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Assessing the urban sustainable development strategy: An application of a smart city services sustainability taxonomy

Ana Jane Benites *, André Felipe Simões *

University of São Paulo School of Arts, Sciences and Humanities, Sustainability Graduate Program and City, Sustainability and Environment Management Research Group, Brazil

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ABSTRACT

This article contextualizes the smart cities paradigm in the panorama of contemporary city challenges, which increasingly encompasses the pursuit of sustainable development goals and the need to incorporate urban resilient behaviors, mainly in response to the impacts of climate change. Such a scenario also comprises the interpretation of smart cities as tools to assist policymakers and city administrators in directing solutions based on emerging information and communication technologies (ICTs) to the materialization of urban strategic plans addressing these confrontations. There are, however, no established indicator systems that attest to the substantiation of such plans by smart city solutions, nor to their alignment with the goals of urban sustainable development. Therefore, an analytical framework is proposed here to address this knowledge gap. It enables guiding the leverage of smart cities' ICTs, not only for the achievement of economic goals, a feature intrinsic to smart city innovations, but also to reach other sustainability dimensions, as the environmental, social, institutional and cultural. To this end, generic sustainability indicator frameworks and also a set of smart city indicators are explored. They are examined as potential sources of specific taxonomies in smart city services for urban sustainable development. From this compilation of options, the Dashboard of Sustainability, once one of the indicator systems most recommended by experts, is revisited. It is adapted as a framework for analyzing and helping to maintain the strategic targeting of smart city solutions, during their entire lifecycle, at sustainability. To complete the qualitative-analytical-taxonomic frame, the services offered by a real smart city solution, the Rio de Janeiro Center of Operations, are employed as a model. This allows investigating its 9-year transition from a wider, larger capacity, strategic and innovative configuration in orientation towards sustainability perspectives, to a more narrow, operational composition, that is predominantly devoted to the economic dimension.

1. Introduction

Cities still cover only 3% of earth's land mass (UN – United Nations, 2016) and account for approximately 80% of the world's GDP (WORLD BANK, 2019; BIS, 2013, p. I). However, the economic dynamism of urban areas results in up to 80% of the planet's total energy consumption and 75% of global anthropic emissions of greenhouse gases (UN – United Nations, 2016). The associated depletion of natural resources, large scale generation of waste and pollutants, and intensification of inequalities are also urban pressures over the ecosystem (ZUCARO et al, p. 16, 2014; UN – United Nations, 2014, p. 03).

Thus, although urban centers are notable for their innovative capacity (TSOLAKIS & ANTHOPOULOS, 2015, p.01), they also represent, at the same time, problem and solution opportunities for local and global sustainable development (ZUCARO et al., 2014, p.16).

Considering that by the year 2050 the world's urban population is estimated to grow from 55% (4.2 billion) to 69% (6.7 billion) of the 9.7 billion people on Earth (UN/DESA - United Nations Department of Economic and Social Affairs, 2018, 2017, p.01), the need to commit to a new model of urbanization is urgent.

Rather than only focusing on the economic dimension, it is of paramount importance that the new urban archetype integrates all perspectives of sustainability (UN – United Nations, 2014, p. 03–04), including the social, environmental, institutional and cultural pillars (BELLEN, 2007).

To achieve this, municipalities face multiple, complex, and unavoidable challenges in maintaining and expanding the infrastructure and services needed to preserve and improve the quality of life in cities

* Corresponding authors.
E-mail addresses: benites.ana@gmail.com (A.J. Benites), afsimoes@usp.br (A.F. Simões).

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(CAIRD et al., 2016, p 01). In addition, climate change threats have stood out as intensifiers of cities' defiances (PACHAURI et al., p. 69, 2014; BPCC - Brazilian Panel of Climate Change, 2013, p16-17), requiring an increasingly resilient behavior from them as well (BPCC, 2013, p.17).

In response to these stimuli, municipalities around the world have been appending goals to their strategic plans that promise to reduce greenhouse gas emissions and lower energy consumption, in addition to the other measures in place for sustainable urban development (COCCHIA, p. 26-27, 2014; MARSAL-LLACUNA et al., p. 612, 2015).

Such engagements require of urban public administrations the competencies to reshape strategies and execute them under ambitious targets which complexity escalates when added to the collection of challenges that, including a shortage of resources, the cities already faced (COCCHIA, p. 27, 2014; CAIRD et al., p 01, 2016).

Smart city technologies have been instrumental in facilitating the affordable tapping of these decisive skills to accelerate reaching the accorded cities' sustainability objectives, by improving environment monitoring capabilities and supporting proactive behaviors based on big data analytics, amongst other features (KITCHIN, 2014, p. 06).

Nevertheless, critics insist that, when it comes to smart city initiatives, the economic dimension of sustainability ends up being prioritized over the others, as a result of large ICT providers draining profits to the benefit of foreign regions (HOLLANDS, 2008, p.311,314).

The actual impact of smart city infrastructures over local sustainable development targets, meanwhile, remain uncertain. This is mainly because intangible elements abound in the environmental, social, cultural and institutional perspectives of sustainable development beyond the economic one and in the open, complex and dynamic ecosystems that constitute the cities in which these technologies are deployed (MAGRO & WILSON, 2013, p. 1647–1648; CAIRD et al., 2016, p.27–28).

As quantitatively assessing the real intensity of contribution to each sustainability dimension is costly and inefficient given today's technological limitations and immaturity in the complex adaptive systems theory, a myriad of qualitative or hybrid approaches have emerged. Some of them advance city rankings which instigate competition instead of cooperation among municipalities (ANTHOPOULOS, 2017, p.09–12). Others are furthering standardization efforts to stimulate a common understanding of the smart city technological paradigm and its constraints, encouraging the sharing of lessons learned and solutions diffusion (International Standards Organization (ISO), 2015).

Aside from their inherent controversies, standardization initiatives have been reasoning that, since there's a multiplicity of technical components and architectural design combinations for any smart city solution, smart city services are a more comprehensive and stable object of analysis (International Standards Organization (ISO), 2015, p.19).

Many standardization groups are, therefore, working on their own services taxonomies (International Standards Organization (ISO), 2014; LEE & LEE, 2014). During this time, city administrations have lacked an effective framework that is capable of integrating their tactic-operational competence of action leveraged by smart city solutions with the strategic competence of shaping, cascading into metrics, and preserving a sustainable development vision and objectives in the long term (CAIRD et al., 2016, p.27–28).

This contribution aims to provide an alternative to such demand by formulating a qualitative analytical framework that assesses the alignment of smart city solutions services to the goals of urban sustainable development in which the environmental, social, cultural and institutional perspectives gain the same attention as the economic dimension.

The article presents the creation process in this framework by building up the research motivation and key issues alongside the correlated literature review in the Conceptual Framework Section, which culminates in appointing the Dashboard of Sustainability (DS) as the underpinning model in the first component of the analytical frame. Then, in the Methodology Section, the steps followed to conceive the services taxonomy are enumerated from a real smart city solution, validating the derived activities through an extensive database compiled by experts.

Finally, the second and final component of the analytical framework is highlighted in the Results and Discussions Section, introducing the services taxonomy and categorization rules aggregated to strategic timeframes. The Concluding Remarks Section completes the related discussions by outlining key considerations, suggesting alternate usages for the analytical framework and convening opportunities for its expansion.

2. Conceptual framework

2.1. Intangibility management in urban sustainable development

The commitment of city authorities to sustainability goals has increased their assortment of challenges with other dilemmas. One of them is the demand for assimilating the complexities of deploying metrics systems in order to ascertain results of actions from short and medium-term plans associated with sustainability strategies (SHEN et al., 2011; TANGUAY et al., 2010). Another is the primordiality to preserve, in the long run, the strategic direction of the initiatives aligned with sustainable development in all its perspectives (UN – United Nations, 2014, p. 03–04), thus assuring broad or comprehensive sustainability (HOLDEN et al., 2014, p. 132).

To quickly and more effectively incorporate these strategic, tactic and operational competencies, many cities are already improving their long-term strategic planning processes, by transferring urban sustainability proposals to smart city services, solutions, and technologies (LEE et al., 2013, p. 288).

Consequently, indicator models to determine the performance of smart cities as sustainable development agents began to multiply, triggered by the spread of smart city solutions (ALBINO et al, 2015. p. 13). These models introduced new taxonomies for the categorization of municipalities from various perspectives (ANTHOPOULOS, 2017, p.09–12; TSOLAKIS & ANTHOPOULOS, 2015, p.05). Amongst them, the ones associated to urban functional services such as transportation, education, health, security, etc. stand out, as do the ones concerned with behavioral classifications, such as proactivity, governance, social inclusion, and innovativeness. These specific indicator taxonomies allowed the comparison of cities' performance in various dimensions, popularizing the dissemination of city rankings (ANTHOPOULOS, p. 09-12, 2017; ANTHOPOULOS et al., p., 2015527).

The geopolitical contexts in which cities are immersed, however, make many of them heterogeneous environments where certain indicators lose or gain importance in proportion to their relationship with critical local problems (BOONS et al., 2013, p. 02). Furthermore, in many scenarios, effects pointed out by certain indicators are a reflection of occurrences that originate in other regions over which the target community has no influence (CAIRD et al., 2016, p. 27-28).

Therefore, many cities have been directing their metrics systems towards demonstrating progress from agreed targets in plans that address locally relevant issues (CAIRD et al., 2016, p. 30, 35). This prevents wasted efforts trying to overcome other cities in perspectives foreign to their reality, or to match them in performance, which is published in rankings that end up creating competition instead of collaboration amongst municipalities (CAIRD et al., p. 11, 30, 2016; HOLLANDS, p 08,12, 2015).

The comparison of a city status in a given period with its own scenario in a past time is, hence, more useful in proving its ability to achieve local strategy objectives for sustainable development than comparing its performance with other municipalities (SCI - Sustainable Cities International, 2012, p. 23,24). In particular, this process favors the preservation of urban management's focus on its strategic plan, and the guidance of reused solutions from other cities on local sustainability proposals (OFFENHUBER, 2019).

An example of such tailoring on locally adapted solutions from other municipalities is the implementation of the Rio de Janeiro Operations Center (COR, from the Portuguese "Centro de Operações Rio"), designed as a solution based on the New York Intelligent Operations Center (IOC) (SINGER, 2012; LINDSAY, 2010).

Occupying prominent positions in international rankings as one of the smartest cities in the world (IESE Business School, 2016, p. 24), New York has an integrated crime-fighting system in its IOC that offers, among other capacities, prevention and response services to terrorist attacks (SINGER, 2012; LINDSAY, 2010; CHEN et al, 2003). After the strike at the Twin Towers in 2001, this became an even more relevant topic in the metropolis' strategic plan (NYS - New York State, 2018, p. 06, 08). Its IOC plays a key role to it (NYS - New York State, 2018, p. 08) and directly contributes to urban resilience, reflecting positively on all dimensions of sustainability. For instance, in the social perspective, guaranteeing security so that citizens can enjoy their lives and freedom developing competencies without safety concerns; in the economic, cultural and environmental pillars, preventing destruction of valuable assets; and in the institutional dimension, introducing innovations embracing processes, tools, services, personnel, etc. to reinforce basic human rights that are essential to exercising freedom.

As such, the New York IOC solution delivers services that are fully compatible with the city's sustainable development strategy (NYS - New York State, 2018, p. 05–06). In Rio de Janeiro city, however, one of the primary motivators for the installation of the COR was the urgent need to establish protocols for preparedness and response to disasters caused by heavy rainfalls, like the ones in April 2010 (SINGER, 2012; FERNANDEZ et al., 2011). Thus, for the Brazilian city to convey such objectives of its sustainability strategy in a similar way to the North American IOC model, it is paramount that the COR architecture supports resiliency services against rains, floods and landslides.

This is the case of the COR services supporting emergency procedures in the face of storms in Rio, starting by monitoring rainfall conditions through intelligent sensors across the city to feed the institutional routine of publishing climate bulletins (NERY, 2014, p. 47). These functions are also integrated to other technologies, processes and people through open service platforms to automatically activate groups responsible for emergency operations during heavy rainfalls (NERY, 2014, p. 48). Moreover, with these competencies, the COR can align itself with a broader set of perspectives on urban sustainability. It promotes the institutional function of everyday access to information in a more strategic practice, benefiting the social dimension by protecting citizens from extreme weather disasters, particularly those living in vulnerable communities. Furthermore, it preserves assets of the economic, environmental and cultural pillars, to mention a few advantages of its smart services.

These reflections also reinforce the principle that, though as yet no standardization for smart city infrastructures exist, what would facilitate the translation of urban sustainability strategic objectives into tangible technological assets (ISO, 2015, p 05–06; SCHÄFFERS et al., 2012, p. 51), it is in the services provided by smart cities that lies the tendency to materialize this uniformization for large-scale dissemination and the consecutive cascading of indicators from cities' sustainable development plans (MARSAL-LLACUNA et al., 2015, p. 621). However, while the positive effect of the alignment in services of a smart city solution to the greatest possible number of sustainability dimensions is evident (UN – United Nations, 2014, p. 02–03), the objective criteria linking a service to a specific sustainability perspective are not very obvious. This categorization becomes even more complex when considering the wide and informal nature of services in innovation processes (WOLFSON et al., 2015, p.15–25; LUNDVALL et al., 2009, p. 02-03), and, similarly, the related intangibility of the concepts of sustainable development (FIKSEL et al. (2012), p. 05; SMITH et al. (2010), p. 437) and smart cities (CAIRD et al. (2016), p. 04,27,28; ISO (2015), p.02; MARSAL-LLACUNA et al. (2015), p. 620; ARNOLD (2004), p. 03,13). This complexity can be circumvented by choosing a smart city service architecture that grants a detailed services taxonomy and a model that determines the refined classification of the activities that make up each service under the respective dimensions of sustainability.

An ideal archetype for categorizing services into corresponding sustainability perspectives would come from a typology provided by a representative and internationally established smart city indicators system. This is likely to result, though not by free access, in the ISO's recent work on the standardization of indicator systems for smart cities (MARSAL-LLACUNA et al., 2015, p.620). However, such a standard is still building up and, instead, there is an abundance of models focused on a plurality of analytical angles (ALBINO et al., p 13, 2015; CAIRD et al., p 01, 2016). Nevertheless, from the experience accumulated with generic indicators of sustainability so far, it is possible to rely on free frameworks that are recommended by experts, such as the Dashboard of Sustainability (BELLEN, 2007, p.97; OLALLA-TÁRRAGA, 2006, p.09–10).

2.2. Strategic analysis of smart city solutions under the Dashboard of sustainability framework

The Dashboard of Sustainability (DS) (BELLEN, p. 127-142, 2007; MORI & CHRISTODOULOU, p. 07, 2012; OLALLA-TÁRRAGA, p., 200609–10) represented the consensus among several international organizations cooperating in the development of a robust and easily understood indicators system (SINGH et al., 2009, p.198; OLALLA-TÁRRAGA, 2006, p.09). It stood out for its flexibility in agglomerating selected indicators in a broader set of sustainability perspectives: environmental, social, economic, and institutional. All presented on a visual interface that facilitated the quick assessment of performance towards sustainable development goals for experts, decision makers or common citizens (MORI & CHRISTODOULOU, p 10, 2012; BELLEN, p. 135, 2007; OLALLA-TÁRRAGA, p., 200609).

Although it was known as the most popular of the indicator frameworks amongst specialists (BELLEN, 2007, p 97) around the time of its well-received software instance presentation at the Johannesburg Summit and World Forum in 2002, the DS lost its relevance from 2005 on. That was the year that the United Nations Division for Sustainable Development (DSD) performed its third review on the set of indicators that had been evolving under pilot initiatives by the countries committed to reaching the Millennium Development Goals (MDGs), which were agreed in 2000 (UN/DESA - United Nations Department of Economic and Social Affairs, 2007, p.06–07). The review retained the thematic/sub-thematic framework adopted in 2001 to organize the indicators tree and the categorization under the four pillars was abandoned, deprecating the DS. Such change addressed the dilemma of multi-dimensional indices which could not prove as integrated amongst the different pillars, like the cross-cutting, multidimensional ones.

Examples of these indices are those related, for example, to consumption (UN/DESA - United Nations Department of Economic and Social Affairs, 2007, p.09–10): this phenomenon is generally interpreted as a three-dimensional one, having roots in the social dimension because of individual preferences that can lead to consumerism. This promptly affects the economic dimension, leveraging production performance to supply the market with even more products. In turn, higher throughput capacity causes resource depletion and waste generation to feed the production processes, impinging upon the environmental dimension. Finally, consumption could even be regarded as a four or five-dimensional indicator theme, since it leans on the institutional pillar, which provides infrastructure to support such continuous cycles, and on the cultural perspective, which, like the social one, constrains or incites consumerism (JACKSON, 2009).

As such, the practical decision of eliminating the four pillars taxonomy favored the inclusion of this kind of new transversal indicators and the regrouping of the indicators set in better alignment to indicator systems that the pilot countries had already been maintaining to monitor their national sustainable development strategies. This facilitated the establishment of a worldwide sustainable development indicators system by the United Nations and the management, along with global key stakeholders, of progress towards associated targets (UN/DESA - United Nations Department of Economic and Social Affairs, 2007, p.09–10).

However, the DS's retirement suppressed debates over causal relationships between metrics, indicators, indices, and the pillars, instrumental in disseminating consciousness and directing relevant strategies connecting interrelated elements to sustainability, like in the previously cited example of consumerism (HOSSEINI & KANEKO, 2012). It also ceased to highlight, as the DS used to make explicit, the emphasis that each sustainability perspective retains from governments' sustainable development plans and actions (OLALLA-TÁRRAGA, 2006, p.10). As a consequence, the usual privileged standing of the economic dimension is subtly upheld, rendering unfeasible the balance between the pillars, embodied in the triple bottom line, which is the backbone of sustainable development definition (REDCLIFT, p. 219, 2005; KAJIKAWA, p. 218, 2008).

This outcome, on top of the critics to the triple bottom line itself as a weak sustainability agenda (MORI & CHRISTODOULOU, 2012, p. 03), amongst other criticisms, contributes to the exhaustion of the sustainable development concept. It is gradually replaced by the one of resilience (ADAMS, p. 03,10,12, 2006; HOLDEN et al., 2014), compromising long-term, proactive sustainability strategies for the advancement of short-term, reactive goals (MEEROW et al., 2016). Considering the complex, non-linear, self-organizing nature of urban ecosystems, permeated by uncertainty and discontinuities, these short-term resilience tactics could also provoke major regime shifts to new undesirable baselines, thwarting a transition backwards (DAVOUDI, 2012, p. 302-303) or regeneration (GOODLAND, 1995, p. 05) of the involved ecosystems.

Such arguments justify rescuing the sustainable development concept and its transparency in the broad coverage of sustainability dimensions conveyed in the DS, since, moreover, the other two indicator systems most cited by experts (BELLEN, 2007, p 97) embrace only subsets of this diverse spectrum: the Ecological Footprint (BELLEN, 2007, p 102-127) is most concerned with environmental and economic dimensions (MORI & CHRISTODOULOU, 2012, p. 06-07) and the Barometer of Sustainability (BELLEN, 2007, p. 142-164), with environmental and social perspectives (SINGH et al., 2009, p. 193). These are important sources of skepticism for such systems.

Nevertheless, beyond the narrowness of sustainability perspectives borne by most indicator systems, all of them are criticized for roundings in scales and in the prioritization or weighting assigned to each indicator to produce a final sustainability index (TANGUAY et al., 2010, p. 408). These idiosyncrasies, common to metric systems in general, are worked around by establishing clear criteria for the categorization of data, which, in its more tuned applications to a broader sustainability concept, assigns equal weight to all dimensions of sustainability, considering them evenly important (TANGUAY et al, p 411, 414, 2010; GEORGE & KIRKPATRICK, p. 99, 2007). Furthermore, the architects of indicator systems sometimes introduce differentiated prioritizations or even reduce or multiply lists of indicators derived from standard systems, according to the most relevant questions for each type of research or application (TANGUAY et al., 2010 , p. 410–411).

Here, the intention is to employ the broad, yet weak, sustainability disposition in the taxonomy suggested by the sustainability dashboard framework (Table 1) to elaborate a detailed and comprehensive model relating smart city services to the corresponding sustainability dimensions. Hence, all of the indicators and sub-indices that are composed of the four pillars of sustainability on the dashboard (environmental, social, economic, and institutional) are considered as holding the same importance or degree of prioritization, including the cultural perspective index of sustainability.

In particular, the logic of this composition can be useful in associating services offered by smart city solutions to the respective sustainability dimensions and to service classes from a typical smart city architecture. These links substantiate the strategy assessment proposed by this article: for the strategic objectives of urban sustainable development to materialize, confirming the cities' smartness, it is not enough to have robust and innovative technical solutions, but also to align them with a larger number of sustainability perspectives that are not limited to the economic dimension.

Some smart city solution services, in fact, can favor all sustainability perspectives, as applicable to the New York IOC response to terrorist attacks previously examined (Section 2.1) and the ones inclined to reduce consumption (Section 2.2).

Table 1
Breakdown of sustainability dashboard indices into sub-indices and indicators for each of the sustainability perspectives.

Index in the sustainability dimension	Definition	Examples of sub-indices and derived indicators
Ecological/ Environmental	Maintenance of the natural capital by protecting the biophysical environment, avoiding exhaustion of raw material sources, overloading of natural sinks and conserving biodiversity (the economy and other pillars are subsystems dependent on the overall ecosystem).	Climate change, ozone layer depletion, air quality, agriculture, forests, desertification, urbanization, coastal zone, fishing, water volume, water quality, ecosystem, and species.
Economic	Maintenance of monetary capital (financial and economic) by means of efficient resource allocation and distribution, while also considering limits to growth (the ecosystem is not a never-ending resource base nor an infinite waste sink).	Economic performance, trading, financial status, material consumption, energy consumption, waste generation and management, and transport.
Social	Human capital or stock of all personal (i.e., intraindividual) assets and capabilities, such as health, knowledge, education, experiences, and skills, as well as socialization, habits, attitudes, orientations, and preferences.	Poverty index, gender equality, nutritional regime, health, mortality, sanitation conditions, drinking water, educational level, literacy, housing, violence, and population.
Institutional	Rules or social structures that enable or constrain human capital, shape governances that integrate and coordinate actions to meet objectives from the environmental, economic, social and cultural sustainability perspectives.	Ethics and trust reinforcement, sustainable development strategic implementation, international cooperation, access to information, communication infrastructure, science and technology, natural disasters - preparedness and response - and sustainable development monitoring.
Cultural	Maintenance of access to tangible (monuments, man-made artifacts, artificial landscapes, etc.) and non-tangible cultural resources (practices, collective and/or inherited knowledge and skills, etc.)	Heritage, cultural identity and diversity, tourism, recreation, art, and aesthetics/design

Source: Adapted from GOODLAND (1995), p. 03,07,10; BELLEN (2007), p. 34, 135; SPANGENBERG (2007), p. 109–110, 115; UNEP/ROLAC - United Nations Environment Programme Regional Office for Latin America and the Caribbean (2012), p.3–5; AXELSSON et al., p. 220 (2013); HAASE et al. (2014), p. 413 and Soini and Birkeland (2014).

As all sustainability perspectives are interdependent, however, each service could be interpreted as furthering all of them. An alternative to avoiding this generalized typological inference process, and obtaining a more accurate judgment of the sustainability amplitude incorporated by a smart city solution service, is to discover its intended use and lessen its generalization level. This allows one to distinguish more specific functional characteristics and main targeted pillars in the disaggregation of indices into sub-indices or indicators, increasing the transparency and refinement of the service structure (FIKSEL et al., 2012, p. 22). Such detailing can be accomplished by breaking smart city services down into their component activities.

In the case of the New York IOC's anti-terrorism service, for instance, the specific activity of monitoring the movement of suspicious individuals is classified as adhering to the institutional dimension, since it is related to the institutional infrastructure that supports sustainability (Table 1, line 4), although it does not necessarily exert the practical impact of preventing such incidents from happening (SPANGENBERG, 2007, p. 110). The action of police mobilization in response to an attack, however, is oriented to the social perspective, since it materializes strategies of security and violence eradication and containment, therefore exerting a positive practical effect on the social dimension of sustainability (Table 1, line 3).

Both of these activities also impact other sustainability perspectives, although the methodological agreement with the taxonomy outlined in Table 1 limits the subjectivity inherent to the interpretation of the service components in relation to the sustainability dimensions and, consequently, the opacity of the concept of sustainable development.

3. Methodology

After the systematic literature review on frameworks to assist municipalities in formulating strategies and reaching sustainable development objectives relying on smart technologies, the DS was retrieved as the core of the analytical frame in the research. This was due to its large span, amongst other sustainable development metrics frameworks, in acknowledging different sustainable development dimensions and its effectiveness in communicating progress towards sustainability goals.

Since services are the real agents of value aggregation to citizens, and of actual impact in all sustainability pillars, the DS indices typology was reclaimed as a reference to derive a smart city services taxonomy based on data collected over 9 years (2011 to 2019) of monitoring the COR infrastructure, since its inauguration. Data from semi-structured interviews involving COR personnel and material from diverse media sources, such as published laws, news, and blogs were analyzed and selected. They were compiled in such a way that each service in the final database had at least two distinct pieces of evidence confirming its legitimacy, and other general properties, prioritizing official material issued by the Rio de Janeiro administration offices.

To corroborate the services taxonomy according to the sustainability dimension that each service potentially targets or intends to impact positively, the second edition of the United Nations guidelines for sustainable development indicators (UNCSD - United Nations Commission on Sustainable Development, 2001) was consulted, due to the fact that its contents still categorized indicators from the social, environmental, economic and institutional sustainability perspectives. The inventory of 2,560 social, environmental and economic sustainability indicators based on worldwide benchmarking compiled by the United States Environmental Protection Agency (FIKSEL, 2012) was also examined. Finally, because the cultural perspective is not considered in the UNCSD's and the EPA's sustainability indices assembles, and the distinction among social, institutional and cultural sustainability is neither very clear nor justified in these references, the work of prominent authors on this kind of sustainability indicators was retrieved. In this step, the literature of Axelsson et al. and Spangenberg on the subject were elected as the main sources for interpretative lenses (AXELSSON et al., 2013; SPANGENBERG, 2007). In this way, clear definitions and indicators examples for these and other sustainability pillars were documented in Table 1, outlining the first component of the analytical frame.

Once gathered the COR services as objects of analysis and the experts' database of previously categorized indices from UNCSD, EPA and notorious authors accompanied by the list of fairly conceptualized sustainability perspectives, an interpretative method was delineated to match information between these data sources. The high level steps involved in this process are detailed in Fig. 1.

This interpretation mechanism is important on the grounds that a large volume of data was assembled and lexicons vary in the documentation of services and indices over the different databases. Moreover, a standard meaning recognition procedure for language terms, beyond enlarging the categorization references, while improving the methodological reliability and validity, allows for future automatization and/or artificial intelligence applications in the taxonomy corroboration.

The lexicon matching procedures involved in such an interpretative routine are listed in detail in Fig. 2.

Lastly, the services DS derived from these processes and consolidated in Table 2 was presented by stage in the radar diagram of Fig. 3 to help monitor progress and complete the analysis of the smart solution lifecycle.

These two final elements depicted in Table 2 and Fig. 3 enclose the second and ultimate component of the proposed analytical framework.

4. Results and discussions

By applying the conceptual body mobilized in Section 2, following the methodological procedures abridged in Section 3, the dedicated multicriteria and qualitative analytical framework was derived, as in Table 2. With the COR case as a baseline, it identifies the typology of activities that make up the services of smart city solutions with respect to their potential practical effect on the respective main sustainability dimensions.

The performance throughout time in expansion of the assessed smart infrastructure's amplitude in terms of the number of services adherent to each sustainability perspective can also be evidenced. An alternative to accomplishing such a feature is by distributing the accumulated count of supported activities over time frames defined according to the relevant transformations experienced by the sociotechnical domain under analysis. This is also arranged in the example of Table 2, where the COR's lifecycle timespan is split into three distinct phases of three years each, devising its construction, steady state and retrenchment stages.

In the first stage of the COR lifecycle, ranging from its inauguration on the 31st of December 2010 (i.e., 2011) to the year 2013, its core protocols were established to monitor and control transit, security agents, host mega events, and respond more effectively to urban incidents. The processes for early detection and faster responses to heavy rain risks were also instituted, launching procedures to proactively warn the civil defense and vulnerable communities of flooding and mudslide incidents. These remain, by the way, typical kinds of disasters every summer in Rio de Janeiro and which motivated the COR's construction initiative. In any case, this initial phase was the one that deployed the largest number of services (34) to the COR's infrastructure, which contemplated all sustainability dimensions and took the IOC's average growing speed of up to 11.3 new functionalities per year.

Even more importantly, however, is that by the end of this construction phase, in 2013, two strategic units were added to the COR's organizational layout: a team of Big Data and predictive analytics named "Grupo Pensa" (or "Think Group") and the Resilience Management Office. The former was responsible for hacking into the urban data cloud, to proactively search for potential problems and effective solutions to diverse local tendencies. The latter, for collaborating in global, regional and local urban resilience networks, by engaging citizens and key stakeholders in risk identification and forging solution project portfolios

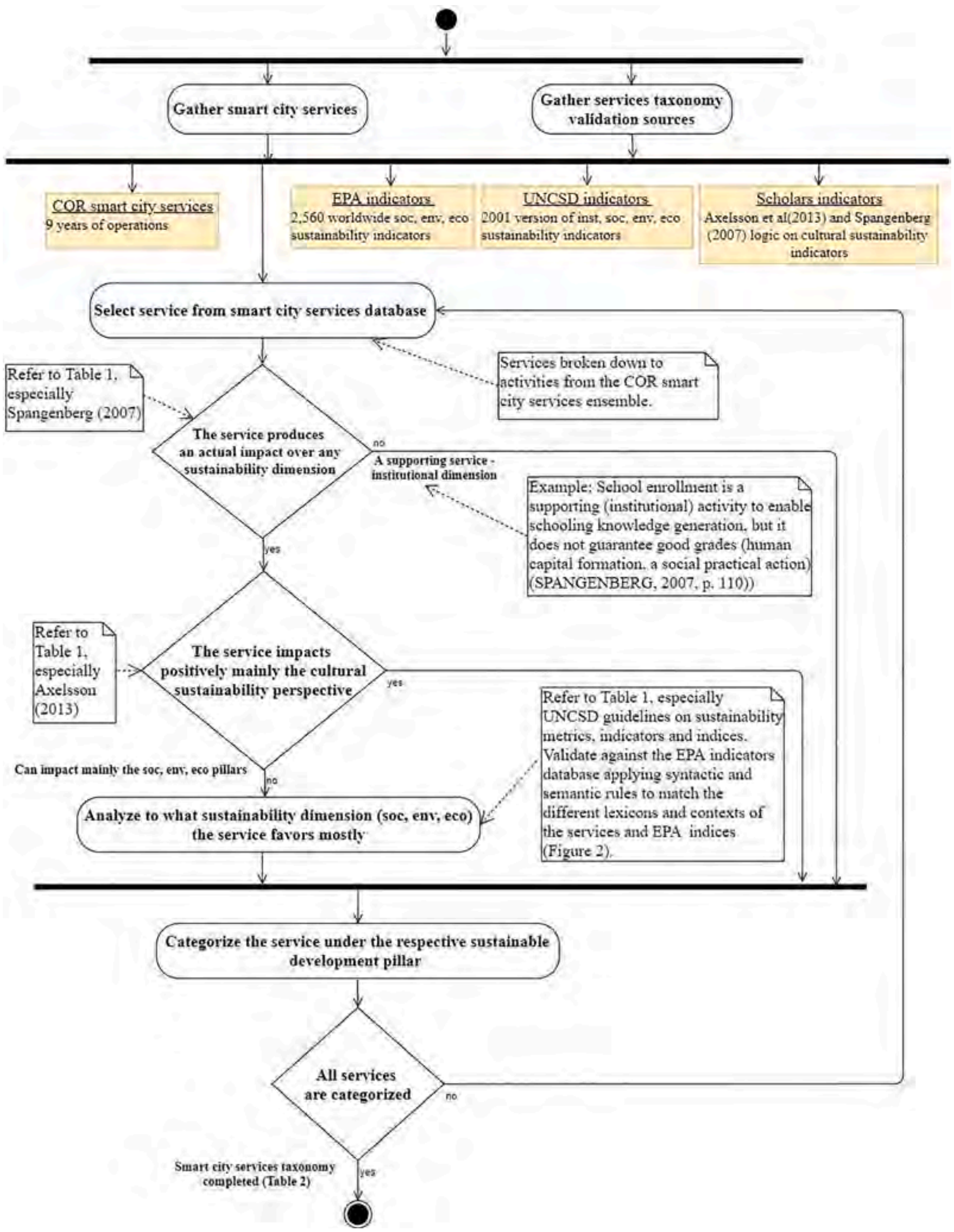

Fig. 1. Overall services taxonomy validation procedure Source: Authors' elaboration.

stimulating social participation and deliberative democracy.

The second stage in the COR's timespan, from 2014 to 2016, featured the maintenance or steady state of the environmental, social and cultural functions aggregated in the first phase. It introduced only 5 institutional and 3 new economic activities, totaling a 2.6 medium per-year rate in functionalities added to the COR.

After these two periods of evolution, however, a stage of decline in quantity and span of sustainability perspectives levered by the COR's smart architecture took place. It began after municipal elections launched a government replacement in 2017. Following this, all sustainability dimensions had functionalities deactivated, particularly with the removal of the Pensa Group and Resilience Management Office from the COR's tactical configuration. The average pace of 4.6 functions terminated per year at this stage culminated in 14 of them shut down. It shrank the whole COR structure by 33%, leaving a remaining total of 28 activities from the 42 available at the end of phase 2, or 67% of the steady state layout. On top of this, the most impaired were the environmental and cultural pillars which, considering all phases together, mobilized only an average of 6% and 4% of all services targetings, respectively.

The final COR composition in its current retrenchment scenario is basically a short-term proactive, predominantly reactive, and operational solution. Despite supporting, for instance, early warnings for heavy weather conditions based on the pre-installed smart infrastructure, it stopped constantly innovating by applying smart analytics to its urban big data cloud. Furthermore, by disabling its resilience office strategic portfolio management initiative, it ceased taking advantage of the COR's instrumentation capacity to encourage deliberative democracy and reflexive learning by involving citizens in debates and projects to improve the city's sustainable development perspectives.

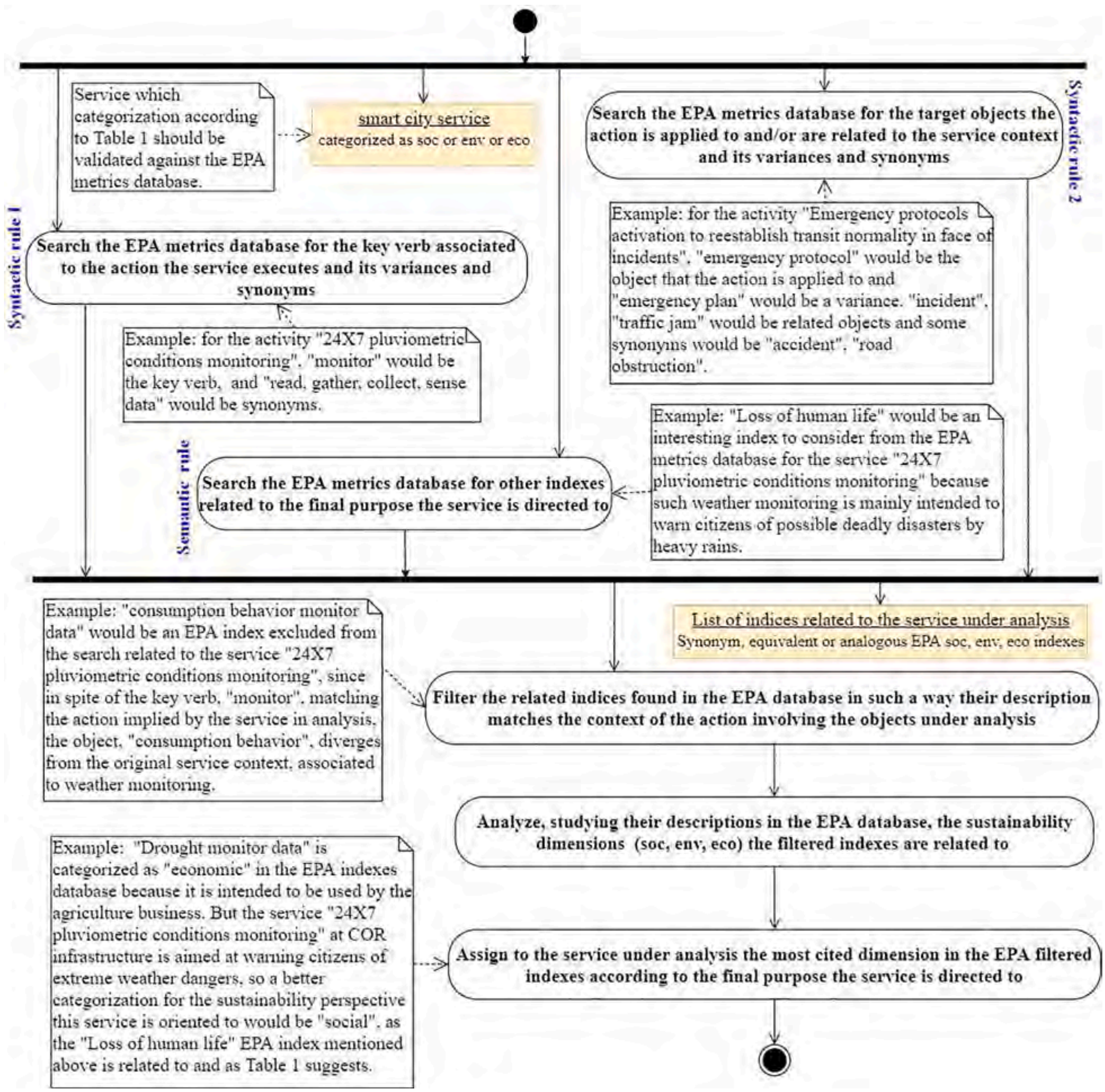

Fig. 2. Lexicon matching procedures to validate each service categorization on economic, social, and environmental dimensions according to the EPA database. Source: Authors' elaboration.

The innovation paths forward and backwards that the COR smart solution underwent as a consequence of administrative government volatility, as demonstrated in Table 2, can be better examined in a spider or radar diagram like the one of Fig. 3. The shapes in the figure emphasize the evolution, stagnation, and involution of the service offering's volume and variety on alignment to different sustainability pillars: the wider the pentagon area and the closer the barycenter is from the center of the circle, that is, the bigger and rounder the resulting polygon, the more ample and balanced is the services portfolio concerning sustainability dimensions, meaning a better affinity to the objectives of sustainable development.

Preventive and corrective actions facilitated by these tools can therefore be more easily formulated, monitored, and controlled, to align with achieving or regaining such equilibrium amongst sustainability perspectives while the services portfolio expands and innovates over time and towards the city's specific strategic plans realization.

Due to this transparency in ascertaining lifecycle evolvement of local infrastructures, the analytical framework combining the elements of Tables 1, 2 and Figs. 1, 2 and 3 can be a more effective and pragmatic mechanism than the smart city rankings. It is, furthermore, an alternative to the multiple metrics systems with their intrinsic side effects. Besides, it prevents cities from consistently making efforts adapting other cities' solutions, which are linked to foreign realities. These conveniences empower an urban administration to achieve the tactic-operational and strategic competencies necessary to extract higher performance from its smart technologies in its aim to achieve sustainable development goals that are in line with its long-term sustainability objectives.

Moreover, the proposed analytical frame aids in the understanding and practice of the upgraded definition of smart cities: the growing number and balance of the distribution on the different sustainability perspectives of activities categorized in services using these taxonomic rules contributes to the strategic competence of the corresponding smart city solution and, hence, to its city smartness.

Table 2
Typology of activities derived from smart city services and their association with sustainability perspectives.

Item	Sustainability Dimension	Accumulative count on sustainability perspectives targeted by services				
		Phase 1 (2011–2013)	Phase 2(2014–2016)	Phase 3 (2017–2019)	Average	%Total average
Profile of activities derived from services						
Examples of activities						
1	Institutional	17	22	16	18.33	52.87%
Activities supporting other sustainability perspectives (Table 1, line 4), but not necessarily exerting a direct and practical impact on them.						
Monitoring of conditions linked to other dimensions' elements (transit, municipal security agents, weather, meteorology, etc.); preparation and publication of reports or strategic studies, news, and other communications through multiple channels to citizens or other stakeholders; information reception and processing from various actors; participation in discussion forums, debates, and other events stimulating participatory governance and transparency; activities coordination in collaboration networks between cities and citizens; planning, monitoring, and control in risk management and urban resilience projects, taxes revenue administration support, and execution of institutional projects.						
2	Environmental	3	3	0	2	5.77%
Activities oriented to exert a direct, positive impact on the ecological/environmental dimension of urban sustainability (Table 1, line 1).						
Execution of environmental projects (reforestation, bicycle paths, etc.), actions to reduce water consumption and to materialize plans derived from risk identification sessions.						
3	Social	6	6	5	5.67	16.35%
Activities oriented towards exerting a direct, positive impact on the social dimension of urban sustainability (Table 1, line 3).						
Activation and coordination of emergency plans and procedures implementation to ensure citizens' safety and the city's resilience; execution of social projects (sanitation, health, safety, etc.) and actions derived from analytical studies and risk sessions to identify and treat, for instance, critical areas in the city for epidemic outbreaks and concentration of floods, as well as other social problems.						
4	Economic	6	9	7	7.33	21.14%
Activities oriented towards exerting a direct, positive impact on the economic dimension of urban sustainability (Table 1, line 2).						
Activation and coordination of contingency plans and procedures materialization to maintain smooth traffic in the face of incidents, special events in the city, or peak times in urban traffic; execution of projects to reinvigorate the local economy (legalization of informal economic practices and combating underemployment and unemployment, conversion of neglected infrastructure in the city into economically dynamic areas, etc.) and actions originating from analytical studies and risk sessions to identify and treat, for instance, critical regions in the city for traffic jams and irregularity in parking lots, as well as other economic problems.						
5	Cultural	2	2	0	1.33	3.83%
Activities oriented towards exerting a direct, positive impact on the cultural dimension of urban sustainability (Table 1, line 5).						
Implementation of projects to stimulate tourism and local cultural production and actions to materialize plans derived from risks identification sessions.						
Total		34	42	28	34.67	100%

Source: Authors' elaboration based on Table 1 taxonomy, the validation procedure from Figs. 1 and 2, and research on the operations of COR services and derived activities over a 9 year period.

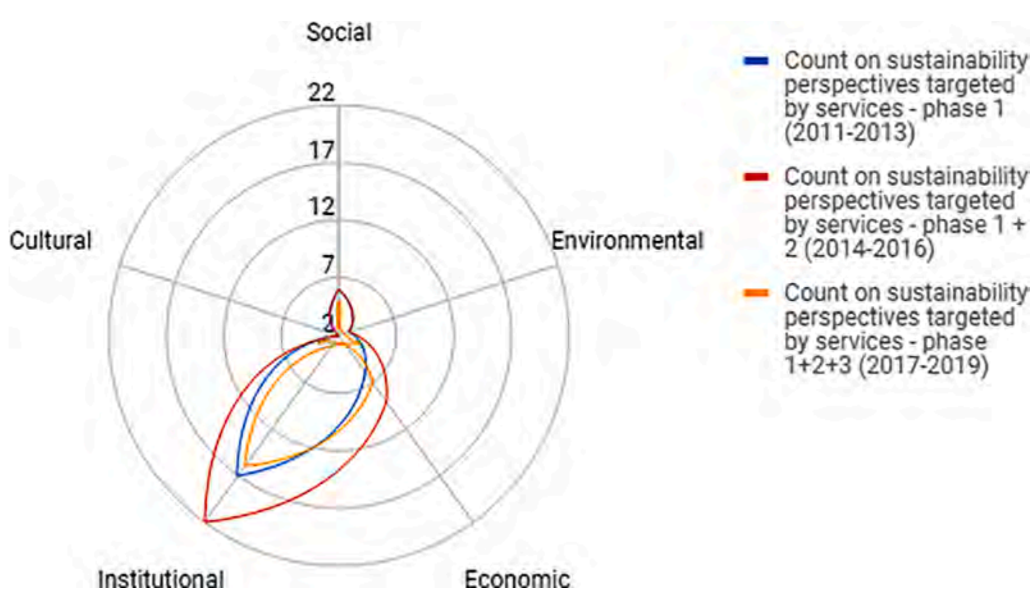

Fig. 3. Construction, steady state, and retrenchment stages on the COR's lifecycle regarding the volume and amplitude in the sustainability perspectives of services provided (2011 to July 2019). Source: Authors' elaboration based on Table 2.

In other words, it is not enough for a smart solution or city to offer a large number of services that prioritize a single sustainability dimension, such as the economic one. This is a feature of early versions of smart cities, which incorporated predominantly neoliberal and deterministic technological attributes (HOLLANDS, 2008). Aligning itself to the broader sustainability ideal integrated into the municipal plans of the most updated versions of smart cities, however, involves incorporating new and pre-established smart services that allocate and direct smart technologies to all sustainability perspectives, as committed to in the city's strategic plans (ETEZADZADEH, 2015, p.53–54).

Nonetheless, an analytical framework grounded in such precepts is dedicated to examining the amplitude of the smart city services' reach across all sustainability dimensions, investigating their strategic targeting but not their actual performance.

The real performance measurement of smart city solutions would imply, in a typical approach, measuring a set of variables related to the target context over which the solution services act before and after their installation. Following this, one would seek to prove the causal relationship between the service operation and the contextual transition from the prior to the post-solution deployment state (ARNOLD, 2004, p. 03). However, as cities and their innovation ecosystems are open, complex and dynamic systems, influenced by forces tracing back to all dimensions of sustainability (MICHAEL et al., p. 493, 2014; JUCEVIČIUS & GRUMADAITĖ, p. 127, 2014; ARNOLD, p. 13, 2004), analogously intricate is the confirmation of the correlation between intelligent city initiatives and their concrete effects on the municipality (CAIRD et al., 2016, p. 27-28): multilevel systemic evolutionary hybrid methodologies are recommended by experts (MAGRO & WILSON, 2013, p. 1647–1648) and even the theory of complex adaptive systems, still immature, is suggested (JUCEVIČIUS & GRUMADAITĖ, 2014, p. 127).

Furthermore, although smart city solutions have been proliferating in recent years (NEIROTTI et al., 2014, p.30) many of them still have an exploratory profile (CAIRD et al., 2016, p, 06, 28) and performance evaluation models present more reliable and definitive results when applied to mature and stable environments (Bergek et al., 2015, p. 25).

This way, the framework conceived of here, to assist in the strategic orientation towards all sustainability perspectives, may be more advantageous at this stage of the smart city solutions life cycles than verification systems to assess their real performance. Among other utilities, the taxonomy and analytical framework suggested may help city administrators and smart city solution providers in designing, procuring, and deploying solutions aligned with broader sustainability objectives. It can also aid in restructuring solution service sets that have deviated from pursuing amplification in their strategic goals for sustainable urban development to regain their span.

5. Concluding remarks

In response to urban wicked problems and other contemporary challenges, which are further intensified by the impacts of climate change, city governments around the world have been committing to sustainable development objectives, such as improvements to urban resilience. This agreement on sustainability has called for public authorities to be able to elaborate and materialize strategic plans oriented towards a broader sustainability in the short and medium terms, that is, focused not only on prioritizing the economic perspective but also the environmental, social, institutional and cultural dimensions.

Seeking assistance in coping with these pressures, public administrations have been relying on smart city services and the institutionalization of indicator systems that are capable of proving the effectiveness of such solutions. However, despite the efforts of standardization bodies and the proliferation of alternative indicator models, there is still no globally recognized standard for smart city architectures, and which moderates the complexity of qualitatively or quantitatively analyzing their performance, particularly in terms of considering all sustainability perspectives. This compromises the effectiveness of generic rankings among cities as incentive mechanisms for their performance improvement and the reuse of successful smart city solutions in other urban contexts.

An alternative to addressing these adversities lies in the standardization of services delivered by smart city solutions and their categorization under the dimensions of sustainability. It also concentrates in assessing the impact of the activities that make up each service in the real environment they exert influence over, both before and after the solution implementation and delivery.

However, since the systems of systems that brace smart city solutions are dynamic and complex, proving the correlation between service action and its practical repercussions is analogously intricate, relying on, in order to be representative, from multilevel and hybrid methodologies to complex adaptive systems theories. Such tools, notwithstanding, are still immature, as the smart cities themselves, whose solutions are mostly in probationary stage.

Thus, in the evolutionary cycle phase in which smart city solutions are positioned, an analytical framework that preserves their strategic direction evenly oriented towards the multiple sustainability perspectives may be more useful for public administrators and policy or solution architects than unreliable methods that are difficult to implement.

These considerations led to the construction, in this article, of a framework for analyzing the strategic competence of smart city solutions from a taxonomy based on the Dashboard of Sustainability, once one of the most popular sustainable development indicator systems among specialists for its intelligibility and amplitude.

The categorization of activities under all dimensions of sustainability derived from this qualitative frame relied on services gathered from a real smart city solution, the Rio de Janeiro Operations Center (COR), in its first 9-years experience since its establishment. The taxonomy built from these elements was validated by crossing a frame containing clear definitions of each sustainability perspective according to reliable authors and the legacy of work on indicators from the United Nations Division for Sustainable Development. Additionally, a vast sustainability index database compiled by experts from the United States Environmental Protection Agency, comprising of around 2,560 registers, was used in the categorization corroboration algorithm. These validation sources circumvent the subjectivity inherent to the qualitative nature of the proposed analytical frame, a limitation of all frameworks of this kind.

The resulting process of analysis involved the aggregation of activities per sustainability pillar and timeframe from the target smart architecture lifecycle. This enabled the identification of peak intervals of innovation and incorporation of new services alongside their alignment with a wider or more narrow set of sustainability dimensions. Associated to the graphical interface of a radar diagram, the stages of construction (2011 to 2013), steady state (2014 to 2016), and retrenchment (2017 to 2019) could clearly be devised in the intelligent operation center's lifetime. Such an approach evidenced how much the institutional and economic perspectives have been remaining prioritized since the inauguration of the COR: they represent an average, respectively, of 53% and 21% of the entire portfolio targeting during the COR's entire lifecycle. In contrast, the environmental and cultural dimensions have been undermined, occupying, on average, only 6% and 4% of the services set during the COR's lifetime.

Appropriating themselves of this instrument, thus, policymakers, municipal administrators, and IT providers are able to guide, by monitoring and controlling procedures, smart city solutions towards the achievement of goals not only linked to the economic sustainability perspective, but to all the other sustainable development dimensions bound to their strategic plans.

Procurement processes and maturity models for smart city solutions committed to broad sustainable development, amongst other frameworks, can also exploit such a qualitative, analytical frame.

Future developments include the expansion of the analytical framework services portfolio by continuing its application to other smart solutions in diverse cities.

CRediT authorship contribution statement

Ana Jane Benites: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Visualization, Project administration, Writing - original draft, Writing - review & editing. **André Felipe Simões:** Conceptualization, Methodology, Resources, Supervision, Funding acquisition, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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