (1/2)	0.06	Households in core need / Total Households	[65]

Results

For each indicator, the values per borough are calculated, and to enable the comparison, they are normalized (between 0 and 1). Based on the weights provided in Table 3, NSS for each borough and based on two weighting methods are calculated and presented in Table 4. This study assesses the neighborhood's environmental sustainability using green area per capita (EN1) and bike path density (EN2). EN1 measures the available parks and gardens in each neighborhood per capita. The green area in each borough is extracted from the data set provided by the Quebec government [62]. Bike path density in boroughs is measured based on the length of the bike lanes ending in the nearest metro stations [63]. Both indicators are normalized between zero and one and weighted based on the EW and AHP methods. Results are presented in **Figure 3**. Côte-des-Neiges (N3) borough has the minimum green spaces, and the Verdun (N17) has the maximum. Therefore, corresponding values are used as minimum and maximum variables to normalize the EN1 indicator. The same pattern is repeated for the rest of the indicators.

Table 4. Neighborhood sustainability score (NSS_{EW} and NSS_{AHP}) for Montreal boroughs

Borough	Index	Population	Area (km)	NSS_{EW}	NSS_{AHP}
Ahuntsic-Cartierville	N1	138923	24.2	0.37	0.36
Anjou	N2	45288	13.7	0.36	0.33
Côte-des-Neiges-Notre-Dame-de-Grâce	N3	173729	21.4	0.27	0.26
L'Île-Bizard-Sainte-Geneviève	N4	46971	17.7	0.43	0.46
LaSalle	N5	110329	8.1	0.34	0.34
Lachine	N6	82933	16.3	0.44	0.37
Le Plateau-Mont-Royal	N7	86347	15.7	0.51	0.45
Le Sud-Ouest	N8	19857	23.7	0.46	0.44
Mercier-Hochelaga-Maisonneuve	N9	142753	25.4	0.26	0.30
Montréal-Nord	N10	86857	11.1	0.43	0.32
Outremont	N11	26505	3.9	0.41	0.41
Pierrefonds-Roxboro	N12	73194	27.1	0.35	0.38
Rivière-des-Prairies-Pointe-aux-Trembles	N13	113868	42.3	0.37	0.38
Rosemont-La Petite-Patrie	N14	146501	15.9	0.30	0.31
Saint-Laurent	N15	104366	42.8	0.33	0.31
Saint-Léonard	N16	80983	42.8	0.30	0.25
Verdun	N17	72820	9.7	0.61	0.62
Ville-Marie	N18	103017	16.5	0.32	0.26
Villeray-Saint-Michel-Parc-Extension	N19	144814	16.5	0.28	0.29

The selected neighborhood social indicators are population density (SO1) and availability of basic services (SO2). The normalized population density value states the population in a square meter unit in each borough (**Figure 4**) based on data from Statistics Canada **[60]**. The considered amenities in indicator SO2 are service points and cultural and community centers. SO2 measures the number of amenities per capita in nineteen boroughs of Montreal. Results are depicted in **Figure 4**.

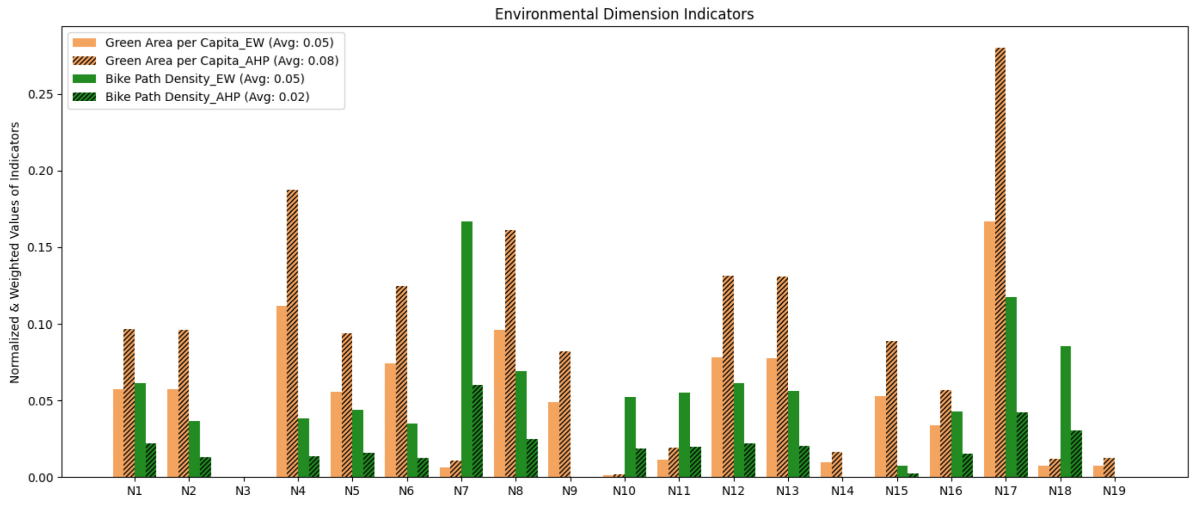

Figure 4. Normalized and weighted values for environmental dimension indicators in Montreal boroughs

Mean household income (EC1) measures the average income of the households in boroughs based on the ranges of incomes. According to the data source, the information is collected by survey and includes ranges of values, from 20000 USD to 100000 USD yearly income for year 2016 [64]. Therefore, the normalization of this indicator is calculated based on the minimum and maximum values of 20000 USD to 100000 USD, accordingly. The second economic indicator is households in core housing needs (EC2), which measures housing affordability, availability and adequacy [65]. The EC2 is the number of households in core housing needs over the total number of households in the Montreal neighborhood. The results of these indicators are shown in **Figure 5**.

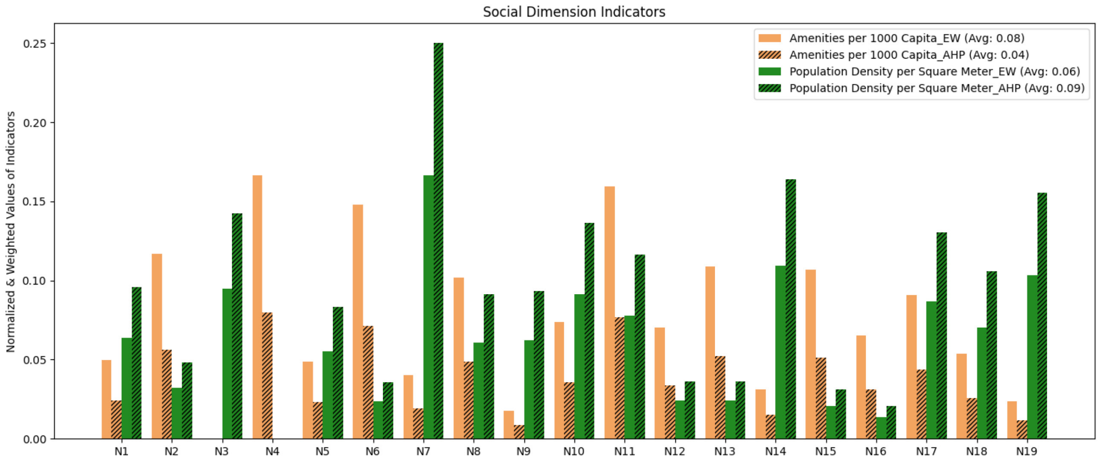

Figure 5. Normalized and weighted values for social dimension indicators in Montreal boroughs

The NSS was calculated after normalizing the indicators' values and based on the defined weights (**Table 3**). The Results of each sustainability dimension for EW and AHP methods are presented in **Figure 3** to **5**, and the neighborhoods' overall scores are shown in the maps in **Figure 6**. The value ranges of the maps are based on the normalized and weighted indicators; green shows the neighborhoods with the highest sustainability condition, whereas red represents boroughs with the poorest sustainability.

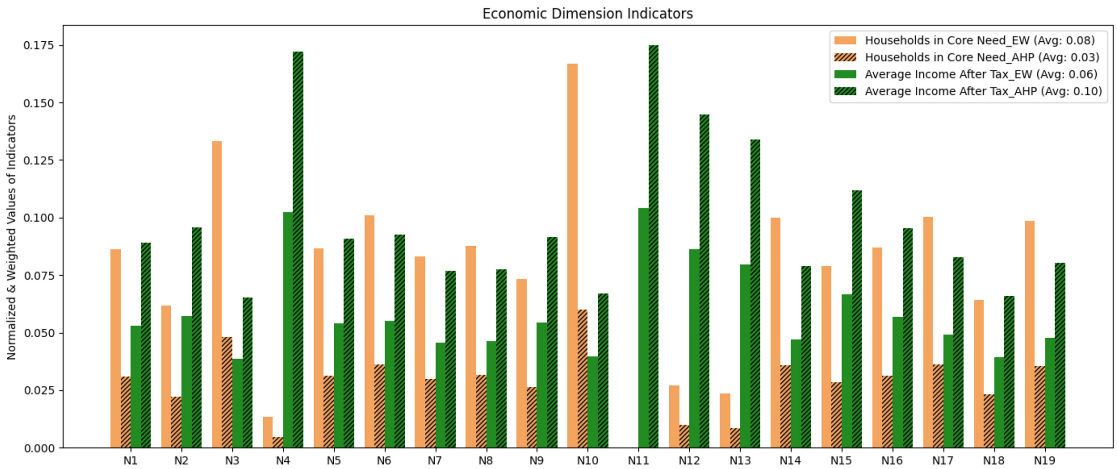

Figure 6. Normalized and weighted values for economic dimension indicators in Montreal boroughs

In the AHP method in environmental sustainability, more weight is given to EN1. Therefore, green area per capita has a higher impact on NSS. For example, N4 and N17 stand out more in the AHP method due to their larger green areas. This demonstrates that the AHP method considers the importance of the presence of green spaces, which results in more environmentally sustainable boroughs. In the EW method, the average value of EN1 and EN2 are equal, whereas in the AHP method, EN1's average is increased by 0.3, and EN2's average is decreased by 0.3.

In the social dimension with EW, SO2 has a higher average than SO1. It has been pointed out in the literature that higher population density contributes to the enhancement of sustainability. Therefore, in the results of the AHP method, the contribution of SO1 in increasing the borough's sustainability is visible. The same story applies to economic sustainability, where the AHP method highlights the importance of household income.

Maps of NSSEW and NSSAHP across Montreal boroughs are presented in **Figure 6**. In both methods, N17 has the highest performance, suggesting acceptable performance of all the indicators. N11 shows a consistently low score in both methods, indicating widespread sustainability challenges across multiple indicators. N4 has moderate performance in the EW method while performing better in the AHP method due to its high average income and green space availability. Boroughs with low sustainability performances, i.e. N3 and N9, could adopt strategies, for example, adding parks and green spaces for public use, expanding the available amenities, providing adequate and affordable housing, and expanding bike lines to improve overall sustainability.

The charts in **Figure 7** and **Figure 8** present the share of each sustainability dimension in the NSSEW and NSSAHP, respectively. In both cases, N17 has the highest score and a similar dimensions distribution. The main contributing dimension is environmental sustainability due to the large amount of green spaces and availability of bike lanes. The EW method assigns equal importance to indicators which results in a balanced distribution across the boroughs.

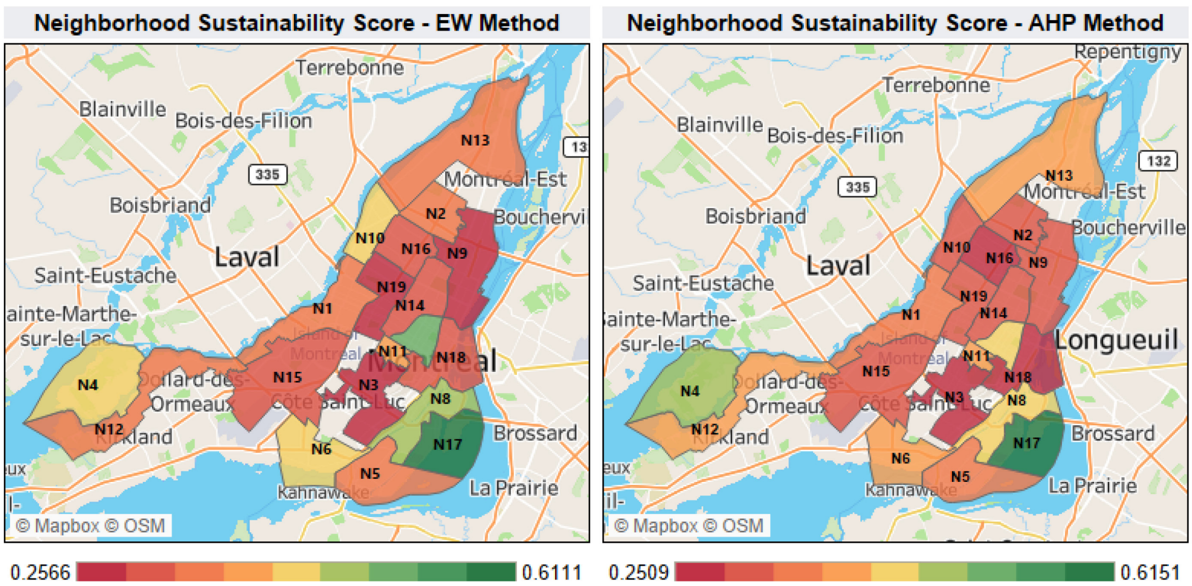

Figure 7. Map of Neighborhood Sustainability Score (NSS) in Montreal boroughs measured by EW and AHP methods

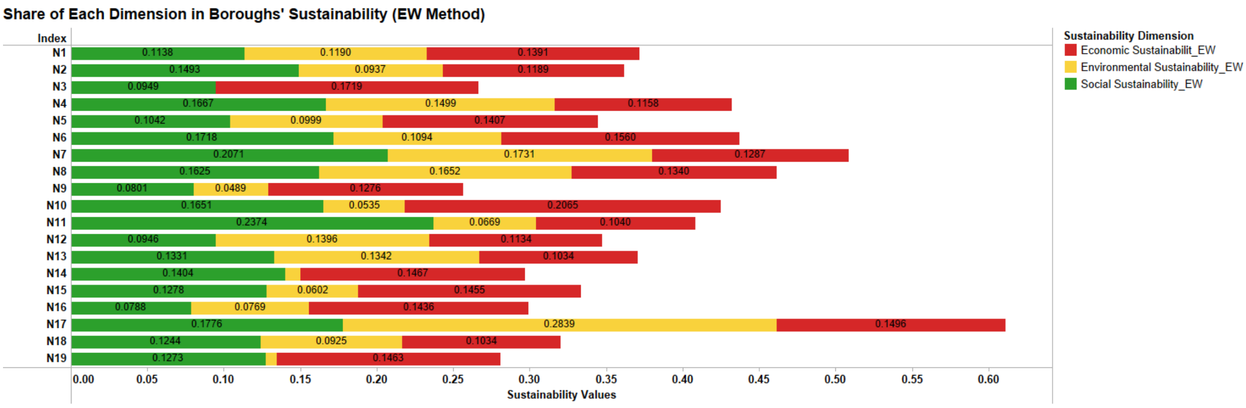

Figure 8. Share of sustainability dimensions in total sustainability of boroughs (EW method)

Clustering results

DBI has been computed for different *k* values to determine the optimal number of clusters. There are nineteen boroughs to be clustered; therefore, $2 < k < 5$ was examined, k=3 is the optimal number of clusters. 19 boroughs have been clustered based on the population, area, NSSEW and NSSAHP features. Normalized plots are presented in **Figure 9**.

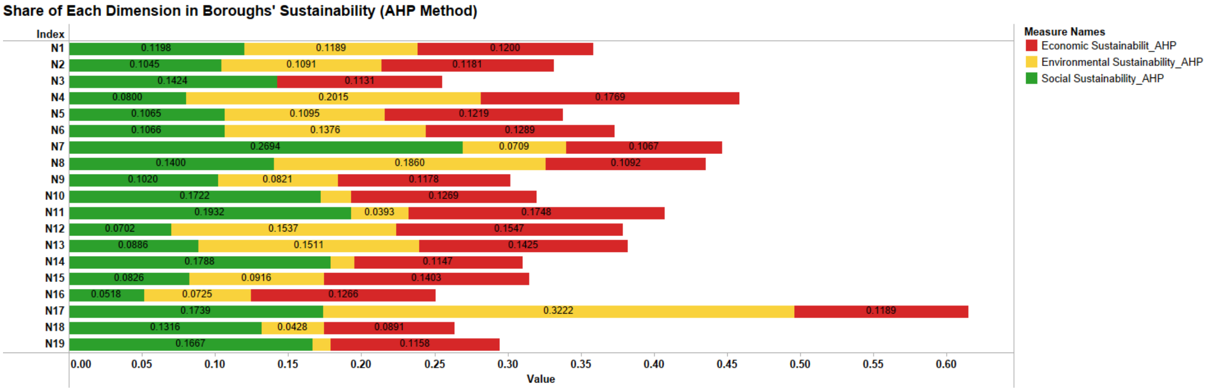

Figure 9. Share of sustainability dimensions in total sustainability of boroughs (AHP method)

Density plots, which are presented diagonally, show the distribution of clusters for each feature. Pairwise comparison of clusters for features population versus NSSEW and population versus NSSAHP shows similar patterns. Population-dense boroughs, cluster one, have the lowest overall score than the less populated areas (cluster 0). Plots presenting area versus NSSEW and NSSAHP follow a pattern similar to that of the population. The trend between the population and area with the overall score (either EW or AHP) depicts a negative correlation.

Plots representing NSSEW versus NSSAHP show that N17 has an exceptionally good performance in both methods. Cluster two has a moderate performance, and cluster one has the lowest. A strategy to improve sustainability across the city is working on cluster one. This could be achieved by incorporating more green space (EN1) and improving access to basic services (SO2). The boroughs in cluster two could benefit from potential economic programs, such as local employment initiatives, to improve income levels.

Visualization tool development

To show the capabilities of this study, a web-based decision support tool was developed. The GeoJSON file of each of the nineteen boroughs was created. The tool integrates GeoJSON data for the borough boundaries and merges it with the sustainability score data to create a visual representation of the spatial distribution of sustainability across the city. The interactive map provides an interface for decision-makers to visualize, analyze, and gain insight into the sustainability of boroughs in Montreal. The tool is developed based on the steps illustrated in **Figure 3**. It presents NSS and other metrics in an interactive format that allows users to explore the data for each borough in detail.

As presented in **Figure 10**, the main part of the tool is the interactive map that displays the boundaries and NSS of the boroughs. The map is colour-coded to reflect the sustainability score. The scores are reflected by colours ranging from red (lowest score) to green (highest score). Users can select a borough on the map and access the information specific to the borough. For the selected borough in **Figure 10**, a window is popped up that contains information about the borough, including name, NSS, population, area and a histogram showing the distribution of the buildings. Buildings are categorized as office, residential, commercial and other groups. Another way to select a borough is using the left side panel. Selecting a borough from the drop-down list at the panel's top will highlight the borough on the map and illustrate various information. As shown in **Figure 10**. Ville Marie is selected from the drop-down list and is highlighted in the map. On the panel, metrics, including a gauge representing the NSS, population, area, social, economic and environmental scores, are presented. This information helps the user understand the borough's performance. All the information is normalized within the minimum and maximum ranges of the boroughs. The distribution of the building functions is also presented. Categories include residential, commercial, office, and others. The analysis in Figure 10 is based on the EW method. The weights are customizable, and other approaches, e.g. AHP, could be deployed.

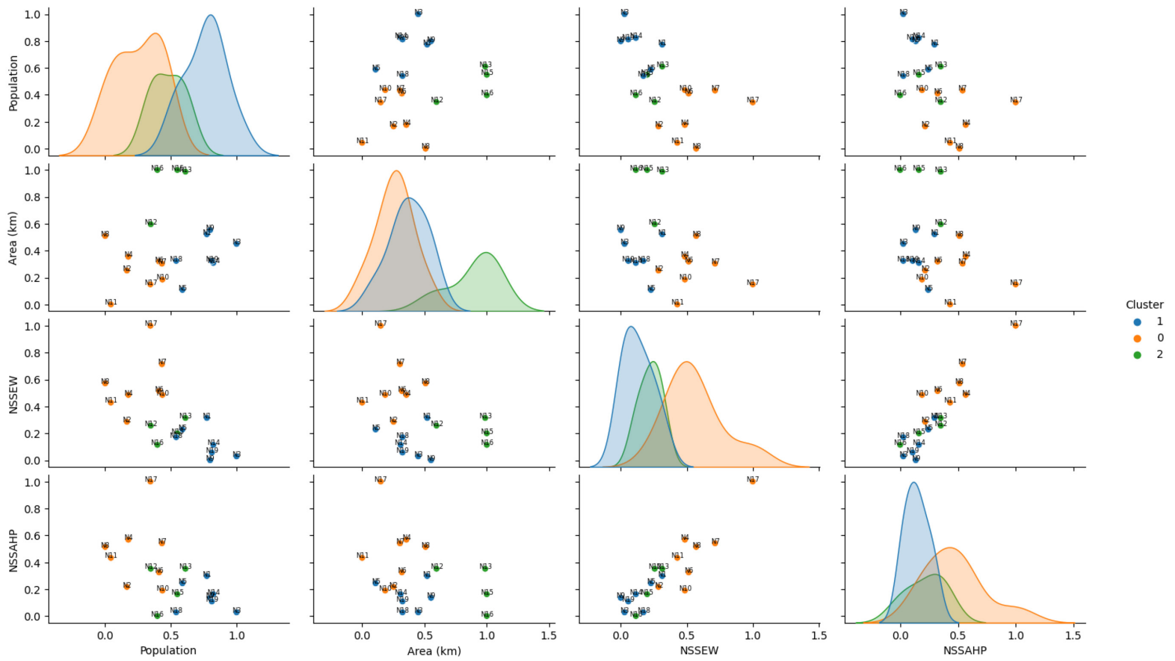

Figure 10. Clustering boroughs based on population, area, NSSEW and NSSAHP features

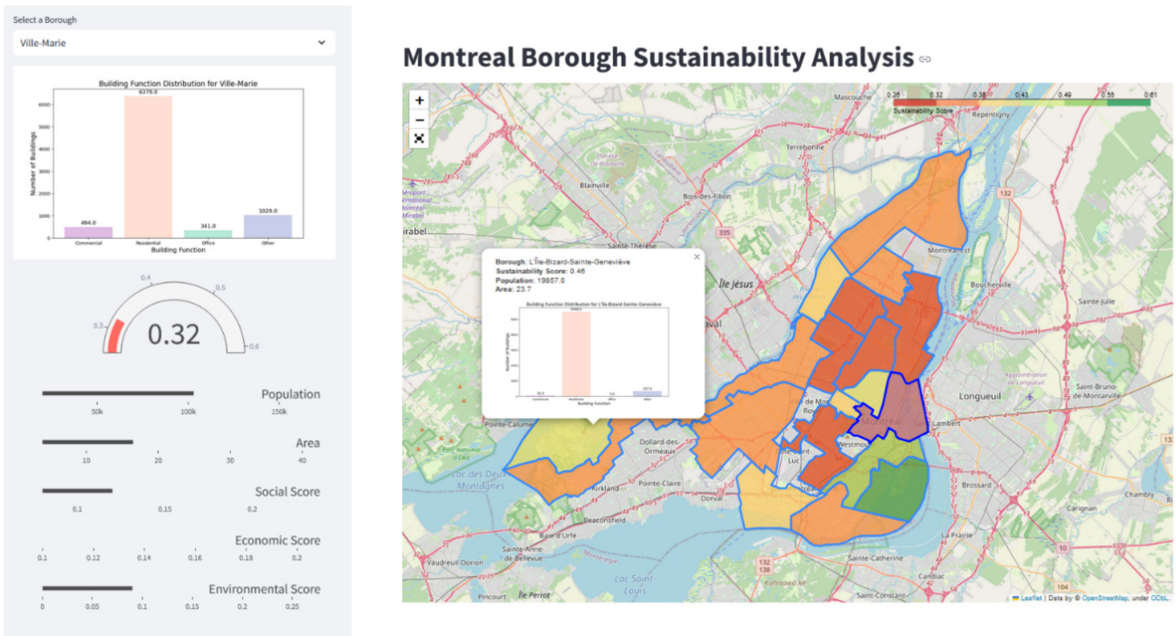

Figure 11. Web-based sustainability decision support tool

The practicality of the assessment method is illustrated by developing the visualization tool. Policymakers could interact with it and gain a deeper understanding of the current performance of the boroughs. Tapsuwan *et al.* identified the significance of stakeholder engagement in effective and targeted decision-making [66]. In [25], [38] authors have used indicators to measure neighborhood sustainability; however, the lack of interactive communication between the research and the policymakers exists.

Due to the limited data available, a selection of indicators has been used for the assessment of Montreal. However, two indicators in each dimension have been recognized, and because of the equal distribution of the indicators, the current selection is representative of the city's behaviour.

CONCLUSIONS

Sustainable development in urban areas is the core objective of SDG 11, which aims to make cities and human settlements inclusive, safe, resilient and sustainable. Benchmarking the current state is crucial to measure the progress toward sustainability goals. Cities are complex systems with various interconnections and dependencies. As a subset of the city, neighborhoods are potential units to investigate social, economic and environmental sustainability.

This work overviews the neighborhood sustainability assessment tools and discusses their limitations. It introduces a methodological approach to neighborhood sustainability assessment by studying key sustainability frameworks: SDG 11, City Prosperity Index, and New Urban Agenda. To assess the impact of different prioritization strategies, two weighting approaches have been suggested to demonstrate how indicator weighting influences results.

A key contribution of this research is the development of a data-driven visualization tool that enables decision-makers to interact with the sustainability assessment results and gain a better understanding of neighborhood sustainability performance. The City of Montreal has been chosen as the case study to demonstrate the method's applicability. Montreal has nineteen boroughs with different socio-economic conditions. The Neighborhood Sustainability Score (NSS) of boroughs is measured Followed by a clustering analysis to categorize boroughs based on their performance.

Results indicate the neighborhoods' sustainability performance in terms of their sustainability score. Findings reveal that borough N17 had the highest score due to the vast green spaces and accessible amenities. On the other hand, boroughs N3 and N9 represent a cluster of boroughs with low performance, highlighting the need for investment and improvement in different aspects, such as increasing green and public spaces. The results can help the decision-makers set strategic goals, address the existing challenges, and implement targeted actions to improve neighborhood sustainability. The visualization tool illustrates key sustainability results and features, for instance, the NSS, population, area, and the distribution of the buildings in Montreal boroughs.

Accurate and reliable data is the vital element of this type of assessment. While the proposed framework was implemented using the available data for certain indicators, the data gap for other indicators (e.g., access to hospitals and other points of interest, air quality, etc.) exists. The updated data sources contribute to reflecting the true status of the neighborhoods. However, in some cases, for example data income, and population census, the most recent data belongs to 2016 and 2021, respectively. Upon the availability of newer versions of data sources in the future, repeating the analysis with the most recent data can improve the analysis accuracy. The authors acknowledge that additional aspects need to be considered to gain a better understanding and enhance the robustness of sustainability assessment. This study presents an ongoing effort, and future research will focus on developing more comprehensive models that incorporate a broader range of sustainability aspects.

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Paper submitted: 20.11.2024
Paper revised: 27.02.2025
Paper accepted: 02.03.2025