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Smart, autonomous and sustainable cities? A critical analysis from the perspective of strong, weak and super weak sustainability☆

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ABSTRACT

Technological innovations are accelerating globally, fostering the diffusion of urban models such as smart cities and, more recently, autonomous cities. While smart cities rely on the strategic use of data and digital technologies to optimize urban services, autonomous cities take a further step by integrating artificial intelligence (AI) into urban decision-making and governance processes. In this context, sustainability remains a core principle of urban development and can be pursued through two distinct paradigms, namely weak sustainability and strong sustainability. This paper examines how smart and autonomous city models relate to these paradigms. Through a literature review, the study collects and compares the key definitions of each paradigm, in order to develop a comparative analytical framework for investigating and positioning the two urban models under examination. The findings offer a critical reflection on the contemporary challenge of harmoniously integrating various forms of capital, both traditional and emerging, and emphasize the importance of ensuring that cities evolve into truly sustainable spaces, capable of balancing technological progress, social inclusion, and environmental protection. Conceptually, the paper advances the notion of *super weak sustainability*, to critically reflect on how, in the age of AI, technology is subordinating natural and human capital.

1. Introduction

Urban growth today involves much more than physical expansion. Cities are increasingly required to evolve in terms of the quality of the services and spaces they provide, responding to the changing needs of contemporary society. As noted in the literature, we are currently living in an era marked by a complex and, at times, contradictory combination of technological revolution, globalisation, and a green transition; transformative forces that are profoundly reshaping the form and function of urban environments (Radovic-Markovic et al., 2022).

Against this backdrop, global forecasts predict a continued increase in urbanization rates, with a growing number of people choosing to live in cities. In Europe, this trend is particularly evident: although urban areas occupy only 4% of the continent's surface, they are home to 75% of its population (European Commission, 2021). These figures point to a persistent and significant expansion of urban environments, highlighting the urgency of understanding how cities can grow not only in size, but also in sustainability and liveability.

The concept of the liveable city refers to urban areas capable of offering citizens a high quality of life through green, healthy, and efficient spaces. According to Javidroozi et al. (2023), achieving this kind of liveability requires the convergence of smart, sustainable, and green city principles. A smart city refers to an urban configuration in which digital and data-driven technologies are systematically integrated into the management of urban functions, enabling more efficient public services, improving living conditions and the pursuit of sustainability objectives (Novotný et al., 2014; Oyadeyi & Oyadeyi, 2025; Sorri et al., 2024; Toli & Murtagh, 2020). Within this perspective, the smart city is understood as a development-oriented urban model in which technological infrastructures are supposed to support sustainability transitions, operating as an enabling mechanism rather than an end in themselves (Bélaïd et al., 2024; José & Rodrigues, 2024; Qian et al., 2024). Alongside this vision, a new paradigm is emerging: the autonomous city, defined as an urban system managed and governed by advanced Artificial Intelligence (AI) technologies, with humans out of the loop (Cugurullo, 2020; Yigitcanlar et al., 2023). This concept introduces another crucial element, AI, to the ongoing redefinition of urban living in the 21st century.

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In this context, while technological progress is advancing rapidly and increasingly shaping the configuration and evolution of cities, sustainability continues to represent a core principle of contemporary urban transformation (Abastante & Mecca, 2015; Lami et al., 2023; Lami et al., 2024; Wang & Peng, 2020), as evidenced by the goals and commitments set out in the 2030 Agenda (United Nations General Assembly, 2024). Sustainability represents a desired equilibrium among environmental protection, economic development, and social equity (Bibri & Krogstie, 2017). Achieving this balance requires strategic approaches aimed at minimising the environmental impacts of urban transformations, such as waste generation, air and water pollution, and the consumption of natural resources like energy and raw materials. Within the field of sustainability economics applied to decision-making processes, two main interpretative perspectives have emerged over time, namely *weak* sustainability and *strong* sustainability, reflecting different ways of balancing economic, social, and environmental dimensions. In this sense, they represent distinct ways of conceptualizing the relationship between natural capital and human capital (Norouzi & Fani, 2021). In essence, weak sustainability, rooted in environmental economics, allows for substitutability among different forms of capital, whereas strong sustainability rejects this assumption, emphasizing the centrality of natural capital and the need to preserve its regenerative and absorptive capacities as a necessary condition for sustainable development (Wilson & Wu, 2016).

The integration of the sustainable city paradigms with those of the smart city and the autonomous city prompts a critical question regarding their relationship to sustainability. Indeed, as stated above, the smart city refers to an urban model that leverages technology and data to enhance the efficiency and effectiveness of service delivery (Javidroozi et al., 2023; Karvonen et al., 2018), while the autonomous city denotes a context in which service provision, decision-making, and data management are increasingly entrusted to AI systems (Cugurullo, 2020). How these emerging urban models are evolving in relation to sustainability remains an open question.

Since sustainable cities should prioritize qualitative improvement over mere quantitative growth (Yanarella et al., 2009), the evolution of urban areas should be framed in relation to the management of both natural and human capital. Improving urban quality, therefore, requires critical reflections on how these two forms of capital should (or can) be governed.

Based on these premises, this research addresses the following question: *How do the concepts of smart and autonomous cities position themselves within contemporary sustainability paradigms?*

To explore this question, the paper first opens with a comprehensive literature review of the key definitions and interpretations of weak and strong sustainability in the context of the urban environment, highlighting their theoretical foundations and practical implications, and then investigates the extent to which the smart and autonomous cities models align with, or diverge from, these two paradigms, considering their structural and functional characteristics.

The paper is structured as follows. Section 2 outlines the design of the research, and Section 3 presents the theoretical background related to the concepts of weak and strong sustainability, highlighting the key elements to be considered when analysing and framing the notions of smart and autonomous cities in relation to sustainability. Sections 4 and 5 examine the positioning of the smart city and the autonomous city, respectively, within contemporary sustainability paradigms. Section 6 discusses the results and summarizes the conclusions.

2. Research design

The research develops through three main phases (Fig. 1). The aim is to construct a comparative analytical framework for positioning the smart city and the autonomous city within the paradigms of weak and strong sustainability. The process proceeds from a theoretical clarification to an analytical construction and, finally, to a critical comparative evaluation.

Phase 1 (Section 3.1) consists of a literature review of the main literature on weak and strong sustainability. The objective is to collect the definitions of the two paradigms, extract the key elements that define each paradigm and clarify the conceptual boundaries between them.

Phase 2 (Section 3.2) includes the systematization of the information collected in phase 1 and the construction of the comparative analytical framework. This grid functions as a simple but consistent interpretative tool for assessing the degree of correspondence between urban models and the principles of weak or strong sustainability.

Phase 3 (Section 4) applies the comparative analytical framework to the smart city and autonomous city models. The analysis examines which paradigm each model tends to reflect, and whether their evolution suggests the need to reconsider the conventional distinction between weak and strong sustainability.

3. Weak and strong sustainability in the urban context

This section deals with the first two phases of the research: phase 1, focused on the review of the literature concerning the paradigms of weak and strong sustainability, and the phase 2, centered on the development of a comparative analytical framework for interpreting urban models.

3.1. Exploration of the literature

Review approaches can appropriately vary in how fully they implement systematic procedures, depending on their purpose (Booth et al., 2016). Accordingly, we frame our work as a systematized review that adopts key elements of systematic searching and selection (database searching, predefined eligibility criteria, and transparent screening) without claiming exhaustive coverage (Grant & Booth, 2009). We complement this with a critical/integrative synthesis aimed at conceptual clarification (Torraco, 2005): developing a coherent framework and critically examining the assumptions underpinning weak versus strong

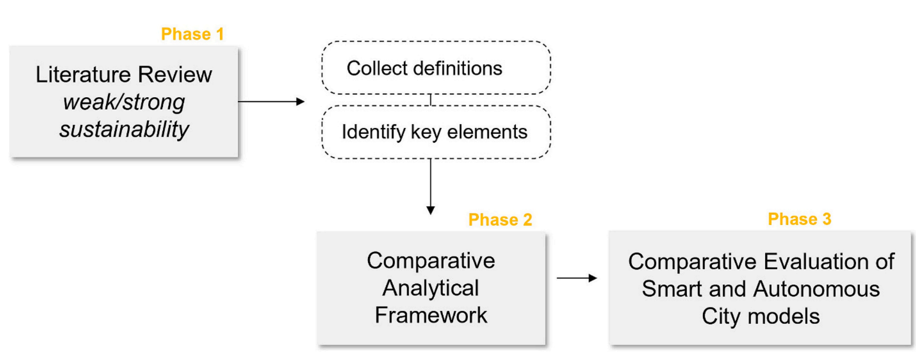

Fig. 1. Research design.

sustainability. In this respect, the review does not seek to compile and aggregate outcome-focused evidence (e.g., measurable impacts or performance indicators), because the focus here is definitional and theoretical.

We searched Scopus and Google Scholar to identify relevant documents. Searches were conducted in titles, abstracts, and keywords combined with AND/OR operators of the following terms: "weak sustainability", "strong sustainability", "urban context", "architectural context", "urban planning", and "architectural design". We considered publications published between 2000 and 2025 and limited the sample to journal articles and official documents, excluding conference papers and editorials.

The search returned 68 records; after applying the document-type and time-period criteria, 59 records remained for screening. These records were screened to retain only contributions that explicitly address definitions or conceptualisations of weak and/or strong sustainability in urban and architectural contexts, resulting in a total of 28 included sources. Included sources were then examined to extract (i) the stated definition(s) of weak and/or strong sustainability, and (ii) the theoretical assumptions invoked (e.g., substitutability, critical natural capital, limits/thresholds, intergenerational equity. Definitions published between 2000 and 2015 were synthesised in Table 1, whereas those from 2016 to 2025 were reported in Table 2; this division was adopted to highlight potential differences or developments following the adoption of the 2030 Agenda in 2015.

3.2. Elaboration of the comparative analytical grid

Looking at the definitions of the concept of weak sustainability, it emerges that the latter represents a paradigm of substitutability between natural capital, i.e. ecosystems and mineral wealth, and human-made capital, i.e. in our context buildings and urban infrastructure (Barinaga-Rementeria & Etxano, 2020; Berardi, 2015; Cabello et al., 2019; D'Amato et al., 2017; de Oliveira Neto et al., 2018; Ekins et al., 2003; Huang et al., 2015; Landrum, 2017; Li & Li, 2017; Pelenc & Ballet, 2015; Ruggerio, 2021; Shi et al., 2019; Walton et al., 2005; Wu, 2013; Yigitcanlar & Kamruzzaman, 2015).

The cornerstone of this paradigm is that total capital, i.e. the combination of natural and human (or artificial) capital, remains unchanged (Wu, 2013; Wu, 2019), so the loss of 'nature' can be compensated for by rapid economic benefits and urbanization (Huang et al., 2015; Landrum, 2017; Usubiaga-Liano & Ekins, 2021; Wu, 2019). Natural capital includes all the resources and services that nature provides, which are essential for human life. It provides raw materials, absorbs waste, offers aesthetic benefits such as the beauty of a landscape, and ensures vital ecosystem functions (Mori & Christodoulou, 2012). This capital includes minerals, air, water, soil, flora, fauna and ecological systems. Today, it is widely recognised that natural capital is limited and subject to degradation, manifesting itself in the depletion of mineral resources, the accumulation of toxic substances in living organisms, soil loss, deforestation and the increase of greenhouse gases in the atmosphere (Ekins et al., 2003; Victor et al., 1998). In contrast, artificial capital consists of human-made resources created through the transformation of raw materials (Daly, 1995). It includes durable goods such as machinery, buildings and infrastructure, which are used for periods longer than a year, and fast-moving consumer goods, such as plastics, metals and everyday objects, whose life cycle is less than a year (Ekins et al., 2003). Considering the definitions collected in our review, the two sustainability paradigms represent different ways of interpreting and applying the concept of sustainability in decision-making processes (Norouzi & Fani, 2021; Press, 2021; Turner, 1993).

In parallel, the main and common element that emerges from the different definitions of strong sustainability provided in the literature in the context of urban and architectural environments, is that this second paradigm stipulates that natural and human-made capital cannot be replaced or compensated for (Walton et al., 2005; Huang et al., 2015;

Table 1
Definitions of the concepts of Weak and Strong Sustainability provided in the literature in the context of the urban environment between 2000 and 2015.

Reference		Definition
Ekins et al., 2003, p. 168	W	"Weak environmental sustainability, which derives from a perception that welfare is not normally dependent on a specific form of capital and can be maintained by substituting manufactured for natural capital, though with exceptions."
	S	"Strong sustainability, which derives from a different perception that substitutability of manufactured for natural capital is seriously limited by such environmental characteristics as irreversibility, uncertainty and the existence of 'critical' components of natural capital, which make a unique contribution to welfare. An even greater importance is placed on natural capital by those who regard it in many instances as a complement to man-made capital (Daly, 1991)."
Walton et al., 2005, p.62	W	"'[…]'weak sustainability' which attempts to express the value of environmental and social capital in financial terms, suggesting a possible ultimate substitution between natural and man-made capital, for consideration in traditional cost–benefit analysis to inform decisions."
	S	"'[…] proponents of 'strong sustainability' hold that the wider natural environment is the necessary support system for all human activity so that natural capital cannot ultimately be fully replaced by capital which is man-made. This has led to attempts to express impacts in bio-physical terms with leading candidates being energy and land area used, the latter through approaches such as the ecological footprint".
Yanarella et al., 2009, p. 298	W	"Embraces rhetoric of Brundtland Commission definition of sustainable development; Identifies sustainability as a never-ending pathway pursued through sustainability indicators marking progress toward an ambiguous, unarticulated goal; Insofar as the goal of sustainability is operationalized, it is treated in terms of the three-legged table metaphor: economic well-being, environmental health, and social equity; Retains the practice in policy making of separating economic "development" (growth) and environmental protection through practices intended to mitigate the negative consequences of the former upon the latter."
	S	"Understands that growth (quantitative increase) is not equivalent to development (qualitative improvement); Works from the five operating principles of sustainability; Recognizes the basic unit and minimum scale of sustainability as the city region; Conceives of sustainability as a local, informed, balance-seeking process, operating within its sustainable area budget, and by so doing, exports no negative imbalances beyond its budgeted territory or into the future, thus opening spaces of possibility and opportunity; Seeks to generate local/regional sustainability policy making metaphorically around the model of a sustainability game involving multiple scenario building as the driving process for generating sustainable solutions to urban development, land use, site selection, etc."
Roome, 2012, p.2, 6, 9	W	"Weak sustainability is not sufficient to bring about the transition to a sustainable future."
	S	"Strong sustainability seeks to integrate the company into environmental or socio-ecological systems, so that the patterns of production and consumption to which the

(continued on next page)

Table 1 (*continued*)

Reference		Definition
		company contributes are within the capacity of the Planet to sustain. […] Strong sustainability requires new ways to appreciate the complex relationships and connections between the parts of a system and the function of the whole (Ackoff, 1999) built on new capacities for organizational learning and change (Senge, 1994; Checkland, 1981)."
Bell & Morse, 2012, p.14	W	"Weak sustainability: the second type of sustainability is referred to as weak sustainability. Costs of attainment (financial or otherwise) are important and are typically based on a cost–benefit analysis (CBA), which inevitably involves trade-offs between environment and social and economic benefits. Weak sustainability equates to a sort of economic sustainability where the emphasis is upon allocation of resources and levels of consumption, and financial value is a key element of system quality".
	S	"Strong sustainability: in strong sustainability there is little, if any, consideration of the financial or other costs of attaining sustainability. It equates to what some call ecological sustainability and the focus is primarily on the environment. In this case, system quality is taken in terms of the physical measures of things (e.g. population, soil erosion and biodiversity)."
Wu, 2013, p. 1003	W	"Weak sustainability permits mutual substitutability between natural capital (e.g., ecosystems and mineral wealth) and human-made or manufactured capital (e.g., factories and urban infrastructure) to the extent that a system is considered sustainable as long as its total capital increases or remains the same".
	S	"Strong sustainability assumes that man-made and natural capital are basically complements" whereas "weak sustainability assumes that man-made and natural capital are basically substitutes" (Daly, 1991, 1995)."
Berardi, 2015, p.501	W	"weak sustainability accepts their substitutability".
	S	"strong sustainability states that it is not possible to accept an exchange between environment and economy".
Huang et al., 2015, p.1176–1177, 1188	W	"Weak sustainability assumes unlimited substitutability between natural capital (i.e., biodiversity and ecosystems) and human-made capital (e.g., machines and urban infrastructure), so that a system is considered sustainable as long as its total amount of capital stocks is not decreasing (Pearce and Atkinson, 1993; Hamilton and Clemens, 1999; Pillarisetti, 2005; Fischer et al., 2007; Greasley et al., 2014). In other words, depleted natural resources can be replaced with human-made substitutes, and degraded ecosystem services can be replaced by some equivalent forms derived from human-made capital. In this case, rapid urbanization with fast economic growth and declining environmental quality may be considered sustainable." P. 1176–1177
	S	"By contrast, strong sustainability assumes that humanmade and natural capital are not substitutes but "basically complements" (Daly, 1995), or that "substitutability of manufactured for natural capital is seriously limited by such environmental characteristics as irreversibility, uncertainty and the existence of 'critical' components of natural capital, which make a unique contribution to welfare" (Ekins and Simon, 1999; Ekins et al., 2003). In this case, urban development cannot be sustainable without a healthy environment.". p. 1177 "From a strong sustainability perspective, a sustainable city or urban region must maintain a "critical" level of local and regional biodiversity and ecosystem functioning so as to provide the most of the essential ecosystem services required for human wellbeing. While making individual cities sustainable on their own may be formidable or even impossible, making urban regions sustainable with limited externalities is not only possible but also desirable (Forman, 2008; Wu, 2013, Wu, 2014).". p. 1188
Mori & Yamashita, 2015, p.10–11	W	–
	S	"It is crucial that the assessments among the three dimensions on the basis of strong sustainability alone e physical, social, human, and natural capitals are non-substitutable (Dietz & Neumayer, 2007; Ekins et al., 2003; Pearce & Barbier, 2000)." p. 10 "Cities should satisfy healthy conditions independently in each dimension. In this respect, CSI should take the perspective of strong sustainability, in which different types of capitals e natural, social, physical, and human - are not substitutable (Brand, 2009; Dietz & Neumayer, 2007; Finco & Nijkamp, 2001)." p. 11
Pelenc & Ballet, 2015, p.37	W	"The weak sustainability approach assumes that natural capital and manufactured capital are essentially substitutable and that there are no essential differences between the kinds of well-being they produce (Ekins et al., 2003; Neumayer, 2003, 2012). The only thing that matters is the total value of the aggregate stock of capital, which should be at least maintained, or ideally added to, for the sake of future generations (Solow, 1993; Neumayer, 2012) […] With this type of approach we can logically compensate the degradation of natural capital by the estimated equivalent amount of manufactured or financial capital. In weak sustainability, technological progress is assumed to constantly generate technical solutions to the environmental problems that are caused by the increased production of goods and services (Ekins et al., 2003; Sébastien & Brodhag, 2004)".
	S	"The strong sustainability approach assumes that the substitutability between natural capital and other forms of capital should be strictly limited to the circumstances where the use of the services provided by natural capital does not lead to the irreversible destruction of this capital because its depletion cannot be compensated for by investing in other forms of capital (Neumayer, 2012). Therefore, the strong sustainability approach holds that certain element of natural capital are "critical" due to their unique contribution to humanwell-being (Ekins et al., 2003; Dedeurwaerdere, 2014). These potentially "critical" elements to human existence and well-being can be conceptualized as ecosystem se. rvices provided by natural capital (Brand, 2009)."
Yigitcanlar & Kamruzzaman, 2015, p.14678	W	"[…] weak sustainability is the substitutability between human and natural capitals in an acceptable level, while strong sustainability is the maintenance and enhancement of the natural capital."
	S	"Strong sustainability is the maintenance and enhancement of the natural capital."

Table 2
Definitions of the concepts of Weak and Strong Sustainability provided in the literature in the context of the urban environment between 2016 and 2025.

Reference		Definition
D'Amato et al., 2017, p.717	W	"According to weak sustainability, natural, social and economic capital are substitutable."
	S	"According to strong sustainability, substitutability is technically impossible or inefficient and/or normatively undesirable (Neumayer, 2003)."
Landrum, 2017, p.4–5	W	"weak sustainability is based on neoclassical economic value principles that require production to remain intact so as to enable consumption (Hediger, 1999). In weak sustainability, manufactured capital includes things which are human made (within the economic and built environment); this can also be referred to as manufactured capital. In the weak sustainability worldview, manufactured or human-made capital can become a substitute for natural capital (Hartwick, 1977, 1978; Solow, 1974, 1993). One example would be the development of human-made flood walls (manufactured or human-made capital) as a substitute for wetlands and floodplains (natural capital). Thus, the weak sustainability worldview allows substitution based on two beliefs: (1) humans' wants must be satisfied (Daly, 1974), and (2) humans control nature and have the ability to develop technology solutions, justified through economic concepts (Ott et al., 2011), that work as well as or better than natural solutions. Another point within the weak sustainability paradigm is transfer of resources between generations. In weak sustainability, natural capital can be used and even exhausted as long as it can be offset by an equal gain or balance through human-made capital. That is, the intergenerational transfer of total capital should be cumulatively equivalent; technology (humanmade capital) can balance natural resource deficiencies (natural capital; Hartwick, 1977, 1978; Solow, 1986). The position of weak sustainability is a modest position, adjusting and accommodating to the demands of environmentalists, while striving to maintain the status quo (O'Riordan, 1989)."
	S	"strong sustainability is based on ecological economics physical principles, and the scientific laws of thermodynamics that recognizes economic activity is bounded by environmental limits (Hediger, 1999); this approach toward sustainability combines insights from economics with the science of ecological principles (Harris & Roach, 2014). Within this worldview, manufactured resources cannot substitute for natural resources (Daly, 1973, 1991; Pearce, 1993). Therefore, natural resources must be preserved and must not be used faster than they can be replaced (thus keeping the *physical* stock constant; Daly, 1991; Pearce, 1993). Strong sustainability proponents suggest the need to preserve the actual "stuff" of the environment and not just its "economic value" (Barry, 2011). Simply put, there is no substitute for the natural environment. In strong sustainability, the intergenerational transfer of capital is a priority and natural capital stock must remain intact (Daly, 1973, 1991). This promotes intergenerational equity since each generation is granted equal rights to equal resources, particularly natural resources. Therefore, proponents of strong sustainability support the preservation of natural resources in the same quantities for current and future generations. Strong sustainability also advocates zero population and economic growth (Daly, 1991). Furthermore, strong sustainability views economic and social relationships as intimately connected where principles of sharing and caring are highly valued (O'Riordan, 1989). This position is more idealistic and values cooperation, social well-being, economic opportunity, and economic and political reform (O'Riordan, 1989)."
Li & Li, 2017, p.2	W	"weak sustainability" (allowing for substitutability)".
	S	"strong sustainability" (not allowing for or setting a limit to substitutability)."
Serafimova, 2017, p.180	W	"Whilst the proponents of weak sustainability 'advocate policies devoted to securing a non-declining level of total capital, […]"
	S	"[..]the proponents of strong sustainability used to believe that maintaining a non-declining level of natural capital is a necessary condition for achieving a non-declining level of welfare, since natural capital cannot be substituted with the human capital."
de Oliveira Neto et al., 2018, p. 1629	W	"In Weak Sustainability (WS), economic, natural, and social capital are considered substitutes".
	S	"In Strong Sustainability (SS), economic activity preserves natural resources and promotes social wellbeing."
Landrum & Ohsowski, 2018, p.130	W	"Weak and strong sustainability are differentiated by their approach to integration, the ambition of the vision of change, the complexity of the innovation and the extent of collaboration among social, political, and economic actors' (Roome, 2012, p. 626). Four worldviews are positioned along the sustainability spectrum. At one end of the spectrum, weak and very weak sustainability are technocentric and require increases in production and consumption, economic growth, valuation and utilization of natural resources, and technocratic solutions to environmental problems; these positions view man's role as one of control over nature (Hartwick, 1977, 1978; Hediger, 1999; Solow, 1974, 1993)."
	S	"At the other end of the spectrum, strong and very strong sustainability are ecocentric and recognize that economic growth is bounded by environmental limits, natural resources need to be preserved to support life and all activity must remain within ecological limits; man's role is that of one equal species among others in nature (Daly, 1973, 1991; Hediger, 1999)."
Cabello et al., 2019, p.5	W	"Weak sustainability means that natural resources can be replaced with goods and services; therefore, when measuring the sustainability of a territory, a good economic indicator can compensate a bad environmental one or viceversa."
	S	"Strong sustainability means that the environmental performances cannot be compensated by economical or social ones."
Wu, 2019, p.174	W	"According to the weak sustainability view, a system is sustainable as long as its total capital (including both natural and manufactured) increases or remains the same. In this case, a region with rapid economic growth but severe environmental degradation may still be considered sustainable".
	S	"On the other hand, the strong sustainability view recognizes that many life-support functions of ecosystems are not substitutable and that long-term socioeconomic prosperity depends ultimately on environmental integrity (Fig. 1). Thus, strong sustainability limits, not precludes, the economy-environment substitutability through, for example, identifying the critical

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Table 2 (*continued*)

Reference		Definition
		natural capital for a particular region or nation (Ekins et al., 2003)."
Shi et al., 2019, p.7	W	"Weak sustainability is a human-centered view that natural capital can be replaced by manufactured capital. As an extension of neoclassical welfare economics [27], weak sustainability considers the total amount of manufactured capital and natural capital as the most important [49]. Therefore, as long as the total amount of capital increases in the process of development, even if the natural capital degrades to an unrecoverable state, it is still sustainable [50]."
	S	"Strong sustainability is a nature-centered view that natural capital plays an irreplaceable role in production and consumption. This concept is mainly based on the steady-state economic theory that manufactured capital cannot be duplicated without the input of natural capital [51]. Therefore, the process of development should not only require an increase in the total amount of capital, but also require the rationality of the capital structure and not crossing ecological thresholds [52]. Moreover, economic development should not exceed the natural limit [53]."
Barinaga-Rementeria & Etxano, 2020, p. 1–2	W	"In line with neoclassical economics and in accordance with the pioneering work of Solow [2], and later of Hartwick [3], weak sustainability is circumscribed in the paradigm of substitutability [1]. With the aim of ensuring that human welfare does not decrease, sustainability is defined in terms of the total utility offered by the sum of the accumulated capital—both the natural capital and the manufactured capital—assuming that the latter can replace the former. Sustainability therefore needs to maintain this capital-derived utility over time [4–7]. From this approach, therefore, it is assumed that all the values and functions, both those coming from the natural capital and the manufactured capital, can be quantified using a single scale, generally the monetary one, thus placing it in the framework of strong comparability [8]. Moreover, weak sustainability implies future uncertainty, both in terms of generational preferences and technological capacity [9]."
	S	"On the other hand, strong sustainability argues that many of the values and services offered by nature cannot be replaced by human-made capital. This approach developed by ecological economics [10] argues that certain natural resources are limited and irreplaceable and therefore a minimum amount of different types of capital must be conserved [11−13]. […] From this perspective, natural capital is neither compensable nor replaceable by manufactured capital, at least not in its entirety, and therefore cannot be perceived as a stock of resources. The fact that they are irreplaceable, places strong sustainability in the context of incomparability or weak comparability [8]. In addition, the existence of critical natural capital requires the setting of minimum conservation limits in the natural capital [15,16]. The critical threshold of a natural resource marks the level at which it loses its resilience, and falls into a position of irreversibility [17–19]. According to this principle, a certain amount of natural capital must be secured if the functions it offers to human welfare are to be maintained."
Ruggerio, 2021, p. 7–8	W	"weak sustainability assumes that the economic system is the subject and its main goal is to achieve sustained economic growth, or, as often referred to, sustainable development (Costanza & Daly, 1992). Pearce and Atkinson provide a mathematical expression of weak sustainability based on the notion of capital (Eq. (2)) disaggregated into three subsets: artificial, natural, and human capital (Pearce & Atkinson, 1992). […] the natural capital includes the natural resources (forests, aquifers, mineral deposits) from which natural commodities (new trees, water supply, minerals) and services (erosion control, carbon sequestration, pollution remediation) flow. Likewise, the concept of capital is applied to refer to human or cultural capital (people's know-how and skills) and artificial capital (products derived from or manufactured by people's economic activities) (Pearce and Atkinson, 1993, 1992). The proposal makes no distinction between natural resources and other marketable commodities, although it acknowledges the existence of a critical natural capital that must be conserved and is unreplaceable (Brand, 2009). […] Two of the most recent conceptual proposals emerging from the weak sustainability approach are circular economy (Bina, 2013; Brand, 2012; Wanner, 2015) and green economy (Sauvé et al., 2016; Schroeder et al., 2019; Suárez-Eiroa et al., 2019), both sharing a lack of questioning of the notions of development and economic growth, and both adhering to the premises of sustainable development and posing that environmental issues can be solved by technological and scientific advancement."
	S	"Opposed to the neoclassical theory, ecology cannot conceive human economy aside from nature, but, to the contrary, it considers the former as part of a SES that exchanges matter, energy, and information with its environment and sees its components as being more than commodities and services traded in markets (Fig. 8) –a reasoning that, to a large extent, has established the theoretical foundation on which the definition of strong sustainability stands. This definition assumes that some attributes of nature cannot be replaced by artificial capital and, because of the degree of uncertainty associated with SESs, the 'precautionary principle' must predominate over the economistic logic of the neoclassical theory (Cózar Escalante, 2005; Kriebel et al., 2001). This does not mean adopting a conservationist point of view toward nature overseeing human societies (very strong sustainability), but assuming that the persistence of SESs depends on reversing the increasing tendency to deteriorate Earth's environments."
Usubiaga-Liano & Ekins, 2021, p. 2, 8	W	"The limited substitution capacity between different types of capital and between the different functions provided by natural capital, and the notion that some elements of natural capital provide irreplaceable functions are much closer aligned with the biophysical reality that governs the natural system and the socioeconomic systems embedded within, than the concept of weak sustainability, which assumes that the loss of nature can be fully compensated by increases in manufactured, human or social capital. For these reasons, metrics of weak sustainability can be misleading and lead to poor decision making "p.8
	S	"Natural capital is a key contributor to human well-being. Its environmental functions that make this contribution can in many cases not be replaced by those provided by other types of capital such as manufactured, social and human capital. The elements of natural capital that fulfil

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Table 2 (*continued*)

Reference		Definition
		irreplaceable functions are termed 'critical natural capital'. The limited substitution capacity between different types of capital and between the different elements of natural capital is at the core of the strong sustainability proposition (Costanza & Daly, 1992; Neumayer, 2003)." p.2
Lo-Iacono-Ferreira et al., 2022, p. 4	W	–
	S	"Following the recent theoretical discussion about when to use weak or strong sustainability indices (Gan et al., 2017), we propose to use both strong and weak aggregation methodologies to construct a strong-weak performance interval rather than a single composite index. Using a performance interval to construct a composite index depending on the level of compensability generates a lower and upper bound of the composite index (Mazziotta & Pareto, 2020; Garcia-Bernabeu et al., 2020a,b). The lower bound corresponds to the hypothesis of individual indicators' non-compensability (strong sustainability index), whereas the upper bound assumes full compensability (weak sustainability index)."
Qasim & Grimes, 2022, p.1 and 4	W	"By contrast, a weak sustainability approach (Pearce and Atkinson, 1993; Pearce et al., 1996) allows for substitutability between different forms of capital (natural, produced and human) in facilitating future wellbeing outcomes." p.1 "The concept of weak sustainability is rooted in the argument that natural, human, financial and produced capital are substitutable. This concept emerged in the 1970s when neoclassical models of economic growth were extended to account for non-renewable natural capital as a factor of production" p.4
	S	"The Dasgupta Review (Dasgupta & Mäler, 2000: 2) states: 'Our economies, livelihoods and wellbeing all rely on Nature.' This emphasis on the criticality of nature for human wellbeing is consistent with a strong sustainability approach that emphasises the importance of protecting natural assets in order to underpin future welfare. "p.1 "By contrast, 'strong sustainability' views natural capital as being largely non-substitutable for the generation of wellbeing (e.g., Georgescu-Roegen, 1971)." p.4
Butt, 2025, p.2	W	"Weak sustainability assumes that natural capital can be substituted by human-made capital, [..]"
	S	[..] while strong sustainability argues that certain natural systems are irreplaceable and must be preserved at all costs.
Haou et al., 2025, p.5	W	"Conversely, advocates of 'weak sustainability' argue that natural capital can be replaced by artificial forms of capital."
	S	"Proponents of 'strong sustainability' contend that populations must not exploit ecological resources beyond the regenerative capacity of nature. In this view, only the surplus generated by ecosystems should be used, leaving the natural capital intact."
Chen et al., 2025, p.7	W	"This necessitates the valuation of all forms of capital, maintaining their constancy over time, which is termed "weak sustainability" (Qasim & Grimes, 2022). The achievement of weak sustainability is contingent on the substitutability of all forms of capital."
	S	"However, to attain "strong sustainability," it is imperative to generate more value from less capital, a feat in which technology plays a pivotal role (Qasim & Grimes, 2022). Technology serves as a crucial catalyst in the evolution from weak to strong sustainability, influencing decision-making processes. The ongoing technological changes aim to enhance the substitutability of capital, as highlighted by Bi et al. (2020)."

Barinaga-Rementeria & Etxano, 2020; Cabello et al., 2019; D'Amato et al., 2017; Ekins et al., 2003; Landrum, 2017; Li & Li, 2017; Pelenc & Ballet, 2015; Serafimova, 2017; Wu, 2019; Usubiaga-Liano & Ekins, 2021). Considering the definition collected, it is understood that an exchange between environment and economy cannot be accepted (Berardi, 2015), i.e. environmental performance cannot be compensated by economic and social performance (Cabello et al., 2019). In addition, economic activity should preserve natural resources and promote social welfare (de Oliveira Neto et al., 2018). In the urban context, natural and human capital, and consequently the economy, environment and society, should be considered as interconnected elements: 'urban development cannot be sustainable without a healthy environment' (Huang et al., 2015, p.1177). Consequently, cities and urban regions should evolve while maintaining a 'critical' level of biodiversity and ecosystem services essential for human well-being (Huang et al., 2015; Pelenc & Ballet, 2015). In other words, cities and their local contexts, understood as fundamental units for realising sustainability, should orient their development by prioritising quality over quantity (Yanarella et al., 2009). This perspective, which rejects the idea of considering natural capital as replaceable by human-made capital, has led, as Walton et al. (2005) point out, to several attempts to monitor and assess impacts in biophysical and ecological footprint terms, through the analysis of emissions and the extent of land used.

An analysis of the definitions proposed between 2000 and 2015 and those from 2016 to 2025 reveals a general consistency and absence of major modifications, even following the introduction of the 2030 Agenda in 2015. Nevertheless, a subtle and gradual incorporation of technology into these definitions can be observed. Technology begins to be explicitly mentioned only from 2015 onwards, which is the period when the smart city model begun to consolidate its popularity and impact globally (De Jong et al., 2015). This techno-urban perspective is notable in the definitions by Pelenc and Ballet (2015) and Landrum (2017), both of which align with the paradigm of weak sustainability. These definitions share the view that total capital should be transmitted to future generations in an equivalent form, assuming that technological progress and human capital can compensate for the depletion of natural capital by providing solutions to environmental challenges arising from economic benefits.

By contrast, the integration of technology within the framework of strong sustainability is a more recent development, as illustrated by the definition proposed by Chen et al. (2025). In this context, technology is not considered a substitute for natural capital (as is the case in weak sustainability) but rather as a strategic tool to optimize resource use, reduce waste, and identify sustainable alternatives, without undermining the preservation of natural assets.

Based on these findings, the key elements distinguishing the two paradigms can be summarized as follows:

1. the key-approach adopted by each paradigm concerning the dimensions of sustainability;
2. the strategy promoted for managing natural and human capital;
3. the criterion used to determine when sustainability is considered ensured;
4. the management model balancing environmental and economic dimensions;
5. the type of compensation accepted by the two paradigms, whether compensatory or non-compensatory;
6. and finally, how each paradigm relates to technology.

These six elements constitute the comparative analytical framework of the study (Fig. 2), with the aim of using it as a tool to classify contemporary and emerging urban models, such as the smart city and the autonomous city, respectively.

	Weak Sustainability	Strong Sustainability
Key-approach	Substitutability	Integration
Capital management strategy	**Interchangeability** between natural and man-made capital	Man-made and natural capital are not interchangeable, but are **complementary**
Sustainability ensured	Sustainability is maintained as long as the **overall capital** remains **constant**	Sustainability is maintained by keeping **both capitals constant**
Environment and Economy	The loss of nature can be **compensated** by economic benefits	Environment and economy are **not exchangeable**
Compensability	**Granted.** This paradigm allows substitutability between elements	**Not granted.** This paradigm limits trade-offs between elements
Technology	Can be a **solution** to solve environmental problems and loss of natural capital	Technology, as a man-made product, **cannot substitute** the natural capital

Fig. 2. Comparative analytical framework

4. Evaluation of the city models

4.1. Positioning the smart city within sustainability paradigms

The concept of the smart city has undergone significant evolution since the 1990s, when it first emerged in response to the growing diffusion of Information and Communication Technologies (ICT), becoming today a complex, multidimensional paradigm encompassing technological, social, environmental, and economic aspects (Correia et al., 2022; Karvonen et al., 2018). As reported by Ibrahim et al. (2018), there are numerous definitions of the concept of smart city in the literature, which are used inconsistently, i.e. they differ depending on the perspective adopted. However, we can narrow down this concept to an urban environment that strategically employs digital technologies, the Internet of Things (IoT), big data, and intelligent systems to collect and analyze data, enhance citizens' quality of life, optimize public services, and promote sustainability (Novotný et al., 2014; Oyadeyi & Oyadeyi, 2025; Sorri et al., 2024; Toli & Murtagh, 2020). Moreover, it is based on participatory governance structures in which citizens, institutions, businesses, and other stakeholders collaborate in the co-creation of innovative solutions (Toli & Murtagh, 2020).

Theoretically, the smart city concept is conceived as functionally integrated with the sustainable city: sustainability constitutes the foundation of contemporary urban transformation, while the smart city serves as an operational means to achieve it (Bélaïd et al., 2024; José & Rodrigues, 2024; Qian et al., 2024). As noted by Silva et al. (2018), who explore the conceptual foundations of the smart city in terms of its definitions and implications, this urban model is conceived as an integrated system that fosters interoperability among various subsystems, ultimately aiming to enhance the quality of life of urban citizens. From this perspective, a city is defined as "intelligent" when it jointly invests in human and social capital as well as in advanced technological infrastructure, in order to foster sustainable economic development and improve the quality of life through inclusive, participatory governance models (Kunzmann, 2014; Toli & Murtagh, 2020).

Intelligent technologies play a key role in achieving these objectives, enabling more efficient urban flow management, accurate demand forecasting, resource optimization, and overall improvement in the quality and accessibility of public services (Blasi et al., 2022; Novotný et al., 2014). In mobility, for example, smart public transport systems, real-time monitoring, bike-sharing services, electric vehicles, and digital traffic management platforms contribute to reducing emissions and alleviating congestion (Gu et al., 2025).

In environmental management, smart cities utilize IoT and advanced sensors to monitor air quality, prevent pollution, and optimize resource use. Similarly, smart meters and management platforms are employed to monitor water consumption, detect contamination, and promote recycling practices. The energy sector also benefits from smart solutions through the integration of renewable sources, intelligent storage systems, real-time consumption monitoring, and bidirectional communication between users and energy providers. Waste management is optimized using predictive technologies and intelligent collection systems designed to minimize environmental impacts and reduce costs associated with inefficient systems (Gu et al., 2025; Novotný et al., 2014; Oyadeyi & Oyadeyi, 2025; Sharifi et al., 2024; Toli & Murtagh, 2020). Overall, smart cities are urban models that transform the complexity of metropolitan dynamics into intelligent, interconnected systems oriented toward sustainability, innovatively addressing the global challenges of urbanization.

Referencing the previously introduced paradigms of strong and weak sustainability and the notions of natural and human capital, these remain foundational even within the smart city context. Human capital, comprising individual skills, knowledge, abilities, social networks, and human-made products (buildings, infrastructure, etc.), constitutes a key strategic asset, contributing to innovation, social cohesion, and economic development. Natural capital, comprising environmental resources such as green spaces, clean air, and water, not only delivers ecosystem benefits but also enhances the experiential value and attractiveness of urban areas dedicated to innovation and daily life (De Jong et al., 2024).

Within the smart city model, a new form of capital emerges with a central role: technological capital. Although a product of human effort and thus linked to human capital, it transcends mere physical ICT infrastructure. It encompasses the entire intangible ecosystem of smart technological networks that permeate and support (or in some cases undermine) human and natural capital. Sensors, digital platforms, and IoT enable real-time monitoring, analysis, and optimization of urban flows, buildings, infrastructure, and city functions (Almarri &

Boussabaine, 2025; Riedmann-Streitz et al., 2025).

Unlike traditional forms of capital, technological capital introduces an interactive, cognitive dimension into the urban space, transforming cities into hybrid environments in which physical infrastructure is connected and capable of generating and consuming data. This capital not only enables new urban services, such as predictive management of traffic, energy, and waste, but also turns cities into nodes interlinking diverse flows of physical and digital capital. These become spaces of experimentation and investment in advanced technologies (De Jong et al., 2024).

Although technological capital holds strong theoretical potential to support sustainable development, substantial critiques also emerge. Several authors argue that smart transformation often accompanies urban development models that prioritize economic growth and profit over social and environmental dimensions (Cugurullo, 2018; José & Rodrigues, 2024; Oyadeyi & Oyadeyi, 2025). De Jong et al. (2024) observe that cities such as Zurich, Oslo, and Copenhagen, which are consistently ranked among the world's leading smart cities, continue to face complex challenges. These include balancing economic growth with environmental objectives and addressing the social implications of technological development. The environmental impact of such technologies is ambiguous: while promising greater efficiency, issues such as light pollution and the high energy consumption of data centres illustrate the limitations of implementations that are not always sustainable. Furthermore, natural spaces are being converted into built environments to accommodate smart city infrastructure (e.g., data centers), which can erode natural capital.

From a social perspective, smart city development has at times exacerbated urban inequality, since the benefits of intelligent technologies are often unevenly distributed among the population (Han & Kim, 2024). The promotion of digital innovation can deepen social disparities, threaten privacy and security, and generate new forms of exclusion and vulnerability, as evidenced during the COVID-19 pandemic. Thus, wellbeing, community, and the environment may be neglected in favor of efficiency and profit for a few (Sharifi et al., 2024).

In this context, technological capital is better conceived not as a neutral add-on to human and natural capital, but as a socio-technical arrangement that reconfigures capabilities, power relations, and ecological throughput. In principle, it can help strengthen those capitals by enabling innovation and efficiency in support of sustainability. Yet its effects are contingent on institutional design: depending on governance arrangements and incentive structures, deployment may redistribute capabilities, risks, and rents, with possible implications for social autonomy. Likewise, the material footprint of digital infrastructures can place additional pressures on natural systems. Technological capital thus warrants careful, rule-based and accountable governance oriented to enhance capability and clear ecological limits.

Recent literature also underlines a hierarchy of capital, where economic–financial capital dominates and functions as the metric by which other resources are evaluated and transformed (De Jong et al., 2024). This dominance often leads to significant compromises, especially against natural capital: environmental and biological resources are instrumentalized in support of production and commerce, sometimes to the detriment of ecological sustainability and ecosystem health). In this sense, smart cities often act primarily as vectors of economic growth permeating society and the environment, which highlights an economic priority over other forms of capital (Qian et al., 2024).

On this basis, it is legitimate to classify the smart city model within the weak sustainability paradigm. Although theoretically based on an integrated approach to different dimensions of sustainable development, in practice it becomes a capital-management strategy grounded in the interchangeability of natural, human, and technological capital. Sustainability is preserved so long as total capital (the sum of these three) remains constant over time. As illustrated previously, the loss of natural resources, such as urbanizing virgin land for technology infrastructure (e.g., data centres), is deemed acceptable if offset by economic returns or technological progress.

Thus, the smart city model reflects a compensatory logic not only between economic and environmental dimensions, but across all urban capital components. Moreover, technology increasingly assumes the role of an autonomous form of capital: theoretically intended to facilitate sustainable development and reinforce human and natural capital, yet in practice it tends to replace them in the face of environmental or social losses. Fig. 3 summarizes our interpretation of the positioning of the smart city within the theoretical spectrum between weak and strong sustainability paradigms.

4.2. From smart to autonomous cities: continuity or paradigm shift?

With the global emergence of AI, we are now witnessing a shift from the smart city model to the so-called autonomous city. This is an emerging model of urban development and governance and, as such, it is considerably younger than the notion of smart urbanism discussed in the previous section, although conceptually the autonomous city is rooted in cybernetics which is a discipline originally developed in the 1940s to “mechanically replace functions that have traditionally been attributed solely to the human brain” (Palmini & Cugurullo, 2023: 4).

From a technological point of view, the shift from smart to autonomous cities is grounded in the new capabilities of AI systems which present a considerable degree of innovation when compared with smart technologies that have been a part of urban contexts for over four decades (Karvonen et al., 2018). It is important to specify that from an historical point of view, the deployment of AI in the operation of urban systems does not represent a rapture with the smart city and, as noted by Caprotti et al. (2024) these dynamics are the culmination of many years of smart-city experiments and point to an intensification of technological and urban strategies initiated by the smart city model.

However, there are important differences to recognize in the way traditional smart technologies function in comparison with emerging AI systems applied to the management of urban spaces. More specifically, while smart technologies tend to operate in an automated manner, by repeating activities and actions pre-programmed and determined by computer scientists, urban planners and city managers, AI acts in an autonomous manner when what it does is neither supervised nor guided by human operators (Cugurullo et al., 2024) Furthermore, while smart technologies operate in-real time, by sensing what is happening in a given city in the present, AI attempts to foresee the evolution of urban metabolism by calculating an unprecedented amount of future possibilities (Xu et al., 2025). In terms of urban management, these different temporal logics represent a considerable shift from what Kitchin (2014) termed the ‘real-time city’ constantly monitored by smart sensors for urban managers to respond to emerging issues, to an anticipatory governance whereby potential issues foreseen by AI are pre-empted in a proactive manner (Xu et al., 2025).

From a sustainability point of view, the application of AI technologies in urban governance is commonly associated with environmental benefits and this is reflected in recent academic interventions regarding the promises of AI in urbanistic terms. For scholars such as Leal Filho et al. (2024), for instance, AI has the potential to foster sustainable cities and thus achieve SDG 11, by producing vast volumes of information regarding cities' metabolism, helpful for understanding how to better reduce energy waste and loss of natural habitat. Similarly, we find several recent studies contemplating future scenarios in which AI can help cities generate renewable energy and reduce their carbon emissions (Al-Raeei, 2025); AI also becoming an instrument to predict traffic flows and avoid congested transportation systems in cities (Chen & Zhang, 2022); and AI supporting the creation of a new generation of air purifiers capable of drastically reducing air pollutants thereby improving cities' air quality (Lazirkha, 2022). In Europe, cities like Berlin, Amsterdam, Copenhagen, Paris, Helsinki and Vienna are already experimenting with AI technologies as part of different climate actions, in an attempt to become carbon neutral in the near future (Hintz et al., 2026).

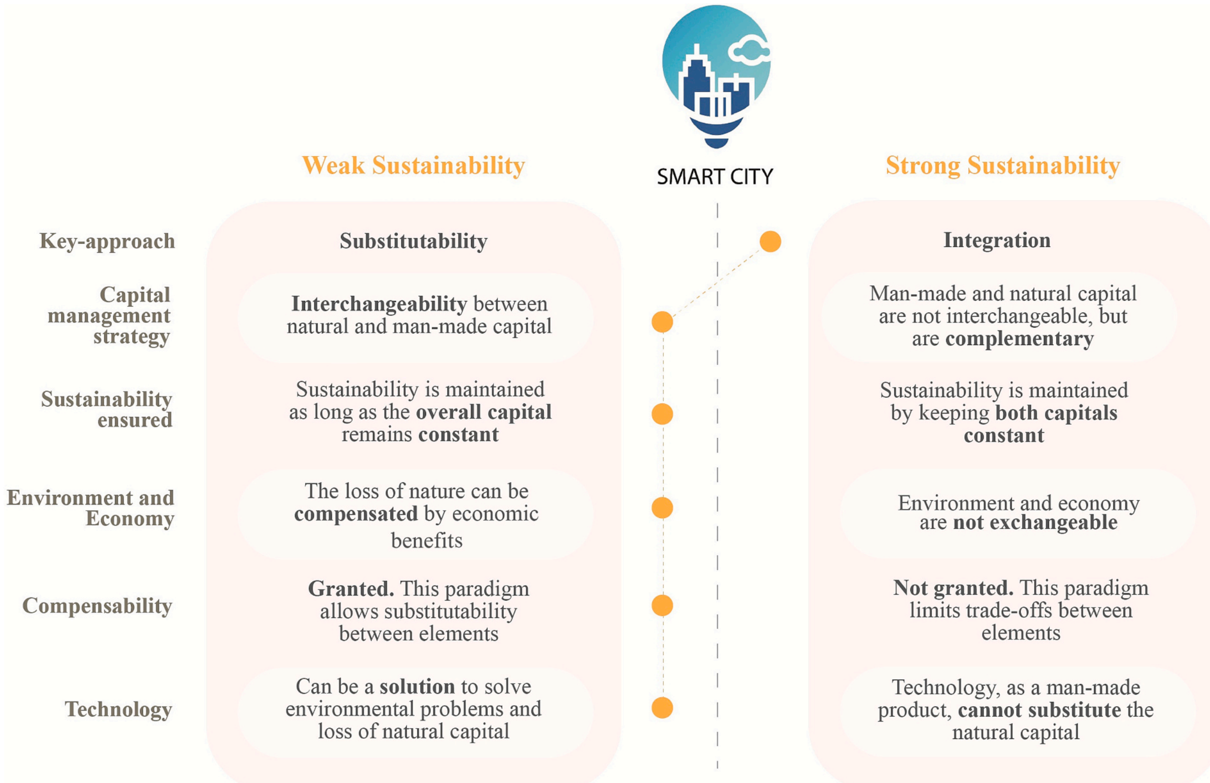

Fig. 3. Positioning of the smart city

These environmental promises constitute a strong continuity with the smart city model as, once again, we find new technologies being presented as a silver bullet to fix urban environmental problems and achieve a condition of sustainability (Taylor Buck & While, 2017). It is of course important to pay attention to these potential scenarios particularly as AI technologies will keep evolving in the future, but it is also equally crucial to reflect on the present cost of such technologies. Here we find other significant continuities between the smart and the autonomous city. In fact, both urban models require a considerable amount of natural resources in order to operate. As stressed by Crawford (2021), AI is an extractive technology. From an environmental perspective, this dynamic can be observed in multiple ways. The first one relates to the extraction of critical raw materials, such as cobalt, coltan, gallium and germanium, which are deployed to build AI systems (Dauvergne, 2022). This is a form of extraction that damages not only natural systems but also local populations, as coltan, for instance, is by and large extracted in politically unstable countries like the Congo where children sustain the supply chain of this material with their own hands, in dire conditions that the UN has repeatedly reported and condemned (Kaika, 2017). The second way concerns the energy that is needed to power AI systems. Today AI is a major driver of growth in relation to the energy that is needed to process data, and as the International Energy Agency reports, electricity demand from data centres is expected to double during the next couple of years (Cugurullo, 2025). From an urban point of view this is even more striking if we take into account the size of data centres which in a country like Ireland can take up over 20 ha of land and consumes as much energy as a small city (Cugurullo, 2025). The third way relates to the water that is consumed to produce and sustain AI technologies. It is a well-known fact that data centres rely on water-based cooling systems that put a strain on already fragile ecosystems, and recent studies have estimated that training GPT-3 cost approximately 700,000 l of freshwater (Li et al., 2025). The fourth way concerns the matter of e-waste. When AI technologies eventually break they are disposed of, often in the Global South, generating e-waste that, as Dauvergne (2022) points out, risks polluting ground water, thereby damaging those agricultural activities that depend on it.

In essence, if we relate the above issues to the models of sustainability discussed earlier in the paper, it is clear that autonomous cities relying extensively on large-scale AI systems and technologies, are not aligned at all with the notion of strong sustainability. In many ways, the autonomous city goes even further away from this understanding of sustainability than the smart city, given that, from an environmental perspective, the costs and repercussions of AI are exponentially higher and bigger than those of smart tech.

The question of human capital poses new challenges in the context of emerging autonomous cities operated by AI. On the one hand, there is a minority of studies showing how, in urban contexts, AI can improve human capital by improving the health of citizens. This has been reported particularly in China where AI and robotics have become a core component of public hospitals and health services, in a way that has been accelerating medical diagnoses, operations and rehabilitation (Guo & Cugurullo, 2025). However, on the other hand, there is abundant evidence of the subtle ways through which AI can damage human capital, particularly in terms of knowledge and skills. This is because AI systems are sustained by human knowledge and, in order to operate, they require information produced by humans. The problem is that this type of knowledge is often appropriated by AI systems in a manner that dispossesses those human workers who have created it in the first place, as demonstrated by the recent accusations against OpenAI and Microsoft for feeding its AI with materials produced by human journalists without their consent (Grynbaum & Mac, 2023).

From an urbanistic perspective, similar dynamics of exploitation of human capital can be seen in the extensive labour performed by so-called *click-workers* who manually filter and classify data to be fed to AI systems, while crammed in data farms located in the margins of the city (Altenried, 2022; Cugurullo, 2025). At the same time, at the heart of the city instead, citizens are constantly observed by AI-equipped sensor technologies that capture their behavioural data without neither consent nor remuneration, for the purpose of training AI systems (Cugurullo et al., 2023).

Overall, we argue that due to the twofold exploitation that characterizes the emerging model of the autonomous city, environmentally and socially, the only possible scenario is a very weak form of sustainability. Not only autonomous cities would require more environmental resources than smart cities: they also risk undermining human capital given their extractive tendencies in relation to human knowledge and labour. In our opinion, this is going below even the expectations of the weak sustainability paradigm, entering a problematic phase of urban development characterised by what we call 'super weak sustainability' which will be further discussed in the next section.

5. Discussion

The analysis shows that current urban development models diverge markedly from the scenarios usually presented as desirable for human and environmental well-being. The smart city aligns with a weak sustainability paradigm, in which the integration of different forms of capital remains more a formal statement than an operative practice. The picture becomes sharper with the autonomous city, which can be read as an early expression of super weak sustainability. In this context, technology progressively shifts from being a support instrument to becoming the central organizing principle. In the smart city, a tension remains between natural and human capital, with technology functioning as a compensatory device. In the autonomous city this relation is inverted: technology is no longer a mediator but a dominant factor, relegating natural and human capital to a secondary role. Technological tools such as AI systems may indeed rationalize decision-making and improve the interaction among capitals, but their assumed capacity to secure overall sustainability is, at this stage, largely unproven (Lami & Moroni, 2026). Fig. 4 illustrates this drift toward super weak sustainability, which appears to characterize the direction of contemporary urban evolution.

The notion of super weak sustainability can be interpreted as the mirror image of so-called *super wicked problems* (Lami, 2019). While super wicked problems describe challenges that resist conventional solutions because of temporal urgency, fragmented authority, self-contributory behaviors of actors, and systemic inertia, super weak sustainability denotes the degeneration of sustainability into a merely rhetorical and technocratic construct. If weak sustainability already allows substitution between forms of capital, its "super weak" form risks extending this substitutability without limits, legitimizing almost any ecological degradation through the promise of future technological solutions or abstract economic benefits. In the smart city, this translates into the systematic postponement of structural choices under the assumption that technological mediation will one day compensate for ecological losses. In the autonomous city, the problem is even more pronounced: the predominance of AI-driven decision-making systems reinforces the idea that sustainability can be secured through technical optimization alone. In both cases, what emerges may not be a sustainability framework in any substantive sense, but rather a narrow focus on optimization that risks sidelining the ecological and social dimensions of urban development.

Fig. 4. Key elements of the Super Weak Sustainability phenomenon.

This condition highlights the need to reconsider the limits of the strong sustainability paradigm, in line with what is proposed in Mecca et al. (2026). In this study, strong sustainability is conceptualized in a dynamic form, articulated in three variations: Strict, Complementary and Integrative Strong Sustainability. The transition between these levels is defined through measurable thresholds. From an operational perspective, indicators are employed as evaluation tools for urban projects, with thresholds set by regulations or expert judgements. The mathematical aggregation of these indicators enables the operationalization of a strong sustainability paradigm with varying degrees of rigidity, depending on the extent of compensation allowed between dimensions of sustainability and the compliance with established thresholds.

In this comparative frame, super weak sustainability and super wicked problems can be seen as two sides of the same coin: both reveal the insufficiency of current paradigms and the risks of deferring responsibility. By contrast, the dynamic reconceptualization of strong sustainability suggests a way forward. By defining explicit thresholds and calibrating the permissible degree of compensation across different dimensions, it anchors sustainability to non-negotiable ecological and social baselines while preserving the flexibility required to operate in complex urban contexts. In essence, we argue that the emergence of a "super weak sustainability" phenomenon in urban development could be mitigated through a reconsideration of the strong sustainability paradigm, which is often regarded as excessively stringent. A reformulation of strong sustainability articulated into three variants Strict, Complementary, and Integrative Strong Sustainability, would allow for limited forms of compensation and substitution among different forms of capital, while firmly maintaining non-negotiable minimum thresholds necessary to prevent the depletion of any single capital.

Such an approach could represent an operational solution for the evaluation of urban scenarios at the pre-design stage, prior to their concrete implementation. This is particularly relevant given that contemporary cities are inherently energy-intensive, and that energy production and consumption, together with the development of new technologies, occupy a central position in current urban policies. However, this centrality should not result in the complete subordination of social, cultural, and environmental dimensions.

For the smart city and, even more so, for the autonomous city, this approach may represent a first step toward reframing sustainability in concrete and applicable terms. Technological capital remains a relevant resource for urban innovation, but it acquires meaning only if its social, environmental and economic consequences are explicitly addressed. The key challenge is therefore to establish a workable balance between traditional and emerging forms of capital, without which claims of sustainability and inclusiveness risk remaining largely declarative.

6. Conclusion

This paper asked how the models of the smart city and the autonomous city position themselves within contemporary sustainability paradigms. The analysis suggests a clear distance from the paradigm of strong sustainability, which is generally taken as the main reference point. This gap is largely due to the growing role of technology as an autonomous form of capital within urban development. In theoretical debates, technology is still often presented as a promising tool for supporting strong sustainability; in practice, however, it tends to reinforce compensatory logics typical of the weak sustainability paradigm.

The review of the literature shows that technology has only recently entered the sustainability debate explicitly (from 2015 onwards), roughly in parallel with the spread of the smart city as a global urban model. In relation to weak sustainability, it is interpreted as a substitute for natural capital, while in terms of strong sustainability, technology is seen as a tool for reducing impacts without compromising ecosystems. Yet the comparative analysis of smart and autonomous cities indicates that neither model seriously pursues strong sustainability. Both rely on capital substitutability and compensation, without a firm commitment to safeguarding biodiversity and critical ecosystem services. In the autonomous city, technology (especially AI) assumes a dominant position, subordinating natural and human capital. This trajectory can be described as what we term "super weak sustainability".

The issue is not simply quantitative growth at the expense of qualitative improvement, but rather the risk that natural and human capital may be progressively eroded in favor of technological capital. This highlights two main needs: (i) to explicitly include technological capital in the discussion as a standalone dimension; and (ii) to revisit the conceptualization of strong sustainability, as proposed by Mecca et al. (2026), in order to allow for limited forms of compensation and substitution among different forms of capital, while firmly maintaining non-negotiable minimum thresholds necessary to prevent the depletion of any single capital. Such a theoretical revision could potentially consider rethinking the boundaries that currently rigidly separate the two paradigms, in order to make them more flexible and operational. AI, initially a human artefact, is becoming an active agent in decision-making, a "cognitive partner" rather than a mere tool (Benanti, 2022). This development challenges existing frameworks and raises the question of whether strong sustainability itself needs to be reformulated to take such forms of capital into account.

While this paper has focused on a conceptual and comparative analysis rather than empirical evidence, this choice was deliberate. The aim was to open a theoretical space for reflection, before moving to the operational level. The discussion of technological capital and AI is therefore exploratory and intended as a first step toward a broader rethinking of sustainability paradigms. Similarly, the proposal of a "super weak sustainability" framework should be read as a provisional conceptual device one that invites further testing, refinement, and empirical grounding. It is further noted that the specific objective of this study is to theoretically frame the positioning of smart and autonomous cities with respect to sustainability paradigms, thereby constituting a preliminary phase in the construction of a theoretical reference framework. This framing may serve as a basis for future research developments, for example through the definition and application of coherent quantitative and qualitative indicators aimed at monitoring urban models and enabling a more in-depth analysis of their performance.

We do not propose a new definition here but suggest that such a rethinking is necessary. Future research should clarify whether strong sustainability can be extended in a dynamic and operational way to include technological capital (while setting non-negotiable ecological thresholds) or whether a new paradigm is required. What is clear is that smart and autonomous cities, in their current forms, cannot be assumed to be aligned with strong sustainability. They illustrate, instead, the ambiguities and risks of sustainability discourses when technological innovation is taken as a surrogate for ecological limits.

CRediT authorship contribution statement

Beatrice Mecca: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Isabella M. Lami:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization. **Federico Cugurullo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

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