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Multidimensional sustainability benchmarking for smart megacities

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ABSTRACT

This paper is focused on sustainability assessment for some of the most prominent global megacities: London, New York, Hong Kong, Los Angeles, Sao Paolo, Rio de Janeiro, Paris, Berlin, Moscow, Beijing, Singapore, Shanghai, Sydney and Tokyo. The alternative city rankings are compared and linkages between different sustainability and smart city dimensions are explored. The paper applied ELECTRE III multi-criteria decision aid tool to a panel of twenty indicators. The proposed approach allowed considering performance under four different policy priorities: environmental, economic, social and smart, changing the focus of the sustainability assessment. The results have shown that Singapore dominates the sustainability rankings under environmental policy priorities. Tokyo leads under economic and social priorities, and London and Tokyo – under smart city priorities. The worst performing cities were Shanghai, Los Angeles and Rio de Janeiro. The paper examines the innovative sustainability strategy and new governance structures that led Singapore to become the most sustainable city under environmental priorities and offers recommendations for the lower-ranking cities of Shanghai, Los Angeles and Rio de Janeiro. The assessment could be a valuable tool for policy makers and investors, and could help identify linkages between different sustainability dimensions, highlighting best practices as well as strategic opportunities in cities with sustainability potential.

1. Introduction

Urban sustainability is defined as a multi-dimensional capacity of a city to operate successfully in economic, social and environmental domains simultaneously (Shmelev and Shmeleva, 2018). The subject of sustainable cities has been explored by Hall and Pfeiffer (2000), Hall, Buijs, Tan, and Tunas (2010), Hall (2014), Girardet (1993, 2004, 2014), Shmelev and Shmeleva (2009). The multidimensional nature of an urban system defines a central analytical approach for sustainability assessment of cities used in this paper, namely the methodology of Multi-Criteria Decision Aid, following an approach outlined in our earlier work (Shmelev, 2017b). Urban sustainability is highlighted as one of the important dimensions in UNEP Green Economy Report (UNEP, 2011). UN Sustainable Development Goals include Goal 11 'Sustainable Cities and Communities', which aims to 'make cites and human settlements inclusive, safe, resilient and sustainable' (UN, 2015b). Urban sustainability has been the focus of the recent HABITAT III forum held in Quito, Ecuador in 2016 where the New Urban Agenda was firmly linked with UN Sustainable Development Goals (2015, 2016). The United for Smart and Sustainable Cities initiative (UNECE and ITU, 2016) pioneered a systemic thinking connecting urban smart and sustainable dimensions at the international scale.

In this paper we compare fourteen major global megacities to assess urban sustainability, identify the sustainability leaders as well as cities experiencing the strongest sustainability challenges. We use a strong sustainability focused Multi-Criteria Decision Aid (MCDA) tool, ELimination Et Choix Traduisant la REalité, ELECTRE III, which is characterised by a limited degree of compensation among criteria. The paper aims to test environmental, economic, social and smart policy priorities within an MCDA framework to assess the balance between sustainability dimensions and provide guidance for policy makers. The assessment is based on a set of twenty urban sustainability indicators. We conclude with a description of sustainability strategies and policies adopted in the leading city of our pool, which could help us to understand its success.

The article is organized as follows. Section 1 offers an introduction to the topic. Section 2 provides a review of ecological-economic applications for urban sustainability. Section 3 discusses data and indicators used. Section 4 presents the cross-sectional analysis of linkages among various urban sustainability indicators. Section 5 discusses the methodology and application of the ELECTRE method. Section 6 discusses the sustainability strategies and policies in the city identified as a sustainability leader and, at the same time, proposes certain steps for lower ranked cities. Section 7 concludes.

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Table 1
Studies focused on application of ecological-economic methods to water, resource waste and CO_2 emissions reduction issues in various cities[1].

Dimensions methods	Water	Resources	Waste	Emissions CO_2	Smart City
MFA	Milan (2014)[2] Berlin (2013)[3] Delhi (2013)[4] Lagos (2013)[5] Oslo (2011)[6] New York (2006)[7] Beijing (2009)[8]	Lisbon (2014)[9] Paris (2009)[10] Singapore (2008)[11] Hambourg (2006)[12] Leipzig (2006)[13] Vienna (2006)[14] Beijing (2009)[15] Hong Kong (1978)[16]	London (2011)	San Francisco (2004)[17] London (2009)[18] Paris (2011)[19] New York (2012)[20] Rio de Janeiro (2011)[21]	Stockholm (2015)[22], Atlanta and London (2013)[23]
Input-Output	Beijing (2012)[24] Chongquing (2006)[25]	Beijing (2010)[26]	Suzhou (2012)[27] Seattle (2012)[28] Chongquing (2006)[29]	Helsinki (2013)[30] Beijing (2013)[31] Copenhagen (2011)[32] Sydney (2004)[33]	South Korea (2016)[34]
Optimization	Tabriz (2010)[35] Shanghai (2012)[36] Sydney (2012)[37]		Mexico (2013)[38] Taichung (2012)[39] Beijing (2011)[40]		Savona, Zaanstad, Sant Cugat (2017)[41]
MCDA	Granada (2012)[42] Athens (2012)[43] Berlin (2004)[44]		Beijing (2010)[45], Kampala (2013)[46], New York (2006)[47], Amsterdam (2006)[48], Moscow (2006)[49], Budapest (2006)[50] Barcelona (2006)[51]	Paris (1982)[52]	Oslo (2015)[53]

1 The sources of relevant case studies are mentioned in subsequent sections further in the text.
2 Vanham and Bidoglio (2014).
3 Hoff et al. (2013).
4 Hoff et al. (2013).
5 Hoff et al. (2013).
6 Venkatesh and Brattebø (2012).
7 Jenerette et al. (2006).
8 Zhang, Yang, and Yu (2009).
9 Rosado, Niza, and Ferrão (2014).
10 Barles (2009).
11 Schulz (2007).
12 Hammer and Giljum (2006).
13 Hammer and Giljum (2006).
14 Hammer and Giljum (2006).
15 Zhang et al. (2009).
16 Newcombe, Kalma, and Aston (1978).
17 San Francisco Department for the Environment (2004).
18 City of London (2009).
19 Marie de Paris (2011).
20 City of New York (2012).
21 City of Rio de Janeiro (2011).
22 Sharokhni, Arman, Lazarevic, Nilsson, and Brand (2015).
23 Beck, Walker, and Thompson (2013).
24 Zhang, Shi, and Yang (2012).
25 Okadera, Watanabe, and Xu (2006).
26 Zhou, Chen, and Li (2010).
27 Liang and Zhang (2012).
28 Leigh, Choi, and Hoelzel (2012).
29 Hui et al. (2006).
30 Ala-Mantila, Heinonen, and Junnila (2013).
31 Chen et al. (2013).
32 Hallegatte et al. (2011).
33 Lenzen, Dey, and Foran (2004).
34 Kim, Jung, and Choi (2016).
35 Zarghami (2010).
36 Lü et al. (2012).
37 Mortazavi, Kuczera, and Cui (2012).
38 Santibañez-Aguilar et al. (2013).
39 Chang, Chu, and Lin (2012).
40 Dai, Li, and Huang (2011).
41 Papastamatiou, Marinakis, Doukas, and Psarras (2017).

[42] Ruiz-Villaverde, González-Gómez, and Picazo-Tadeo (2012).
[43] Kandilioti and Makropoulos (2012).
[44] Simon, Brüggemann, and Pudenz (2004).
[45] Xi et al. (2010).
[46] Oyoo, Leemans, and Mol (2013).
[47] Munda (2006).
[48] Munda (2006).
[49] Munda (2006).
[50] Munda (2006).
[51] Bautista and Pereira (2006).
[52] Roy and Hugonnard (1982).
[53] Milan, Kin, Verlinde, and Macharis (2015).

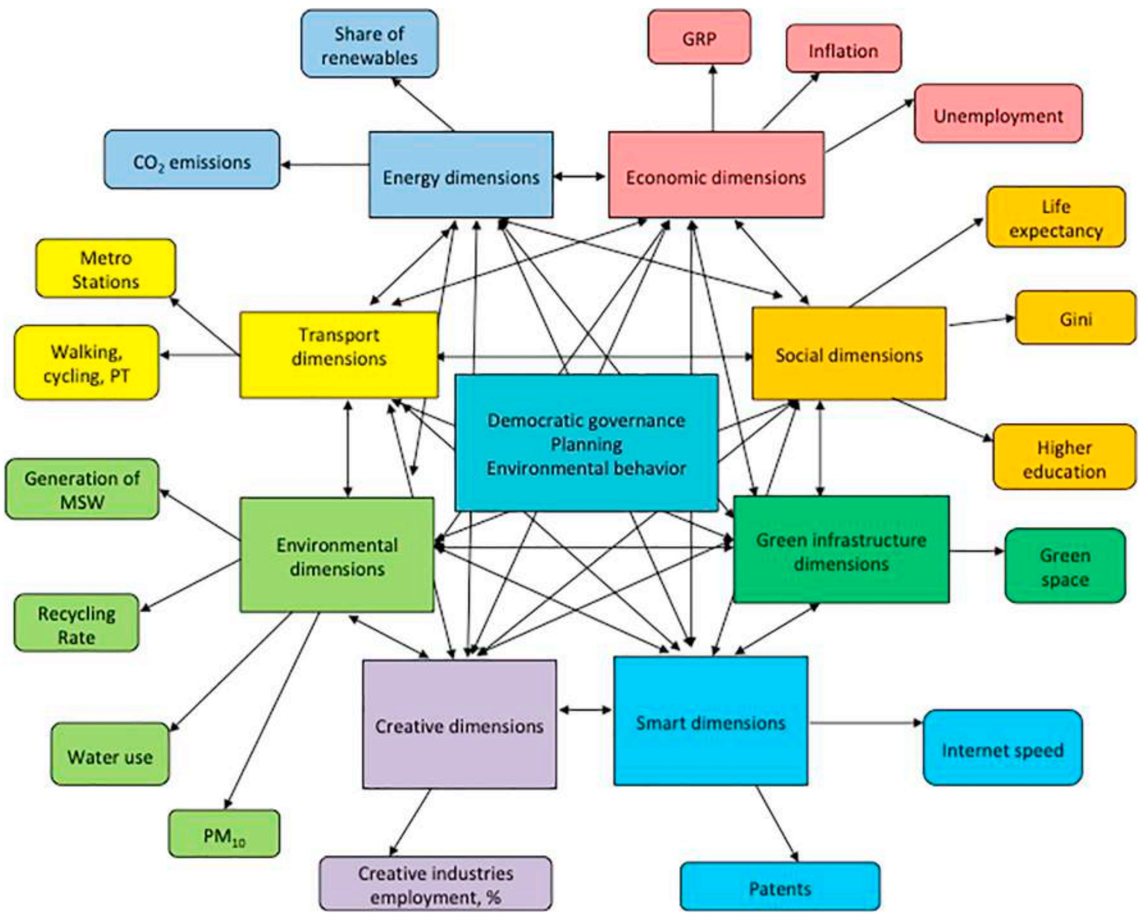

Fig. 1. Conceptual diagram of a Smart and Sustainable City Assessment Methodology.

2. Urban sustainability analysis methods

A spectrum of tools and methods used in sustainability science includes material flows analysis, input-output analysis, optimization and multi-criteria decision aid (Shmelev, 2012). These methods, traditionally used in ecological economics, industrial ecology and operations research could be successfully applied to urban systems to improve their sustainability performance. Table 1 reviews applications of ecological-economic methods mentioned above to urban systems, illustrating how the chosen methods were applied to several sustainability issues in urban systems: water, resources, waste and CO_2 emission.

Material flows analysis (MFA), is a tool invented by Robert Ayres, accounting for the weight of resources extracted domestically, imported and accumulated, processed or recycled in the national economy, and then emitted into nature in the form of gaseous, liquid or solid residues or exported (Eurostat, 2001), was first applied to cities in a study focused on Hong Kong (Newcombe et al., 1978). Later on, studies focused on Hamburg, Vienna and Leipzig appeared (Hammer & Giljum, 2006), followed by Singapore (Schulz, 2007), Beijing (Zhang et al., 2009), Paris (Barles, 2009) and Lisbon (Rosado et al., 2014). This research enhanced our understanding of the material flows at the city scale and contributed towards filling the gap in data availability. The method requires statistical datasets that exist at the national scale and are still very rare at the urban and regional level. Water and carbon footprints could be considered as partial cases of MFA.

Water Footprint[1] focuses on production-based and consumption-based water use, which illustrates the water requirements of an urban

[1] (http://waterfootprint.org/).

Table 2
Alternative urban smart and sustainability indicator systems.

Rating	Year	Organization	Number of indicators	Indicators	Cities	Source	Criticism	Results
Global Liveability Index	2018	Economist Intelligence Unit	30	Stability: 25%, 5; Healthcare: 20%, 6; Culture and the Environment: 25%, 9; Education: 10%, 3; Infrastructure: 20%, 7.	140	EIU (2018)	No sustainability: renewables, recycling,	Top: Vienna (1), Melbourne (2), Osaka (3), Calgary (4), Sydney (5), Vancouver (6), Toronto (7), Tokyo (8), Copenhagen (9), Adelaide (10); Bottom: Dakar, Algiers, Douala, Tripoli, Harare, Port Moresby, Karachi, Lagos, Dhaka, Damascus.
Resilient City Index	2016	Rockefeller Foundation	52	Health and wellbeing; Economy and society; Infrastructure and Environment; Leadership and strategy; 52 indicators	100	Rockefeller Foundation (2016)	Indicators are often qualitative and not concrete, huge data gaps: 56% in Liverpool	Not available
Global Prosperity Initiative	2015	UN HABITAT	72	Productivity: city product per capita, unemployment rate; Infrastructure: Improved shelter, improved water, physical density, internet access; traffic fatalities; Quality of life: life expectancy at birth, under-five mortality rate, literacy rate, mean years of schooling, homicide rate; Equity and Social Inclusion: Gini coefficient, poverty rate, slum households, youth unemployment, equitable secondary school enrolment; Environmental Sustainability: PM2.5 concentration; solid waste collection; CO2 emissions, share of renewable energy; Governance and Legislation: Voter turnout, days to start a business. 72 indicators	295	UN HABITAT (2016)	No track of Inflation; FDI, patents, creative industry employment, No trips made by public transport, no metro; no internet speed; No higher education or suicide rates; No water consumption, green space, waste generation, waste recycling, PM10, NO_2, SO_2	Oslo (1), Copenhagen (2), Stockholm (3), Helsinki (4), Paris (5), Vienna (6), Melbourne (7), Montreal (8), Toronto (9), Sydney (10).
Sustainable Cities Index	2016	Arcadis	32	People Planet Profit. Education: Literacy rate, University rankings, Share of population with tertiary education; Health: Life expectancy, Obesity rate; Demographics: Dependency ratio; Income Inequality: Gini coefficient; Affordability: Consumer Price Index, Property Prices; Work Life Balance: Average annual hours worked; Crime: Homicide rate; Environmental risks: Natural catastrophes exposure; Green Spaces: Green Space as % of city area; Energy: Energy use, Renewables share, Energy consumption per GDP; Air Pollution: mean level of pollutants; GHG emission per capita; Waste Management: Landfill vs Recycling; Wastewater treatment; Drinking water and sanitation: Access to drinking water %, Access to improved sanitation; Transport infrastructure: Congestion, Rail infrastructure, Airport satisfaction; Economic Development: GDP per capita; Ease of Doing Business: Index; Tourism: International visitors per year (absolute and per capita); Connectivity: mobile connectivity; Broadband connectivity; Importance in Global Networks; Employment: Number of people employed %.,	100	Arcadis (2016)	No track of inflation, patents, creative industry employment, public transport, metro, specific pollution metrics on PM_{10}, NO_2, SO_2, water consumption, waste generation.	Zurich (1), Singapore (2), Stockholm (3), Vienna (4), London (5), Frankfurt (6), Seoul (7), Hamburg (8), Prague (9), Munich (10).

(continued on next page)

Table 2 (*continued*)

Rating	Year	Organization	Number of indicators	Indicators	Cities	Source	Criticism	Results
Global Power City Index	2017	MORI Foundation	70	Economy: Nominal GDP, GDP per capita, GDP growth rate; Level of economic freedom; Total market value of listed shares on stock exchanges; World's to 500 companies; Total employment; Number of employees in service; Wage level; Ease of securing human resources; Office space per desk; Corporate Tax rate; Political, economic and business risk (13 all in all); Research and Development: Number of Researchers, Worlds top 200 universities; Academic Performance in Mathematics and Science; Readiness for Accepting Researchers; Research and Development Expenditure; Number of patents; Number of prize winners; Interaction opportunities between researchers (8 all in all); Cultural Interaction: Number of international conferences held; Number of world class cultural events held; Trade value of audio-visual and related services; Environment of creative activities; Number of world heritage sites; Opportunities for cultural, historical and traditional interaction; number of theatres and concert halls; number of museums; number of stadiums; number of luxury hotel guest rooms; number of hotels; attractiveness of shopping options; attractiveness of dining options; number of foreign residents; number of visitors from abroad, number of foreign students (16 all in all); Liveability: Total unemployment rate; Total working hours; Level of satisfaction of employees; Average housing rent; Price level; Murders per million; Economic risk of natural disaster; Life expectancy; Degree of social freedom, fairness and equality; Risk to mental health; Number of doctors per million people; ICT readiness; Variety of retail shops; Variety of restaurants (14 all in all); Environment: Companies with ISO 14000 certification; Renewables; Recycling; CO_2, PM, SO_2; NO_2; Water quality in rivers, Green coverage; Comfort level of temperature (9 all in all); Accessibility: Number of cities with direct international flights; International freight flows; Departing and arriving passengers; Runways; Density of railways stations; Punctuality and coverage of public transportation; Travel time between centre and international airports; Commuting convenience; Transportation fatalities per million; Taxi fare.	44	Mori Foundation (2017)	Most indicators reflected. Lack of coverage of health or creative economies, galleries.	London (1), New York (2), Tokyo (3), Paris (4), Singapore (5), Seoul (6), Amsterdam (7), Berlin (8), Hong Kong (9), Sydney (10).

(*continued on next page*)

Table 2 (*continued*)

Rating	Year	Organization	Number of indicators	Indicators	Cities	Source	Criticism	Results
Quality of Life Survey	2018	MONOCLE	ND	Safety/crime, international connectivity, climate/sunshine, quality of architecture, public transportation, tolerance, environmental issues and access to nature, urban design, business conditions, pro-active policy developments and medical care	25	Monocle (2018)	Relative lack of transparency as to which specific indicators were used	Munich (1), Tokyo (2), Vienna (3), Zurich (4), Copenhagen (5), Berlin (6), Madrid (7), Hamburg (8), Melbourne (9), Helsinki (10), Stockholm (11), Lisbon (12), Sydney (13), Hong Kong (14), Vancouver (15), Amsterdam (16), Kyoto (17), Dusseldorf (18), Barcelona (19), Paris (20), Singapore (21), Fukoka (22), Auckland (23), Brisbane (24), Oslo (25)

economy. Urban water footprint studies include applications for New York and Beijing (Jenerette et al., 2006), Oslo (Venkatesh & Brattebø, 2012), Berlin, Delhi and Lagos (Hoff et al., 2013) and Milan.

Input-Output analysis is an economic tool designed by Wassily Leontief (1936, 1970). It considers the economic system as a web of interconnected types of economic activity or sectors, namely agriculture, energy generation, oil and gas extraction, computer manufacturing, education, health care, etc. Existing environmental applications include studies focused on multidimensional sustainability (Shmelev, 2010), CO_2 emissions (Peters & Hertwich, 2006) and water use (Dietzenbacher & Velázquez, 2007) at the macro scale. Urban scale remains a promising new area of research, where input-output models were applied to assess the water use of such Chinese cities like Chongquing (Okadera et al., 2006) and Beijing (Zhang: et al., 2012), urban metabolism with a focus on waste for Shenzhen (Ni et al., 2001), resources in Chongquing (Hui et al., 2006), Beijing (Zhou et al., 2010) and Suzhou (Liang & Zhang, 2012). One paper focused on the application of input-output analysis to E-waste recycling in Seattle (Leigh et al., 2012). Research on input-output analysis of CO_2 emissions for urban systems has been quite abundant: Sydney (Lenzen et al., 2004), Vienna (Ornetzeder et al., 2008), Copenhagen (Hallegatte et al., 2011), Suzhou (Liang et al., 2012), Beijing (Chen et al., 2013) and Helsinki (Ala-Mantila et al., 2013).

Optimization - a group of mathematical methods aimed at finding a minimum or a maximum of a certain goal function on a large constrained set of possible alternatives, is a tool widely applied in urban sustainability research. Optimization techniques include mixed integer programming, multiobjective optimization, linear programming and were applied in water management for Tabriz (Zarghami, 2010), Sydney (Mortazavi et al., 2012), Shanghai (Lü et al., 2012); waste management in Genova (Minciardi et al., 2008), Palermo (Galante et al., 2010), Beijing (Xi et al., 2010) and (Dai et al., 2011), Taichung (Chang et al., 2012), and Mexico city (Santibañez-Aguilar et al., 2013).

Multi-criteria decision aid (*MCDA*), originally developed by Bernard Roy (1985, 1991, 1996) has been applied widely for urban sustainability assessments and decision support due to its ability to find compromise between conflicting goals and priorities Munda (1995, 2005a, 2005b). The MCDA tool ELECTRE was used to assess possible locations for new underground stations in Paris (Roy & Hugonnard, 1982), which ultimately reduces CO_2 emissions by providing easier access to public transport for residents. In the context of urban sustainability assessment (Munda, 2006) has been one of the first to suggest using MCDA tools to compare cities on their sustainable development performance. MCDA tools were used for addressing the urban water management issues in the case of Berlin (Simon et al., 2004), Granada (Ruiz-Villaverde et al., 2012) and Athens (Kandilioti & Makropoulos, 2012). Waste management issues were explored with MCDA in the context of Beijing (Xi et al., 2010), Kampala (Oyoo et al., 2013), Dakar (Kapepula et al., 2007) and Barcelona (Bautista & Pereira, 2006).

The application of ecological-economic tools in the field of smart city analysis has started in early 2010s. Kim et al., 2016apply input-output analysis to reveal the role played by the smart cities in South Korean economy, focusing on employment and economic impacts. Milan et al. (2015) used MCDA for smart city scenarios for Oslo. Sharokhni et al. (2015) and Beck et al. (2013) focus on material flow impacts of the smart city in Stockholm, and London and Atlanta respectively. The applications of optimization tools to the smart city analysis are abundant, a good example being the study by Papastamatiou et al. (2017).

It would be very practical here to discuss the advantages and disadvantages of using the methods discussed above for the sustainability analysis in the urban context. MFA for water has the following advantages: it is relatively simple and focus on one dimension only; it allows exploring issues of embodied water use through treating international trade in goods and services and could assist in exploring the

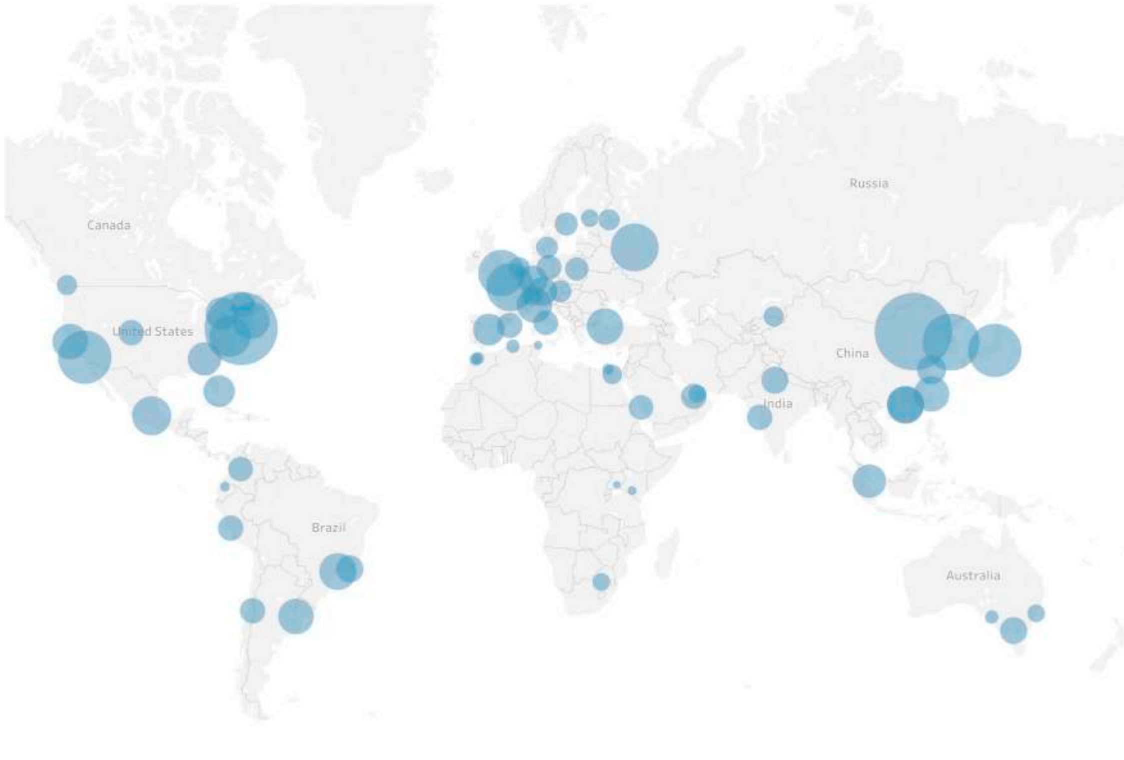

Fig. 2. Gross Regional Product per capita, Environment Europe Sustainable Cities Database, 2018.

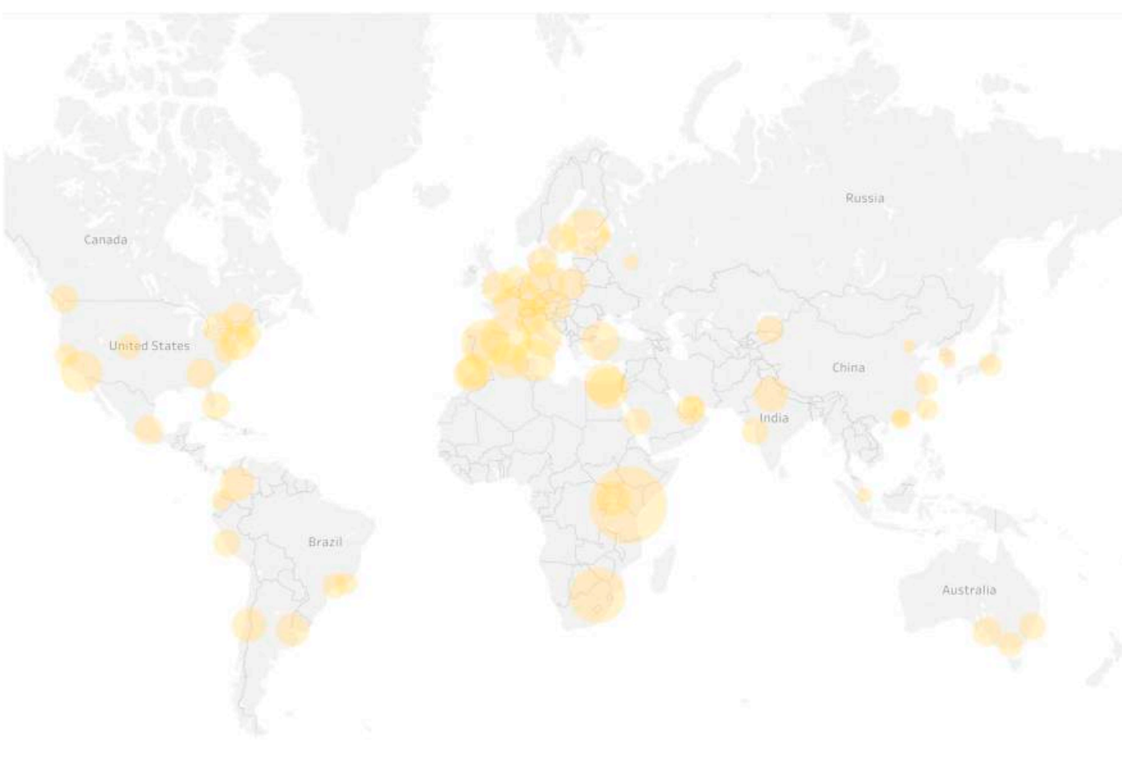

Fig. 3. Unemployment, Environment Europe Sustainable Cities Database, 2018.

Fig. 4. Gini Index of Income Inequality, Environment Europe Sustainable Cities Database, 2018.

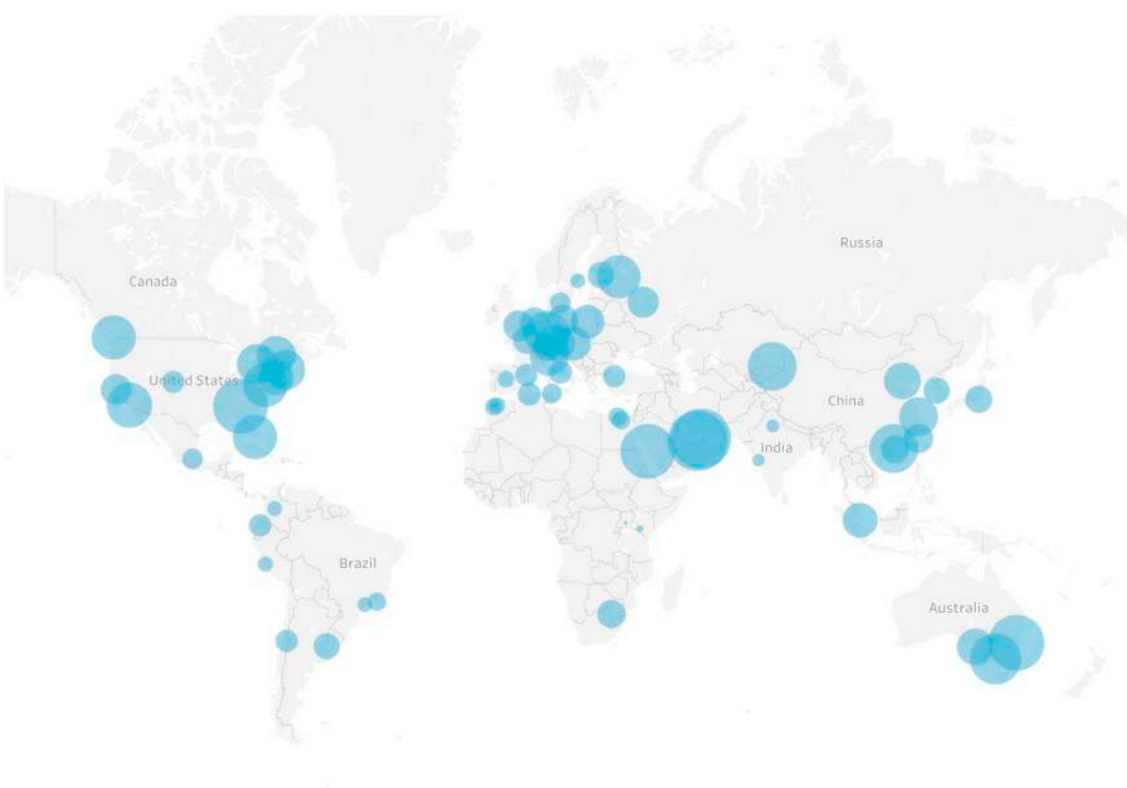

Fig. 5. CO_2 emissions per capita, Environment Europe Sustainable Cities Database, 2018.

Fig. 6. PM_{10} concentrations, Environment Europe Sustainable Cities Database, 2018.

Fig. 7. Water use per capita, Environment Europe Sustainable Cities Database, 2018.

Fig. 8. Waste generation per capita, Environment Europe Sustainable Cities Database, 2018.

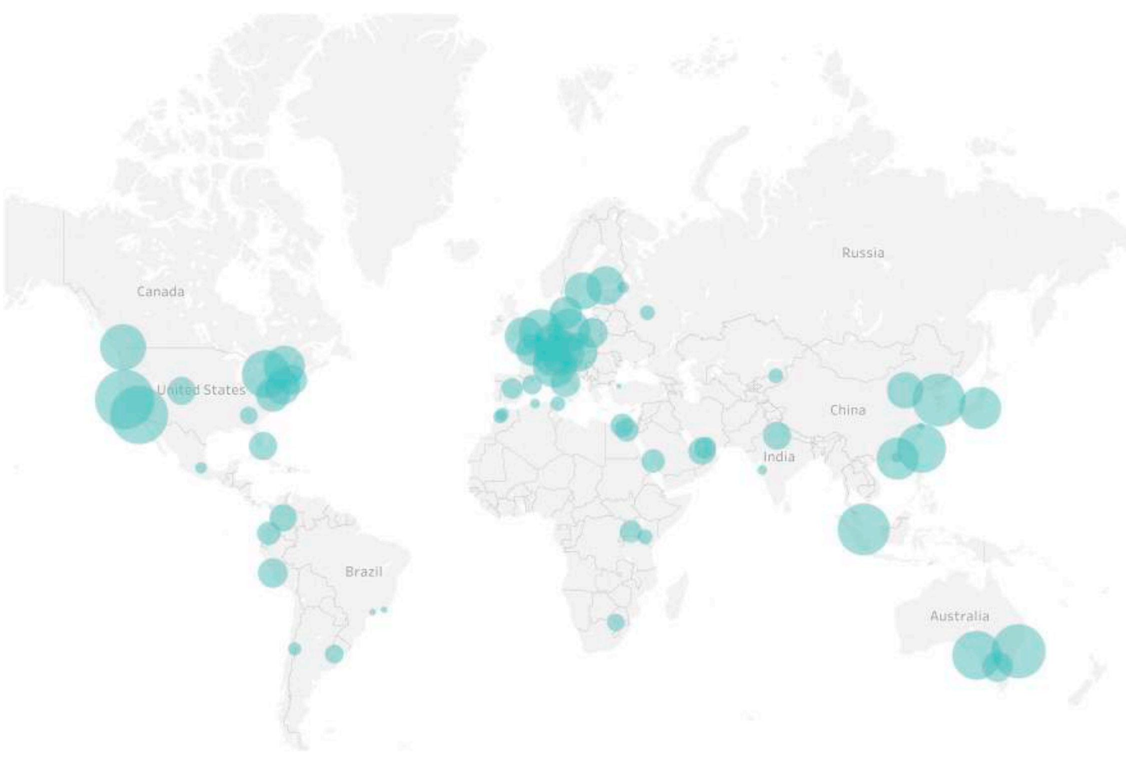

Fig. 9. Recycling rate, %, Environment Europe Sustainable Cities Database, 2018.

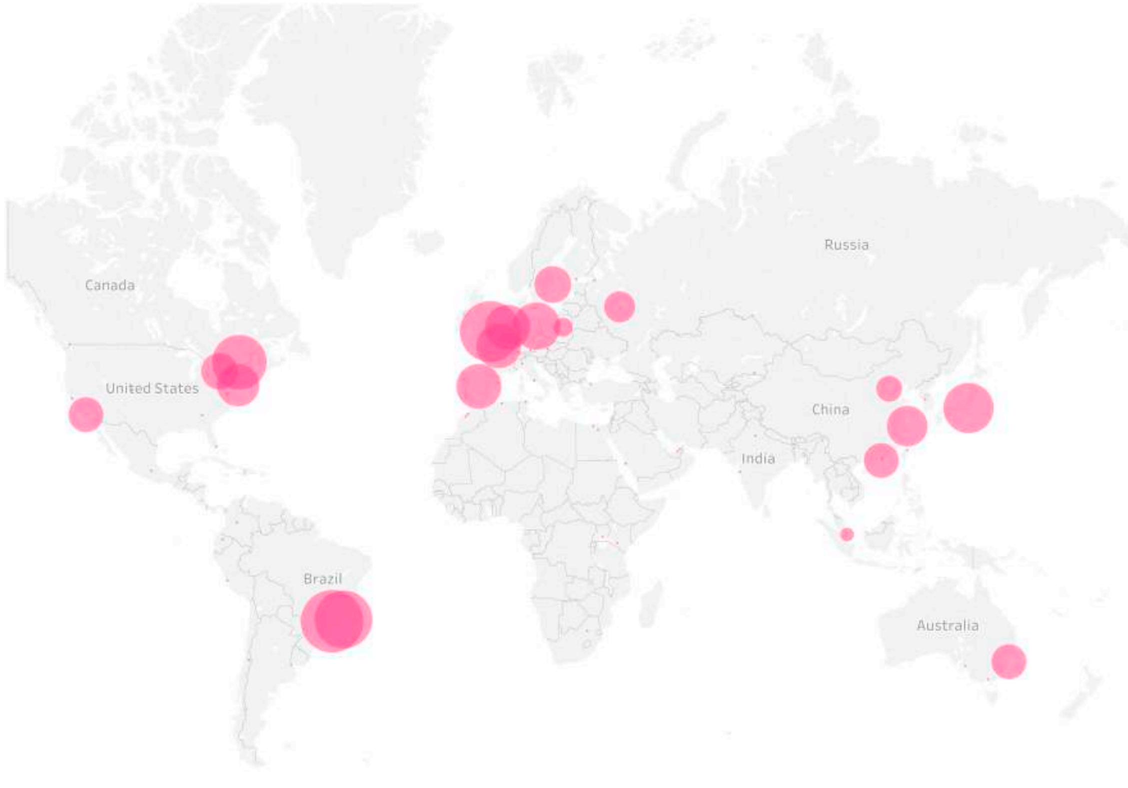

Fig. 10. Creative industries employment, %, Environment Europe Sustainable Cities Database, 2018.

different degree to which cities depend on imported water. At the same time, there are certain disadvantages: international trade flows are normally not available for cities and exist for countries only, water use figures for cities could only reflect direct use components by residents, industry and services. Potentially extremely useful, this method has only been applied to a handful of cities and is not a standard internationally applied at the city level.

MFA for resources allows analysis of material flows into and from the city. It assumes a large taxonomy of flows with a possibility of treating dynamics of resource use and allows exploring issues not possible with other methods (e.g. aluminium use in renewable energy, use of rare metals in computer manufacturing). There is a possibility of analysing embodied flows occurring through trade, including unused components. On the other hand, cities are not required by law to compile material flows accounts; cross-city comparisons might be problematic for the lack of unifying international methodology; input-output tables that are required to attribute resource flows at the urban level are often missing.

MFA for waste allows tracing flows at a city scale including both municipal and industrial components; it helps to determine the degree of circularity and identify problematic flows. Theoretically it is possible to trace waste flows across borders. On the other hand information on waste flows at city scale is often incomplete; cities in the developing world do not have recycling facilities and composition of the waste stream in cities may need additional research.

MFA for CO_2 allows detailed consideration of urban CO_2 emissions, attributing them to climatic, economic, technological factors and policies; it also allows transferring knowledge to developing countries on the effects of technological change, policies and lifestyle adjustments. On the other hand, urban CO_2 figures are estimated and frequently contain estimation errors; not all factors influencing CO_2 emissions at the urban scale can be identified.

Input-output analysis allows considering urban intersectoral economic flows and makes it possible to analyse employment patterns, resource use and emissions on a sector-by-sector basis, making it possible to identify key sectors capable of above-average knock-on effects. At the same time, there are certain weaknesses: input-output tables for cities are not available in most cases, Singapore being a rare exception. Approximation from national tables risks oversimplifying the differences between the nation and the city leading to underrepresentation of concentrated industries. At the very best a monetary and not a physical table could be made available, which might lead to discrepancies in mapping resource use and pollution.

Optimization allows detailed analysis of systems change, e.g. in cases of waste and renewable energy, potentially highlighting trade-offs in case of multicriteria optimization. At the same time, the method has extensive data requirements including spatial and temporal data; it requires high level of computational complexity, especially for multicriteria optimization.

MCDA has been selected in this paper due to the following clear advantages in the urban context. First, due to its ability to compare multidimensional alternatives; second, the possibility of dealing with

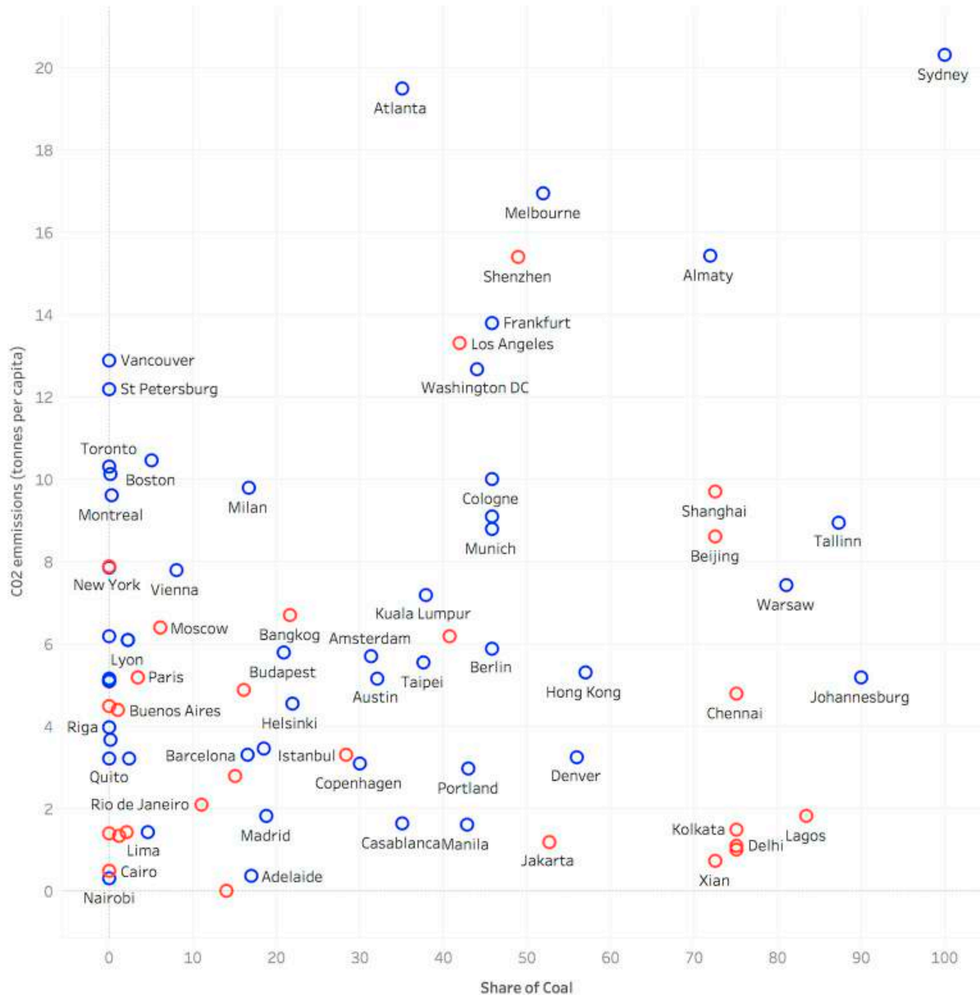

Fig. 11. Correlation between CO_2 emissions and the share of coal in the energy mix for global cities (megacities are shown in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

different types of information; third, for allowing analysis of performance under different policy priorities through changing weights, and, finally, for adopting a stronger sustainability perspective through outranking approaches that do not accept trade-offs so easily. At the same time, MCDA requires the full dataset covering all cities and all indicators in the pool, which implied that we had to start with cities for which those data were available. Recycling, biodiversity and income differentiation indicators might be difficult to obtain for cities in many developing countries; the basket of indicators must be balanced in terms of social, economic, environmental and smart dimensions; finally, fine-tuning is required based on indifference and preference thresholds, cut-off points and weights.

3. Indicators for smart sustainable cities

There has been a strong interest in using indicator-based frameworks for sustainability analysis, manifested in a wide spectrum of studies: (Valentin & Spangenberg, 2000), Spangenberg (2002a, 2002b), Spangenberg (2005), Monfaredzadeh and Berardi (2015), Hara, Nagao, Hannoe, & Nakamura, 2016, Manitiu and Pedrini (2016), Ahvenniemi, Huovila, Pinto-Seppä, and Airaksinen (2017), García-Fuentes et al. (2017) Girardi and Temporelli (2017), Klopp and Petretta (2017) and Pierce, Ricciardi, and Zardini (2017). This research has been driven by the United Nations Guidelines and Methodologies on Sustainable Development Indicators (UN, 2007), EU Sustainable Development Indicators (EC, 2009), Sustainable Development Indicators Framework (UNECE, 2013), new ISO 37120 standards on Sustainable Development of Communities (ISO, 2014), Sustainable Development Goals framework (UN, 2015a, 2015b), and Smart Sustainable City Indicator Framework (UN ECOSOC, 2015).

Indicator-based sustainability assessments for cities have been conducted by many researches in the past decade: (Shmelev & Shmeleva, 2009), (Shen, Ochoa, Shah, & Zhang, 2011), (Shen & Zhou, 2014), (Michael et al., 2014), (Mori & Yamashita, 2015),

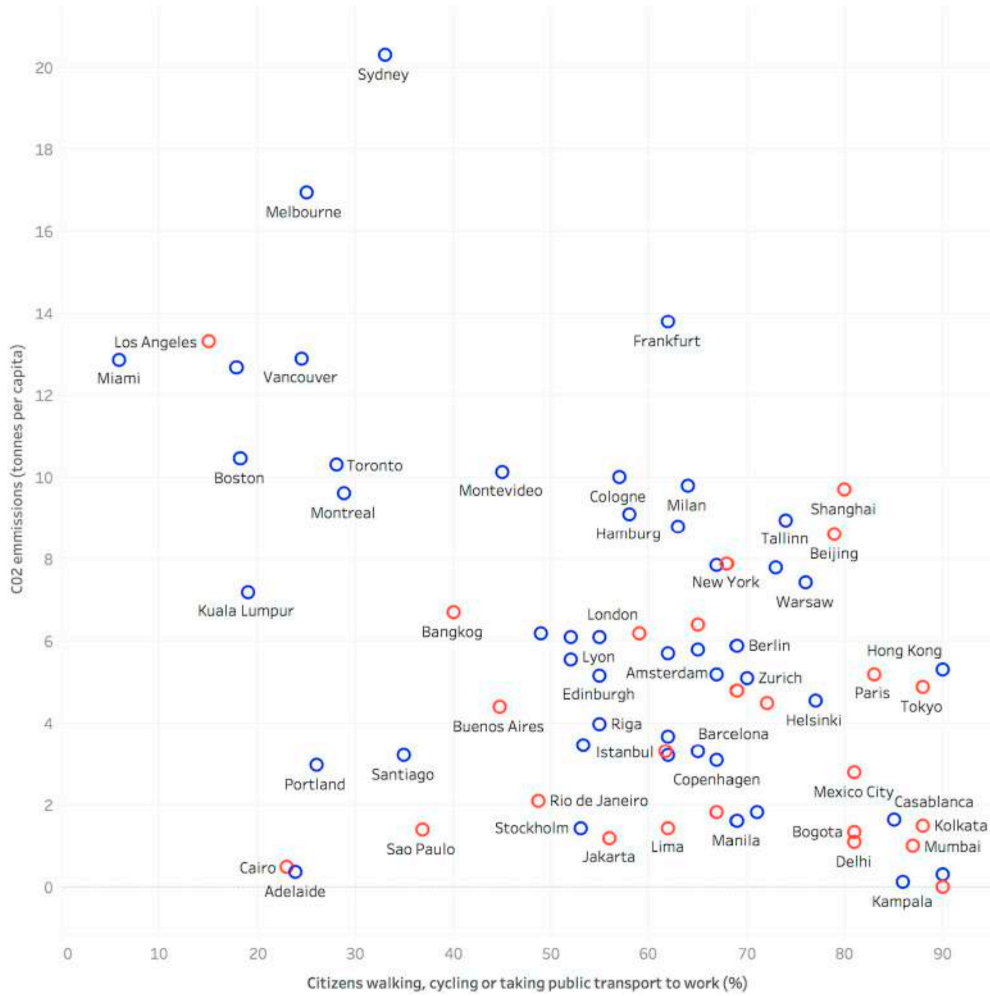

Fig. 12. Correlation between CO_2 emissions and the share of trips made by walking, cycling and taking public transport for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Wong, 2015), (Yigitcanlar, Dur, & Dizdaroglu, 2015), (Wei, Huang, Lam, & Yuan, 2015), (Wei, Huang, Li, & Xie, 2016). Several assessment frameworks are widely accepted today: UN SDG indicators, ISO 37120 Sustainable Development of Communities and UNECE-ITU Smart Sustainable City Indicators, which we took into account in designing our methodology.

The UN SDG indicator framework comprises 232 indicators, which often becomes unmanageable for the sheer quantity of data. The ISO 37120 standard featuring 116 indicators exhibits indicators that are more precisely defined, although social and environmental aspects are given slightly greater prominence than economic and smart indicators. UNECE-ITU Smart Sustainable Cities Indicator framework is more balanced between different dimensions of sustainability and formulated with a lot more clarity and a forward-looking strategic vision in mind featuring 72 indicators, a much more manageable set. Selection of individual indicators for cities, chosen for the present paper (Fig. 1), was based on an earlier sustainable cities framework (Shmelev & Shmeleva, 2009), inspired by our dynamic sustainability assessments carried out for countries (Shmelev, 2011, 2017) and adapted for the urban scale Shmelev (2017a, 2017b), cross-checked with the indicators from the three frameworks described above and based on data availability across the database.

The final set of smart and sustainable indicators included a range of economic, environmental, social and smart cities indicators following an approach identified by the UNECE and ITU United for Smart and Sustainable Cities initiative (Fig. 1).

Additional existing benchmarking frameworks include (Table 2): Economist Intelligence Unit's Global Liveability Index, which uses 30 indicators to rank 140 cities placing on top Vienna (1), Melbourne (2), Osaka (3), Calgary (4), Sydney (5), Vancouver (6), Toronto (7), Tokyo (8), Copenhagen (9), Adelaide (10); Rockefeller Foundation's Resilient Cities Index, employing 52 indicators to benchmark 100 cities; UN HABITAT's Global Prosperity Index, focusing on 72 indicators and 295 cities highlighting the leading position of Oslo (1), Copenhagen (2),

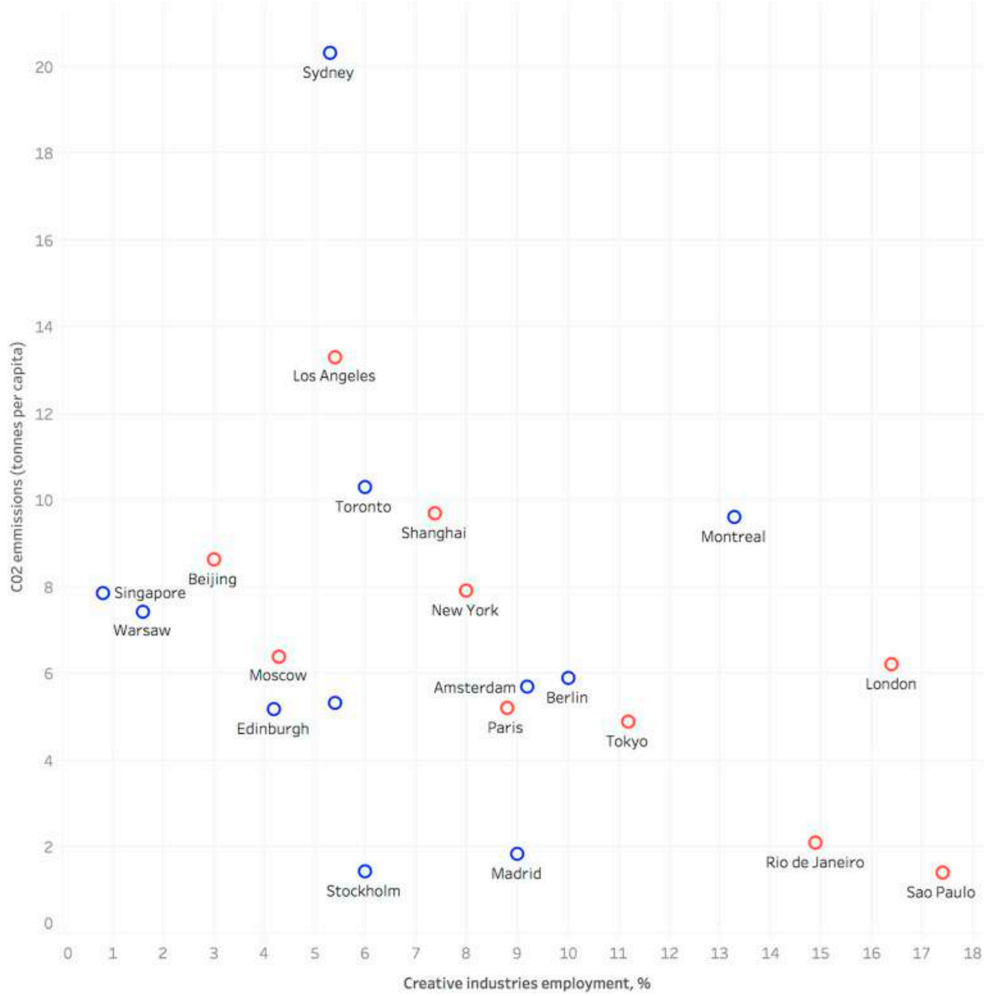

Fig. 13. Correlation between CO_2 emissions and the share of creative industries employment for global cities.

Stockholm (3), Helsinki (4), Paris (5), Vienna (6), Melbourne (7), Montreal (8), Toronto (9), Sydney (10); Arcadia's Sustainable Cities Index based on 32 indicators applied to 100 cities, selecting Zurich (1), Singapore (2), Stockholm (3), Vienna (4), London (5), Frankfurt (6), Seoul (7), Hamburg (8), Prague (9), Munich (10) as most sustainable; Mori Foundation's Global Power City Index focusing on 70 indicators as applied to 44 cities emphasizing London (1), New York (2), Tokyo (3), Paris (4), Singapore (5), Seoul (6), Amsterdam (7), Berlin (8), Hong Kong (9), Sydney (10) and, finally, Monocles's Quality of Life Survey presenting the 25.

cities with the best quality of life in the world, including Munich (1), Tokyo (2), Vienna (3), Zurich (4), Copenhagen (5), Berlin (6), Madrid (7), Hamburg (8), Melbourne (9), Helsinki (10). Because the composition of the indicator sets varies tremendously as are the cities involved, different assessment systems place emphasis on different aspects of urban performance.

The cities chosen for our analysis include: New York, Los Angeles, Rio de Janeiro, São Paulo, London, Paris, Berlin, Moscow, Beijing, Tokyo, Hong Kong, Shanghai, Singapore and Sydney. Criteria for selecting the cities were economic importance and environmental impacts (all cities feature in world top 30 cities by GDP, comprising over 8% of global GDP, employing nearly 130 mln people; most cities are part of the C40 network focused on greenhouse gas emissions mitigation, producing around 3% of global CO_2 emissions, use more than 15 bln tonnes of water per year and generate over 55 mln tonnes of municipal solid waste per year). Our study draws on a wide range of sources from Eurostat (2016), city governments (City of London, 2009; City of New York, 2012; City of Rio de Janeiro, 2011; Marie de Paris, 2011; San Francisco Department for the Environment, 2004; Singapore, 2009), Siemens European Green City Index (Siemens, 2009), World Cities Culture Forum (Mayor of London, 2014), UN Habitat (UN HABITAT, 2013) and World Bank publications (World Bank, 2013), LSE Going Green Report (LSE, 2013) as well as considerations on availability of data.

Below we will illustrate the diversity in sustainability performance of global cities on various individual dimensions (Figs. 2-10). As can be

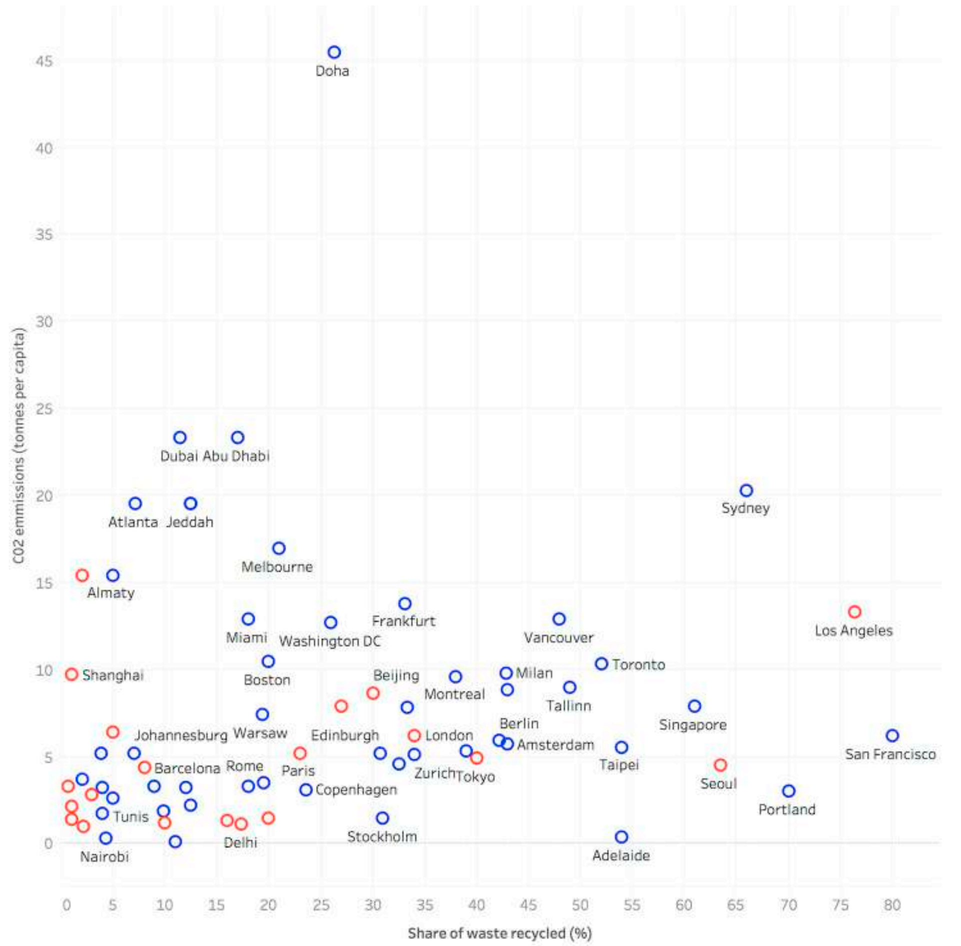

Fig. 14. Correlation between CO_2 emissions and the share of the wastes recycled for global cities.

seen from Fig. 2, cities like Beijing, New York, Los Angeles, Tokyo, Paris, Moscow, London exhibit the highest levels of Gross Regional Product at PPP. At the same time, unemployment has been largest in Africa and cities like Madrid, Los Angeles, Berlin, Rome, New York, London, and lowest in Hong Kong, Moscow, Beijing and Singapore (Fig. 3). The income differentiation (Fig. 4) has been largest in Washington DC, Rio de Janeiro, Hong Kong, New York, Sao Paolo, Paris, Beijing, Los Angeles, Moscow and lowest in Tokyo, Berlin, Stockholm. CO_2 emissions per capita (Fig. 5) were very large in Melbourne and Sydney, and significant in Los Angeles, Shanghai, Washington DC, Beijing, and somehow lower in Moscow, Berlin, Hong Kong, Paris, Tokyo and very low in Rio de Janeiro and Sao Paolo. PM_{10} concentrations (Fig. 6), on the other hand are very high in cities of the Middle East and Africa, Delhi, Beijing, Shanghai, Rio de Janeiro, Hong Kong and much lower in Sydney, Toronto, Washington DC, New York, Tokyo, Los Angeles and Berlin.

Water use (Fig. 7) has been highest in cities of the Middle East, Los Angeles, Washington DC, Toronto, Shanghai, Moscow Hong Kong and Tokyo and was lower in Copenhagen, Barcelona, Vienna, Berlin, London, Sydney, Sao Paolo and New York. More solid waste was generated per capita in Miami, Los Angeles, Rio de Janeiro, New York, Paris, Hong Kong, and less in London, Moscow, Sydney, Berlin, Shanghai, Beijing and Tokyo (Fig. 8). Recycling was a major success in Los Angeles, Sydney, Singapore, with slightly more moderate rates of recycling observed in Berlin, Tokyo, Hong Kong, London, Beijing, New York, and much lower rates in Moscow, Rio de Janeiro, Sao Paolo and Shanghai (Fig. 9).

Many of the top world's cities developed significant creative industries sectors, with leaders being Paris, New York, Tokyo, London, Sao Paolo, Rio de Janeiro, Berlin, and somehow lower levels of development of creative industries recorded in Los Angeles, Hong, Kong, Moscow, Beijing and Singapore (Fig. 10). We consider creative industries as a significant factor in stimulating smart economy and ultimately urban sustainability.

Figs. 2-10 illustrate the heterogeneous performance of cities based on the level of economic development, geography, climatic conditions, lifestyles, policies, technological development and taxation regimes. There are no two cities that are alike and therefore multidimensional

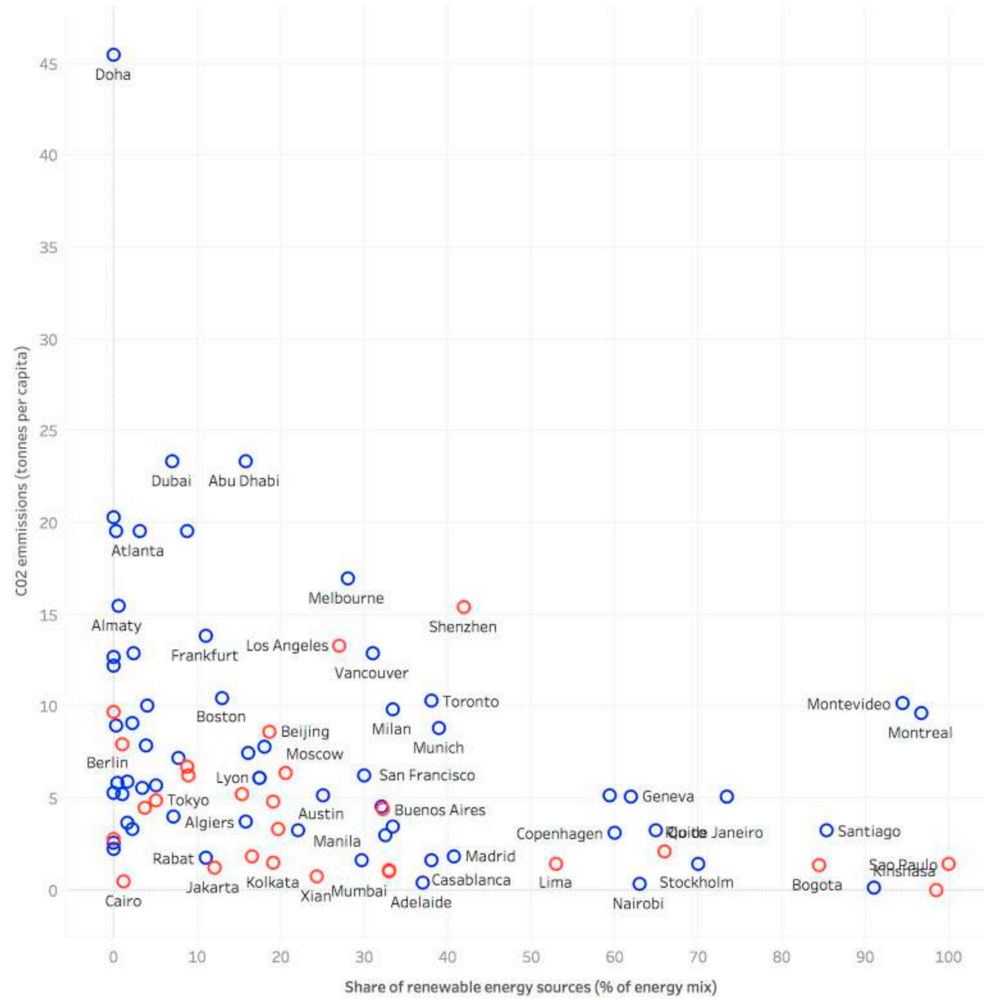

Fig. 15. Correlation between CO_2 emissions and the share of the renewable energy for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

analysis is required to explain urban sustainability performance. For example, in Los Angeles we observe higher than average GRP, high CO_2 emissions, high water use and waste generation. At the same time, the city is characterised by high unemployment, high Gini index and success in recycling performance. Understanding heterogeneity of their urban performance could allow cities to assess their policies and forge new strategies and innovations that deal with problem areas on a systemic level.

4. Cross-section regression analysis

It would be highly beneficial to explore the world cities database from the point of view of interdependencies and trade-offs among various sustainability indicators, which will help us understand causes for certain performance across the whole pool of cities and the inherent trade-offs between indicators. Our goal in this section was to test several hypotheses regarding the inter-disciplinary links among urban sustainability dimensions, which were emphasized in the UN Guidelines on Sustainable Development Indicators (UN, 2007). In Figs. 11-24 we explored a database of world cities, currently featuring 140+ cities from all inhabited continents and tried to see if there are any statistically significant relationships between pairs of indicator variables across the whole spectrum of cities. Megacities in these charts are denoted in red.

The confirmation of our hypothesis of a highly significant correlation between the amount of CO_2 emissions and the share of coal, the most carbon-intensive technology at present in the energy mix (Fig. 11), reinforces the need for an urgent transformation and decarbonisation of the energy sector. Such cities as Sydney, Warsaw, Hong Kong, Denver, Portland, Los Angeles, Washington, Shenzhen have above-average levels of coal in the energy mix and exhibit high per capita CO_2 emission. On the other hand such cities as Sao Paolo, Rio de Janeiro, Bogota, Quito, Madrid, Adelaide, Copenhagen, Rome have relatively low share of coal in the energy mix and lower levels of CO_2 emissions per capita.

A significant correlation between CO_2 emissions and the share of

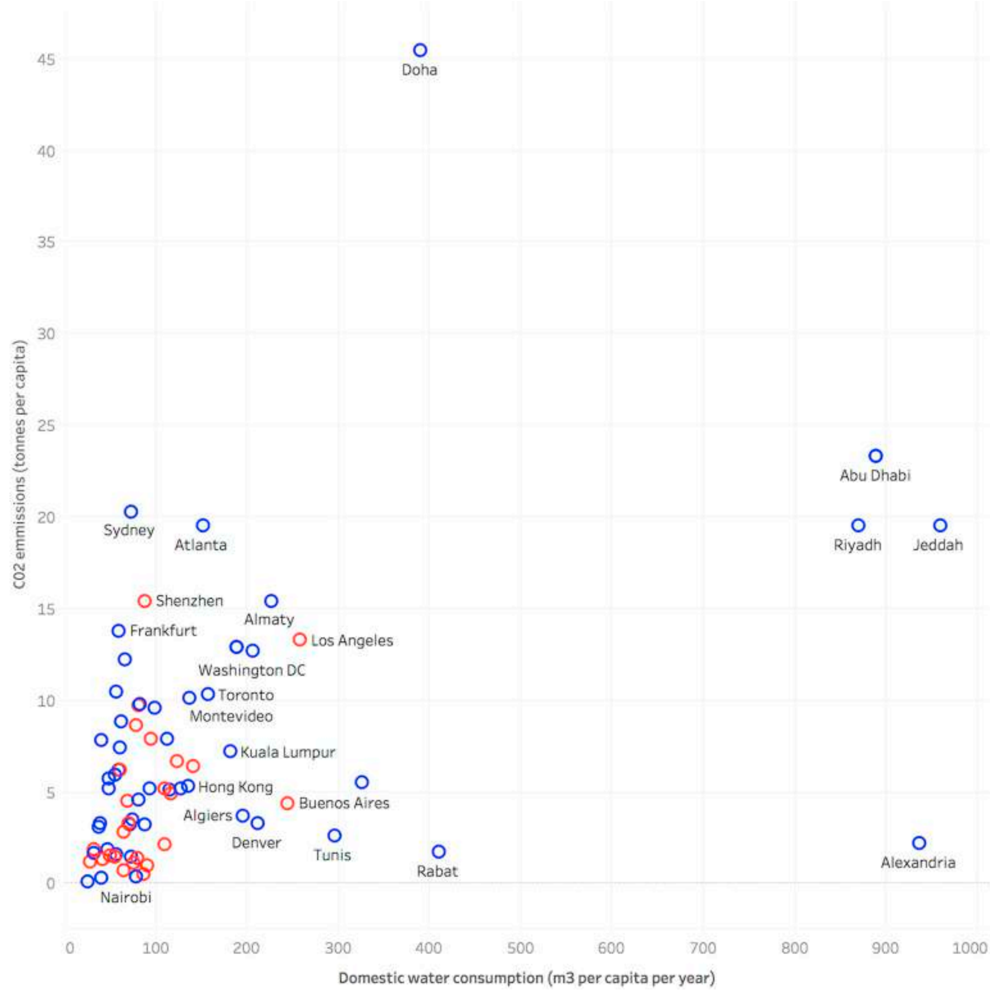

Fig. 16. Correlation between CO_2 emissions and water consumption for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

trips made by walking, cycling and public transport has been confirmed (Fig. 12), which enriches our understanding of this wonderful urban planning tool for improving air quality and making the cities greener.

Such cities as Stockholm, Paris, Amsterdam, Seoul, Berlin, Singapore, Mumbai, Delhi, Bogota, Mexico city, Sao Paolo, Barcelona have a significant percentage of trips made by walking, cycling and using public transport and are associated with lower per capita CO_2 emissions. On the other hand, such cities as Sydney, Shenzhen, Almaty, Los Angeles, Miami, Kuala Lumpur, Boston, Vancouver, Toronto rely on a private car in a much more pronounced way and therefore have significantly higher CO_2 emissions per capita.

One should not disregard the importance of the weak links and our hypothesis about the relationship between the share of creative economy and CO_2 emissions has been confirmed at a somehow less significant, but nevertheless interesting level with a logically consistent negative coefficient of correlation between the share of creative industries employment and CO_2 emissions (Fig. 13), shows us a yet another alternative strategy for creating a greener city.

Our hypothesis about the often observed trade-off between recycling and CO_2 emissions has not been confirmed (Fig. 14). Often more recycling requires more energy and under ceteris paribus assumption means more emissions of CO_2. Although this hypothesis has not been confirmed in a strict statistical sense, we could still interpret the observed tendency as a weak signal. The is confirmed when the cities of the Middle East, which have very high CO_2 emissions and low recycling rates are excluded from the database. Recycling systems will be significantly cleaner where there is access to renewable energy.

The role of renewable energy in reducing CO_2 emissions in global cities has been confirmed at a very high level of statistical significance (Fig. 15). This clearly reinstates the tendency in such cities like Sao Paolo, Bogota, Montreal, Stockholm, Rio de Janeiro, Zurich and Copenhagen that are largely powered by hydro energy to have lower per capita CO_2 emissions. At the same time cities like Sydney, Atlanta, Almaty, Frankfurt, Miami, St Petersburg, Shanghai, Boston, Los Angeles, Vancouver, Shenzhen that tend to have lower levels of renewables in the energy mix, tend to exhibit higher per capita CO_2 emissions.

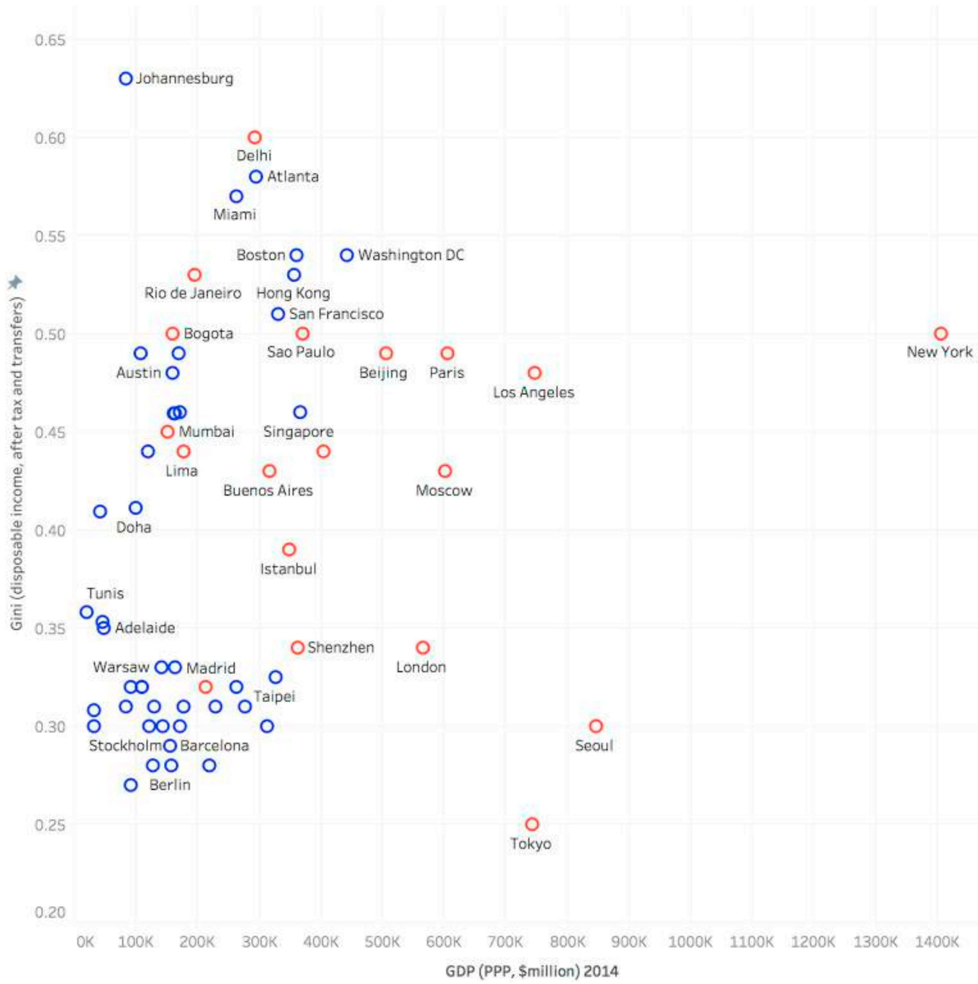

Fig. 17. Correlation between Gross Regional Product and Gini coefficient of income inequality for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The hypothesis of a strong water-energy nexus, whereby larger CO_2 emissions tend to go hand in hand with higher water consumption has been confirmed. Fig. 16 presents an illustration of such phenomenon and shows cities like Los Angeles, Almaty, Atlanta, Miami, Toronto, Kuala Lumpur using larger amounts of water with higher per capita CO_2 emissions. At the same time, cities like Bogota, Lima, Lagos, Madrid, Adelaide, Barcelona, Copenhagen, Seoul, Rome exhibit lower levels of per capita CO_2 emissions accompanied by lower water consumption.

The hypothesis about a significant correlation between GDP and a measure of income differentiation expressed in Gini coefficient of income inequality has not been confirmed, which illustrates the fact that economic growth as such around the world doesn't automatically lead to higher inequality, but it is rather complimentary factors like income taxes perhaps that are responsible (Fig. 17).

The hypothesis of an ‘Urban Phillips Curve’ exhibiting a correlation between the rates of inflation and unemployment levels across the whole spectrum of world cities has not been confirmed (Fig. 18). Cities with high inflation (Moscow) tend to exhibit lower levels of unemployment, the opposite holds in the case of Madrid. Such relationship was shown to hold with a smaller sample of cities that did not include such cities of the global South as Nairobi, Lagos and Johannesburg.

The hypothesis on the relationship between GDP and unemployment has been confirmed at 10% significance level, which could be seen in Fig. 19.

On the other hand, there has been enough statistical evidence to support a hypothesis about a link between higher inflation and higher income differentiation, which is observed in Fig. 20.

Our hypothesis on the relationship between the levels of higher education and income differentiation has not been confirmed (Fig. 21). At the same time, two separate clusters exist of largely European and Canadian cities on the one hand with high education levels and low inequalities and American, Russian and Latin American cities with higher income inequalities and a wide spread of education levels.

The hypothesis of a strong statistical link between life expectancy and PM_{10} concentrations presented in Fig. 22 echoes the recent WHO

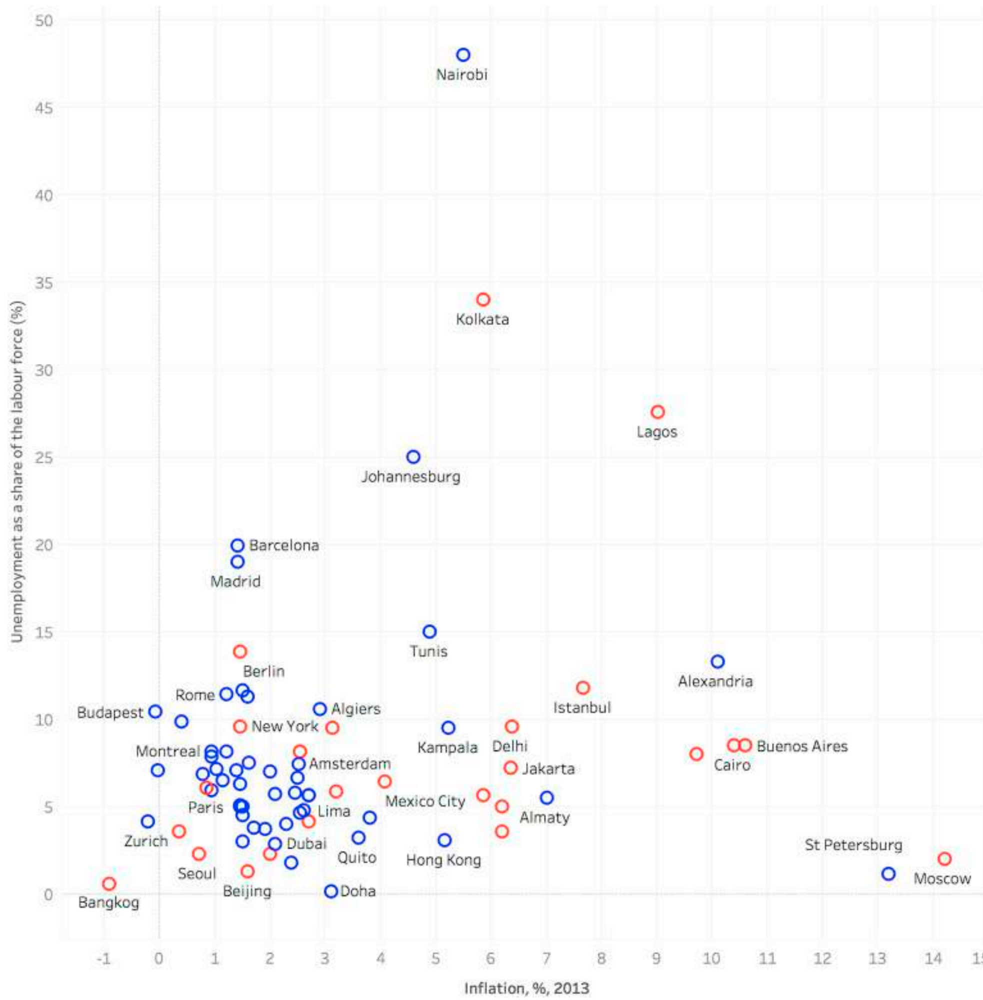

Fig. 18. Correlation between inflation and unemployment for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

report on ambient air pollution and diseases it causes, WHO (2016). Cities with lower PM_{10} concentrations have significantly higher life expectancy, which confirms the WHO estimates. On average 10 extra micrograms of PM10 per cubic meter of air means a lowering one's life expectancy by 0.7 year. Such cities like Delhi, Kampala, Mumbai, Cairo, Johannesburg exhibit considerably lower levels of life expectancy on the background of higher PM_{10} concentrations. On the positive end of spectrum Tokyo, Madrid, Stockholm, Copenhagen have higher life expectancy and lower levels of PM10.

The correlation between PM_{10} concentrations and availability of underground stations depicted in Fig. 23 illustrates one possible way of tackling high PM_{10} pollutions in cities like Bogota, which do not currently have an underground network, as well as Delhi, Xian, Cairo, Kampala, Mumbai or Kolkata.Our hypothesis on the existence of such a relationship has been confirmed at a high level of statistical significance. In this regard such cities as Washington DC, Paris, Barcelona, Lille, Frankfurt, Madrid show the way in offering their residents a diversified and reliable underground system, which could be responsible for avoiding unnecessary PM_{10} emissions associated with private transportation.

On the other hand, such often neglected phenomenon as inflation could have a profound effect on life expectancy through stress (Fig. 24). Our hypothesis about such a statistical link has been confirmed. Such cities like Lagos, Kinshasa, Moscow, St Petersburg, Buenos Aires, Cairo exhibit high level of inflation and lower levels of life expectancy. On the other hand Tokyo, Milan, Madrid, Barcelona, Paris, Seoul, Toronto, Copenhagen, Vienna show low levels of inflation and higher life expectancy.

Figs. 11-24 clearly show that there are very complex and diverse relationships among variables linking environmental, social and economic performance indicators and technologies (energy mix), lifestyles (travel patterns), economic factors (GRP) and infrastructure (underground stations) that could be highly helpful to understand the drivers to improve sustainability performance of cities worldwide. It becomes really clear that more detailed econometric multivariate research is required to make the next step to see how technologies, infrastructure,

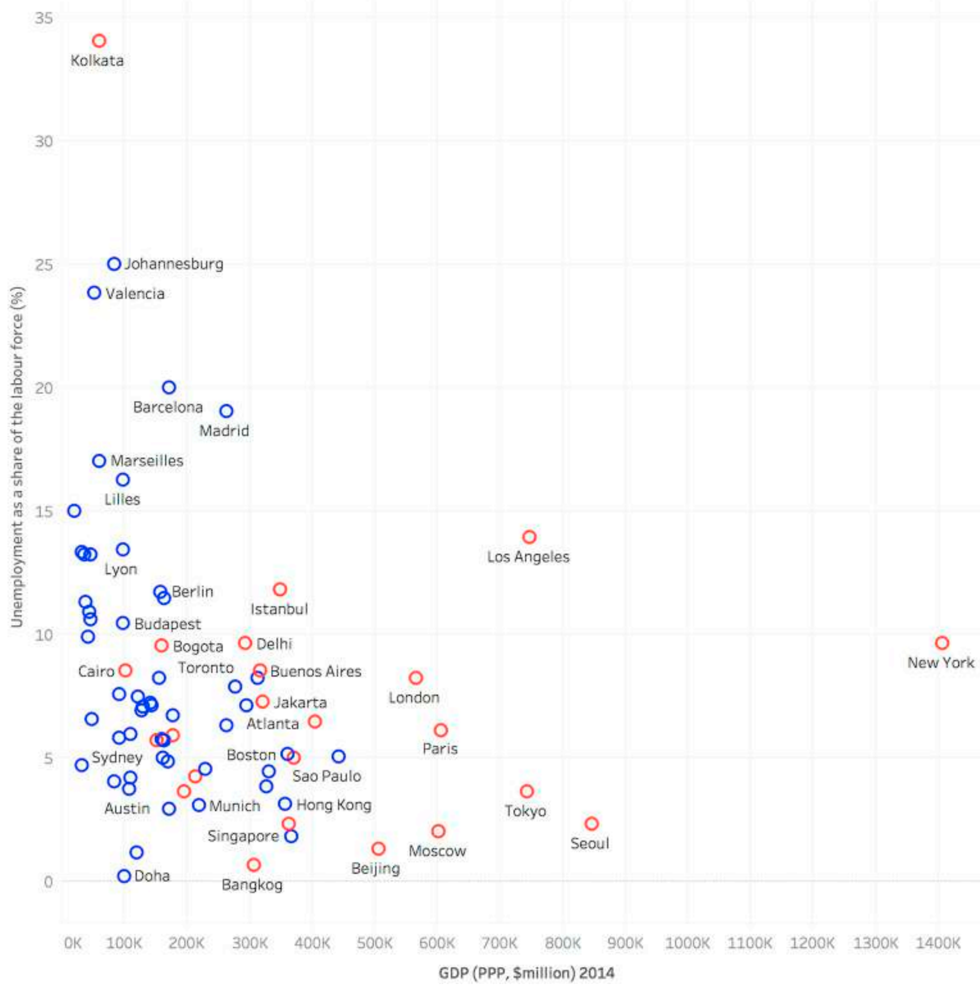

Fig. 19. Correlation between GDP and unemployment for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

policies, lifestyles and economic factors influence performance in different domains.

5. Multi-criteria decision aid methodology and applications

Multi-Criteria Decision Aid (MCDA) methodology was chosen here for its ability to treat several dimensions of data simultaneously and its capacity to integrate such information via multi-criteria aggregation procedure (MCAP) with or without converting the data of different nature into a single composite index. MCDA requires the following components: alternatives that need to be compared; criteria used to assess performance of these alternatives; a multi-criteria aggregation procedure (MCAP) and policy recommendations resulting from the method's application. MCDA tools, namely outranking methods based on pair-wise comparisons of alternatives, allow strong sustainability assessment understood here as a setting where less compensation is allowed among criteria accepted (Martinez-Alier, Munda, & O'Neill, 1998). The MCDA method “ELimination Et Choix Traduisant la REalité” III (ELECTRE III, “ELimination and Choice Expressing Reality”) is discrete multicriteria outranking method well suited for this task. For modelling various policy priorities focusing on environmental, economic, social and smart dimensions, we have chosen to use different sets of weights in the ELECTRE III method, allowing us to adopt various assessment perspectives.

The application of ELECTRE III method for comparative sustainability benchmarking of largest world cities rests on the following assumptions. According to the set of 20 criteria selected for this assessment (Fig. 1), a 10% difference in the value of each criterion is sufficient for domination and less than 5% presents an indifference. The results are presented in the form of the webs of domination relationships among the cities obtained through the pair-wise comparisons within the ELECTRE III tool under four different policy priorities: environmental, economic, social and smart (Figs. 25-28). An arrow between two cities denotes a relationship of domination in the sense of the criteria chosen but lack of such an arrow points to incomparability.

Under environmental priorities (Fig. 25), Singapore outranks all the

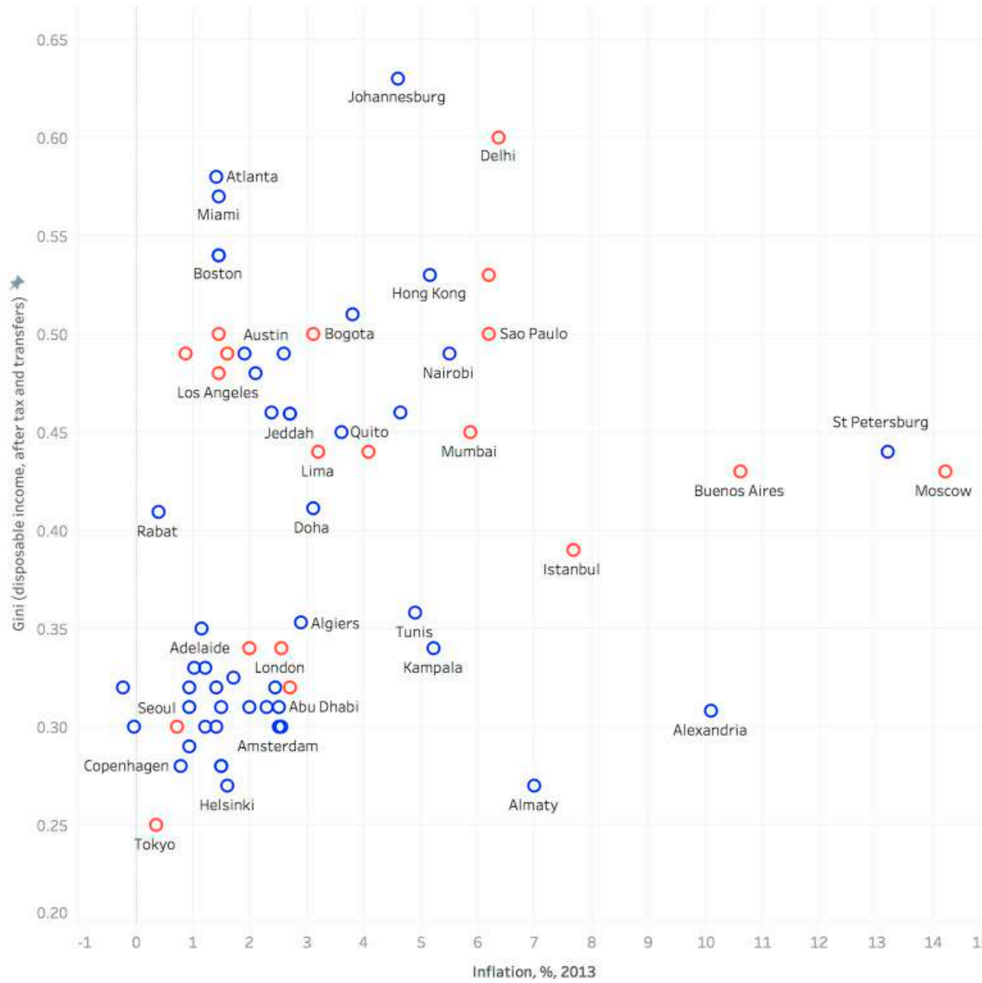

Fig. 20. Correlation between inflation and income differentiation for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cities in the set, followed by Sydney and London, and then Tokyo. The worst performing cities in this setting were also Rio de Janeiro, Shanghai and Los Angeles. Mid-range, Moscow performed better than Beijing under the environmental policy priorities.

If economic priorities are chosen (Fig. 26), then Tokyo clearly dominates in the assessment, followed by London and Beijing, Hong Kong and Sydney. At the bottom of the web of domination relationships in this setting are Rio de Janeiro, Sao Paolo, Los Angeles and Shanghai.

When social priorities are considered (Fig. 27), the clear leaders are Tokyo, London, Sydney, Berlin and Paris. Somewhat lagging behind are Rio de Janeiro, Sao Paolo, Beijing, Shanghai and Los Angeles. In this assessment performance of Moscow and Beijing are close, although Moscow performs somewhat better.

Based on the smart city performance (Fig. 28), London and Tokyo lead, followed by Paris, New York, Sydney, Singapore and Berlin. Still lagging behind are Rio de Janeiro, Shanghai, Los Angeles, Sao Paolo and Honk Kong. Performance of Moscow and Beijing is close, although Moscow performed somewhat better.

It would be insightful to compare the present rankings with multiple existing urban rankings presented in Table 2. It should be mentioned that overall the rankings mentioned in Table 2 feature Sydney, Paris, Singapore, London, Tokyo, New York among top 5, which is broadly consistent with our ranking of top megacities, the obvious advantage of our outranking ELECTRE III approach being in a stronger sustainability focus. It should be added that the goals of the rankings presented in Table 2 are absolutely different: liveability in EIU (2018); resilience in Rockefeller Foundation (2016); prosperity in UN HABITAT (2015, 2016); sustainability in Arcadis (2018); power in Mori Foundation (2017) and quality of life in Monocle (2018). In our analysis this diversity equates to varying policy priorities, making our methodology a more general and overarching case. It appears that the cities featured at top 10 positions in our mega city rating: Singapore, Sydney, London, Tokyo, Paris, New York, Hong Kong can be found at the very top of the Mori Foundation Global Power City Index, which clearly indicates the key characteristic of our sample. The sustainability-focused Arcadis index features Singapore follow by London at the top of the global ranking, which close corresponds to our setting with environmental priorities. According to social, economic and smart priorities Tokyo in

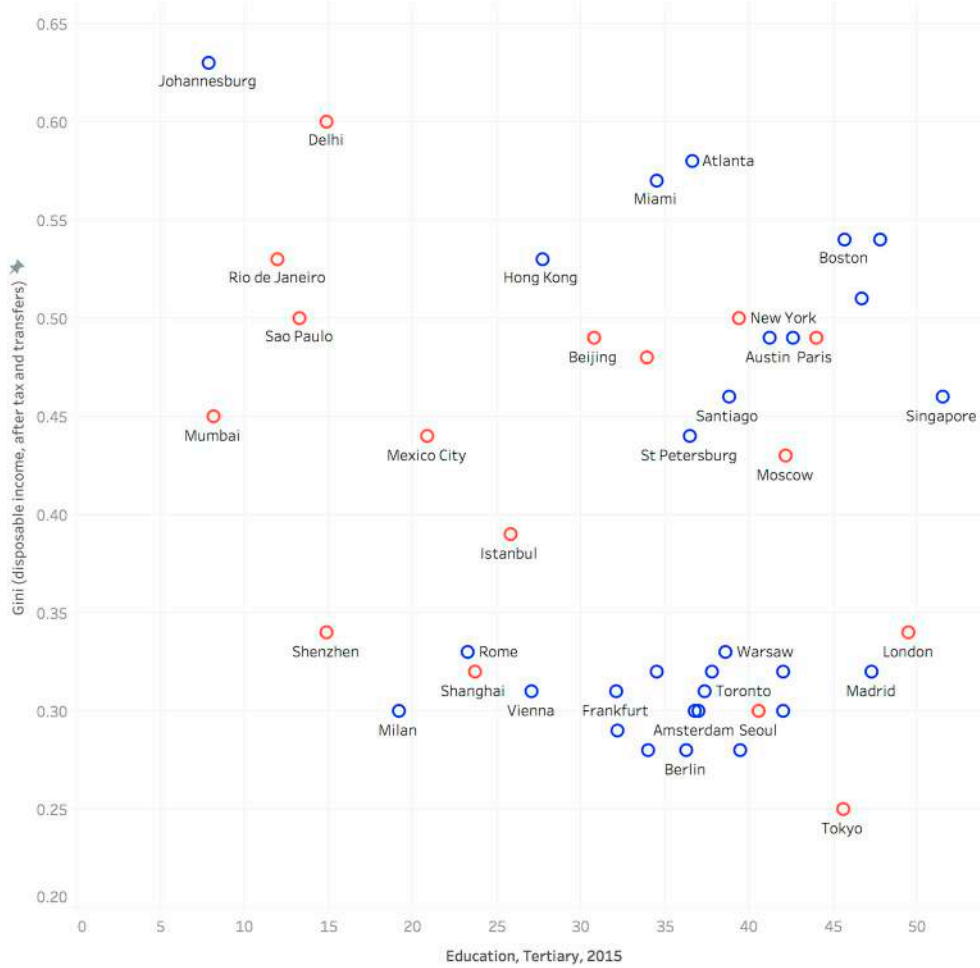

Fig. 21. Correlation between tertiary educational attainment level and Gini coefficient of income differentiation for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

our assessment is performing better than other cities, which closely corresponds to the Monocle quality of life index. According to environmental priorities, Sydney features very high in our ranking and at the same time, Tokyo, performs very well under social, economic and smart priorities, which corresponds to the EIU liveability index.

It should be noted that sensitivity analysis is often performed to understand the robustness of MCDA assessment results. Within the ELECTRE III method, a range of technical parameters, namely the indifference and preference thresholds, weights and the cut-off points are the essential dimensions of the method's sensitivity and are capable of modelling a stronger or weaker sustainability perspective. In this paper we were able to model sensitivity of the model's results to the particular stakeholder worldview and incorporated those by means of the economic, social, environmental and smart priorities. We have dealt with the sensitivity analysis at greater length in Shmelev (2017a, 2017b), where one of the methods employed, APIS, allowed conducting Monte Carlo analysis of weights from step one.

6. Discussion

In the light of the information presented above using four different weighing schemes under various sustainability priorities using ELECTRE III, there is a considerable degree of convergence in the results pointing towards Singapore as one of the most sustainable of all fourteen cities in the pool on environmental performance, and Tokyo closely followed by London on economic and social performance.

In this regard it would be highly beneficial to turn to the experience of Singapore in implementing a sustainability strategy and using policy instruments to achieve sustainability at the city-state level, which is more significant than that of other world capitals.

Singapore created an Inter-Ministerial Committee on Sustainable Development (IMCSD) in January 2008 (Singapore, 2009). This body was set up to formulate a national strategy for Singapore's sustainable development. The IMCSD was co-chaired by the Minister for National Development and the Minister for the Environment and Water Resources. The members included the Ministers for Finance, Transport, and the Senior Minister of State for Trade and Industry. Setting very high aims of reaching a 70% recycling rate by 2030, achieving a 35% improvement in energy efficiency from 2005 levels by 2030 and reaching a level of domestic water consumption of 140 l per person per day by 2030, the Strategy for Sustainable Growth formulated in 2009 presented a road map to the situation we observe today. The aim of the

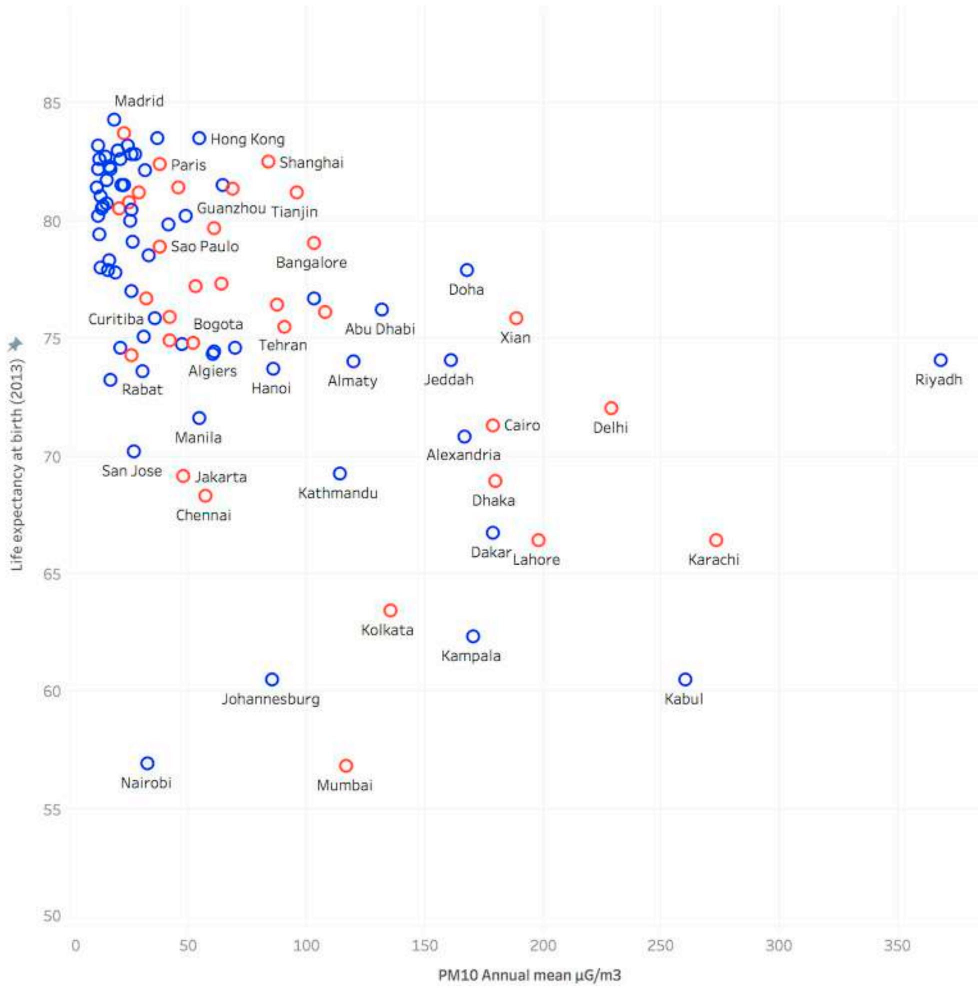

Fig. 22. Correlation between PM_{10} concentrations and life expectancy for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

strategy for Singapore was to become the top city in Asia in terms of quality of life and to develop as a sustainable, high density city that is clean and green, with excellent connectivity and a sense of space. The strategy set the aims to reduce the levels of $PM_{2.5}$ to 12 mg/m^3 by 2020, to have 0.8 ha of green space for every 1000 residents and at the same time ensure that70% of all journeys in the city are made by public transport. As of 2011, Singapore achieved a recycling level of 61%. In the process of designing the Blueprint 700, people from the non-governmental organisations, businesses, grassroots organisations, academia, media and mayors were consulted and over 1300 suggestions were received from the public. Knowing that Singapore, being a small island, does not have a wide diversity of renewable energy resources available apart from solar (wind, geothermal or hydropower), the strategy focused on: 1) *raising energy efficiency* by pricing energy appropriately to reduce environmental impacts, providing information for better decisions, boosting energy-efficient industry designs, processes and technologies, building capabilities in renewable energy, promoting resource-efficient buildings, promoting public transport, expanding water supply, improving water efficiency, and minimizing waste. At the same time the decision was taken to stimulate facilitation of household recycling and enhance land use planning. The further priority of 2) *enhancing urban environment* was aimed at reviewing emission standards, adopting new technologies, pricing pollution, improving water quality, making the city cleaner, improving transport links, enhancing the city's greenery and conserving urban biodiversity. The third priority of 3) *building capabilities* implied investment in R&D and facilitation of international sharing of knowledge and, finally, the fourth goal of 4) *fostering community action* was focused on promoting community efforts, promoting industrial efficiency and stimulating development of the public sector (Singapore, 2009). Singapore keeps anticipating the future change and in the recent foresight volume (Quah, 2016) a projection is made that by 2065 Singapore will generate 65 TWh/year of electricity from renewable sources, which constitutes 50% of electricity demand. Among the technologies of the immediate future for Singapore the authors mention solar PV, biogas, marine energy, wind, biofuel from algae, co-generation, power from biomass as well as off-shore floating PV.

In the past ten years, Singapore estimated the potential damages

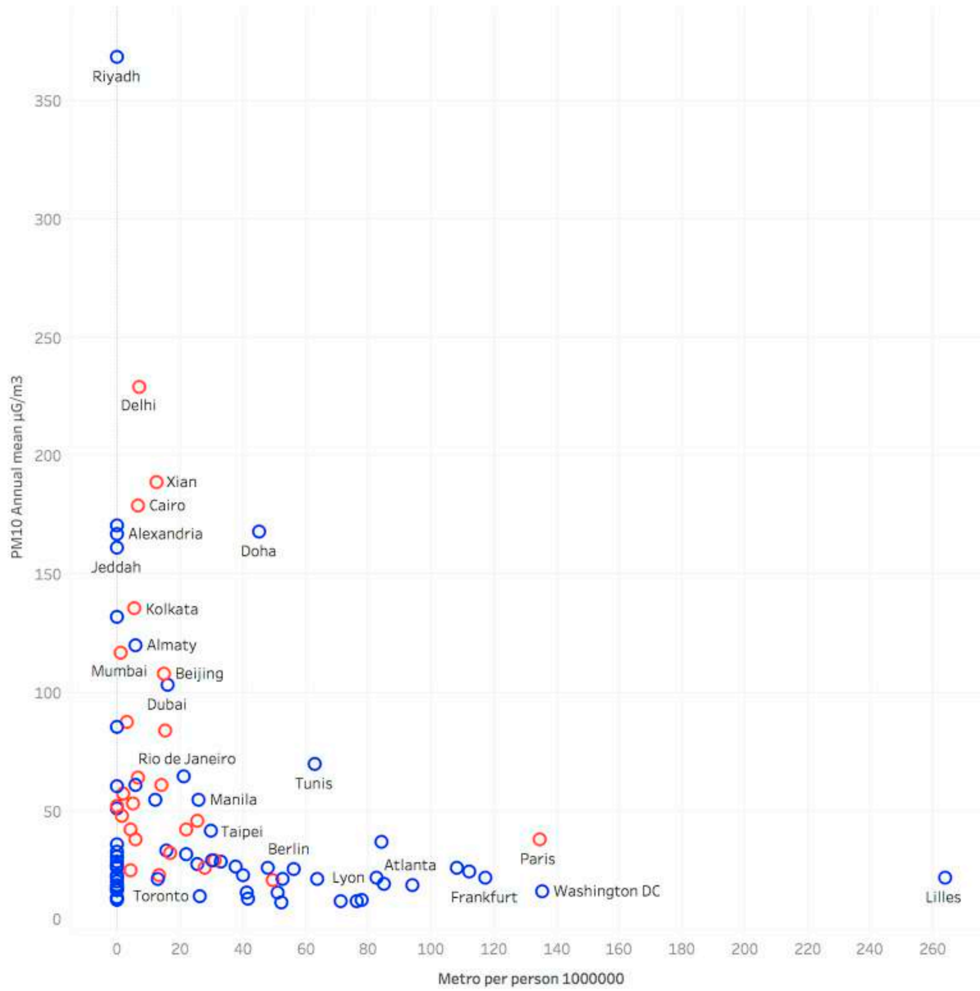

Fig. 23. Correlation between availability of underground stations per 1,000,000 inhabitants and PM_{10} concentrations for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from congestion to be in the range of \$2–3 bln per annum and introduced a smart-card innovation for public transport, designed by IBM, which covered road tolls, bus travel, taxis, metro and even shopping and was capable of registering 20 mln transactions per day and collected extensive traffic data, allowing city administration to constantly change routes to minimize congestion. The National Water Agency developed the Newater initative, through which a new Siemens-designed desalination plant and a water recycling scheme provide up to 30% of Singapore's water needs, and two thirds of the Singapore's land surface became a water catchment area. Between 2000 and 2007 the share of electricity produced by natural gas increased from 19% to 79% in Singapore, thereby reducing the harmful CO_2 emissions. Since 2005, over 1650 buildings in Singapore were made environmentally friendly. At the moment around 80% of residents of Singapore are living in public housing provided by the Housing and Development Board. In a short space of time using a highly focused and strategic approach, Singapore achieved a great deal in the *economic* sphere by attracting 7000 international companies and securing one of the highest per capita income levels in the world, in the *social* sphere by keeping very low unemployment at 1.8% and achieving success in the *environmental* sphere by reducing the amount of waste generated per person and increasing recycling levels to 61%, keeping PM_{10} pollution at a relatively low level of 32 $\mu G/m^3$ through developing public transport and increasing the green space to 47% of its territory.

It is particularly reassuring to see such tremendous success achieved in Singapore through intensive interdepartmental and interdisciplinary collaboration (Singapore, 2009); the case for which was outlined in our earlier paper (Shmelev & Shmeleva, 2009).

Although one might argue that the import of palm oil, which is growing in Singapore tends to ruin the biodiversity in neighbouring Malaysia, there isn't yet a comparative dataset on imports of agricultural commodities at the city scale to take this dimension in into account in London, New York and other megacities.

It would be highly beneficial to consider cities of Rio de Janeiro, Los Angeles and Shanghai that are consistently ranked lower in our set.

Rio de Janeiro (Fig. 29) faces the following major challenges: relatively low economic potential and low incomes, insufficient development of innovation potential of the economy, undeveloped public

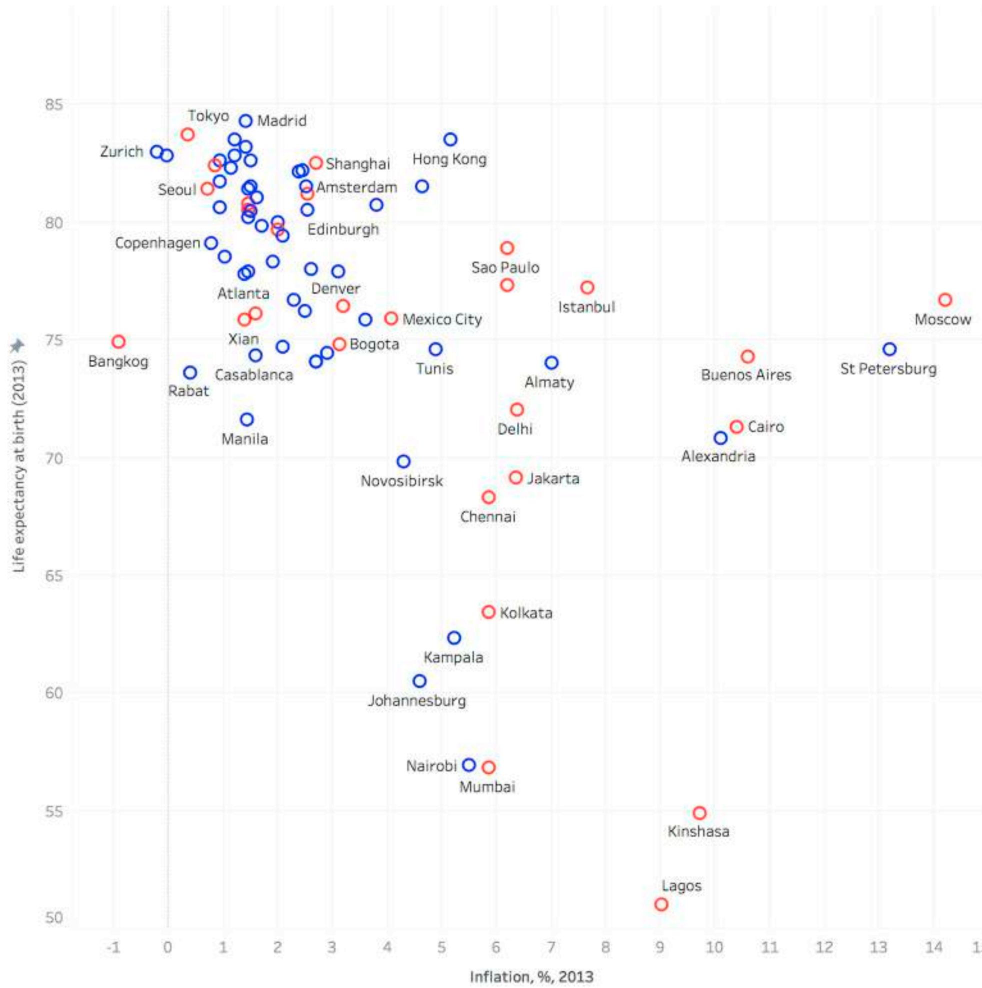

Fig. 24. Correlation between inflation and life expectancy for global cities (megacities are marked in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

transport infrastructure apart from several new metro lines, low level of higher education, high discrepancy between the rich and the poor and low recycling rates. On our opinion, to improve sustainability performance, Rio would clearly benefit from increased focus on innovation, stimulated by a faster Internet connection and stronger involvement into research and education, further stimulating regional economic development. The infrastructure would benefit from an expansion of the underground system and pioneering a robust waste recycling system, which is currently not in place. It would be advantageous to introduce some progressive policies to aim to reduce the gap between the rich and the poor.

Los Angeles (Fig. 30) is characterised by wasteful consumption lifestyles, relatively high water consumption, low uptake of renewables, despite sunny climate, quite high discrepancy between the rich and the poor, relatively low level of development of public transport and reasonably modest average incomes. It would be highly advisable for Los Angeles to look at ways to reduce unemployment. There is a strong potential to improve infrastructure by expanding the currently very small underground network and bringing in high-speed trams. Los Angeles is in a strong position to expand its solar electricity capacity by utilizing all existing roof and wall space that could be adapted for solar panels. There is a potential to rethink the consumption model and try minimizing water use. Additional green space, creative use of vertical greening and green roofs could be expanded to retain the water the city so badly needs.

The main challenges faced by Shanghai (Fig. 31) are relatively low average incomes, relatively low level of innovation in the economy, insufficient development of public transport infrastructure for the city of this size, relative low uptake of renewables, and low recycling. Shanghai has a lot of potential to strengthen its strategic position on innovation it currently loses to neighbouring innovation giants like Shenzhen and Taipei. At the same time, Shanghai could expand its public transport system, undertake additional efforts to expand renewables and build the capacity for recycling its waste. Doing this could strengthen its overall economic performance further.

7. Conclusion

In this paper we focused on megacities; which are global centres for economic activity and are responsible for a considerable share of global

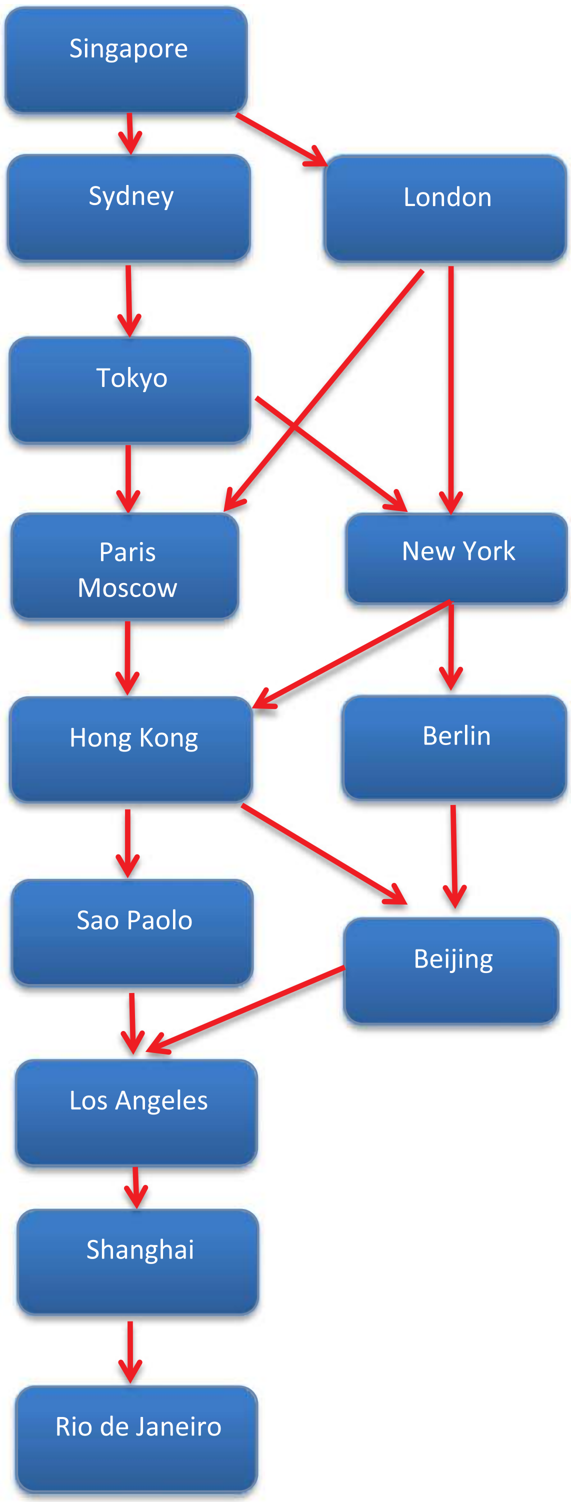

Fig. 25. Multi-criteria sustainability performance assessment web of domination relationships among megacities, ELECTRE III: environmental priorities, A = 0.05 for indifference A = 0.1 for preference.

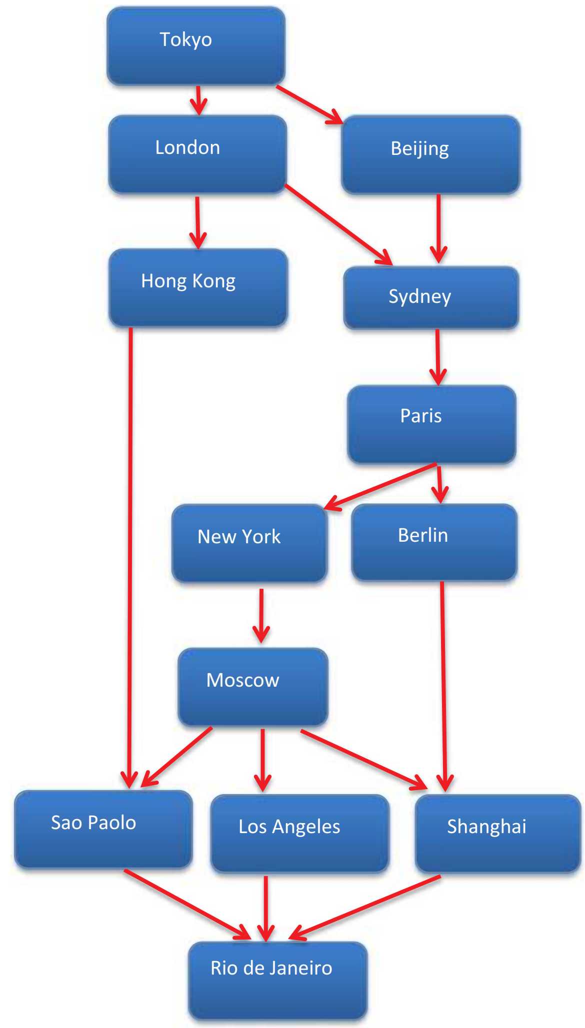

Fig. 26. Multi-criteria sustainability performance assessment web of domination relationships among megacities, ELECTRE III: economic priorities, A = 0.05 for indifference A = 0.1 for preference.

emissions of greenhouse gases, require considerable amounts of water and produce substantial volumes of waste. The application of multi-criteria decision aid allowed us to produce a multidimensional web of domination relationships among the top fourteen world cities on twenty sustainability criteria with the help of ELECTRE III tool. At the same time, varying indicator weights produced aggregate performance scores for megacities under four policy priorities: environmental, economic, social, and smart city criteria. The assessment carried out using the multi-criteria tool identified sustainability leaders (Singapore, Tokyo, London) and those that are lagging behind (Shanghai, Rio de Janeiro, Los Angeles). Application of environmental policy focused ELECTRE III identified Singapore as the leader, Tokyo as the leader under economic and social priorities and Tokyo and London under smart city priorities. The result has put the performance of individual cities within the global context and presented the indicator- based sustainable development

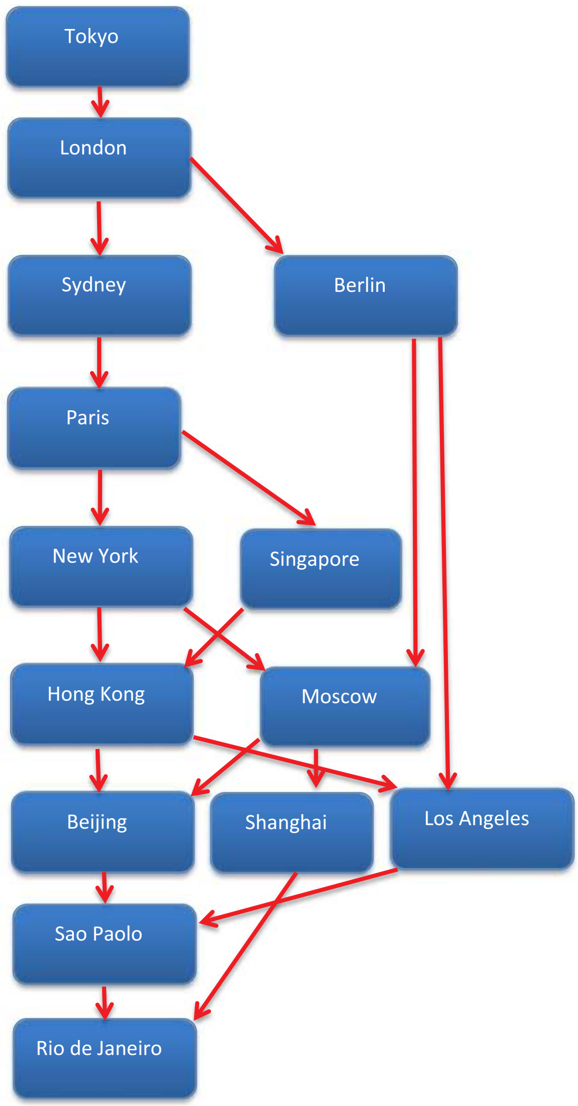

Fig. 27. Multi-criteria sustainability performance assessment web of domination relationships among megacities, ELECTRE III: social priorities, A = 0.05 for indifference A = 0.1 for preference.

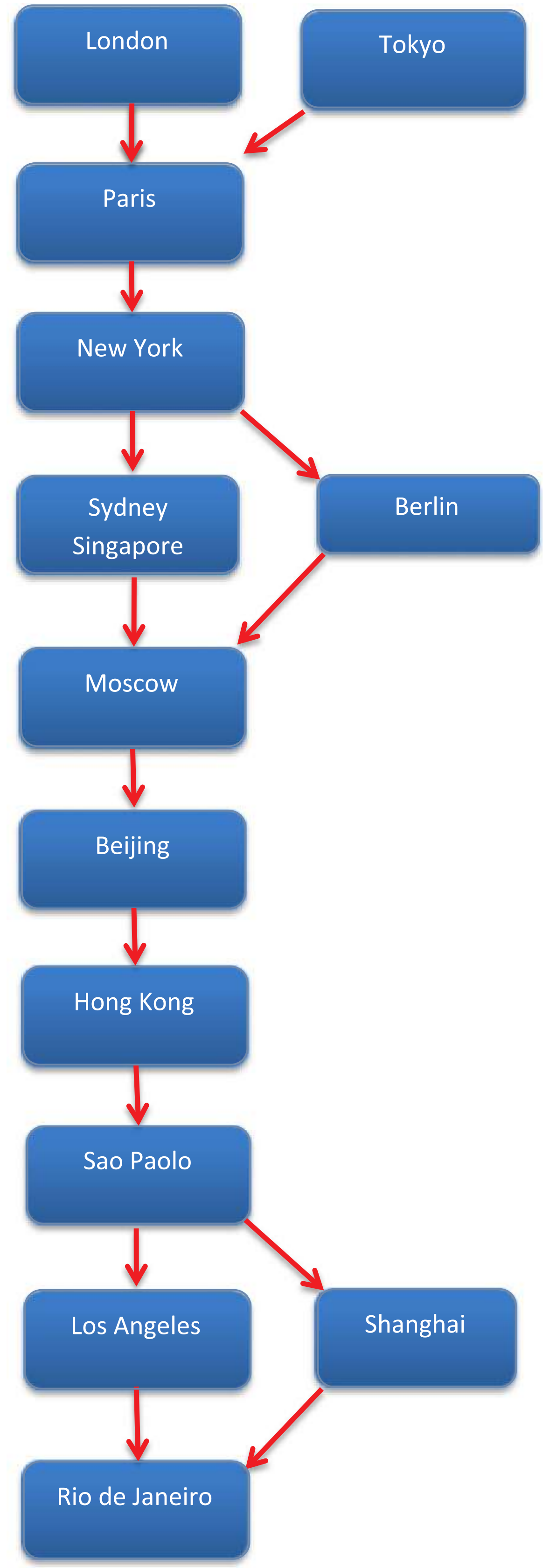

Fig. 28. Multi-criteria sustainability performance assessment web of domination relationships among megacities, ELECTRE III: smart city priorities, A = 0.05 for indifference A = 0.1 for preference.

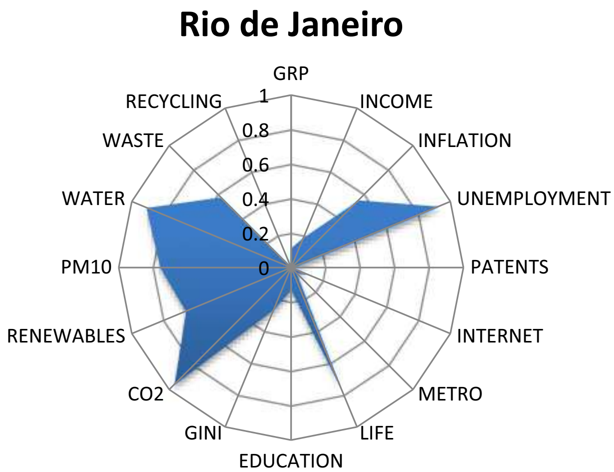

Fig. 29. Rio de Janeiro Sustainability Performance, 2014.

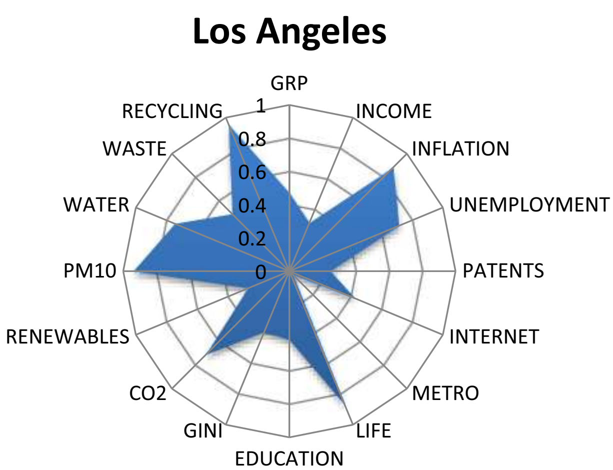

Fig. 30. Los Angeles Sustainability Performance, 2014.

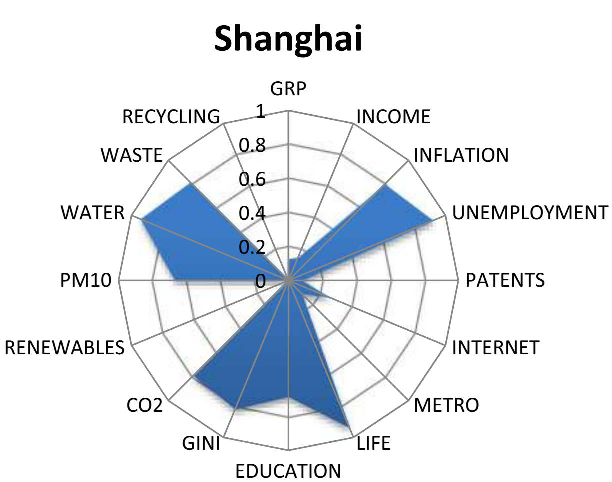

Fig. 31. Shanghai Sustainability Performance, 2014.

performance of individual cities within a coherent framework of multi-criteria decision aid. Learning from best practices and worst cases in this context provides an invaluable insight for policy reform to create smarter, greener, more compact, socially diverse, economically strong and less polluting cities around the world.

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