Building Research & Information
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/rbri20

Assessing cities: a new system of cross-scale spatial indicators

Loeiz Bourdic [a], Serge Salat [a] & Caroline Nowacki [a]
[a] Urban Morphology Lab, CSTB, 4 avenue Poincaré, F-75016, Paris, France
Published online: 20 Jul 2012.

To cite this article: Loeiz Bourdic, Serge Salat & Caroline Nowacki (2012) Assessing cities: a new system of cross-scale spatial indicators, Building Research & Information, 40:5, 592-605, DOI: 10.1080/09613218.2012.703488

To link to this article: http://dx.doi.org/10.1080/09613218.2012.703488

BRI Building Research & Information (2012) 40(5), 592–605

Routledge Taylor & Francis Group

RESEARCH PAPER

Assessing cities: a new system of cross-scale spatial indicators

Loeiz Bourdic, Serge Salat and Caroline Nowacki

Urban Morphology Lab, CSTB, 4 avenue Poincaré, F-75016 Paris, France
E-mails: loeiz.bourdic@m4x.org, serge.salat@free.fr and nowackicaroline@gmail.com

Urban stakeholders require quantitative and robust tools to implement new paths to urban sustainability. Urban form, the spatial distribution of activities and urban organization are crucial aspects of cities' sustainability. Many tools and assessment systems have been developed to improve cities' energy efficiency and environmental footprint. However, most of these tools are based on the building scale. Most urban stakeholders are now convinced that a building scale approach is not sufficient: the scale of analysis should evolve from the building to the neighbourhood, district and city scales. An innovative system of indicators is presented that answers the need for multi-scale and cross-scale indicators and encompasses the intrinsic complexity of the city. Based on a morphologic approach, new mathematical formulas are used to generate urban sustainability indicators. These indicators can assist with the comparison of urban projects by using a structural point of view to assess the energy efficiency, social and environmental consequences of different urban forms. A comprehensive table displays 60 indicators and methods to quantify them. Some of these indicators have been quantified for real cities and are presented.

Keywords: built environment efficiency, environmental assessment, spatial indicators, sustainable cities, urban efficiency, urban resilience, urban tools

Les acteurs du cadre urbain ont besoin de solides outils quantitatifs afin de mettre en oeuvre de nouvelles pistes pour parvenir à la durabilité urbaine. La forme urbaine, la répartition spatiale des activités et l'organisation urbaine sont des aspects déterminants de la durabilité des villes. De nombreux outils et systèmes d'évaluation ont été mis au point pour améliorer l'efficacité énergétique des villes et l'empreinte environnementale. Cependant, la plupart de ces outils reposent sur une approche à l'échelle du bâtiment. La plupart des acteurs du cadre urbain sont maintenant convaincus qu'une approche à l'échelle du bâtiment n'est pas suffisante : l'échelle d'analyse devrait évoluer de l'échelle du bâtiment à l'échelle du quartier, de l'arrondissement et de la ville. Il est présenté un système innovant d'indicateurs qui répond aux besoins d'indicateurs multi-échelles et trans-échelles et qui englobe la complexité intrinsèque de la ville. En se basant sur une approche morphologique, de nouvelles formules mathématiques sont utilisées pour générer des indicateurs de durabilité urbaine. Ces indicateurs peuvent aider à comparer les projets de construction urbains en utilisant un point de vue structurel pour évaluer l'efficacité énergétique, les conséquences sociales et environnementales des différentes formes urbaines. Un tableau exhaustif affiche 60 indicateurs et les méthodes pour les quantifier. Certains de ces indicateurs ont été quantifiés pour des villes réelles et sont présentés.

Mots clés: efficacité du cadre bâti, évaluation environnementale, indicateurs spatiaux, villes durables, efficacité urbaine, résilience urbaine, outils urbains

Introduction

Urban energy consumption is a growing concern due to the acknowledged need to mitigate climate change and the large proportion of energy used in cities. While some governments are committing themselves to reducing energy consumption and carbon emissions, they need tools to measure the current performance of their cities, to find the levers to reduce it and to assess the efficiency of the actions engaged. This is why assessment systems play such a key role. However, cities are incredibly complex systems, made of components that can be identified using

Building Research & Information ISSN 0961-3218 print/ISSN 1466-4321 online
http://www.tandfonline.com/journals
http://dx.doi.org/10.1080/09613218.2012.703488

different point of views. Assessments based on single or simple metrics such as energy flows are insufficient to address the wider socio-ecological aspects of cities.

An analysis underlining the different views and their interactions is crucial to a better understanding of the urban environment. The list of indicators presented here offers a new analysis of the layers of the city, of its components and of the interactions between them. These indicators enable the built environment of different cities in the world to be described and compared, along with an assessment of the energy consumption and environmental consequences linked to urban forms. Such an approach focusing on urban morphology at different scales is exceptional and promising.

The indicators were constructed using mathematical theories, and are embedded in the thought and work of Ernst von Weizsäcker *et al.* (1997). Their approach to reducing resource consumption was based on the identification of key factors that played a significant role and should be targeted. Their idea of identifying essential factors and using them to reduce the energy footprint has been a crucial move in the research on sustainable development. Ratti *et al.* (2005) adapted this concept specifically to the urban environment. Their work is expanded in this paper, deepening the morphological aspect and building on some of their mathematical theories and equations. It is argued that the focus on urban morphology can contribute to halving energy consumption and greenhouse gas emissions. The current paper identifies the essential factors to achieve this potential.

Governments, citizens, urban planners, architects, property developers as well as other stakeholders could use this system to understand better the interactions between built forms and energy consumption, and to nurture a dialogue-based investigative approach. However, any attempt to use the indicators as absolute target values would be misguided. Doing so would fragment the whole urban concept into a series of technical targets, thereby losing the relation of the parts to the whole. Instead of stipulating absolute targets for the indicators, a range of advisable values is advocated. This provides stakeholders with some latitude and to account for the complexity of urban issues. This system has to be adapted to the specificity of the projects by changing the variables to reach the structural objectives defined by local governments and planning agencies.

The next two sections present the method that has been used to implement this assessment tool, as well as the way it has been structured. Critical attention has then been paid to some specific concepts for which quantification raises important issues: urban morphology, mixed-use and diversity. A comprehensive table then displays 60 cross-scale spatial indicators, for which a mathematical formula is provided in the Appendix. The last section is dedicated to presenting operational outputs of this assessment tool, with some benchmarks calculated on several cities.

Organization of the assessment system

Existing assessment tools

Many tools for assessing urban sustainability have emerged recently, but most of them are based on the building scale. However, according to Cole (2011) one of the most significant achievements of the past few years has been the introduction of new versions of these tools for communities and urban design. The scale has increased from individual buildings to a larger scale. Instead of looking only at the building, these methods started to take into account the context of the building. Besides insisting on the need for neighbourhood-, district- and city-scales assessment tools, Bourdic and Salat (2012) provide a review of neighbourhood, district and city scales sustainability assessment tool, with a focus on building energy consumptions. Urban assessment tools on these critical urban scales for the United States (Leadership in Energy and Environmental Design (LEED), 2009), Japan (Comprehensive Assessment System for Building Environmental Efficiency (CASBEE), 2007; Murakami *et al.*, 2011), and Europe (Building Research Establishment (BRE), 2011) reveal a lack of robustness. According to Bourdic and Salat (2012) this problem is caused by a confusing use of qualitative and quantitative criteria, mixed into a unique aggregated rating. Building on these conclusions, the main objective of this paper is to provide urban stakeholders with robust, quantitative, science-based and cross-scale indicators for urban sustainability.

Three pillars

Sustainable development involves many disciplines and it has become increasingly obvious that an innovative combination of these disciplines is necessary to reduce greenhouse gas emissions while improving quality of life. Urban forms influence the environmental, social and economic aspects of sustainable development, but urban forms continue to maintain their own autonomy. Social and economic factors play a key role in the design of the city, but are not sufficient to explain it. The dynamic of urban forms deserves to be set apart for purposes of analysis. The three pillars have thus been retained: urban form; economic and social; and environment. This organization thereby allows a variety of combinations between the urban and the social, the urban and the economic or the urban and the environmental.

Major themes

A thematic layout makes the system easy to understand for the reader. This grid has been incorporated in the system, while detailing it by other classification means. Classical parts have been chosen, inspired from the Canada Mortgage and Housing Corporation (Kellett, 2009a) assessment tool: 'land use', 'mobility', 'water management', 'biodiversity', 'energy', 'equity', 'economy', 'well-being and culture', 'waste and materials'.

A set of indicators was then developed in this theme-based framework (land use, mobility, water, biodiversity, etc.), observing the nature, scope and role of each indicator. The decisive questions were: Why choose it? What information does it provide? These were necessary to find the most appropriate name and mathematical formula for each indicator. This forced the research team to think thoroughly about the meaning of commonly used words, *e.g.* diversity. It also led to an innovative classification based on seven types: intensity, diversity, proximity, complexity, form, connectivity and distribution. Each type defines the nature, the provided information and the use of each indicator.

Spatial scales

Spatial scales specify the area for which each indicator computation makes sense. These are the city, the district, the neighbourhood, the block and the building. Defining smaller scales than the entire urban area was necessary to ensure the best relevance of the results and effectiveness of recommendations, considering data availability.

The city scale is the most comprehensive. On this scale, cities' overall consumption per resident, energy and resource consumption, and waste production can be compared. Streets can also be mapped, as well as connectivity and road distribution between users. Public transit networks and connections between different transit modes can be analysed.

The district scale needs sufficient aggregated yield data to take into account the structure, complexity and connectivity, in particular of the street networks (for pedestrians, bikes, cars, public transport). This scale also enables one to examine diversity issues. This includes social mix (diversity of housing sizes and prices), but also sectoral mix (distribution and concentration of different activities), and housing/office mix. These issues can be examined within the boundaries of a district or between several districts.

The city and district scales focus primarily on connectivity, but this loses its significance at the neighbourhood scale, save perhaps for the pedestrian and bicycle grids. On the other hand, morphology plays a significant role on the neighbourhood scale, as do physical phenomena within the urban fabric: wind speed, wind directions, and solar potential (sky view factor) (Oke, 1981, 1988). These physical parameters are influenced by the form of streets (the height-to-width ratio of urban canyons), their orientation to the sun and dominant winds, etc. The indicators of mixed use get a different meaning on the smaller scale of the neighbourhood. Segregation (social, residential, sectoral) that may have been masked by this indicator on the district scale may show up on the neighbourhood scale. This is also an interesting scale to measure proximity parameters: green spaces, public transport, public spaces and facilities, etc. This scale corresponds to a selection of 200×200 m in the Haussmannian fabric, or between one and four blocks. For an American grid, or for Brasilia, the appropriate scale will be approximately 400×400 m to maintain the coherence of the urban fabric.

Morphological parameters are particularly interesting on the block scale and in urban configurations consisting of adjoining or homogenous buildings (Salat, 2009). The block area depends highly on local architecture and on the form and relationships between buildings. The block is a highly versatile form with a millennia-old history, and looks different for each civilization around the world. The block is the built part framed by streets. In many historical cities, like Paris, it corresponds to a series of buildings that usually surround courtyards. But for skyscrapers it corresponds to the building itself. It can be used notably to calculate heat energy needs on the district scale without having to calculate it building by building, as is usually done. It is possible to extend the results to the block and even district scales, when buildings have the same technology and level of insulation, in homogenous fabrics (buildings with similar envelope area-to-volume ratio or adjoining walls).

A typology of indicators

The recurrent concepts are translated by seven types of indicators to evaluate the following aspects: intensity, distribution, proximity, connectivity, complexity, diversity and form. These concepts constitute an analysis grid that serves to pinpoint the meaning of the indicator's value and its objective.

Indicators of intensity

Intensity is an increasingly used type of indicator. It can measure the density or concentration of an object on a given scale. It can then describe a concentration of people or a density of housing. It implies a relationship of efficiency between the result and the means employed. This is the case for the carbon emissions intensity. It measures the amount of carbon emitted to achieve a result and allows one to compare the energy efficiency of activities. Some intensity indicators have already been published, notably by the Agència d'Ecologia Urbana de Barcelona (2007) and the

Canada Mortgage and Housing Corporation (Kellett, 2009a, 2009b).

Indicators of spatial distribution

Indicators of spatial distribution give the relative concentration or dispersion of objects on a given scale compared with all known objects on a bigger scale – for instance, the distribution of parks or social housing in specific districts compared with the whole city. The point is to quantify the distribution of objects in order to evaluate the equitability. Usually a good distribution is homogenous. This is sometimes conflated with an indicator of diversity, which is why these indicators will be described below.

Indicators of proximity

Proximity corresponds to the distance between two elements, *e.g.* between homes and leisure activities or between offices and public transit stations. This distance must be minimized to reduce travel needs for day-to-day activities.

Indicators of connectivity

Connectivity corresponds to the relative accessibility or spatial interconnection of a system or a network (network of streets, for example). It describes the number of different ways to go from one point to another, which makes the network more resilient: if one way is blocked, alternate ways can be used.

Indicators of diversity

Diversity refers to the mix and variety of objects of a similar type on a given scale, *e.g.* the diversity of land use or of housing size on the scale of a district. Unlike spatial distribution, diversity focuses on the proportion of different objects but not on their more or less homogenous location in space.

Indicators of form

Indicators of form refer to the geometry of elements, their volume and their footprint in space. They take this information into account as a basis for building formulas that describe energy consumption or the relationship of people to their environment.

Ongoing issues

Indicators of intensity are increasingly applied in most of urban sustainability assessment systems, be it in the United States (LEED, 2009), in Japan (CASBEE, 2007; Murakami *et al.*, 2011) or in Europe (BRE, 2011). They are often defined by a ratio, and are easy to understand and compute. The indicators of form and connectivity have been more and more developed theoretically but are rarely found in practice. The indicators of proximity are fairly intuitive and provide average travel distances, which remain relatively easy for readers to imagine and transpose. On the other hand, the indicators of diversity are almost never used and cover different meanings and computation formulas. The indicators of distribution are sometimes conflated with those of diversity, which is why it seemed appropriate to expand at greater length on these two types of indicators.

Focus on a few concepts

Parameters of urban form

Indicators of the urban form type describe the components of the urban fabric. These indicators give details on the morphology of buildings, streets and urban networks.

Volumetric Compactness is one of the most useful indicators to analyse heating needs. There are three varieties of compactness, shown in Table 1: Traditional Compactness, equal to the surface area, *S*, of the building's envelope over the volume of the building; the Size Factor, corresponding to the equivalent cube of its length; and the Form Factor, which is adimensional and from which the bias introduced by the different size of the analysed objects has been removed.

Other relevant indicators shown in Table 2 assess the morphology of streets and the verticality. For example, the Index of Street Form is a determining factor for the wind flow throughout the city, impacting as much natural cooling as the dispersion of pollutants. The Verticality Index simply measures the city's verticality: the higher the index, the more vertical the city.

Mixed-use, diversity and variety

Mixed use and diversity have been advocated by numerous authors. Breheny (1992) argues in favour of mixed use, and suggests that zoning should be avoided and discouraged for more sustainable cities. According to Jabareen (2006), numerous authors have shown the impact of mixed-use on transportation patterns and on associated energy consumptions. By decreasing the travel distances between activities (Parker, 1994), it decreases car use (Alberti, 2000; Van and Senior, 2000) and encourages cycling and walking (Thorn and Filmer-Sankey, 2003). Kenworthy

Table 1 Three formulas for building compactness

Traditional compactness	Size factor	Form factor
$C = \frac{S}{V}$	$V^{1/3}$	$C = \frac{S}{V^{2/3}}$

Note: C = compactness, S = surface, V = volume

Table 2 Indexes for streets morphology

Street form index	Verticality index
$\frac{H}{W}$	$\frac{H^2}{S}$
where *H* designates the height of buildings; and *W* is street width	where *H* designates the height of buildings; and *S* is the surface area of the selection (building, district or city)

(2006) presents it as the first key dimension for sustainable city, along with compactness.

Jane Jacobs has popularized diversity as an essential aspect of urban sustainability:

> In dense, diversified city areas, people still walk, an activity that is impractical in the suburbs and in most grey areas. The more intensely various and close-grained the diversity in an area, the more walking. Even people who come into a lively, diverse area from outside, whether by car or by public transportation, walk when they get there.
> (Jacobs, 1961, p. 230)

According to Wheeler (2002), it is a key point to produce attractive urban landscapes. Diversity is even promoted by the Congress for the New Urbanism and US Department of Housing and Urban Development (2000) that advocates for greater variety of housing types, building densities, household sizes, ages, cultures and incomes.

Assessing mixed use, variety and diversity within a city though is a complex task, and very little literature tackles this issue properly. This section aims to distinguish between the different concepts and finds the appropriate tool for each.

Mixed use and diversity

The LEED Neighborhood Development (US Green Building Council (USGBC), 2011) grants points for mixed-use projects. One of the criteria is to locate 50% of the dwelling units within a quarter mile walk distance of the number of diverse amenities. To assess the diversity of households, it uses Simpson's index, given by equation (1):

$$I_{\text{Simpson}} = 1 - \Sigma_{i=1}^{20}\left(\frac{n_i}{N}\right)^2 \quad (1)$$

where n_i is the number of households of the ith category; and N is the total number of households. The diversity of households aims at promoting:

> socially equitable and engaging communities by enabling residents from a wide range of economic levels, households, and age groups to live in a community.
> (USGBC, 2011)

The more equitable the distribution, the closer to 1 it is. If the households belong to only one category, the index equals zero. The project is granted points if this index is greater than 0.5. This index is maximal and equal to 1 for an isodistribution: there is the same number of housing for each category. The use of this type of index can be widened to many other fields of urban sustainability, notably to assess the spatial distribution of elements in the city.

Spatial distribution

The spatial distribution of urban elements such as parks, shops or amenities is a fundamental aspect of urban equity. Spatial distribution stands for the way these elements are – equitably or inequitably – distributed on a given zone. To assess a spatial distribution, one needs to choose a couple of scales: a city and its districts; or a district and its neighbourhoods, for instance. An equitable spatial distribution is achieved when the quantity of elements (*e.g.* the area of parks) on the wider scale (*e.g.* the city) is distributed equitably among districts. If there are 100 ha of parks within a city constituted of ten districts of the same area, an equitable spatial distribution is 10 ha in each district.

Simpson's index provides a mathematical formula for this. Assume that Q districts exist in the city, each having an overall area of S_i (m^2) and A_i of green areas (m^2). This index quantifies how evenly the green areas are distributed within a city. The bigger the index, the better the distribution. The ratio in front of the formula aims at normalizing the indicator to allow comparisons more easily (Salat *et al.*, 2010):

$$I_{\text{spatial distribution}} = \frac{Q}{Q-1}\left[1 - \Sigma_{\text{district}=1}^{Q}\left(\frac{A_i}{S_i}\right)^2\right] \quad (2)$$

Structural objective

However, Simpson's index is not adequate in many cases. It notably fails for situations in which an even-distribution is not a good objective. For a wide range of situations indeed, the 'right' distribution of elements is not the isodistribution that is implicitly targeted by Simpson's index. The optimal distribution often relies on a wide range of constraints: socio-economic, policy orientations, etc. Consider the mix between offices, shops and housings within a district. Using Simpson's index boils down to recommend an isodistribution: 33% offices, 33% shops and 33% housing. This would be absolutely arbitrary. In this case, the building-use mix may instead be decided by taking into account numerous socio-economic factors. An objective has to be set by policy-makers and local authorities, for instance 25% of offices, 25% of shops and 50% of housing as a ten-year objective. The index proposed is a steering tool for such policy, quantifying the distance of the current distribution (n_i) to the targeted distribution (n_i^{obj}). The smaller this indicator, the closer is the distribution to the target:

$$I_{\text{obj}} = \frac{1}{\text{Cat}}\Sigma_{i=1}^{\text{Cat}}\left[\frac{n_i - n_i^{\text{obj}}}{n_i^{\text{obj}}}\right]^2 = \frac{1}{\text{Cat}}\Sigma_{i=1}^{\text{Cat}}\left[1 - \frac{n_i}{n_i^{\text{obj}}}\right]^2 \quad (3)$$

An example of this follows. If the 2020 objective is the arbitrary example cited above (25%, 25%, 50%) and if the 2010 current distribution is 50%, 25%, 25%, then the index assesses the relative deviation of the actual distribution to the objective:

$$I_{\text{obj}\,2010} = \frac{1}{3}\left[\left(1-\left(\frac{\frac{1}{2}}{\frac{1}{4}}\right)\right)^2 + \left(1-\left(\frac{\frac{1}{4}}{\frac{1}{4}}\right)\right)^2 + \left(1-\left(\frac{\frac{1}{4}}{\frac{1}{2}}\right)\right)^2\right] = 0.42$$

If the distribution improves to 33%, 33%, 33% in 2015, the index decreases (the deviation is smaller):

$$I_{\text{obj 2015}} = 0.11$$

Scale hierarchy

The last situation concerns objects with different spatial scales. Several papers have stressed the role of scale hierarchic structures on the structural efficiency of cities (Salingaros and West, 1999; Salat and Bourdic, 2011a, 2011b). The scale hierarchy of urban structures and networks has a tremendous influence on energy efficiency. Following Alexander's *et al.*'s (1987) recommendations, it also has a significant role in urban projects financing.

This formula quantifies the distance of the actual distribution of elements (n_i elements of size x_i) to the optimal scale hierarchic distribution p_i which is given by the following formula from Salingaros and West (1999):

$$p_i = \frac{A}{x_i^m} \quad (4)$$

where A is a constant; and m is the exponent of the inverse power law distribution. Salat *et al.* (2010) provides detailed calculations for A and m parameters. The deviation of the actual distribution to this optimal one is calculated as follows:

$$Cpx_{\text{scale}} = \frac{1}{\text{Cat}}\Sigma_{i=1}^{\text{Cat}}\left[\frac{n_i - \frac{A}{x_i^m}}{\frac{A}{x_i^m}}\right]^2 = \frac{1}{\text{Cat}}\Sigma_{i=1}^{\text{Cat}}\left[1 - \frac{n_i x_i^m}{A}\right]^2 \quad (5)$$

where Cat is the number of scale categories within the urban structure analysed. The smaller the index, the closer the distribution is to a scale-hierarchic distribution. This complexity index is for instance useful to quantify the efficiency of street networks, urban parcels distributions, urban projects financing, etc.

Indicator system

Table 3 provides the system of spatial indicators described above, ranging from classic intensities (energy intensity, job intensity, etc.) to more specific indexes dealing with urban complexity:

- the first column of Table 3 indicates the theme of the indicator: land use, mobility, etc.
- the second column stands for the three pillars of urban sustainability: socio-economic, environment and urban form.
- the third column stands for the type of indicator: intensity, distribution, proximity, etc.; a brief explanation of the indicators is given in the third column
- the scale on which the indicator should be calculated stands in the fourth column; five scales are used: the city scale (City), district scale (D), neighbourhood scale (N), block scale (bl) and building scale (B)

The full system is given in the Appendix, with all mathematical formulas to calculate the indicators' values.

Some benchmarks

This section provides further details on several indicators. The objective of each indicator is explained, as well as the method to quantify it. Eventually, benchmarks of these indicators have been calculated for existing cities and displayed in Figures 1–3.

The connectivity of the street network is a critical aspect of transport resilience. Creating enough intersections multiplies the number of possible routes, reduces distances and traffic jams, and makes places more easily accessible to pedestrians. This connectivity of the street network can be assessed using the

Table 3 New system of spatial indicators for urban sustainability

Theme	Concepts of triptych	Indicator type	Name	Scale
Land use	Urban form	Intensity	Human density	D/N
			Building density	D/N
			Housing density	D/N
			Density of legal entities	D/N
			Job density	D/N
			Coefficient of land occupancy	D/N
			Subdivision intensity	D/N
		Diversity	Diversity of subdivisions size	D/N
			Diversity of land use (road network, built environment, courtyards, green spaces)	D/N
			Diversity of subdivision use (housing, offices, shops, public facilities, etc.)	D/N
Mobility	Urban form	Intensity	Surface occupied by pedestrian and bicycle paths	D/N
			Surface occupied by the road network	City/D
			Proportion of the road network dedicated to public transport	D
		Connectivity	Connectivity of the pedestrian/bike grid	D/N
			Connectivity of the car grid	D
			Cyclomatic complexity of the car grid	D
			Cyclomatic complexity of the pedestrian/bike grid	N
			Average distance between intersections (bike/pedestrian grid)	D/N
			Average distance between intersections (car grid)	D
		Proximity	Percentage of the population more than 300 m away from a public transport stop	City/D
		Diversity	Number of public transport modes accessible within of 300 m	D
		Complexity	Scale hierarchy of the street network	City/D
Water	Environmental	Intensity	Hydrological intensity	D
			Impermeability of land	D
			Intensity of water treatment: rate of wastewater collection and treatment	City/D
			Efficiency of water use	City
			Accessibility of drinking water	City/D
Biodiversity	Environmental/ urban form	Intensity	Proportion of agricultural surfaces	City/D
			Proportion of green fabric	D
		Connectivity	Connectivity of green habitats	D
		Distribution	Distribution of green spaces (distance from an even distribution)	City/D
Equity	Socio-economic	Intensity	Proportion of jobs in relation to housing	D/N
			Proportion of social housing	D/N
		Diversity	Diversity of ages (structural distribution)	D/N/bl
			Diversity of incomes (structural diversity)	D/N/bl
Economy	Socio-economic	Intensity	Resource productivity	City
			Intensity of learning activities	D
			Job potential	D
		Diversity	Structural diversity of jobs	
			Structural diversity of uses (shops, offices, housing, public buildings: schools, administrations, etc.)	City/D
	Urban form/ socio-economy	Proximity	Percentage of residents living less than *x* from a convenience store	D
		Distribution	Distance of the distribution of each district from the global distribution of shops, offices, housing or public buildings	City
Waste	Environmental	Intensity	Proportion of recycled materials in the construction of new buildings	City/D
			Productivity of urban metabolism	City/D
			Intensity of greenhouse gas emissions per resident	City/D
			Intensity of emissions to produce wealth	City/D
Culture/well-being	Social	Intensity	Noise pollution	D/N
			Intensity of cultural activities	City/D
	Urban/social	Proximity	Proximity of leisure facilities	D

(*Table continued*)

Table 3 Continued

Theme	Concepts of triptych	Indicator type	Name	Scale
Energy and bioclimatic	Environmental	Intensity	Energy intensity per resident	D/N
			Surface energy intensity	D/N
			Proportion of local production	D/N
			Rate of renewable energy used	City D
			Rate of energy reuse	City D
	Urban form	Form	Volumetric compactness	N/B
			Size factor	N/B
			Form factor	N/B
			Rate of passive volume	N/B
			Energy consumed for heating	D/N/bl/B
			Energy consumed for air-conditioning	D/N/bl/B

Note: City = city scale; D = district scale; N = neighbourhood scale; and B = block scale.

intensity of intersections. Having numerous intersections points in a street network increases the number of possible ways and reduces the distances to go from one point to another, since the traveller's journey is closer to a diagonal. In a circle with a radius of 500 m, if there are many close intersections, the number of accessible places is greater as compared with a star-shaped configuration of roads with no intersections. Consequently, minimizing the number of intersections does not necessarily help the flow of traffic. But maximizing it is not the solution either. It would turn the city into a maze, and increase the area occupied by the streets at the expense of buildings, parks and green spaces.

The indicator can be calculated using the following formula:

$$\text{Connectivity} = \frac{\text{number of intersections}}{\text{seletion area (km}^2)} \qquad (6)$$

Figure 1 displays this indicator for several cities, from car-oriented cities (low values), to pedestrian friendly cities like central *arrondissements* in Paris, Tokyo or Venice.

The average distance between intersections is also a proxy of how pedestrian-friendly a city is. It ultimately determines the distances to be crossed and the sense of whether or not it is possible to walk to one's destination. People will decide to walk instead of using another mode of transportation if their destination is less than 500 m away, on average. To increase the number of destinations that can be reached by walking, cities have to be dense, but distances between intersections must be reduced. Figure 2 displays this indicator (in metres) for several cities.

The cyclomatic number is another indicator of connectivity. It is linked to the number of existing roads to go from one point to another. In this sense, it is a good way to quantify redundancy in a transport network, be it a street network or a public transport network. The cyclomatic number represents the number of primary loops in the network. The greater the number of loops, the greater the number of possible routes in the city. Having straight roads to make travel as direct as possible and to accommodate as many vehicles as possible would seem to be the best way to resolve traffic problems. This configuration, however, tends to lead to increasingly wide roads and quickly reaches its limits. In actual fact, since particular travel routes are varied, it is more efficient to propose a multiplicity of smaller roads so users can choose and spread over these paths, which are ultimately better suited to the variety of their destinations. The cyclomatic number refers to this multiplicity of loops that increase the number of possible paths. In a public transport network with a high cyclomatic number, a failure in one station will not freeze an entire zone. Instead, the high redundancy will allow users to take

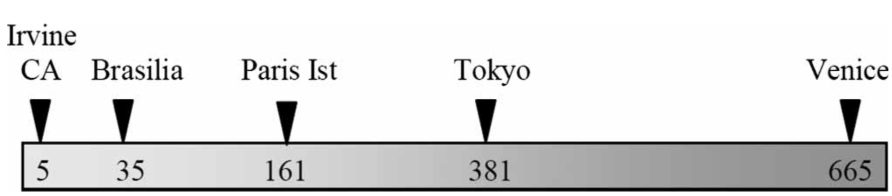

Figure 1 Street network connectivity for several cities (connexions per km^2)

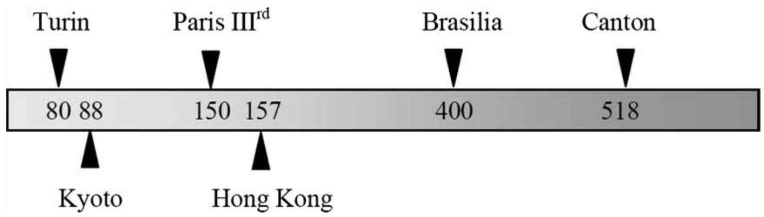

Figure 2 Average distance (m) between intersections for several cities

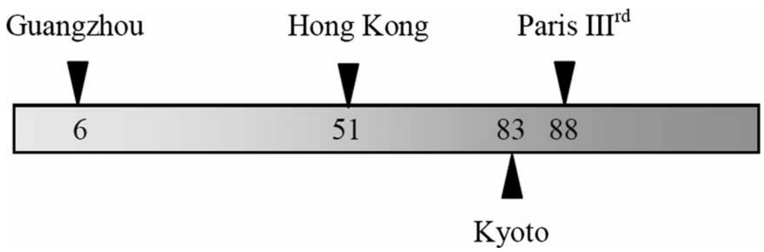

Figure 3 Cyclomatic number for several cities (for a 800 × 800 m mesh)

one of the various other paths to join their destination. This indicator is calculated using the following formula:

$$\mu = L - N + 1 \qquad (7)$$

where L is the number of links, corresponding to the different sections of streets between every intersections; and N is the number of nodes, corresponding in road networks to intersections.

This number is an adimensional parameter, but it cannot serve as a basis for a comparison of cities, unless identical surfaces are being compared. Either the same size selections have to be analysed, or this indicator has to be divided by the area, leading to a cyclomatic number per km^2. In Paris, for instance, the cyclomatic number of the street network is approximately 80 on the district scale (of 800 × 800 m). The cyclomatic number in a mixed-used city designed for pedestrians is between 40 and 100 on the district scale. Figure 3 displays the cyclomatic number for several cities.

Conclusions

Urban sustainability is deeply rooted in urban morphology. Although density is the most popular issue when it comes to urban form, this factor is only the visible part of the much larger iceberg. Urban morphology is significant for both socio-economic as well as environmental issues. It offers a point of view favouring an integrative and systemic approach, necessary to face and adapt to the challenges to come.

The presented research addresses a wide range of common sustainable development issues, while identifying new categories to describe the urban built environment. Urban morphology has an impact on the three common dimensions of sustainable development: economics, environment and society. It has also its place in each of their subgroups, very often identified in other assessment systems such as 'land use', 'mobility', 'water management', 'biodiversity', 'energy', 'equity', 'economy', 'well-being and culture', 'waste and materials'. These indicators can therefore easily complement other systems while offering innovative subcategories based on the underlying mathematic formula.

In fact, indicators used so far in most of the assessment systems can be confusing. They mix different mathematic equations without revealing them or explaining in detail what exact information they give. The categorization separating between 'intensity', 'spatial distribution', 'proximity', 'connectivity', 'diversity' and 'urban form' enables one to specify the meaning of the indicator, revealing what is computed in the indicator formula. Taking these variations into account, a weighting can be applied to the indicators, depending on chosen social, economic or environmental priorities, and on the study scale. However, it should not be forgotten that any weighting and aggregation of indicators into one global sustainability indicator would lead to a dramatic loss of information. The user can therefore balance the results and comprehend the converging or contradictory forces linking the indicators in the system. Highly flexible, without sacrificing details and precision in the analysis, this system offers an innovative view on urban sustainability.

These spatial indicators are useful tools to assess existing urban neighbourhood and districts, but they also provide beneficial insights for new urban developments. They do not aim at being prescriptive but should foster the policy-making and communication process. No exact target values should be given. Trying to optimize every indicator is inappropriate, as some of them are conflicting. Instead of exact target values, prescriptive ranges are preferred. Finally, this system of multiple scales and categories provides insights into today's urban world, while being flexible and empowering people to question and adapt it everywhere in the world.

References

Agència d'Ecologia Urbana de Barcelona (2007) *Plan Especial de indicadores de Sostenibilidad Ambiental de la Actividad Urbanistica de Sevilla*, Ayuntamiento de Sevilla, Seville.

Alberti, M. (2000) Urban form and ecosystem dynamics: empirical evidence and practical implications, in K. Williams, E. Burton and M. Jenks (eds): *Achieving Sustainable Urban Form*, E&FN Spon, London, pp. 84–96.

Alexander, C., Neis, H. and Anninou, A. (1987) *A New Theory of Urban Design*, Oxford University Press, New York, NY.

Bourdic, L. and Salat, S. (2012). Building energy models and assessment systems at the district and city scales: a review. *Building & Research Information*, **40**(4), 518–526.

Breheny, M. (ed.) (1992) *Sustainable Development and Urban Form*, Plon, London.

Building Research Establishment (BRE) (2011) *BREEAM for Communities: Stage 2. Technical Guidance Manual: Version 1*, BRE, Watford.

Cole, R. (2011) Envromental issues past, present & future: changing priorities & responsibilities for building design. Keynote Introduction presented at SB11 Conference, Helsinki, Finland, 18 October, 2011.

Comprehensive Assessment System for Building Environmental Efficiency (CASBEE) (2007) *CASBEE UD* (available at: http://www.ibec.or.jp/CASBEE/english/download.htm) (accessed on 12 November 2011).

Congress for the New Urbanism and US Department of Housing and Urban Development (2000) *Principles for Inner City Neighborhood Design* (availableat: http://www.huduser.org/Publications/pdf/principles.pdf) (accessed on 24 April 2012).

Jacobs, J. (1961) *The Death and Life of Great American Cities*, Random House, New York, NY.

Kellett, R. (2009a) Sustainability Indicators for Computer-based Tools in Community Design, Volume 1. Canada Mortgage and Housing Corporation, Ottawa, ON.

Kellett, R. (2009b) Sustainability Indicators for Computer-based Tools in Community Design, Volume 2. Canada Mortgage and Housing Corporation, Ottawa, ON.

Kenworthy, J. (2006) The eco-city: ten key transport and planning dimensions for sustainable city development. *Environment and Urbanization*, **18**, 67–85.

Leadership in Energy and Environmental Design (LEED) (2009) *LEED 2009 for Neighborhood Development Rating System*, Congress for the New Urbanism, Natural Ressources Defense Council and the US Green Building Council, Washington, DC.

Murakami, S., Kawakubo, S. and Asami, Y. (2011) Development of a comprehensive city assessment tool: CASBEE-City. *Building Research & Information*, **39**(3), 195–210.

Oke, T. (1981) Canyon geometry and the nocturnal urban heat island: comparison of scale model and field observation. *Internal Journal of Climatology*, **1**(3), 237–254.

Oke, T. (1988) Street design and urban canopy layer climate. *Energy and Building*, **11**(1–3), 103–113.

Parker, T. (1994) *The Land Use–Air Quality Linkage: How Land Use and Transportation affect Air Quality*, California Air Resources Board, Sacramento, CA.

Ratti, C., Baker, N. and Steemers, K. (2005) Energy consumption and urban texture. *Energy and Buildings*, **37**(7), 762–776.

Salat, S. (2009) Energy loads, CO_2 emissions and building stocks: morphologies, typologies, energy systems and behavior. *Building Research & Information*, **37**(5/6), 598–609.

Salat, S. and Bourdic, L. (2011a) Power laws for energy efficient and resilient cities. *Procedia Engineering*, **21**, 1193–1198.

Salat, S. and Bourdic, L. (2011b) Scale hierarchy, exergy maximisation and urban efficiency, *Proceedings of the 2nd International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium (ELCAS-2)*, 19–21 June, Nisyros, Greece.

Salat, S., Bourdic, L. and Nowacki, C. (2010) Assessing urban complexity. *SUSB*, **1**(2), 160–167.

Salingaros, N. and West, B. (1999) A universal rule for the distribution of sizes. *Environment and Planning B: Planning and Design*, **26**, 909–923.

Thorn, R. and Filmer-Sankey, W. (2003) Transportation, in T. Randall and M. Fordham (eds): *Sustainable Urban Design*, Spon, London, pp. 25–32.

US Green Building Council (USGBC) (2011) *LEED Neighborhood Development*. LEED Rating System 2nd Public Comment Draft, USGBC, Washington, DC.

Van, U.-P. and Senior, M. (2000) The contribution of mixed land uses to sustainable travel in cities, in K. Williams, E. Burton and M. Jenks (eds): *Achieving Sustainable Urban Form*. E&FN Spon, London, pp. 139–148.

Von Weizsäcker, E., Lovins, A. and Lovins, L. (1997) *Factor Four, Doubling Wealth, Halving Resource Use – A Report to the Club of Rome*, Earthscan, London.

Wheeler, S. (2002) Constructing sustainable development/safeguarding our common future: rethinking sustainable development. *Journal of the American Planning Association*, **68**(1), 110–111.

Appendix: Spatial cross scale indicators

Theme	Concepts of triptych	Indicator type	Name	Scale	Formula
LAND USE	Urban form	Intensity	Human density	D/N	$\frac{population}{area\ of\ the\ selection\ (m^2)}$
			Building density	D/N	$\frac{floor\ area\ (m^2)}{area\ of\ the\ selection\ (m^2)}$
			Housing density	D/N	$\frac{Nb\ of\ housings}{area\ of\ the\ selection\ (m^2)}$
			Density of legal entities	D/N	$\frac{Nb\ of\ legal\ entities}{area\ of\ the\ selection\ (m^2)}$
			Job density	D/N	$\frac{Nb\ of\ jobs}{area\ of\ the\ selection\ (m^2)}$
			Coefficient of land occupancy	D/N	$\frac{land\ occupancy\ (m^2)}{area\ of\ the\ selection\ (m^2)}$
			Subdivision intensity	D/N	$\frac{Nb\ of\ parcels}{area\ of\ the\ selection\ (m^2)}$
		Diversity	Diversity of subdivisions size	D/N	$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{S_{tot\,i}S_i{}^{m}}{A}\right]^2$
			Diversity of land use (road network, built environment, courtyards, green spaces)	D/N	$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{obj}}\right]^2$
			Diversity of subdivision use (housing, offices, shops, public facilities, etc.)	D/N	$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{S_i}{S_i^{obj}}\right]^2$
MOBILITY	Urban form	Intensity	Surface occupied by pedestrian and bicycle paths	D/N	$\frac{area\ occupied\ by\ pedestrian\ and\ bicycle\ paths}{area\ of\ the\ selection\ (m^2)}\ X\ 1$
			Surface occupied by the road network	City /D	$\frac{area\ of\ the\ road\ network\ (m^2)}{area\ of\ the\ selection\ (m^2)}\ X\ 100$
			Proportion of the road network dedicated to public transport	D	$\frac{area\ dedicated\ to\ public\ transport (m^2)}{total\ area\ dedicated\ for\ transport\ \ (m^2)}\ X\ 100$
		Connectivity	Connectivity of the pedestrian/bike grid	D/N	$\frac{Nb\ of\ intersections\ of\ the\ pedestrian/bike\ grid}{area\ of\ the\ selection\ (m^2)}$
			Connectivity of the car grid	D	$\frac{Nb\ of\ intersections\ of\ the\ car\ grid}{area\ of\ the\ selection\ (m^2)}$
			Cyclomatic complexity of the car grid	D	$\mu = L - N + 1$; L= Nb of links; N=Nb of nodes
			Cyclomatic complexity of the pedestrian/bike grid	N	$\mu = L - N + 1$; L= Nb of links; N=Nb of nodes
			Average dist. btw intersections (bike/ped. grid)	D/N	

			Average distance between intersections (car grid)	D	
		Proximity	Proportion of the population more than 300 meters away from a public transport stop	City /D	$\frac{Pop.\ more\ than\ 300\ m\ away\ from\ p.t.}{Population}\ X\ 100$
		Diversity	Number of public transport modes accessible within of 300 meters	D	
		Complexity	Scale hierarchy of the street network	City /D	$S=\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{n_i x_i{}^m}{A}\right]^2$ n_i the nb of streets of width x_i (per category)
WATER	Environmental	Intensity	Hydrological intensity	D	% of natural hydrological functions preserved or restored
			Impermeability of land	D	$\frac{Impermeable\ area(m^2)}{area\ of\ the\ selection\ (m^2)}$
			Intensity of water treatment: Rate of wastewater collection and treatment	City /D	$\frac{volume\ of\ collected\ and\ treated\ water\ (m^3)}{volume\ of\ water\ consumed\ (m^3)}$
			Efficiency of water use	City	$\frac{water\ needs(m^3)}{water\ consumption\ (m^3)}\ X100$
			Accessibility of drinking water	City /D	% of the population with access to drinking water
BIODIVERSITY	Environmental/ urban form	Intensity	Proportion of agricultural surfaces	City /D	$\frac{agricultural\ land\ area(m^2)}{area\ of\ the\ selection\ (m^2)}\ X100$
			Proportion of green fabric	D	$\frac{green\ fabric\ area\ (m^2)}{area\ of\ the\ selection\ (m^2)}\ X100$
		Connectivity	Connectivity of green habitats	D	$\frac{area\ of\ connected\ green\ habitats\ (m^2)}{total\ area\ of\ green\ habitats\ (m^2)}\ X100$
		Distribution	Distribution of green spaces (distance from an even distribution)	City /D	$\frac{Q}{Q-1}\left[1-\sum_{quartier=1}^{Q}\left(\frac{S_{green\ area_{district\ i}}}{S_{district\ i}}\right)^2\right]$
EQUITY	Socio-economic	Intensity	Proportion of jobs in relation to housing	D/N	$\frac{Nb\ of\ jobs}{Nb\ of\ housings}$
			Proportion of social housing	D/N	$\frac{Nb\ of\ social\ housing}{Nb\ of\ housing}$

		Diversity	Diversity of ages (structural distribution)	D/N /bl	$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{nb\ of\ people_{cat\ age\ i}}{\text{nb of people}_{\text{cat age i}}^{\text{obj}}}\right]^2$
		Diversity	Diversity of incomes (structural diversity)	D/N /bl	$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{nb\ of\ people_{income\ i}}{\text{nb of people}_{\text{income i}}^{\text{obj}}}\right]^2$
ECONOMY	Socio-economic	Intensity	Resource productivity	City	$\frac{material\ consumption\ (kg)}{GDP}$
ECONOMY	Socio-economic	Intensity	Intensity of learning activities	D	$\frac{learning\ activies\ (Nb\ legal\ entities)}{Total\ number\ of\ legal\ entities}$
ECONOMY	Socio-economic	Intensity	Job potential	D	$\frac{Nb\ of\ jobs}{Nb\ of\ active\ people}$
ECONOMY	Socio-economic	Diversity	Structural diversity of jobs		$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{nb\ jobs_{cat\ i}}{\text{nb jobs}_{\text{i}}^{\text{obj}}}\right]^2$
ECONOMY	Socio-economic	Diversity	Structural diversity of uses (shops, offices, housing, public buildings: schools, administrations, etc.)	City /D	$\frac{1}{Cat}\sum_{i=1}^{Cat}\left[1-\frac{Nb\ legal\ entities_{cat\ i}}{Nb\ legal\ entities_{\text{cat i}}^{\text{obj}}}\right]^2$
ECONOMY	Urban form/socio-economy	Proximity	% of residents living less than X from a convenience store	D	
ECONOMY	Urban form/socio-economy	Distribution	Distance of the distribution of each district from the global distribution of shops (in equation), or offices, or housing, or public buildings (schools, administrations, etc.)	City	$\frac{Q}{Q-1}\left[1-\sum_{quartier=1}^{Q}\left(\frac{Nb\ legal\ ent_{shops_{district\ i}}}{Nb\ legal\ ent_{district\ i}}\right)^2\right]$
WASTE	Environmental	Intensity	Proportion of recycled materials in the construction of new buildings	City /D	$\frac{quantity\ of\ recycled\ materials\ (m^3)}{total\ quantity\ of\ material\ used(m^3)}$
WASTE	Environmental	Intensity	Productivity of urban metabolism	City /D	$\frac{quantity\ of\ waste\ produced\ (kg)}{quantity\ of\ waste\ imported\ in\ the\ city\ (kg)}$
WASTE	Environmental	Intensity	Intensity of GHG emissions per resident	City /D	$\frac{GHG\ emissions\ (kg\ eq\ C02)}{population}$
WASTE	Environmental	Intensity	Intensity of emissions to produce wealth	City /D	$\frac{GHG\ emissions\ (kg\ eq\ C02)}{GDP}$
CULTURE / WELL-BEING	Social	Intensity	Noise pollution	D/N	% of people exposed to noises louder than 70 decibels between 8 am and 8 pm
CULTURE / WELL-BEING	Social	Intensity	Intensity of cultural activities	City /D	$\frac{Nb\ of\ cultural\ activities\ per\ year}{population}$

	Urban / social	Proximity	Proximity of leisure facilities	D	% residents less than X m from a leisure facility
ENERGY and BIOCLIMATIQUE	Environmental	Intensity	Energy intensity per resident	D/N	$\frac{Energy\ consumption\ (kWh)}{population}$
			Surface energy intensity	D/N	$\frac{Energy\ consumption\ (kWh)}{floor\ area}$
			Proportion of local production	D/N	$\frac{locally\ produced\ energy\ (kWh)}{energy\ consumption\ (kWh)} X100$
			Rate of renewable energy used	City D	$\frac{renewable\ energy\ (kWh)}{energy\ consumption\ (kWh)} X100$
			Rate of energy reuse	City D	$\frac{reused\ energy\ (kWh)}{energy\ consumption\ (kWh)} X100$
	Urban form	Form	Volumetric compactness	N/B	$C = \frac{\sum S_i}{\sum V_i}$
			Size factor	N/B	$\alpha = \frac{1}{(\sum V_i)^{\frac{1}{3}}}$
			Form factor	N/B	$C_{adim} = \frac{\sum S_i}{(\sum V_i)^{\frac{2}{3}}}$
			Rate of passive volume	N/B	$Rate_{passive\ volume} = \sum V_{i\ passive} / \sum V_i$
			Energy consumed for heating	D/N /bl/B	$\frac{energy\ consumption\ for\ heating (kWh)}{floor\ area\ (m^2)}$
			Energy consumed for air-conditioning	D/N /bl/B	$\frac{energy\ consumption\ for\ cooling\ (kWh)}{floor\ area\ (m^2)}$