SUSTAINABLE URBAN INFRASTRUCTURE: A REVIEW

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Introduction

Nowadays the majority of the world population lives in cities, for the first time in human history, and 66% of this population might live in urban areas by 2050 [1]. About 80% of the total greenhouse gas (GHG) emissions come from cities, with 25% attributed to urban transportation, 32% to urban built environment, and an additional 5% to municipal solid waste. Urban transportation accounts approximately 20% for the global energy consumption and urban built environment responds to an additional 25% [2]. Climate change and the additional burden it imposes on the environment, economy, and life of the population aggravate concerns of sustainable urban infrastructure (SUI), including deleterious effects in urban water management [3], urban heat island effects [4], pavement production and construction [5], among others.

Urban infrastructure (UI), by itself, is a multifaceted concept that goes beyond a set of engineered utilities. It is equally a place for local governance, intertwining issues of economic growth, climate change, and municipal waste. There are different levels to tackle UI issues as well, from supranational institutions, to national, regional, and local governments. The UI functioning affects regulators, consumers, citizens, businesses, and households alike [6]. From an engineering perspective, it refers to engineered systems that provide water, energy, transport, sanitation, information, and built environment. It covers irrigation (e.g. dams, locks, and canals), facilities (e.g. schools or hospitals), and municipal utilities (e.g. electric, telecommunication, gas, water, and wastewater along with urban street and highway elements) [7]. In this sense, the urban space is a place for extreme pressure and for political and economic power, as much as a set of engineered utilities and facilities.

The sustainability concept is relatively new and it encompasses a multidisciplinary field made of engineering, environmental, economic, and social sciences [7]. Sustainability in the definition of the Brundtland Commission is the ability to meet the needs of the present generation without compromising the chances of the future generations to fulfil their own needs [8 and 9]. Under the triple bottom line (TBL) approach, sustainability encompasses social, economic, and environmental concerns [10]. Sustainability is an all-inclusive concept designating a process of achieving human development over time and space, embracing the interdependencies of the ecology with social and economic aspects, in an equitable and safe manner that requires technological, scientific, and political discernment [11 and 12]. In this context and borrowing from Martos et al. (p. 480) [2], “a sustainable, resource efficient city can be defined as a city that is significantly decoupled from resource exploitation and ecological impacts and is socio-economically and ecologically sustainable in the long term.”

The SUI multidisciplinary and multi-layered concept evolved over time. This paper aims to disentangle the prevailing themes pursued under SUI and to respond two basic research questions (RQ): RQ1 – What are the prevailing themes in sustainable urban infrastructure; and RQ2 – How did the themes of sustainable urban infrastructure evolve? The study comprises this introduction, followed by the description of the methodology of the literature review and basic statistics. Results from citation, co-citation, and co-word analyses ensue. Conclusions close the paper.

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Methodology

This section comprises the methods and basic statistics from the systematic literature review (SLR) and methods applied to the longitudinal analysis of the thematic areas.

A. The systematic literature review and basic statistics

A SLR was conducted using the Thomé et al.’s [13] step-by-step approach. This approach, based on [14], consists of eight basic steps: (i) planning and formulating the problem; (ii) searching the literature; (iii) data gathering; (iv) quality evaluation; (v) data analysis and synthesis; (vi) interpretation; (vii) presenting results; and (viii) updating the review.

For the first step, the co-authors of this paper gathered to clarify and discuss the SUI concept, defining the research questions and expected research results. This step anticipated the attainment of a taxonomy of themes, an understanding of their evolution over the past years, and possible impending areas of this study.

The second step comprised selecting databases, defining search keywords and applying exclusion criteria for papers, with no time restrictions. Elsevier’s Scopus database was selected for its vast abstract and citation collection of over 22,000 journals [15]. At first, the search keywords were “urban infrastructure” and “green” yielding 258 papers. Next, the keyword “sustainab*” (referring to any keyword produced by the combination of the root “sustainab” and a suffix) was added, resulting in 645 papers. The inclusion of the keyword “environment*” expanded the selection to 1,180 papers. The limiting of the search by document type (articles, conference papers, reviews, and articles in press) refined the search to 1,059 papers. Moreover, the exclusion of papers published in languages other than English, narrowed the selection to a final set of 995 papers. The full bibliographic reference is available upon request to the corresponding author.

For the third and fourth steps, the co-authors of this paper used basic statistics on the selected papers with Scopus’ built-in bibliometric software that provides basic statistics on research subject areas, publications per year, journals, institutions, citations, and h-index per authors, among others. The h-index definition is simply the number of papers with citation number ≤ h and it is a measure of the influence of a publication, a Journal or an author in the research field [16].

The top SUI subject areas have not surprisingly spread over several research fields denoting the SUI eminent multi-disciplinary nature. With 367 and 346 papers respectively, social sciences and environmental science have clearly been the most common subject areas with roughly one third of all papers each. It is also worth to mention that 294 papers have been classified in engineering, 130 in earth and planetary sciences, and 114 in computer science. Agricultural and biological sciences; business, management, and accounting; energy; and medicine have figured equally among the top ten recurring subject areas. The prominence of publications from the social and environmental sciences reflects on the co-citation analysis and in the approaches to SUI adopted by the most cited authors analysed in Section B of the Results.

The first published paper dated back to 1984 and until 1995 there was a yearly average of three papers. A sudden increase has occurred after 1996. As of 1999, there has been a continuous and exponential growth in the number of documents published until today, with a peak in 2015, the year with most papers issued (132 publications). The distribution of papers by journals enlists 131 different sources, reflecting a large array of multidisciplinary sources. The top eight journals, ranked in decreasing order of the number of citations, are related to urbanism and/or the
environment. The number of publications and the total number of citations have not strongly been related since only one of the top five journals in number of papers was equally among the top five in number of citations (Pearson-\( r = 0.39; \ p < 0.1 \)). In other words, the most prolific sources have not always been necessarily the ones carrying the larger impact in the research field. Moreover, of the top ten research institutions, ranked by number of citations, four have been located in Europe, five in North America, and one in Asia (China).

Data analysis and interpretation are the fifth and sixth SLR steps [13]. Data analysis resorts to qualitative content analysis using an inductive approach [17], complemented with quantitative co-citation and co-word analysis of papers selected for the systematic review, as described in the next section. This paper corresponds to step seven of the SLR, presentation of results. The updating of the review would be step eight. However, updates are beyond the scope of this study.

B. Bibliometric analysis of thematic areas

Two key assumptions of bibliometrics drive the analysis: co-citation denotes relatedness of authors treating the same subject and co-occurrence of keywords indicates common themes [18]. A co-citation occurs when paper A and paper B quote paper C. Two keywords co-occur when word A and word B are associated in at least one document. A document with two or more keywords from a list of keywords is a “core document.” If the document has only one keyword association it is classified as a “secondary document” [19].

BibExcel [20] software prepared the matrix of co-citations and generated the clusters of co-citation applying Persson’s party clustering algorithm [21 and 22]. Pajek software [23] (http://mrvar.fdv.uni-lj.si/pajek) prepared the network analysis. SciMAT software provided the dynamic co-word longitudinal analysis of themes [24 and 25]. The SciMAT software uses Callon’s thematic strategic diagram [25 and 26] to depict the co-occurrence of keywords in a bipartite graph showing the density and centrality of co-occurrences. The co-occurrence is measured by the index \( e_{ij} = c_{ij}^2 / c_i c_j \), where \( e_{ij} \) is the equivalence index, \( c_{ij} \) is the number of documents in which two keywords i and j co-occur, \( c_i \) and \( c_j \) are the number of documents in which each one occurs [19]. Clusters are formed with the application of the ‘simple centre algorithm’ [19, 22 and 27]. Centrality is calculated as \( c=10\sum e_{kh} \), where k is a keyword belonging to the theme and h a keyword belonging to other themes. It is a measure of the interaction among networks of keywords. A network of keywords denotes a theme and centrality is a measure of the inter-relations among themes. Density is calculated as \( d=100(\sum e_{ij}/w) \), where i and j are keywords belonging to the theme and w is the total number of keywords in the theme. It measures the internal strength of the network or theme. The Callon’s thematic diagram has four quadrants represented in Figure 1.

![Figure 1 – The Callon’s thematic diagram](image)
From top right clockwise, the diagram displays the core themes with high centrality and high density. Central themes are also key for the research field, but not well developed: they combine high centrality with low density and they should be explored further. Emerging or declining themes present low centrality and low density. Isolated themes are usually well-researched areas with high density, but of marginal value for the research field as denoted by low centrality.

The longitudinal analysis of themes consists in the observation of themes in successive periods. It is measured by the inclusion index \( \text{index} = \frac{\#(U \cap V)}{\min(\#U, \#V)} \). U and V are disjoint sets in a bipartite graph, in which the edges can only connect elements from the subset U to the subset V. The inclusion index varies between zero (non-inclusion) and one (if the elements of V are fully contained in U).

**Results from the citation, co-citation, and co-word analyses**

The results section presents first the most prolific and influential SUI authors, based on the number of publications and the h-index. The co-citation and co-word analyses ensue.

**A. The citation analysis**

The ten most prolific authors (with greater number of publications) are predominantly from civil and environmental engineering. They are located in Europe, North America and Asia. It is equally worth to mention that Rieradevall and Gabarell are frequent co-authors, as well as Zhu and Bamler. Some authors have large h-index, indicating an influential position in the field. As it was the case in the analysis of the most prolific journals (Section A of the Methodology), the most prolific authors are not necessarily the most influential ones (the correlation between the number of papers and the h-index is not statistically significant, with Pearson-\( r = -0.018 \)).

**B. The co-citation analysis**

The co-citation analysis examines the relationship between papers cited together. This method allows the outlining and better understanding of a research area [20]. The network in Figure 2 illustrates the co-citation relationships between the top 23 papers with the greater number of citations. The first author’s name only and publication year identify papers in the graph, to facilitate readability.

There are a larger cluster led by Star [28] and by Peck and Tickell [29] and four smaller clusters with two nodes each. The larger cluster emphasized the relationship between society and infrastructure. The smaller clusters focused on modernity, urban metabolism, predicting future deteriorations of infrastructure systems, and urban ecology. Jacobs [30], Huang [31], Ariaratnam et al. [32], and Grimm et al. [33] respectively led them. The description of cluster is in chronological order.
The main theme in the cluster made-up of Jacobs [30] and Kaika and Swyngedouw [34] was modernity. Jacobs [30] led the cluster by condemning modernist urban planning policies in the 1950s, which she argued were responsible for the destruction of numerous communities in inner cities. Kaika and Swyngedouw [34] then resumed the topic by addressing the shift in perception of urban technological networks (particularly water) from esteem in early modernity to invisibility in high modernity, representing the failure of the modernist “ideology of progress.”

The cluster formed by Huang [31] and Sahely et al. [35] had urban metabolism as its theme. Huang [31] used ecological energetic analysis to link urban economic and ecological systems. Although this association had been oftentimes overlooked, Huang believed in interdependency between both systems. Sahely et al. [35] used urban metabolism as a tool to gather fundamental information about infrastructure in cities. Both authors used of case studies to strengthen their findings.

Within the larger cluster, Star [28] led on one end by studying the relationship between ethnography and infrastructure. For Star [28], infrastructure was both relational and ecological, linking technical systems to both society and environment. Graham and Marvin [36] supported Star’s [28] view of a relational aspect of infrastructure by taking up on the conflicting social interests regarding privatization and its consequences to the urban community. They believed that privatization frequently resulted in the creation of an alternative infrastructure network, purposed to serve privileged members of society, which, in turn, led to what Graham and Marvin [36] called “splintering urbanism.” Citing Star [28], Graham and Marvin [36] also brought to light the overlooking and “invisibility” of urban networks, which usually only became evident at the event of an infrastructural collapse.

In his book “Planet of Slums”, Davis [37] scrutinized the unexpected and still exponential growth of slums. He investigated the bleak long-term effects that the alienation from world economy of these low-income and improvised housing projects might have in cities. Davis [37] cited Graham and Marvin [36] on the MOUT (Military Operations on Urbanized Terrain)
doctrine, which expanded upon both Graham and Marvin’s [36] “splintering urbanism” and Davis’ [37] views.

Gandy’s [38] findings concurred with Star [28] and Graham and Marvin [36]. Gandy [38] used water systems to point out the humongous disparity between post-Industrial Revolution urban ideals and actuality. Instead of closing in XIX century ideals of dialogue between infrastructure and citizen needs, most present-day cities have actually pulled away from it. The drop in investments on infrastructure and the prioritization of private over public demands attest the existence of polarized rather than functional urban metabolic systems.

Geels [39] looked into the co-evolution of society and technology and he explored socio-technical systems in cities by incorporating a social factor to sectoral systems of innovation. Combining institutional theory to the aforementioned systems, he built a hierarchical multi-level perspective (MLP), describing from bottom-up transformations in niches (places of radical innovations), regimes (a set of stabilizing rules and paradigms for innovation), and landscape (the broader surrounding spatial arrangements of cities, factories, highways, and electricity infrastructure that cannot be changed at will). The distinction is important because it is a lens used by Hodson and Marvin [6], among others, to analyse further the UI in the second decade of this century.

At another end, Peck and Tickell [29] introduced neoliberalism to the larger cluster, suggesting the transformative potential of this economic theory and identifying its role in city governance. Peck and Tickell [29] also called attention to how neoliberalism could shape cities in a local sphere. Similarly, Brenner [40] identified in his work that key cities or spaces could be crucial to transformations at a national level. With this, he proposed a “rescaling of statehood” and a development of unprecedented forms of state power based on city governance.

Co-cited by Star [28], Graham and Marvin [36], Gandy [38], Geels [39], Peck and Tickell [29], and Brenner [40]. Gullberg and Kaijser [41] were pivotal in bringing together the two initial branches of ethnography and political economy. Combining the interrelation between urban and technology studies from Star [28] and local transformations from Peck and Tickell [29], Gullberg and Kaijser [41] studied urban morphological transformations as resulting from the connection between buildings and networked landscapes. They proposed “City-Building Regime,” a novel approach that encompassed both political and economic aspects. Gullberg and Kaijser [41] also demonstrated a concern for urban environmental sustainability, which appeared for the first time in this cluster.

Smith et al. [42] proceeded with socio-technical transitions. Within an array of transition scenarios, regime changes occurred as a result of selection pressures. Governance affected transitions, regulated by factors such as regime association, resource circulation, and public expectation. Co-citing Star [28] and Graham and Marvin [36], Hommels [43] resumed the themes of linkages between technology and urban studies. He criticized the lack of dialogue between both fields and resistance in changing this condition. Emphasizing the importance of this dialogue, Hommels [43] hoped for the start of a common ground between technology and urban studies. Paralleling Graham and Marvin’s [36] remark about the UI “invisibility,” Hommels [43] presented the scarcity of technology research in urban studies.

Gandy [44] used cyborgs as a metaphor for cities. Cyborgs are “hybrid creatures, composed of organism and machine”; like cities, they have both a human feature and a technological feature. Gandy [44] went beyond traditional areas of urban study and deepened into the “cyborg city”: a city embodied by information rather than material circulation. He highlighted social polarization and obsolete remnants of modernity in metropolitan environments in contemporary cities. Gandy [44] did not co-cite any works prior to his and he was co-cited solely by McFarlane
and Rutherford [45], which also had connections to Gandy [38], Gullberg and Kaijser [41], and Smith et al. [42]. McFarlane and Rutherford [45] reinforced the impact of politics and governance on infrastructures, a topic previously presented by Gullberg and Kaijser [41] and Smith et al. [42], by analysing three aspects: fragmentation, inequality, and crisis. They also cited Gandy [44] on urban fabric and they mentioned the increase in social research on infrastructure. McFarlane and Rutherford [45] presented, still again, the “invisibility” of infrastructures in cities by citing Gandy [38]. In an unprecedented manner, however, McFarlane and Rutherford [45] defied Gandy’s [38] view and argued “Infrastructures have always mattered.”

With Hodson and Marvin [46] and Monstadt [47], ecological sustainability was finally solidified within this cluster, illustrating the somewhat recent global interest in the subject. Hodson and Marvin [46] analysed urban ecological security (UES). The newfound and increasing universal concern for UES and sustainability as a whole had produced a fresh demand for approaches to ensure secure ecological and material growth. With this in mind, Hodson and Marvin [46] analysed current secure urban and resilient infrastructure (SURI) strategies and obstacles and they suggested alternatives and directions of study. A central work in his cluster, Monstadt [47] identified the massive impact infrastructure had on urban ecology, among other areas. As do Hodson and Marvin [46], Monstadt [47] also believed in the need for novel approaches involving infrastructure reconfiguration in order to guarantee environmental success. Judging current strategies inadequate, Monstadt [47] considered cooperation among urban and technology studies in search for alternative solutions for SUI. Finally, Hodson and Marvin [6], citing Graham and Marvin [36], observed that UI plays a key role in the success of cities. This led them to debate whether or not cities have the power and capability to shape socio-technical transitions. Hodson and Marvin [6] found evidence to support that some global cities indeed made efforts to transform paradigmatic regimes of governance. Citing Smith et al. [42], they also examined multi-level perspective (MLP) of city transformation based on landscape, regimes, and niches of innovation.

The cluster composed of Ariaratnam et al. [32] and Baur and Herz [48] focused on predicting future deteriorations of infrastructure systems. While Ariaratnam et al. [32] led the cluster by proposing a methodology for forecasting the failing of a given infrastructure system based on previous deterioration models, Baur and Herz [48] concentrated on the prediction of the deterioration of sewers.

Whilst other clusters were either lacking or had environmental sustainability as a secondary theme, the cluster containing Grimm et al. [33] and Evans et al. [49] addressed urban ecology. Grimm et al. [33] led the cluster by presenting the topic of global and local environmental change. They stressed the challenges faced by sustainability with the universal growth of urbanization. With a more specific take, Evans et al. [49] gave continuity to the matter with their article on urban avian assemblages, advocating the need for conservation of developed areas.

The social sciences research clearly marked the UI field from the beginning and progressively moved towards incorporating sustainability. The analysis of most influential authors in this field based on the total number of citations received suffers from the effect of time lag, attributing a heavier weight to more ancient and fundamental research, as older papers have more time to accrue citations. The analysis of the evolution of themes from the co-word analysis in the next section partially overcomes this time lag effect, looking into contributions that are more recent.
C. The co-word analysis

To allow a more in-depth co-word analysis and further understanding of the evolution of themes, documents were divided into two successive periods: 1984-2009 and 2010-2015; the first period with 379 documents and the latter period with 616 documents. SciMAT used the keywords exported from the Scopus database to build the thematic clusters; they were: cities, investments, urban-area, developing-countries, environmental-impact and storm-water for 1984-2009, and climate-change, urban-infrastructure, cities, storm-water, life-cycle and vulnerability for 2010-2015. It is important to notice that all 995 documents were electronically analysed and scrutinized for the co-occurrence of keywords. After classifying the papers in different thematic clusters, the core documents (those with more than one co-occurrence of keywords) corresponding to up to 80% of total citations in each thematic cluster were hand selected for full text reading and content analysis. In total, 55 documents were selected: 20 from the first period and 35 from the latter.

For each cluster, documents were subdivided into core and secondary documents (documents with a single co-occurrence of keywords in the thematic network). The thematic area was analysed based on the full text of the 55 papers responding to 80% of total citations in each cluster and period.

Figure 3 illustrates the number of keywords per period, those keywords that reappeared in the following period, and those keywords that did not.

![Figure 3 – Overlapping map of keywords of the two periods](image)

The number of keywords went from 240 in 1984-2009 to 367 in 2010-2015, a 53% growth. It indicates that the SUI thematic scope is diversifying. Of the 240 keywords introduced in the first period, 88% reappeared in the following period, that is: 28 words did not reappear and 212 words remained. This high number of keywords remaining in the two periods shows some consistency in the main SUI thematic areas. In 2010-2015, there was an addition of 155 new keywords as compared to 1984-2009, which is a characteristic of somewhat new and still evolving research fields.

Figure 4 depicts the SUI thematic evolution. The association strength, represented in Figure 4 by the thickness of the lines connecting each cluster is calculated according to the inclusion index (see Section B of the Methodology). The continuous lines represent a name association between thematic clusters (either two clusters have the same name in consecutive periods or one thematic cluster contains the other one) and the dotted lines represent associations regarding aspects other than name. The sphere sizes correspond to document count.
In the first period, the thematic clusters had a somewhat evenly distributed document count. Investments and urban area, however, could be identified as having the greatest document count; followed by cities, developing countries, and environmental impact; and finally storm-water with slightly less documents. In the second period, urban infrastructure had a discernibly larger document count than the other themes. Climate change followed next, but with a considerable gap in the number of documents. Cities, storm-water, life cycle, and vulnerability appeared with fewer documents.

Cities and urban areas in 1984-2009 split into cities and climate change in 2010-2015. Investments became urban infrastructure and life cycle in 2010-2014, with stronger ties with the latter period, as depicted by the thicker line joining the two in Figure 4. Urban infrastructure was clearly the dominant theme in 2010-2015, attesting the relevance of the research area and its actuality. The earlier themes of investments, developing countries, and environmental impact from 1984-2009 merged into urban infrastructure in 2010-2015. Storm-water remained with strong thematic areas with the same designation in the two periods. Vulnerability appeared as an isolated new thematic cluster in 2010-2015. Figures 5a and 5b depict the strategic diagrams in respectively 1984-2009 and 2010-2015.
In 1984-2009 cities, investments, and developing countries were core themes with average to high density and centrality meaning that they were highly quoted themes and are often associated with other SUI themes. There was great concern regarding catastrophic events in cities. Kates et al. [50] advocated the incorporation of natural risks considerations during city planning, such as acknowledging a history of natural hazard in the reconstruction of New Orleans after Hurricane Katrina. Qureshi et al. [51] studied the responsiveness of healthcare workers during catastrophic disasters. In their study, they found that many of the barriers preventing the responsiveness of healthcare workers were actually surmountable and that responsiveness could be enhanced with measures such as the provision of more adequate personal protection equipment or arrangements to contour urban transportation drawbacks. Kovats and Akhtar [52] reviewed scientific evidence of the effects of temperature, rainfall, and extreme events on human health, in particular the impacts of heat waves and floods with an emphasis in Asian cities. They concurred that improvements in urban infrastructure, housing in particular, are a necessary step towards the endurance of cities to climate change, but fear a long wait might hinder their effectiveness. Ruth and Coelho [53] turned to the analysis of the relationships between climate change and urban infrastructure in cities through the lenses of complexity theory, which they believed might be a useful tool in handling investments and in decision-making. Wang [54] zoomed in the major consequences of environmental degradation in China (e.g. air pollution on large cities, water pollution of rivers, deforestation, and soil degradation). He called for state environmental protection laws and public education on environment protection as a means to mitigate the situation.

Clark et al. [55] reviewed the elaboration of cost models to help meet demands for investments on urban infrastructure, focusing on water systems. Torrance [56] addressed investments on infrastructure transformation with the privatization of urban infrastructure. Lee et al. [57] introduced a ‘new paradigm’ of ubiquitous infrastructure, defined as ‘an urban infrastructure system where any citizen can access any infrastructure and services via any electronic devices regardless of time and location,’ and examined its application to sustainable urban development in Korea. Wang et al. [58] discussed the improvement of pump scheduling methods in water distribution for economic and environmental benefits.

Finally, under developing countries, Bishop et al. [59] argued that spatial data on infrastructure could aid the management of urban infrastructure growth. Hinks et al [60] proposed different algorithms for 3D models of aerial light detection of human settlement in cities, emphasizing a wide range of applications of such models as improved noise and pollution prevention and disaster mitigation.

Storm-water appeared in Figure 5a as an isolated and secondary research field with high density, denoting its SUI importance, but with low centrality, which denoted a theme in relative isolation from the remaining themes of the research front. The highest citation score in this cluster was Sansalone et al.’s [61] study on the effects of city transportation on storm-water quality. Considerations about urban transportation along with runoff composition are important when examining treatability, structural or non-structural regulations and discharges from paved infrastructure.

Urban area concentrated the largest number of documents in 1984-2009 and still it is a promising cluster for additional research as it associates a high centrality (being interrelated to other clusters) with a low density (denoting a relatively low proportion of co-occurrences among all SUI themes). Chang [62] evaluated the costs-benefits of disaster mitigation efforts by applying life cycle cost analysis to disasters and considering urban infrastructure degradation and maintenance, urban growth and societal impacts. Ziara et al. [63] developed a strategy for
implementing urban infrastructure projects that took into account project prioritization. Sansalone and Teng [64] simulated the effects of a partial exfiltration reactor on both the quantity and quality of urban rainfall-runoff under different soil conditions. Sohail et al. [65] explored the constraints to operation, maintenance, and sustainability of urban services through a multiple case study research in India, Pakistan, and Sri Lanka. The authors advocate partnership between local communities and government as being key to improve operation and maintenance, thus sustainability of urban infrastructure. Stapleton et al. [66] aimed to quantify catchment-derived fluxes of faecal indicator compliance parameters originating from both point and diffuse sources in the UK Ribble drainage basin sentinel research catchment and discharges station, in conformance with EU water quality control management. The study found that untreated storm sewage spills from urban infrastructure and storm-water retention tanks are the dominant components of high flow flux of faecal indicators to receiving waters. Scalenghe and Marsan [67] analysed the negative impacts of soil sealing by impervious material in urban areas, with a special mention to European cities.

Environmental impact was the emergent theme of the last decade. Two documents concentrated 70% of total citations in this cluster. Sahely et al. [68] offered one of the first case studies on urban metabolism analysis, applied to Great Toronto, Canada, and compared with other urban areas worldwide. Urban metabolism quantified the global fluxes of energy, water, material and wastes in and out of an urban region. The conclusion was that inputs exceeded outputs contributing to urban infrastructure pollution and degradation. Denault et al. [69] looked at hydraulic infrastructure design and developed a framework for examining the potential impacts of future increases in short duration rainfall intensity due to climate change on urban infrastructure and natural ecosystems of small watersheds. Results indicated a considerable vulnerability for the environment and that the upgrading of drainage systems would only require moderate effort and expenses.

Figure 5b depicts the strategic diagram for 2010-2015. Climate change and life cycle were the motor themes for the period. Authors in the climate change identified the importance of considering the impacts of climate change in several research areas. Horton et al. [70] described the incorporation of climate change into stakeholder adaptation planning in New York City. Their study indicates major changes in the frequency of coastal flooding and dangerous heat events, among other extreme events, and, thus, the authors find long-term adaptation planning worth considering for these circumstances. Karamouz et al. [71] studied the adverse impacts of climate change on urban floods and their consequences to society and urban infrastructure, highlighting the need to integrate climate change into urban water studies and the importance of improvements in the urban drainage system. Qi and Chang [72] reviewed municipal water demand forecasting models and studied the interrelation between water demand and the economy. Broto and Bulkeley [73], as well as Broto and Bulkeley [74], focused on climate change experiments, defined as “purposive interventions that seek to reconfigure urban sociotechnical systems to achieve low-carbon and resilient cities” [73]. The first examined the maintenance of climate change experiments and the latter analysed climate change experiments in cities throughout the world. Ferguson et al. [75] developed a strategy to aid urban water systems efforts to increase sustainability and resilience. Demuzere et al. [76] examined the contribution of green spaces to climate change mitigation and adaptation.

Venkatesh and Brattebo [77] examine the environmental life cycle performance of Oslo water supply pipelines by analysing annual resource consumption and emissions as well as life cycle assessment (LCA) impact potentials over a period of 16 years. Their study indicates global warming and abiotic depletion are affected the most by the water pipeline system in Oslo.
Furthermore, they identify cost optimization, energy efficiency and environmental friendliness as areas in need of attention. Chavez and Ramaswami [78] analysed the mathematical relationships and political relevance of articulating a trans-boundary infrastructure supply chain’s GHG footprint for cities. The authors explored the production and consumption-based GHG footprints going beyond the confines of the cities and into its infrastructure supply chain. Aylett [79] presented a qualitative case study research aiming to demonstrate the role of the organized civil society in promoting renewable energy and exemplified it with the Solarize Portland project.

Under the life-cycle cluster, Punkkinen et al. [80] focused on the waste collection phase of the waste management life cycle, comparing the environmental sustainability of pneumatic and conventional door-to-door waste systems. Results revealed that the replacement of the conventional system with stationary pneumatic waste collection would increase atmospheric emissions in an existing urban infrastructure, but decrease emissions in the waste collection area (due to less transportation). The production of the waste collection system components played a key role in air emissions. Loijos et al. [81] carried out a LCA on pavements, analysing their environmental impacts. They found that, in a 40-year analysis period, the bulk of GHG emissions concerning pavements could be attributed to the first year – owing to cement production for the most part – and that traffic intensity and cement production specifications affected results the most. For this reason, LCA results proposed reducing embodied use phase and end-of-life emissions. The urban infrastructure cluster concentrated the larger number of publications in 2010-2015. It had a high centrality emphasizing its SUI relevance, associated with a low density indicating the potential for further research to consolidate the thematic area. The main paper based on the number of citations received was Chen et al.’s [82] study of municipal solid waste management in China, the world’s leading municipal solid waste producer. Mahalingam [83] and Misra [84] focused in Indian urban infrastructure development. While Mahalingam [83] analysed public-private partnerships, Misra [84] analysed urban drainage in the increasingly urbanized Ganga basin. Misra [84] claimed climate change might aggravate the already existing need for action regarding the sustainable water management, as well as for education regarding conservation and pollution. Neuman and Smith [85] made an historic review of the connections between city planning and infrastructure. Hayhoe et al. [86] described a case study in the Chicago area focusing on the economic impact of climate change on energy consumption and urban infrastructure and concluded that cutbacks in emissions could result in significant economic cost reductions at various levels. Wu [87] researched the relationships between urban infrastructure and economic development in China, using lagged input and output variables and contrasting cities in different Chinese regions. Coutinho-Rodrigues et al. [88] developed a decision support system for urban infrastructure planning. Horton et al. [70] examined the integration of climate change by decision makers into adaptation planning in New York City. Karamouz et al. [71] offered a case study of urban drainage systems under climate change in the Iranian city of Tehran. An algorithm to select best management practices was proposed and applied to different scenarios under rainfall patterns induced by climate change simulations. El-Diraby and Osman [7] proposed an ontology for informatics applied to SUI. Intertwined networks of actors, processes, and products (e.g. bridges, traffic signals, decisions, and knowledge) composed the framework for an e-city. Masson et al. [89] placed geographic and natural aspects at the SUI forefront in the Paris metropolitan area and they suggested that they should replace the urban infrastructure as a driver for planning urban development.

Cities appeared with lower density and centrality in 2010-2015 than in 1984-2009, showing a declining SUI thematic influence. There was an interest for Chinese cities: Chen et al. [82] studied municipal solid waste management in China, while Peng et al. [90] investigated Chinese
migrant workers’ health seeking behaviour and impediments to the attainment of healthcare in Beijing. Broto and Bulkeley [74] examined climate change experiments in a myriad of cities throughout the world. Hodson et al. [91] proposed to bridge material flow and transition analysis to look critically at resource flows and SUI that provided the linkages between cities, urban infrastructure, ecosystem services, and natural resources. Demuzere et al. [76] offered a holistic framework looking at green urban infrastructure in different types of cities, climates, and social contexts that took into account the interactions and trade-offs between many benefits from green infrastructure. It emphasized the contribution of green spaces to climate change mitigation.

Vulnerability was a cluster of low centrality and average density. In 2010-2015, it mattered as a new theme not strongly related to the other themes. Kalyanapu et al. [92] looked at the vulnerability assessment of flood hazards at the vicinity of dams in cases of severe floods from rainstorms and at the development of suitable mitigation and adaptation options for a resilient urban infrastructure, examining probable maximum flood on the downstream of the American River. De la Torre et al. [93] analysed coastal vulnerability to extreme storms with damage to harbour facilities, coastal tourism infrastructures, and urban infrastructures in the coastal area of the French Gulf of Lyon. They described a monitoring system and wave-forecasting model which allow a better comprehension of coastal threats and aid in the anticipation and development of mitigation strategies. Marcinkowsky and Szmytkiewicz [94] focused on reducing coastal vulnerabilities in the Gulf of Gdansk in the Gdynia municipality through the improvement of beach fill effectiveness due to construction of submerged breakwaters. Tscheikner-Gratl et al. [95] aimed to test to which degree it was possible to reduce urban flooding by adapting the parts of the urban water network that required rehabilitation, reducing vulnerabilities to flood.

The storm-water cluster remained in the same upper left quadrant of the strategic diagram in 2010-2015 that it was in the previous period, as a relatively isolated and well-known SUI theme. Davis et al. [96] led the cluster with 72% of total citations within the cluster. Their study examined control measures of bio retention for mitigating impacts of rainfall runoff from impervious surfaces.

Finally, the Figure 6 depicts how the groups of new and modern themes from the SUI strategic diagram formed in 2010-2015 and what are the links among them. The circles in Figure 6 are proportional to the number of papers in which the keywords appear. The thickness of the lines joining two themes are proportional to the strength of the association between them. The colours distinguish different clusters.

Figure 6 – Thematic clusters relationships: 2010-2015
Note: shows only arcs with weight over 0.4.
The larger cluster labelled urban infrastructure comprises predominantly the clusters labelled investments and urban infrastructure systems. Decision supports formed a group with decision support systems and geographic information systems. The remaining groups formed in Figure 6 are intertwined, forming a web of inter-related subjects treated in association with each other. Climate change is a core theme and it comprises the groups of subjects labelled stakeholders, extreme event, urban climate, climate change impact, greenhouse gas, and urban area. Cities are part of a group formed by the keywords human, economic growth, and infrastructure. Life cycle is associated with costs and life cycle assessment, and liaise with climate change through the associations with greenhouse gas and environmental impact assessment. Storm water forms a group with storm water management and storms, linked with water resources and floods. The cluster of vulnerability is shown close to storm water, forming a group with floods and numerical models, which reflects the nature of the subjects treated under this cluster: flood hazards [92 and 95], and coastal vulnerability [93 and 94].

Discussions and conclusion

This paper applied a rigorous and reproducible SLR protocol resulting in the selection of 995 SUI papers. The field is relatively new, with a persistent and exponential growth in the number of publications since 1999. The large array of research areas and academic journals represented in the literature review portrays well the multidisciplinary nature of urban infrastructure research. It evolves from social science to engineering, from concerns with “urbanism” in the middle of the last century to the engineered network of facilities, infrastructure, and communication of urban spaces nowadays. However, keywords describing the research area remain stable, with 88% of keywords from previous periods reappearing in the publications of 2010-2015, which denotes stability in a maturing yet still evolving research field.

Consistent with the socio-technical theory and the early research in urbanism, urban infrastructure remains a place for power and economic growth as well as of engineered utilities. The larger number of papers in SUI belongs to social and environmental sciences. The most prominent authors measured by the number of citations describe urban infrastructural issues through the lenses of the interplay of economy, society, and technology. In answering RQ1 – “What are the SUI prevailing themes,” this paper lists the themes for 1984-2009: storm-water, urban infrastructure in developing countries, cities, investments, urban area, and environmental impact. The prevailing themes in SUI for 2010-2015 were storm-water, life cycle, climate change, urban infrastructure, cities, and vulnerability.

There are several mechanisms to construct and develop sustainable urban infrastructure to take precautions against the deleterious effects of adverse sustainability conditions. The main sustainability areas covered with concrete suggestions for enhancement in the literature are climate change, investments and decision-making, use of modern technology, waste disposal, storm water, rainfall runoff and urban drainage, partnership, life cycle and vulnerability.

In answering RQ2 – “How did the themes of sustainable urban infrastructure evolve?” the analysis of urban infrastructure evolved from the original considerations about housing and city segregation to a systemic view of modern and new facilities and utilities that take into consideration urban metabolism and vulnerabilities, e-cities and communication networks. In this sense, SUI is not only concerned with utilities, housing and transportation network, but equally in ascertaining if the intake and consumption of resources are renewable and that all aspects of a complex network of people intertwine in the urban space through electronic equipment and communication networks. Future research should encompass this new, modern and extended
conceptualization of urban infrastructure, in addition to the more traditional themes of physical infrastructure and its socio-technical aspects.

The positioning of themes in the strategic diagram assists in tracing the agenda for the future research. The core themes were developing countries, cities and investments in 1984-2009, and life cycle and climate change in 2010-2015. The promising new areas for research in urban infrastructure are under the headings of urban area and environmental impact in 1984-2009. The themes of municipal solid waste management, public-private partnership for infrastructure development including rainfall management and drainage in urbanized areas of the developing world emerge as promising new areas of research under the label of urban infrastructure in 2010-2015. City planning, energy consumption, the economic impact of climate change, the urban infrastructure effects on economic development, best practices in management of rainfall and drainage systems, e-city and a regain of interest in the ecology of urban planning complete the research forefront of themes for 2010-2015. Disaster mitigation, maintenance and sustainability of urban services (water systems, waste management, renewable energy, energy consumption, drainage basins sentinel projects, urban soil sealing), metabolism analysis, climate change forecasts, vulnerability assessment and resilient cities, as well as e-city communications appear as promising research topics for SUI future research.

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