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Elements and Indicators of Urban Form: A Meta-Synthesis Study

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Abstract

Various approaches have been adopted to urban form and many elements and indicators have been proposed on spatial scales. However, a comprehensive scale-based study of urban form is lacking. This study seeks to identify the elements and indicators of urban form on different spatial scales. The current study is a meta-synthesis based on a systematic review. A search for the keywords in information databases resulted in 12104 studies, which were reduced to 18 after being screened by means of elimination criteria and quality evaluation. Qualitative content analysis was used for the analysis of the results. Thus, 89 codes (indicators) were extracted and classified into 14 concepts (sub-elements) and 5 categories (main-elements) in terms of 3 scales of city and metropolitan area, neighborhoods and urban blocks. Using Shannon entropy method, the significant coefficient of the indicators was determined and the elements of urban form were ranked. Based on findings, the most important sub-elements on the macro-scale are land use mix, density distribution and type of density. In addition, land use mix, street network and type of density have the highest rank on the meso-scale and street design is placed at the first grade on the micro-scale. According to the rank of sub-elements, land use and density are the most important elements of urban form.

***Keywords*:** Meta-synthesis; Systematic review; Shannon entropy; Elements of urban form; Indicators

1. Introduction

There are multiple definitions for urban form, which cannot be easily integrated into a single definition. This is due to the complicated nature of urban form and its connection with various economic, social, cultural, and environmental issues entailing various approaches, definitions, and frameworks (Conzen, 1960; Lynch, 1981; Kropf, 2009; 2017; Conzen, 2001). In the comprehensive study of the multidisciplinary approach to urban form, Clifton et al. (2008) recognized five main fields including landscape ecology, economic structure, transportation planning, community design, and urban design. This classification incorporates different hierarchies and spatial scales from regional and metropolitan to urban blocks and buildings.

Urban form has been studied from the perspective of different geographical scales (Tsai, 2005). In fact, urban form is closely related to scale and it has been described as the morphological features of an urban area on all scales (Williams and Shiels, 2000). These features range from local-scale characteristics such as facades and details of buildings to large-scale features such as spatial design of streets (Dempsey et al., 2010), which have been mentioned in various studies.

Urban form is dependent on many factors such as location and topography, demographic and economic development, and planning efforts in the past (Schwarz, 2010). It is the response of human society to specific circumstances in specific places (Kropf, 2017). In other words, urban form is the spatial pattern of human activities in a specific place (Tsai, 2005) and includes whatever made, modified, preserved, or maintained by humans (Bartuska & McClure, 2011).

Various elements and indicators have been proposed for urban form in the literature. These elements are measured either independently or as a combinationes of indicators and coefficients, with a variety of methods, and on different spatial scales (Tsai, 2005). For example, Galster et al (2001) suggested density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity as the main features of urban form and tried to quantify this concept. Song and Knaap (2004, 2007) mentioned street design, density, land use mix, accessibility, pedestrian access, transportation and natural environment as the elements of urban form in neighborhoods and suggested 21 indicators. In another study, street network design (internal and external connectivity), land use mix and density (Commercial and Residential) were proposed as the elements and indicators of urban form (Nedovic-Budic et al., 2016).

Some other researchers have adopted a more comprehensive approach to these elements and indicators. For instance, Schwarz (2010) investigated urban form in European cities and proposed 41 indicators on the city scale drawing on the landscape ecology and economic perspectives. Another instance is the approach of Clifton

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et al (2008) who analyzed urban form into five classes. The majority of these studies, however, either are limited to one scale of urban form or do not offer indicators.
To sum up, elements and indicators of urban form have been carefully researched, but there is no comprehensive, scale-based study that classifies these elements and indicators. The present study is a meta-synthesis of the previous studies of the elements and indicators of urban form through a systematic review. The purposes of study are to identify the elements and indicators of urban form on different spatial scales. The scale-based approach helps to understand the elements and their relationships within a scale-based hierarchy better.

2. Method

This study, first using a meta-synthesis method, the elements and indicators of the urban form are identified and then to determine the significant coefficient of the indicators and ranking of elements using Shannon entropy method.
Meta-synthesis is the process of searching, evaluating, interpreting, and synthesizing previous studies in a specific field that helps to gain a more in-depth understanding of a topic (Zimmer, 2006; Walsh & Downe, 2005). Meta-synthesis is beyond a summary of research findings and helps to make an integrated, comprehensive and new interpretation of findings (Sandelowski et al., 1997). Meta-synthesis of qualitative studies is a technique, which is parallel to the meta-analysis of quantitative studies. Like meta-analysis, meta-synthesis is based on the systematic review (Walsh & Downe, 2005). Sandelowski and Barroso (2007) proposed a seven-step method to synthesize qualitative studies, which is used in this study. The steps for this method are shown in Figure 1.

2.1. Setting the research question

Main research questions are as follows:
1) What are the indicators of urban form on different spatial scales?
2) What are the elements of urban form?
3) Which elements and indicators are the most important ones?

2.2. Systematic literature review

The systematic review was carried out using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Liberati et al., 2009).
The statistic sample of the study includes all the studies of the elements and indicators of urban form that were conducted up to November 2018 and published in English. The two databases used were 'Web of Science' and 'Scopus'.
The search keywords were divided into two groups. The first group included 'city', 'city form', 'urban morphology', 'morphology', and 'urban form'. The second group included 'aspect', 'component', 'dimension', 'analyze', 'analysis', 'element', 'quantitative', 'quantify', 'assess', 'objective', 'indicate', 'evaluate', 'operation', 'operational', 'indicator', 'index', 'evaluation', 'metrics', 'measuring', 'measure', and 'principle'. Similar keywords relating to a group of words were linked with 'OR' and two groups were linked with 'AND'.

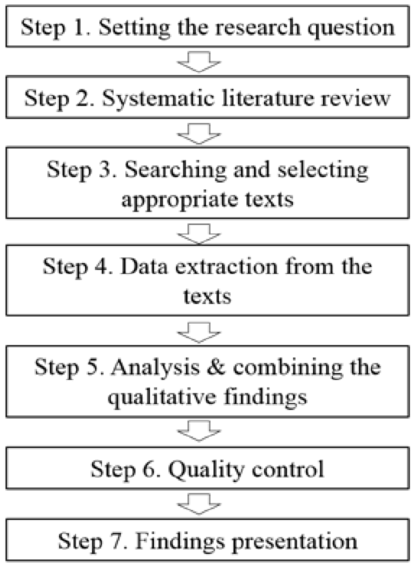

Fig. 1. Steps in conducting the meta-synthesis method (Sandelowski and Barroso, 2007)

2.3. Searching and selecting the appropriate texts

In the first step, information databases were searched for the elements and indicators of urban form. The purpose of this step was twofold: first, to ensure that no similar study had been previously conducted and, second, appropriate keywords had been selected for the search.
In the next step, the keywords were used to perform a comprehensive and systematic search in the studies published before November 2018. The search was performed on the title, abstract, and keywords of all the sources up to November 2018. The search identified 12089 records with an additional 15 records identified from other sources. After removing duplicates, 9988 records remained. Next, the title, abstract, and full text of the studies were surveyed and screened according to criteria, thereby resulting in some 20 relevant studies. Critical Appraisal Skills Programme (CASP) method was used to evaluate the quality of the studies. CASP Systematic Review Checklist contained 10 questions to provide a better perspective of the qualitative meta-synthesis and to evaluate the accuracy, validity and importance of each study. In order to evaluate the studies, each question was scored quantitatively and then, the study's total score was summed. Finally, any study with a total score of less than 30 was removed from the analysis based on a 50-option Rubik scale. Each question was assigned 0-5 points, therefore, the CASP score range was 0 to 50 points including 0–10 (weak), 11–20 (medium), 21–30 (good), 31–40 (very good) and 41–50 (excellent) (Finfgeld-Connett, 2018). Thus, after quality evaluation of these 20 studies by CASP method, two of

them were removed and 18 studies remained for meta-synthesis. The steps of this systematic review are displayed in Figure 2.

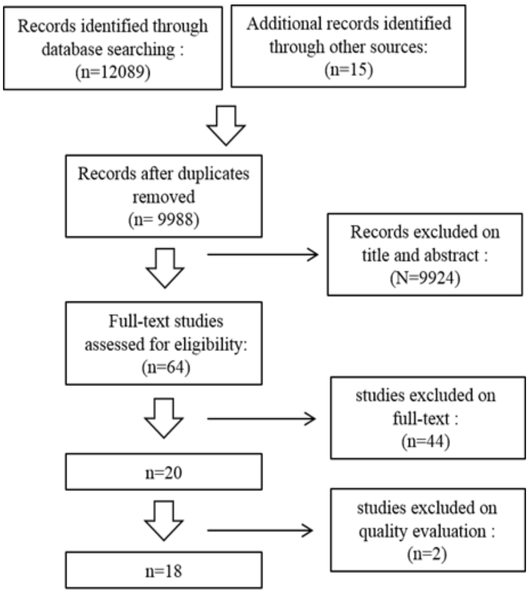

Fig. 2. Flow chart for access to relevant papers

Exclusion criteria for studies are as follows:

- Studies that did not propose the elements and indicators for urban form;
- Studies that proposed only a few general indicators for urban form;
- Studies that limited urban form to a specific geographical area and had not generalized their criteria;
- Studies that dealt with urban form in terms of a specific aspect (e.g. the issue of energy or transportation system);

Given the overlap of the issue of urban form and urban sprawl as well as compactness, many studies, which had dealt with urban form in terms of sprawl and compactness, were included. Studies that had specifically addressed urban sprawl without considering the concept of urban form were excluded from the list.

2.4. Data extraction from the texts

The results extracted from the studies were classified by their characteristics (paper title and author, year of publication, etc.), Research Objectives and methodology. The scales of urban form in the studies varied from the building to metropolitan that were divided into three groups: the scale of city and metropolitan area (macro-scale), the scale of neighborhood (meso-scale), and the scale of urban block and building (micro-scale). Three studies addressed urban form on different spatial scales (Yamagata & Sharifi, 2018; Clifton et al., 2018; Zeng, 2014) and one study proposed elements for urban form in general (Seto et al., 2014). Overall, 3 studies were on the micro-scale, 10 on the meso-scale, and 12 on the macro-scale. Table 1 shows a Features of included studies.

Table 1
Features of included studies

Study Number	Author(s)	Year of Publication	Publisher	Urban Form Spatial Scale
(1)	Clifton et al	2008	Journal of Urbanism	Macro, Meso & Micro-Scale
(2)	Dempsey et al	2010	springer	Meso-Scale
(3)	Ewing et al	2002	Smart Growth America	Macro-Scale
(4)	Frenkel & Ashkenazi	2008	Environment and Planning B: Planning and Design	Macro-Scale
(5)	Galster et al	2001	Housing Policy Debate	Macro-Scale
(6)	Hamidi & Ewing	2014	Landscape and Urban Planning	Macro-Scale
(7)	Huang, et al	2007	Landscape and Urban Planning	Macro-Scale
(8)	Kotharkar et al	2014	Sustainability	Macro-Scale
(9)	Lowrya & Lowry	2014	Computers, Environment and Urban Systems	Meso-Scale
(10)	Nedovic et al	2016	Cities	Meso-Scale
(11)	Schwarz	2010	Landscape and Urban Planning	Macro-Scale
(12)	Seto et al	2014	Cambridge University Press	Macro, Meso & Micro-Scale
(13)	Sharifi & Yamagata	2018	Springer	Macro, Meso & Micro-Scale
(14)	Song & Knaap	2004	Journal of the American Planning Association	Meso-Scale
(15)	Song & Knaap	2007	Journal of Urban Design	Meso-Scale
(16)	Song et al	2013	Landscape and Urban Planning	Meso-Scale
(17)	Tsai	2005	Urban Studies	Macro-Scale
(18)	Zeng et al	2014	sustainability	Macro, Meso-Scale

2.5. Analysis & combining the qualitative findings

Qualitative content analysis was used to analyze the studies. To this end, the full text of the studies was examined and the indicators of urban form, which had been implicitly or explicitly mentioned in the studies, were extracted. The obtained indicators were considered as a code. MAXQDA software package was used for extracting codes. Then codes were classified into concepts (sub-elements) based on their similarity of their concepts and the concepts were categorized under the category (main-elements). Thus, analysis and synthesis of the studies resulted in a list of 5 main elements, 14 sub-elements, and 89 indicators of urban form.

Based on the analysis, the main-elements (category) included 'density', 'land use', 'connectivity', 'configuration', and 'Design'. The sub-elements (concepts) on three different scales included 'types of density', 'density distribution', 'type of building', 'land use mix', 'access to uses', 'street network', 'transportation infrastructure', 'complexity', 'clustering degree', 'centrality and nuclearity', 'compactness', 'building design, 'design of urban blocks and plots', and 'street design'. The mathematic formulas related to the indicators can be found in the appendix. The final codes relating to each category and concept are shown in Tables 2, 3 and 4.

2.5.1. Elements and indicators of urban form on the macro-scale

The macro-scale of urban form is related to the overall structure of the city, major metropolitan areas, and their connection to each other. The majority of studies conducted on this scale have addressed urban forms in terms of urban sprawl. There is considerable diversity in the indicators of urban form on this scale. 44 codes (indicators) were extracted and classified into 10 concepts (sub-elements) and 4 categories on the macro-scale, as shown in Table 2.

Density: Density is a complicated notion that is related to all other elements. It has both subjective and objective aspects. In objective physical terms, density refers to the number of people, buildings, and workers based on the unit of area whereas subjective density refers to how it is perceived by people, which varies among different individuals and communities (Dempsey et al, 2010; Nedovic-Budic et al., 2016). In this study, we only consider objective density.

- Types of Density: There are different types of density and various methods can be used for measuring it (Burton, 2000). The three main types include the number of people per unit of area, the area of built land, and the number of employment.
- Density Distribution (Distribution of Population and Jobs): On the macro-scale, distribution of density is important in addition to the type of density. Distribution of population and jobs in urban areas may be equal or unequal (i.e. concentrated in some areas). The indicators of this sub-element include Gini coefficient (measures the population distribution in different regions), Delta index, Shannon's entropy, variations coefficient, Profile and gradient of density (ratio of density in central areas to density in suburbs), and the percentage of population in low-density areas and areas with medium-to-high density.

Land Use

- Land use Mix: On the macro-scale, land use mix refers to the proximity of residential areas to commercial and administrative areas. Separation of land uses is a feature of urban sprawl. In cities with low land use mix, residential development is far away from commercial centers, which may lead to prolonged daily trips and increased dependence on private transportation (Seto et al., 2014; Galster et al., 2001). The indicators include the balance and proportion of jobs to residents, the entropy of mixing degree of jobs (indicates various jobs such as those related to health care, recreation, sports, etc.), the percentage of residential use and its ratio to non-residential uses, the ratio of built spaces to open spaces, the percentage of transportation-related area, recreational area, tourist area, commercial area, industrial area, and area built for special use.
- Access to uses: Accessibility specifies the ease of reaching places, spaces, and buildings (Dempsey et al., 2010). Access to uses on the macro-scale, which has also been referred to as proximity, denotes the spatial distribution of services, facilities, and open spaces over the city as well as how and in what time they can be accessed (Clifton et al., 2008). The indicators are distance and time to arrive at public transportation stations, and the distance and time to arrive at one's workplace.

Connectivity

- Transportation Infrastructure: Transportation network is the backbone of a city and transportation-related factors play a vital role in the creation of urban form. The historical evolution of spatial configuration in a city is strongly influenced by its transportation system (Yamagata & Sharifi, 2018). Increased connections and facilitation of transportation is important for reducing the use of motor vehicles, particularly private cars, and promoting walking (Kotharkar et al., 2014). The main indicators include pedestrian paths and their related facilities within main corridors, highways, railways, and aviation index, and proportion of using various types of transportation systems.
- Street Network: Connectivity depends on the design of street network. The proportion, number, and density of intersections in urban roads determine connectivity in the street network. Urban roads have two functions, i.e. access and transfer. In a hierarchical system, local roads and collector roads are designed to provide the higher degree of access to the destination. However, they have relatively low capacity for managing the speed and volume of traffic. In contrast, arterial highways and main roads have high traffic capacity but low access to local destinations. Highways are at the top of the roads hierarchy, with highest traffic capacity and highest speed limit (Clifton et al., 2008). Road network congestion index and road network density are two indicators for street network. Density of street network (total length of road per hectare) shows the degree of the penetration of transportation network into the residential areas as well as

their accessibility whereas congestion is indicative of the speed and duration of trips (Kotharkar et al., 2014). Other indicators include roads hierarchy, the number and proportion of intersections, and the length and size of urban blocks.

Table 2
The main-elements (category), sub-elements (concepts), and indicators (Codes) of urban form on the macro-scale

Main Elements (Category)	Sub-Elements (Concepts)	Indicators (Codes)	Refrences (According to Table 1)
Density	Type of Density	Population density	(1), (3), (4), (5), (6), (7), (8), (11), (12), (13), (17), (18)
		Built-up area density	
		Employment density	
	Density Distribution (Distribution of population and jobs)	Profile and gradient of density	(1), (3), (5), (6), (7), (8), (11), (13), (17), (18)
		Percentage of population in low-density area	
		Percentage of population in areas with medium-to-high density	
		Coefficient of variation	
		Gini coefficient	
		Delta Index	
		Shannon's entropy	
Land use	Land use Mix	Balance and proportion of jobs to residents	(1), (3), (4), (5), (6), (8), (11), (12), (13), (18)
		Degree of job mixing (entropy)	
		Percentage of residential use and its ratio to non-residential uses	
		Ratio of built-up area to open space	
		Percentage of transportation-related area; Recreational, tourist, commercial and industrial area and area built for special use	
	Access to uses	Distance and time to arrive at public transportation stations	(1), (5), (8), (11), (12), (18)
		Distance and time to arrive at workplace	
Connectivity	Street Network	Ratio of Roads Hierarchy	(1), (3), (6), (8), (13)
		Road network density	
		Road network congestion index	
		Number, density and ratio of intersections	
		Length and dimention of blocks	
	Transportation Infrastructure	Pedestrian paths and their related amenities within main corridors	(1), (3), (4), (6), (8), (11), (12), (18)
		Highways, railways and aviation index	
		Proportion of using various types of transportation systems.	
Urban Configuration	Complexity	Area weighted mean patch fractal dimension	(4), (7), (18), (11)
		Shape index	
		Mean patch edge and edge density	
		Fractal dimension	
		Sum of perimeters of all sealed urban patches	
		Area weighted mean shape index	
	Degree of Clustering	Moran coefficient	(5), (6), (11), (13), (17), (18)
		Geary coefficient	
		Clustering index	
	Centrality and Nuclearity	Distance of uses and population from the central business districts	(1), (3), (4), (5), (6), (7), (8), (11), (12), (13), (17), (18)
		Population and employment density in urban centers	
		Centrality index	
		Number of urban nuclei and centers	
	Compactness (Dispersion)	Compactness index	(4), (5), (7), (11), (13), (17)
		Compactness index of the largest patch	
		Contagion index	
		Mean patch size and Number of patches	
		Gross leapfrog index and Net leapfrog index	
		Index of continuity of developable land with urban areas	

Urban Configuration

Urban configuration, which has the broadest sense among the elements of urban form on this scale, is concerned with the spatial geometry of urban form. Degree of clustering, centrality and nuclearity, complexity, and compactness are the indicators of urban configuration.

- Degree of Clustering: This index represents the distribution of density in urban areas in a clustered or scattered form and estimates the degree to which high-density sub-areas are clustered or randomly distributed (Galster et al., 2001; Tsai, 2005). Moran and Geary coefficients are indicators for measuring the degree of clustering.

- Centrality and Nuclearity: An urban center is a place where commercial uses and activities are concentrated in a way that pedestrian-orientedness and multipurpose trips are promoted. Lack of centrality will lead to longer trip times and dependence upon private cars due to greater distance between uses. Cities are either monocentric or polycentric. Being monocentric (mononuclear) is indicative of high concentration of activities and functions in a spot that can be accessed through certain paths. On the other hand, a polycentric pattern means that activities and functions are distributed over several centers (Galster et al., 2001; Sharifi, 2019). The indicators include the distance of uses and population from the central business districts, population and employment density in urban centers, centrality index, and the number of urban nuclei and centers.
- Complexity: It refers to lack of order and complexity on the borders of the city and land patches. The indicators of complexity include area weighted mean shape index (AWMSI, indicates the regularity of the patches), area weighted mean patch fractal dimension (AWMPFD, indicates the raggedness of the urban boundary), shape index, fractal dimension, mean patch edge (the average complexity of land patches), edge density (the ratio of the sum of urban edges to the area of urban land), and sum of perimeters of all sealed urban patches.
- Compactness: Compactness or Dispersion is here considered as a sub-element that refers to the shape of urban lands and their surrounding patches. Urban sprawl is an urban form that is related to all its elements and includes a set of features. Mean patch size, number of patches, compactness index, and compactness of the largest patch are the indicators. Other indicators include continuity of developable land with urban areas, net leapfrog index (measures the residential use fragmentation), gross leapfrog index (measures the built areas which are separate and distant from the central area), and contagion index (describes fragmentation of a landscape by the probability of a patch type being adjacent to another patch type).

2.5.2. Elements and indicators of urban form on the meso-scale

The meso-scale of urban form is concerned with the structure of neighborhoods and districts. On this scale, a zone buffer is specified around the area under study and the elements of urban form are studied within this buffer because the residents who live on the edges of the area tend to use services and facilities in their proximity that are located outside the area. 29 codes (indicators) were extracted and classified into 9 concepts (sub-elements) and 4 categories on the meso-scale, as shown in Table 3.

Density

- Types of Density: There are wide variety indicators to create a clear image of density on this scale. The indicators of density are concerned with gross and net density. Gross density refers to the number of people, households, or dwelling units per unit of area whereas net density denotes the same number only when applied to areas with residential uses (Dempsey et al., 2010). In addition, the average size of residential plots is also an indicator of density.
- Building Type: Type of housing (terraced housing, apartments, detached housing, semi- detached housing, etc.), coverage ratio (ratio of building footprint to site area), and floor area ratio are the indicators of this sub-element.

Land Use

- Land use Mix: Land use mix on this scale refers to the existence of land uses, services, and local facilities for the residents, which depends on the needs of the local population. Land use mix in residential areas could promote walking and cycling while lack of it could result in increased duration of trips and dependence of residents on private cars (Seto et al., 2014; Burton, 2002; Knaap & Song, 2004). Land use mix can be measured using the area of different uses such as residential, commercial, retail, administrative, industrial, recreational, abandoned and undeveloped land. Other indicators include Shannon and Simpson's Diversity Index (measures the distribution of different uses over the area), the ratio of tenants to owners, the ratio of different uses to residential units, the size, design and distribution pattern of open spaces and green spaces, and mixed vertical uses (buildings with several uses).

Table 3
The main-elements (category), sub-elements (concepts), and indicators (Codes) of urban form on the meso-scale

Main Elements (Category)	Sub-Elements (Concepts)	Indicators (Codes)	Refrences (According to Table 1)
Density	Type of Density	Gross Density	(1), (2), (9), (10), (12), (14), (15), (16), (18)
		Net Residential Density	
		Average size of residential plots	
	Building Type	Coverage ratio	(2), (12)
		Floor area ratio	
		Type of housing	
Land Use	Land use Mix	Mixed vertical uses	(1), (2), (9), (10), (12), (13), (14), (15), (16), (18)
		Ratio of tenants to owners	
		Ratio of different uses to residential units	

Main Elements (Category)	Sub-Elements (Concepts)	Indicators (Codes)	Refrences (According to Table 1)
		Size, design and distribution pattern of open space and green space	
		Land use diversity (Shannon and Simpson's Diversity Index)	
		Area of different uses such as residential, commercial, retail ect.	
	Access to Uses	Distance and time to arrive at transportation stations	(1), (2), (9), (10), (12), (13), (14), (15), (16),
		Distance and time to arrive at local jobs and services	
Connectivity	Street Network	Number and density of road intersections within and between neighborhoods	(1), (2), (9), (10), (12), (13), (14), (15), (16),
		Length, orientation and width of streets	
		Proportion of different types of roads (local roads, collector etc.)	
		length and size of urban blocks and plots	
		Number, density and length of cul-de-sacs	
	Transportation Infrastructure	location of public transportation stations, the paths and continuity of services	(1), (2), (9), (10), (12), (13), (14), (15),
		location of pedestrians and bike paths	
		location and types of parking lots	
Neighborhood Configuration	Complexity	Fractal Dimension Index and Perimeter-area fractal	(2), (16), (18)
		Shape Index	
		Complexity index	
	Compactness	Contagion index	(2), (16), (18)
		Compactness index	
	Centrality	Distance-area and distance-density correlation coefficient	(2), (18)
		Multiple Centrality Analysis (MCA)	

• Access to Uses: Accessibility is a multi-layered concept that is closely related to land use mix and street network design (Seto et al., 2014). On the scale of neighborhoods, accessibility refers to the potential of different destinations to be accessed from one's home. Two main indicators are the distance and time to arrive at transportation stations, and the distance and time to arrive at local jobs and services such as retails, supermarkets, parks, and schools.

Connectivity

• Street Network: The network of streets denotes the arrangement of urban blocks, streets, and public spaces in relation to each other. The network of streets has a great influence on the movement of pedestrians as well as on the way in which spaces and places are connected (Dempsey et al., 2010). Many modern street networks contain complicated street structures and cul-de-sac that decrease accessibility and permeability. Increased connections may bring about many advantages including pedestrian-orientedness (Ewing et al., 2002; Song et al., 2013; Gehl, 2010; Knaap & Song, 2004). The indicators of street network include the proportion of different types of roads (local roads, collector etc.), the number and density of road intersections within and between neighborhoods, the length and size of urban blocks and plots, and the number, density, and length of cul-de-sacs.

• Transportation Infrastructure: On the scale of local community, this sub-element refers to different options for transportation. The indicators are the location of public transportation stations, the paths and continuity of transportation services, the location and types of parking lots, and the location of pedestrians and bike paths.

Neighborhood Configuration

• Centrality: This sub-element refers to centrality in a neighborhood on the meso-scale. Dempsey et al. (2010) proposed a method called Multiple Centrality Analysis (MCA) for determining centrality. This method is based on the representation of spatial relationships in a city or neighborhood in the form of an initial diagram and calculation of a centrality space by its location in the network or by its distance to other spaces in the network. This method also deals with the design of streets (as a network, with trees, etc.) as well as their compactness and complexity. Other indicators include the distance-area correlation coefficient and distance-density correlation coefficient, which are different from the multiple centrality analysis method and are related to the distance of the built area from the center.

• Complexity and Compactness: The indicators are the fractal dimension index, the perimeter-area fractal dimension (indicates the complexity of shape and the surrounding environment), the contagion index, shape index (indicates the complexity of shape), and the compactness and complexity index[1].

2.5.3. Elements and indicators of urban form on the micro-scale

[1] See the Multiple Centrality Analysis (MCA).

The micro-scale of urban form is related to urban blocks, the structure of buildings, and the arrangement of buildings in relation to each other. Only three of the analyzed studies mention the micro-scale of urban form, hence the lowest number of elements and indicators on this scale. 16 codes (indicators) were extracted and classified into 6 concepts (sub-elements) and 3 categories on a macro-scale, as shown in Table 4.

Density

- Density on a micro-scale refers to floor area ratio and coverage ratio. Floor area ratio is the ratio of total floor area of a building to the lot area and coverage ratio is the portion of the lot area that is covered by a building (Dempsey et al., 2010).

Land Use

- Land use Mix: Land use mix on the scale of buildings and urban blocks makes it possible to combine occupational and residential spaces on a small scale and it provides places for both working and living (Seto et al., 2014). On the micro-scale, land use refers to mixed vertical uses (buildings with multiple uses) and existence of commercial units on the sides of a street.
- Access to uses: Accessibility at this scale refers to the permeability of the walls of streets and urban blocks. In physical qualities, can be achieved through shorter length of plots that face the street and existence of numerous access points and openings whereas, in the non-physical qualities, it means existence of commercial units on the edges of blocks and street that create active frontages (Yamagata & Sharifi, 2018).

Design

- Buildings Design: The building is the smallest element of urban form. The indicators of this sub-element are the location and orientation of building in a plot, the type of building (with courtyard, apartment, with a terrace, etc.), and other features such as height and position of windows.
- Design of Urban Blocks and Plots: A block is an essential unit of urban form. It is an area of land surrounded by streets. Each urban block is divided into several plots (Sharifi, 2019). Plot is the basic unit of urban form and land divisions (Kropf, 2014). The dimensions and structure of urban blocks and plots have a strong effect on other elements of urban form such as accessibility and land use mix. Large blocks are, on the one hand, occupied by a single use, which has a negative impact on land use diversity; on the other hand, they reduce connectivity, access, and permeability (Yamagata & Sharifi, 2018). The type, size, and proportions of urban blocks and plots are the indicators of this sub-element.
- Streets Design: On the micro-scale, this sub-element refers to the details of streets and involves factors such as ratio of buildings height to street width, the number of parking spaces for bicycles and cars, existence of sidewalk and its physical conditions, existence of shade in the afternoon, street lighting and other physical features, and qualitative aspects like security and cleanliness.

Table 4
The main- elements (category), sub-elements (concepts), and indicators (Codes) of urban form on the micro-scale

Main Elements (Category)	Sub-Elements (Concepts)	Indicators (Codes)	Refrences (According to Table 1)
Density	Type of Density	Floor Area Ratio	(12), (13)
		Coverage Ratio	
Land Use	Land use Mix	Vertical mixed use	(1), (12), (13)
		Scale and type of commercial activities on the street	
	Access to Uses	Routes designed for emergencies	(1), (13)
		Existence of access points and building openings to the street	
Design	Buildings Design	location and orientation of building in a plot	(1), (12), (13)
		Building types	
		Building features such as height and position of windows	
	Design of Urban Blocks and Plots	Type, size and proportions of urban blocks	(12), (13)
		Shape, size and proportions of urban plots	
	Street Design	The ratio of buildings height to street width	(1), (12), (13)
		Number of parking spaces for bicycles and cars	
		Existence of sidewalk and its physical conditions	
		Existence of shade in the afternoon, street lighting and other physical features	
		Qualitative aspects like security and cleanliness	

2.6. Quality control

Throughout the meta-synthesis process, researchers must assess the quality of their study by using a combination of electronic and hand searching techniques to obtain desired studies and also, by applying the CASP appraisal tool to evaluate meta-synthesis. Moreover, in the current study, the Kappa index was used to evaluate the quality of content. During the research process, the researcher's viewpoints have been compared with the opinions of another expert in the field of urban design to ensure their extracted concepts. Thus, some chosen studies were presented to the expert without any perception about the concepts and the way of coding ahead of locating codes in separated concepts.

The Kappa coefficient was calculated by comparing similarities and differences of the two categories made by the researchers and the expert, representing the reliability of the model. The Kappa indicator calculation process can be observed in Equations 1 and 2. As shown in Table 5, the expert created 16 categories while 14 categories were made by the researchers and there were 13 categories in common. Furthermore, the Kappa value was 0.75, which is equivalent to the level of valid acceptance (Table 6)

Table 5
Kappa Indicator condition

		Researchers view		
		Yes	No	Total
Expert view	Yes	A: 13	B:3	16
	No	C: 1	D: 0	1
	Total	14	3	N: 17

Equation 1: observed agreement= $\frac{\text{A+D}}{\text{N}} = 0.76$ and agreement chance= $\frac{\text{A+B}}{\text{N}} \times \frac{\text{A+C}}{\text{N}} \times \frac{\text{C+D}}{\text{N}} \times \frac{\text{B+D}}{\text{N}} = 0.008$

Equation 2: K= $\frac{observed\ agreement - agreement\ chance}{1 - agreement\ chance} = \frac{0.76-0.008}{1-0.008} = 0.75$

Table 6
Kappa Indicator condition

Status agreement	Status agreement Numerical value of Kappa indicator
Poor	K < 0
Unimportant	0 < K < 0.2
Fair	0.21 < K < 0.4
Good	0.41 < K < 0.46
Valid	0.61 < K < 0.8
Excellent	0.81 < K < 1

2-7. Findings

Content analysis is a research method used to analyze the content of information by determining the existence of specific words, themes or ideas. Using content analysis, researchers can analyze qualitative data systematically and convert it into quantitative data. There are several methods for determining the weight of cods, and Shannon entropy is one of the best methods in this regard (Azar and et.al, 2009). Using the Shannon Entropy method, the frequency of codes in each of the concepts should be first counted in conformity with each contents. The significant coefficient of codes and concepts can be then calculated using their informational load. The degree of uncertainty (d_j) of each code and its significance coefficient (W_j) has been measured using the following equations. Finally, the relative importance of each concept has been obtained from the total weight of the codes of that concept. Accordingly, the support level of the previous studies for the findings of this research has been presented statistically in Tables 7, 8 and 9.

Equation 3: $E_j = -K \sum_{i=1}^{m} P_{ij} In P_{ij} \quad i = 1,2,\dots,m$

Equation 4: $K = \frac{1}{In\, m}$

Equation 5: $d_j = 1 - E_j$

Equation 6: $W_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$

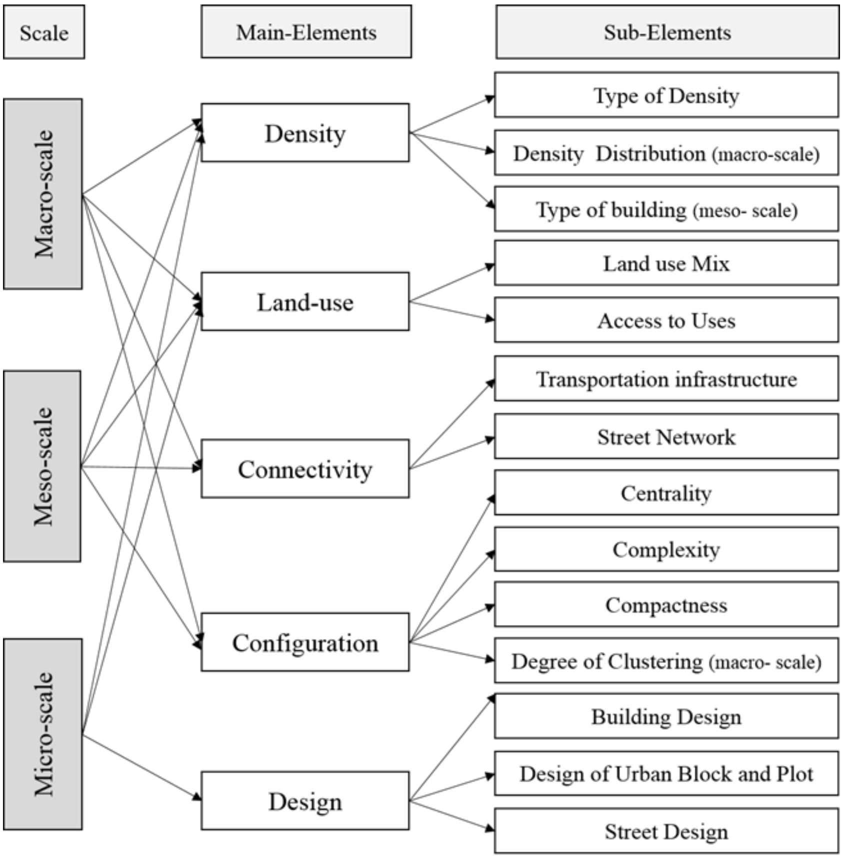

Fig. 3. Model of urban form elements on macro, meso and micro scales

Table 7
Results of ranking indicators and sub-elements using Shannon entropy on the macro-scale

Sub-Elements (Concepts)	Indicators (Codes)	Frequency	Entropy (Ej)	Uncertainty (dj)	significance coefficient (Wj)	Ranking in Concepts	Total Rank	Sub-Element Wj	Sub-Element Rank
Type of Density	Population density	12	0.9419	0.0581	0.0618	1	1	0.1370	3
	Built-up area density	5	0.9669	0.0331	0.0352	3	6		
	Employment density	6	0.9625	0.0375	0.0399	2	4		
Density Distribution	Profile and gradient of density	4	0.9717	0.0283	0.0301	1	8	0.1483	2
	Percentage of population in low-d	3	0.9770	0.0230	0.0245	3	13		
	Percentage of population in areas with medium-to-high density	3	0.9770	0.0230	0.0245	3	13		
	Coefficient of variation	1	0.9901	0.0099	0.0105	6	35		
	Gini coefficient	2	0.9830	0.0170	0.0181	5	19		
	Delta Index	1	0.9901	0.0099	0.0105	6	35		
	Shannon's entropy	4	0.9717	0.0283	0.0301	1	8		
Land use Mix	proportion of jobs to residents	6	0.9625	0.0375	0.0399	2	4	0.1504	1
	Degree of job mixing (entropy)	2	0.9830	0.0170	0.0181	4	19		
	Percentage of residential use and its ratio to non-residential uses	4	0.9717	0.0283	0.0301	3	8		
	Ratio of built-up area to open space	2	0.9830	0.0170	0.0181	4	19		
	Percentage of transportation area, etc	7	0.9584	0.0416	0.0442	1	3		
Access to uses	Distance and time to arrive at public transportation stations	5	0.9669	0.0331	0.0352	1	6	0.0654	8
	Distance and time to arrive at workplace	4	0.9717	0.0283	0.0301	2	8		
Street Network	Ratio of Roads Hierarchy	3	0.9770	0.0230	0.0245	1	13	0.0181	7
	Road network density	1	0.9901	0.0099	0.0105	4	35		
	Road network congestion index	1	0.9901	0.0099	0.0105	4	35		
	Number, density and ratio of intersections	3	0.9770	0.0230	0.0245	1	13		
	Length and dimention of blocks	2	0.9830	0.0170	0.0181	3	19		

Sub-Elements (Concepts)	Indicators (Codes)	Frequency	Entropy (Ej)	Uncertainty (dj)	significance coefficient (Wj)	Ranking in Concepts	Total Rank	Sub-Element Wj	Sub-Element Rank
Transportation Infrastructure	Pedestrian paths and their related amenities	2	0.9830	0.0170	0.0181	1	19	0.0466	10
	Highways, railways and aviation index	1	0.9901	0.0099	0.0105	3	35		
	Proportion of using various types of transportation systems.	2	0.9830	0.0170	0.0181	1	19		
Complexity	Area weighted mean patch fractal dimension	2	0.9830	0.0170	0.0181	1	19	0.0933	6
	Shape index	2	0.9830	0.0170	0.0181	1	19		
	Mean patch edge and edge density	1	0.9901	0.0099	0.0105	5	35		
	Fractal dimension	2	0.9830	0.0170	0.0181	1	19		
	Sum of perimeters of all urban patches	1	0.9901	0.0099	0.0105	5	35		
	Area weighted mean shape index	2	0.9830	0.0170	0.0181	1	19		
Degree of Clustering	Moran coefficient	4	0.9717	0.0283	0.0301	1	8	0.0587	9
	Geary coefficient	2	0.9830	0.0170	0.0181	2	19		
	Clustering index	1	0.9901	0.0099	0.0105	3	35		
Centrality and Nuclearity	Distance of uses and population from the central business districts	9	0.9511	0.0489	0.0520	1	2	0.1126	4
	Population and employment density in centers	2	0.9830	0.0170	0.0181	3	19		
	Centrality index	3	0.9770	0.0230	0.0245	2	13		
	Number of urban nuclei and centers	2	0.9830	0.0170	0.0181	3	19		
Compactness (Dispersion)	Compactness index	3	0.9770	0.0230	0.0245	1	13	0.0997	5
	Compactness index of the largest patch	2	0.9830	0.0170	0.0181	2	19		
	Contagion index	2	0.9830	0.0170	0.0181	2	19		
	Mean patch size and Number of patches	2	0.9830	0.0170	0.0181	2	19		
	Gross leapfrog and Net leapfrog index	1	0.9901	0.0099	0.0105	5	35		
	Index of continuity of developable land	1	0.9901	0.0099	0.0105	5	35		

Table 8
Results of ranking indicators and sub-elements using Shannon entropy on the meso-scale

Sub-Elements (Concepts)	Indicators (Codes)	Frequency	Entropy (Ej)	Uncertainty (dj)	significance coefficient (Wj)	Ranking in Concepts	Total Rank	Sub-Element Wj	Sub-Element Rank
Type of Density	Gross Density	8	0.9377	0.0623	0.0662	1	1	0.1503	3
	Net Residential Density	3	0.9674	0.0326	0.0347	3	11		
	Average size of residential plots	5	0.9537	0.0463	0.0493	2	5		
Building Type	Coverage ratio	3	0.9674	0.0326	0.0347	1	11	0.0953	6
	Floor area ratio	3	0.9674	0.0326	0.0347	1	11		
	Type of housing	2	0.9757	0.0243	0.0259	3	17		
Land use Mix	Mixed vertical uses	3	0.9674	0.0326	0.0347	3	11	0.2085	1
	Ratio of tenants to owners	1	0.9856	0.0144	0.0153	6	23		
	Ratio of different uses to residential	2	0.9757	0.0243	0.0259	5	17		
	Size, design and distribution pattern of open space and green space	4	0.9601	0.0399	0.0424	2	8		
	Land use diversity (Shannon and Simpson's Diversity Index)	3	0.9674	0.0326	0.0347	3	11		
	Area of different uses such as residential, commercial, retail ect.	6	0.9478	0.0522	0.0555	1	4		
Access to Uses	Distance and time to arrive at transportation stations	5	0.9537	0.0463	0.0493	2	5	0.1155	4
	Distance and time to arrive at local jobs and services	8	0.9377	0.0623	0.0662	1	1		
Street Network	Number and density of road intersections	8	0.9377	0.0623	0.0662	1	1	0.1923	2
	Length, orientation and width of streets	2	0.9757	0.0243	0.0259	4	17		
	Proportion of different types of roads (local roads, collector etc.)	1	0.9856	0.0144	0.0153	5	23		
	length and size of blocks and plots	4	0.9601	0.0399	0.0424	2	8		
	Number,density and of cul-de-sacs	4	0.9601	0.0399	0.0424	2	8		
Transportation Infrastructure	location of public transportation stations and continuity of services	3	0.9674	0.0326	0.0347	2	11	0.0993	5

Sub-Elements (Concepts)	Indicators (Codes)	Frequency	Entropy (Ej)	Uncertainty (dj)	significance coefficient (Wj)	Ranking in Concepts	Total Rank	Sub-Element Wj	Sub-Element Rank
	location of pedestrians and bike paths	5	0.9537	0.0463	0.0493	1	5		
	location and types of parking lots	1	0.9856	0.0144	0.0153	3	23		
Complexity	Fractal Dimension Index and Perimeter-area fractal	2	0.9757	0.0243	0.0259	1	17	0.0670	7
	Shape Index	2	0.9757	0.0243	0.0259	1	17		
	Complexity index	1	0.9856	0.0144	0.0153	3	23		
Compactness	Contagion index	2	0.9757	0.0243	0.0259	1	17	0.0411	8
	Compactness index	1	0.9856	0.0144	0.0153	2	23		
Centrality	Distance-area and distance-density correlation coefficient	1	0.9856	0.0144	0.0153	1	23	0.0305	9
	Multiple Centrality Analysis (MCA)	1	0.9856	0.0144	0.0153	1	23		

Table 9
Results of ranking indicators and sub-elements using Shannon entropy on the micro-scale

Sub-Elements (Concepts)	Indicators (Codes)	Frequency	Entropy (Ej)	Uncertainty (dj)	significance coefficient (Wj)	Ranking in Concepts	Total Rank	Sub-Element Wj	Sub-Element Rank
Type of Density	Floor Area Ratio	2	0.930	0.070	0.071	1	1	0.1153	4
	Coverage Ratio	1	0.956	0.044	0.045	2	12		
Land use Mix	Vertical mixed use	2	0.930	0.070	0.071	1	1	0.1412	3
	Scale and type of commercial activities	2	0.930	0.070	0.071	1	1		
Access to Uses	Routes designed for emergencies	1	0.956	0.044	0.045	2	12	0.1153	4
	Existence of access points and building openings to the street	2	0.930	0.070	0.071	1	1		
Building Design	location and orientation of building	1	0.956	0.044	0.045	3	12	0.1859	2
	Building types	2	0.930	0.070	0.071	1	1		
	Building features	2	0.930	0.070	0.071	1	1		
Design of Block and Plot	Type, size and proportions of urban blocks	2	0.930	0.070	0.071	1	1	0.1153	4
	Shape, size and proportions of urban plots	1	0.956	0.044	0.045	2	12		
Street Design	The ratio of buildings height to street width	2	0.930	0.070	0.071	1	1	0.3271	1
	Number of parking spaces	2	0.930	0.070	0.071	1	1		
	Existence of sidewalk and its physical conditions	2	0.930	0.070	0.071	1	1		
	Existence of shade in the afternoon, street lighting and other physical features	2	0.930	0.070	0.071	1	1		
	Qualitative aspects	1	0.956	0.044	0.045	5	12		

According to the coefficients obtained in Table 7, the most important code is population density that has the significant coefficient of 0.0618, and after that, distance of uses and population from the central business districts (0.0520) and the percentage of different land uses (0.0442), have the highest importance coefficients and the highest rank among the codes on the macro-scale. Based on the total weight of the codes of each concept, land use mix (0.1504), density distribution (0.1483) and type of density (0.1370) are the most important sub-elements of urban form on the macro-scale, respectively.
On the meso-scale of urban form, gross density, distance and time to arrive at local jobs and services and density of road intersections with the significant coefficient of 0.0662, have the highest importance coefficients and more reproducibility than other codes. Land use mix (0.2085), street network (0.1923) and type of density (0.1503) have the highest rank among the sub-elements on the meso-scale (Table 8). On the micro scale, due to the limited frequency of codes between one and two, the weights of the codes are similar. According to Table 9, street design is the most important sub-element of urban form on this scale.
According to the rank of sub-elements of urban form, land use and density are the most important elements of urban form. Finally, model of urban form elements based on qualitative findings of meta-synthesis are shown in Figure 3.

3. Conclusion

Urban form is the spatial representation of various physical, environmental, economic, social, and cultural factors and has a strong effect on human activities as well as the historical evolution of cities (Conzen, 1960; Lynch, 1981; Kropf, 2009; Sharifi, 2019). Studies from disciplines as various as landscape ecology, Transportation planning, and urban design have addressed the elements and indicators of urban form. Urban form is also studied on different scales from single buildings and blocks to neighborhoods, cities, and metropolitan areas.

Some studies have attempted to review the literature and sum up these elements and indicators, but they either are limited to only one scale or do not specifically deal with the indicators. Thus, the present study adopted a comprehensive scale-based approach to offer a meta-synthesis of the previous studies of the elements and indicators of urban form through a systematic review.

From systematic review, 18 studies were obtained of which 12 studies (66.66%) addressed the macro-scale (city and metropolitan area), 10 studies (55.55%) addressed the meso-scale (neighborhood), and 3 studies (16.66%) addressed the micro-scale (urban blocks and buildings). Based on analysis, 89 indicators, 14 sub-elements and 5 main elements were obtained for urban form. Some of the sub-elements of urban form like ‘distribution of population and jobs’ are only related to one scale while others such as ‘types of density’, ‘land use mix’, and ‘access to uses’ are working on all scales, although with different contents.

The elements of urban form on one scale are strongly related and they affect each other. For example, the design of streets affects access to facilities, and density is related to land use mix and the residents’ needs. All of these elements contribute to the formation of urban form. These elements are also vertically interrelated within a hierarchy of scales. For instance, the elements of the micro-scale both directly and indirectly affect factors such as access to uses, degree of clustering, and street network.

As the aim of this meta-synthesis was to identify the elements and indicators of urban form on different scales, only a brief description of the indicators was provided without elaborating on the techniques and information sources for measuring them. Therefore, directions for further research may include in-depth discussion of the indicators of urban form and examination of the techniques and information sources for measuring indicators on the three scales of urban form. Another suggestion for further research is to apply these indicators in practical investigations of urban form in different cities and neighborhoods and to compare the obtained results. The findings of this study can be a reference for future studies of urban form and help to determine standards for elements and indicators of urban form.

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Appendix

- Area weighted mean patch fractal dimension:

$$\text{AWMPFD}=\frac{\sum_{i=1}^{i=n} {}^{2\ln 0.25P_i}/_{\ln S_i}}{N} \times \frac{S_i}{\sum_{i=1}^{i=N} S_i}$$

S_i and p_i are the area and perimeter of patch i, and N is the total number of patches.

- Area weighted mean shape Index:

$$\text{AWMSI}=\frac{\sum_{i=1}^{i=N} {}^{p_i}/_{4\sqrt{S_i}}}{N} \times \frac{S_i}{\sum_{i=1}^{i=N} S_i}$$

S_i and p_i are the area and perimeter of patch i, and N is the total number of patches.

- Centrality index:

1. Centrality index= $\frac{\sum_{i=1}^{N-1} {}^{D_i}/_{N-1}}{R} = \frac{\sum_{i=1}^{N-1} {}^{D_i}/_{N-1}}{\sqrt{S/\pi}}$

D_i is the distance of centroid of patch i to centroid of the largest patch, N is the total number of patches, R is the radius of a circle with area of s, and s is summarization area of all patches.

2. centralization index

$$= \sum_{h=1}^{H}[T(i)h-1][Ah] - \sum_{h=1}^{H}[T(i)h][Ah-1]$$

- Compactness index

$$CI = \frac{\sum_i {}^{P_i}/_{P_i}}{N^2} = \frac{\sum_i 2\pi \sqrt{{}^{S_i}/_{\pi}} / P_i}{N^2}$$

S_i and p_i are the area and perimeter of patch i, P_i is the perimeter of a circle with the area of s_i and N is the total number of patches.

- Compactness index of the largest patch

$$\text{CILP}=\frac{2\pi\sqrt{S/\pi}}{P}$$

S and p are the area and perimeter of largest patch.

- Gini coefficient

1. $\text{Gini}=\frac{\sum_i^N \sum_j^N |Y_i-Y_j|}{2N^2\bar{Y}}$
2. $\text{Gini}=0.5\sum_{i=1}^{N}|X_i - Y_i|$

N is the number of sub-city districts, X_i is the proportion of land in sub-city district i, Y_i is the proportion of population in sub-city district i and $\bar{y}$ is the mean of population density in all sub-city districts.

- Moran coefficient

$$\text{Moran}=\frac{N\sum_{i=1}^{N}\sum_{j}^{N} W_{ij(-X)(X_j-X)}}{\left(\sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}\right)(X_i-X)^2}$$

N is the number of sub-city districts , X_i is the population or employment in sub-city district I, X_j is the population or employment in sub-city district j, X is the mean of population or Employment, W_{ij} is the distance between sub-city district i and j.

• Geary coefficient

$$\text{Geary}=\frac{(N-1)\left[\sum_{i=1}^{N}\sum_{j=1}^{N}W_{ij}\left(X_i-X_j\right)^2\right]}{2\left(\sum_{i=1}^{N}\sum_{j=1}^{N}W_{ij}\right)\sum_{i=1}^{N}(X_i-X)^2}$$

N is the number of sub-city districts , X_i is the population or employment in district i, X_j is the population or employment in district j, X is the mean of population or Employment, W_{ij} is the distance between district i and j.

• Gross leapfrog index

$$I_{gi}=\frac{A_i^{out}}{A_i^{u}}$$

A_i^{out} is the leap-frog areas in settlement I and A_i^{u} is the urban built-up area of settlement i.

• Net leapfrog index

$$I_{ni}=\frac{R_i^{out}}{R_i}$$

R_i^{out} is the residential areas outside central built-up areas of settlement i; R_i is the residentail area of settlement i.

• coefficient of variation

$$\left(\sum_{m=1}^{M}[D(i)m-D(i)u]^2/_M\right)^{1/2}\Big/\left[\sum_{m=1}^{M}D(i)m/_M\right]$$

D(i)u is the density of land use i over the developable urban area, D(i)m is the density of land use i over the developable area in medium spatial scale, m is the medium spatial scale (one square mile)

• degree of job mixing (entropy)

$$\sum_{i=1}^{n}\sum_{k}\frac{P_k*LN(P_k)}{LN(k)}\times\frac{BJ_i+BP_i}{TJ+TP}$$

• job-population balance

$$\sum_{i=0}^{i=n}\left(1-\frac{ABS(J_i-JP\times P_i)}{J_i+JP\times P_i}\times\frac{BJ_i+BP_i}{TJ+TP}\right)$$

i is the block group number, n is the number of block groups, k is the number of sectors, P_k is the proportion of jobs in sector k, JP is the jobs per, BJ is the jobs in the block group, BP is the residents in the block group, TJ is the total jobs, TP is the total residents in the urbanized areas.

• Contagion index

$$DCI=\{1+\frac{1}{2Inm}[(\sum_{i=1}^{m}\sum_{k=1}^{m}P_i\frac{g_i}{\sum_{k=1}^{m}g_{ik}})-InP_i\frac{g_{ik}}{\sum_{k=1}^{m}g_{ik}}]\}100$$

P_i is the proportion of landscape occupied with patch type i, g_k is the number of adgencies between pixels of classes i and k, i, k are different patch types, m is the number of patch types.

• Perimieter-area fractal index

$$PAFRAC=\frac{2}{\frac{\left(N\sum_{i=1}^{m}\sum_{j=1}^{n}\ln P_{ij}\ln a_{ij}\right)-\left[\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\ln P_{ij}\right)\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\ln a_{ij}\right)\right]}{\left(N\sum_{i=1}^{m}\sum_{j=1}^{n}\ln P_{ij}^{2}\right)\left(\sum_{i=1}^{m}\sum_{j=1}^{n}\ln P_{ij}\right)}}$$

P_{ij} is the perimeter of patch ij, a_{ij} is the area of patch ij, N is the total number of patches in the landscape, m is the number of land uses i in the study area, n is the number of patches j.

• Shape index

$$SI=\sum_{k=1}^{n}\frac{0.25\times P_{ij}}{\sqrt{A_{ij}}},P_{ij}$$

P_{ij} is the perimeter of patch ij, a_{ij} is the area of patch ij, k is the number of patches in each land area.

• Fractal Dimension

$$FD=\frac{2\,InP_i}{In\,s_i}$$

S_i is the area patch I, p_i is the perimeter patch I, n is the total number of patches.

• Shannon Entropy

$$SE=\sum_{i=1}^{n}\frac{P_i\log\left(\frac{1}{P_i}\right)}{\log(n)}\quad P_i=\frac{x_i}{\sum_{i=1}^{n}x_i}$$

N is the number of sub-areas and X_i is the density of sub-area i.

• Juxtaposition and Interspersion Index

$$\frac{-\sum_{i=1}^{m}\sum_{k=i+1}^{m}[(E_{ik})*ln(E_{ik})]}{ln\left(\frac{m(m-1)}{2}\right)}$$

M is the number of land use types in the neighborhood, E_{ik} the length of the edge between land use type i and land use type k.

• Clustering

$$\left(\sum_{m=1}^{M}(\sum_{s=1}^{4}[D(i)s-D(i)m]^2/4)^{1/2}/_M\right)\Big/\left[\sum_{m=1}^{M}D(i)m/_M\right]$$

M is the medium spatial scale (one square mile), D(i)m is the density of land use i over the developable area in medium spatial scale, D(i)s is the density of land use i over the developable area in small spatial scale.

• Simpson's diversity index

$$SIDI=1-\frac{\sum_{i=1}mn_i(n_i-1)}{N(N-1)}$$

m is the number of land use types in the neighborhood, n_i the number of parcels of a land use type i in the neighborhood ,and N is the number of parcels in the neighborhood.

• Shannon's diversity Index

$$SHDI = -\sum_{i=1}^{m} p_i \, In \, p_i$$

.

m is the different patch types, Pi is the proportion of landscape área occupied by patches of type i.

• Comprehensive highway, railway and aviation index

Comprehensive highway index:

$$\text{CHI} = \frac{v_{\text{HDP}} + v_{\text{HDF}}}{2}$$

VHDP and VHDF are the standardized values calculated from two indicators 'Freight ton kilometers' and 'passenger kilometers'