Circularity assessment in buildings and built environment: an integrated multiscale framework

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Abstract. Circular transition requires systematic interventions in the built environment, particularly at the urban level, to close resource loops locally. The adoption of a design-operational approach focused on the life-cycle perspective and circularity, in line with the Green Building Approach, at the same time responds to resource scarcity and cuts CO_2 emissions in the regeneration and integration of urban settlements. In this view, the dimension of the urban neighbourhood offers an ideal field of experimentation to test and scale up circular strategies and solutions, starting from the building scale. The contribution reports the results of an ongoing research whose aim is to propose a methodology to identify basic characteristics and performances allowing a neighbourhood to be defined as circular, and to promote their spread through design both in regeneration and new construction. Thus, the research addresses an important gap due to the limited number of studies on circularity metrics at the neighbourhood scale. From a methodological point of view, the research analyses a selection of case studies and, in parallel, existing circularity metrics at different levels, systematizing them with a set of indicators coming from sustainability protocols at the neighbourhood scale. The research therefore defines an integrated multiscale framework supporting circular design and assessment, valid at the building level but also - in a multiscale perspective - at the neighbourhood level, aiming to develop a support tool for public administrations and designers.

Keywords: life cycle approach, circularity, circularity indicators, environmental sustainability protocols, circular neighborhood.

1. Introduction. Circularity and the city: the role of neighborhoods, the need for indicators

Circular transition requires widespread, systematic interventions in the built environment, particularly at the urban level, to improve resource efficiency (primarily energy, water, nutrients and physical-material resources, including building materials, from bio-based and technical cycles), by closing resource loops locally. In fact, 75% of natural resource consumption occurs in cities, which produce 50% of global waste and 60-80% of greenhouse gas emissions [1]. The redefinition of the way resources are used in the cities is needed, though, is needed to address the major interconnected challenges of climate change and resource depletion, while meeting shared EU targets [2]. In fact, the adoption of a design-operational approach focused on the life-cycle perspective and circularity, in line with the Green

Building Approach [3], is able at the same time to respond to (material and immaterial) resource scarcity and to cut CO_2 emissions in the regeneration and integration of urban settlements [4].

With the objective of defining useful models for cities' green and circular transition, the dimension of the urban neighbourhood/district offers an ideal field of experimentation to test and scale up innovative strategies and solutions, starting from the building scale [5]. This is also highlighted in frameworks for emissions assessment at the neighbourhood level, such as C40 and ARUP's "Green and Thriving Neighbourhoods" [6], which identifies resource circularity as one of the ten key approaches to minimize carbon over the whole life-cycle of an urban settlement.

"A circular neighbourhood aims to embed circular economy principles in all economic activity that takes place within it" [5]. Therefore, all flows of resources are involved and a benefcial impact is ensured on the surrounding city: "waste and pollution are eliminated and natural systems in and around the local environment are regenerated, underpinned by a transition to renewable energy and materials" [5].

The scale of the neighborhood or urban district is in fact fruitful for circularity-oriented experimentations [7, 8], allowing for - compared to cities - an easier monitoring of sustainability and circularity levels, and easer adaptations of the strategies and actions. In this sense, though, looking at international initiatives it is clear that – though many studies regard circularity indicators in general [9], specific metrics at such scale are missing, and also, data referring to them.

At its core, the role of indicators is to "simplify, focus, and compress the immense complexity of our changing environment to a manageable amount of relevant information" [10].

Considering this context, an effective framework of indicators for a circular economy transition in cities is required to assess progress and performance and, if necessary, alter ongoing activities [11]. Such approach has been adopted for example in the Amsterdam Circular City project, whose Circularity Monitor is currently a very important testbed for this challenging topic [12].

Measuring circularity in cities is crucial for the transition and. At the European level, this approach is supported by initiatives such as the CCRI Methodology, which divides the process into three steps to map the territory, identify circular solutions and implement them. Another example is the City Loops project, funded by EU Horizon 2020, aimed at circularising the material flows of seven European cities using the Accounting Method. In general, it is essential to develop increasingly shared sustainability and circularity indicators to obtain comparable data and to compare different cities on the same level. In Italy, since 2020, the UNI/CT Technical Commission 'Sustainable Cities, Communities and Infrastructures' has been working in this direction for the development of requirements, frameworks, guidelines and supporting regulatory tools, through the elaboration of draft national standards and, in the international sphere, by interfacing with the respective CEN and ISO committees: ISO/TC 268 'Sustainable cities and communities' and CEN/TC 465 'Sustainable and Smart Cities and Communities'. Reference can also be made to environmental energy certification protocols on a neighbourhood scale, which, by providing an assessment methodology with relevant indicators and reference threshold values, support the measurement of sustainability levels, albeit always on a smaller scale than the overall urban scale (neighbourhood/building).

2. Research aims. Circularity assessment to support design in the built environment

The aim of the ongoing research reported in this contribution is to propose a methodology to identify basic characteristics and performances allowing a neighbourhood/district to be defined as circular. Main objective is therefore to promote their spread both in regeneration and new construction. Thus, the research addresses an important gap due to the limited number of studies on circularity metrics at the neighbourhood scale.

From a methodological point of view, the research analyses existing circularity metrics at the building level, systematising them with a set of sustainability assessment/certification protocols and green design frameworks at the neighbourhood scale, as well as with a selection of case studies. The objective is to identify assessment criteria and indicators valid at the building level but also - in a multiscale perspective - scalable at the neighbourhood level, integrating them with further parameters.

Therefore, the research works to define an integrated framework allowing firstly to establish reference circularity levels for a building/neighbourhood/urban district to be considered 'circular', and secondly to carry out a rapid assessment of circularity levels achievable through different project actions, aiming to develop a support tool for public administrations and designers. On the one hand, the research activity on the topic of circularity assessment derived from the observation of an existing gap in circularity assessment systems at the neighbourhood/district level. On the other side, it was contextualised within the construction of a framework of existing circularity policies among those enacted by individual cities in the EU, which highlighted the lack of integrated, multi-scalar policy and monitoring tools for increasing circularity at the neighbourhood level. The framework was constructed from the survey of urban policies carried out in the Circular Cities Declaration Report 2022 [13].

3. Research methodology

The methodological framework of the research is divided into four fields of activity (definitions, case studies, strategies and criteria for evaluating the level of circularity) within an operational model characterised by a progressive order of depth, thematic connections and internal references including feedback. Below (Fig. 1) is an outline of the phases and activities of the research, with their sources and achieved/expected outcomes.

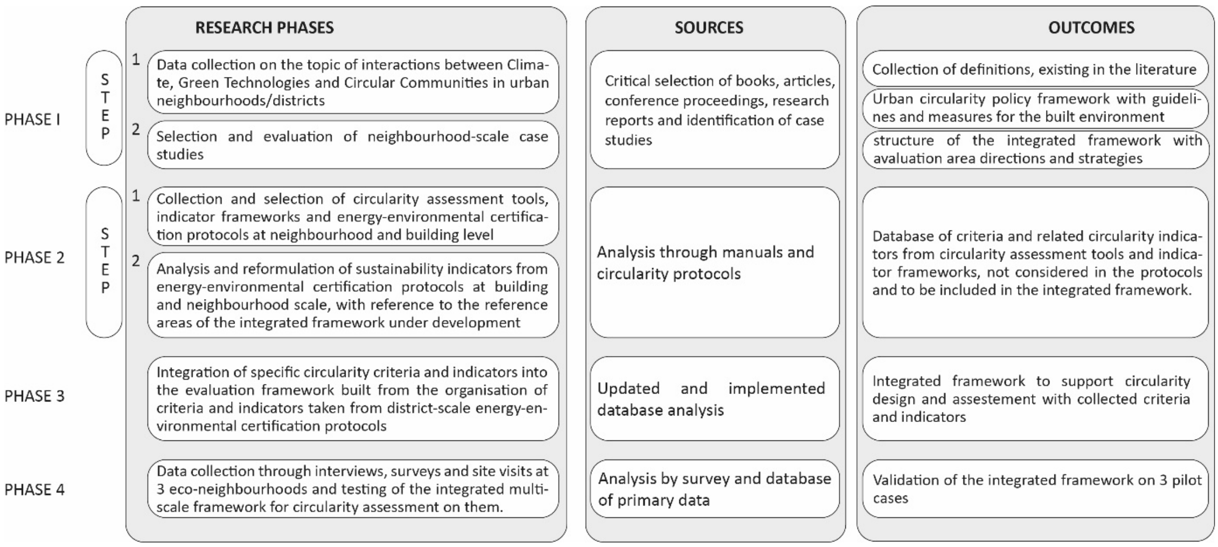

Figure 1. Research phases, steps, methodology, sources and outcomes.

Phase 1 - Step 1. Literature review. This step consisted of collecting information and basic data on the topic of interactions between the three reference factors of Climate, Green Technologies and Circular Communities in urban neighbourhoods/districts. The activity was developed on two parallel levels. Firstly, by means of a literature review focusing on the subject matter of the research, starting from the collection of definitions, existing in literature (selection of volumes, articles, conference proceedings, research reports) of circular neighbourhood and circular city. In parallel, thematically related regulatory aspects were studied through the construction of an urban circularity policy framework, mapping existing policies and guidelines at the city and neighbourhood level. This mapping included 34 policies, related to as many European cities, for which the following parameters were analysed: geographic location; size of the city (number of inhabitants); year of publication of the policy (from 2016 to 2023); presence of a super-ordinate reference policy at regional, national or European level; presence of specific indications/guidelines for the built environment, found in 13 policies, i.e. approximately 40%; reference to the neighbourhood/district scale, with the identification of possible projects/interventions on urban districts in the city in question, referable to the policy under examination. The 13 policies were examined in detail with individual fact sheets, through which 5 policies with specific implications on the neighbourhood scale were identified: the Roadmap for Circular and Sharing Economy of Helsinki (FL) related to the renovation plan of Hämeentie (2018); the City of Malmö's (SW) Environmental Programme, concerning Augustenborg Eco-City and Bo01-Western Harbour (2019); the Sustainable Espoo (FL), with reference to the Kera District (2021); Circular Economy Roadmap for the City of Oulu (FL), related to the Tahkokangas district (2021); the Prato Circular City/Next Generation Prato policies addressing the District Macrolotto zero in Prato (IT).

Phase 1 - Step 2. Neighbourhood scale case studies selection and assessment. The specific purpose of this step, based on the findings of the literature review dedicated to the concept of the circular city and neighbourhood, was the collection, selection and analysis of significant case studies, on an international, national and local scale, in order to extrapolate the strategies and recurring characteristics of circular and sustainable neighboorhoods. Therefore, 15 case studies at the neighbourhood scale were selected and analysed (Table 1), identified from among the 'eco-quartiers' and neighbourhoods explicitly classified as circular (implemented between 2000 and today), in which circularity strategies were implemented in at least three resource flows. The selected cases were analysed in as many analytical sheets, systematising the information gathered to construct a methodological framework. Thus, the critical analysis was developed, preparatory to the operational phase of the research, structuring an integrated multiscale framework for circular design and assessment articulated in reference areas, addresses and strategies, to which specific indicators will subsequently be attributed.

Table 1. Neighbourhood-scale case studies examined in the research.

	District/neighbourhood	City, Country	Year	Circular resource flows
1	Western Harbor	Malmö, Sweden	2000	Waste, water, energy
2	Hammarby Sjöstad	Stockholm, Sweden	2004	Materials, waste, water, energy
3	Greenwich Millennium Village	London, UK	2006	Materials, waste, water, energy
4	Hyllie District	Malmö, Sweden	2010	Materials, waste, water, energy
5	Eco-Viikki	Helsinki, Finland	2015	Materials, waste, water, energy
6	Werkstadt Grasbrook	Hamburg, Germany	2019	Materials, waste, water, energy
7	New South District	Antwerp, Belgium	2020	Materials, waste, water, energy
8	TaiSugar Circular Village	Tainan, Taiwan	2021	Materials, waste, water, energy
9	Bo01	Malmö, Sweden	2001 - 2020	Waste, water, energy
10	Augustenborg	Malmö, Sweden	2001 - 2002	Waste, water, energy
11	Olympic Park	London, UK	2007 - 2012	Materials, water, energy
12	Aspern Seestadt	Malmö, Sweden	2007 – ongoing	Materials, waste, water, energy
13	La Fleuriaye	Nantes, France	2013 - 2022	Waste, water, energy
14	Buiksloterham	Amsterdam, NL	2021 – ongoing	Materials, waste, water, energy
15	Kera District	Espoo, Finland	2023 - ongoing	Materials, waste, water, energy

From the case studies, in particular, input was drawn - with a bottom-up approach - for the construction of a reference framework on which to structure a design and evaluation support tool, starting from the identification of circularity reference areas and relative addresses and strategies within the case studies. In particular, the identified reference areas were used to systematically organize the addresses and strategies, with a view to the subsequent definition of the design and evaluation framework supporting experimentation. The research activity then saw the integration of further addresses, strategies and specific technical actions/solutions, either drawn from literature - with a top-down approach - or defined from scratch.

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Phase 2 – Step 1. Collection and selection of relevant circularity assessment tools and indicators frameworks and of neighbourhood and building scale energy-environmental certification protocols.

Phase 2 - Step 2. Analysis of and re-framing of sustainability indicators from building and neighbourhood scale energy-environmental certification protocols, pertaining to the areas of reference of the integrated framework under development. In parallel, criteria and related circularity indicators were extracted from circularity assessment tools/frameworks, which were not considered in the protocols and have to be included in the integrated framework under development.

Phase 3 *(ongoing)*. Integration of specific circularity criteria and indicators into the framework's evaluation structure, built from the systematisation of addresses and strategies drawn from the case studies, matched with criteria and indicators drawn from district-scale energy-environmental certification protocols.

Phase 4 *(step foreseen for the next year).* Collection of primary data through interviews, surveys and site visits at 3 eco-neighbourhoods, pilot cases chosen from the 15 case studies, and validation of the integrated multiscale framework for circularity through its implementation on them.

In the research, the role of the case studies is therefore twofold: as a field of investigation for the construction of the framework (input) and as a testbed for it, with 3 neighbourhoods chosen as pilot cases for the testing of the framework in order to verify their level of circularity (output).

4. Results and discussion

This paragraph summarizes 3 sets of results achieved so far by the Research Group.

4.1. *Framework of directions and strategies for circularity relative to 7 selected reference areas*

Within Phase 1 - Step 2, based on the results of the literature review and on the assessment of the 15 case studies (Fig. 2), 7 reference areas were identified as a structure for the integrated framework: Materials (M), Energy and Comfort (EC) (including carbon emissions related aspects), Waste (W), Water (WT), Mobility (MB), Biosphere (B) and Social Welfare (SW).

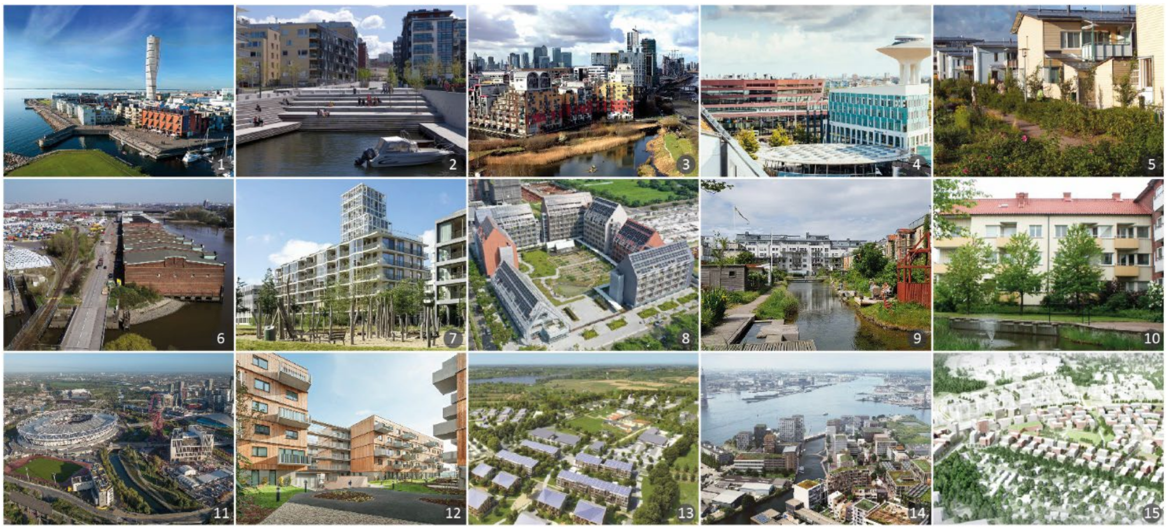

Figure 2. Overview of the 15 case studies selected in the research. Numbers refer to Table 1.

In fact, the cases studies were analysed to map all the design directions and relative strategies pertaining to each of the 7 reference areas. For each of the latter, two main directions and a varying number of strategies were identified and extracted from the 15 case studies. The mapping included relating each single strategy to the 3 interconnected global goals of Circularity, Mitigation and Adaptation to climate change, so as to highlight how strategies and actions aiming at a closed-loop use of resources can actively contribute not just to mitigation goals – according to the nexus now widely recognised by the scientific community between circularity and decarbonisation – but also to urban areas adaptation, in particular for strategies pertaining to the Biosphere area.

From the results of this mapping and analysis (Fig. 3), the strategies related to MB, B and EC appear as the ones with more occurrences in the case studies, followed by SW and M, with waste related strategies being present but not so differentiated in the case studies (limited number of strategies occurring in all cases). This means that even in the selected eco-quartiers/circular neighbourhoods, there is still space for innovation in terms of municipal solid waste management, especially for organic waste management. Construction and demolition (C&D) waste related strategies, instead, have been placed in the M reference area.

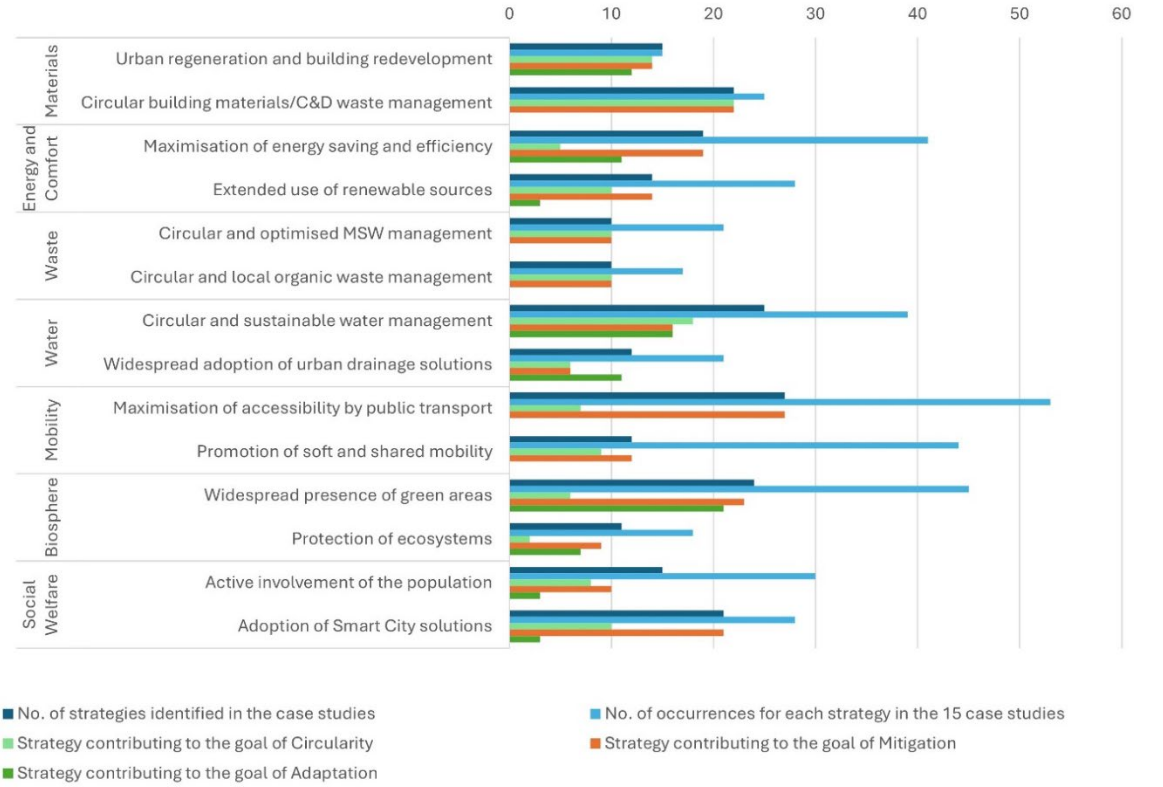

Figure 3. Chart showing the no. of strategies identified for each of the 7 evaluation areas of the integrated framework, each one split into 2 main directions; the no. of occurrences for all the strategies pertaining to a single direction are also shown; moreover, the 3 bottom bars show the number of strategies contributing to the Circularity, Mitigation and Adaptation goals.

4.2. *Selection of relevant circularity assessment tools and indicators frameworks*

Research Phase 2, Step 1, focused on the collection of existing circularity assessment tools and indicators frameworks, pertaining to different levels: from product, to organization, building, city and even broader scales, since few circularity assessment methods relate to meso and macro scale (regional and national). The selection shows 14 schemes (Table 2), whose typology ranges from proper assessment tools to framework of indicators or – in single cases - inventory of indicators or policies.

Among the selected tools, the Circular Buildings Toolkit (Fig. 4) is worth being mentioned. Translating circular economy principles into a prioritized set of strategies and actions for construction/renovation projects, this framework is based on relevant international best practices and aligned with international policies such as EU Taxonomy and EU LEVEL(s) [14]. The indicators refer mainly to materials efficient and circular use, to life-cycle design, but also to design for nature.

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Table 2. Comparative chart of the 14 selected circularity assessment tools / indicators frameworks, highlighting the reference to the 7 areas of evaluation of the integrated framework for neighborhoods.

Name	Institution	Year	Typology	Level	Areas of evaluation
CIRCiT Norden	DTU, RISE, NTNU, Innovation Center Iceland, Technology Industries of FL	2017	Tool	Product	M, EC, SW
Circulytics	EMF, Granta Design	2022	Framework of indicators	Organisation	M, EC, WT, SW
Circular Transition Indicators	World Business Council for Sustainable Development	2022	Framework of indicators	Organisation	M, EC, W, SW
UNI/TS 11820	UNI CT057	2022	Framework of indicators	Organisation	M, EC, W, WT, B, SW
Circular Buildings Toolkit	ARUP, EMF	2022	Framework of indicators	Building	M, EC, W, SW
Circularity Builder	ARUP	2021	Tool	Building element	M, EC, W
Indicators for possible inclusion in BREEAM New construction and In-use	Dutch Green Building Council	2021	Framework of indicators	Building	M, EC, WT, MB, B, SW
Circularity Passport	EPEA	2019	Certification	Building	M, W
Circular economy indicators for buildings and housing	Circular Economy Policy Research Center	2021	Framework of indicators	Building	M, EC, W, WT, B, SW
Italian GPP Minimum Environmental Criteria for Buildings	Italian Ministry of Environment	2016	Policy	Building, group of buildings	M, EC, W, WT, B
Urban Circularity Assessment	City Loops EU Project	2023	Framework of indicators	City	M, EC, W, MB, B, SW
Amsterdam Circular Monitor	Geemente Amsterdam	2022	Framework of indicators	City	M, EC, W, SW
Inventory of Circular Economy indicators	OECD	2021	Inventory of indicators	Macro, meso, micro (nation, region, city)	M, EC, W, WT, S
Indicators for measuring Circular Economy	Italian Ministries of Environment and Economic Development	2018	Framework of indicators	Macro, meso, micro (nation, region, organisation)	M, EC, W, WT, MB, SW

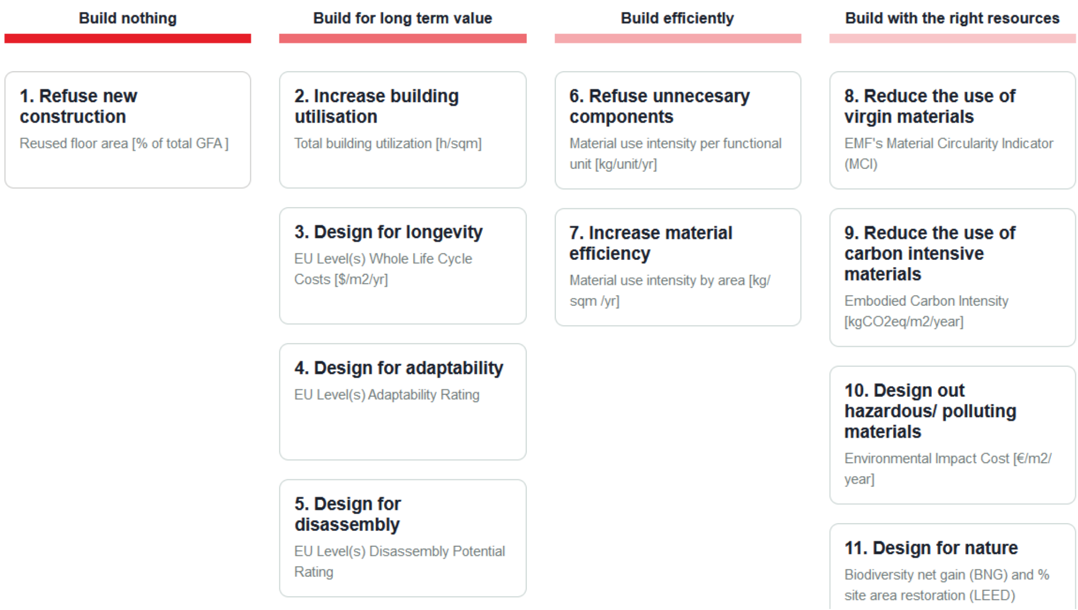

Figure 4. Circular Buildings Toolkit, ARUP. Source: https://ce-toolkit.dhub.arup.com/framework

4.3. *Analysis and re-framing of sustainability indicators from building and neighborhood scale sustainability certification protocols*

Research Phase 2 focused on the analysis of 16 existing sustainability (energy-environmental) certification protocols: 9 at building level, including the EU LCA-based reference framework LEVEL(S); 7 at neighborhood/district level (Table 3). This activity led to the selection of 5 relevant schemes at the neighborhood/district level, to be assessed in detail based on their specific areas of evaluation, criteria and indicators, chosen on the basis of the diversity of protocol structure and the level of integrability of key aspects of circularity, to have a various sample with some schemes already oriented to circular economy, and others less so.

The selected 5 schemes (DGNB System Districts, LEED Neighborhoods, ITACA Quartieri, GBC Quartieri, HQE Sustainable Urban Planning) were analyzed in relation to the weight of their criteria in the different evaluation areas (Fig. 5, left column); then the criteria and relative indicators were re-group and re-framed with reference to the 7 areas structuring the integrated framework. This re-framing (Fig. 5, right column) shows how some protocols only have few criteria and indicators in some of circularity key reference areas, in particular Materials and Waste. The Energy and Comfort related criteria are the more numerous in 3 out 5 protocols (DGNB, GBC, LEED), while Social Welfare related ones dominate in the other 2 (HQE and ITACA).

Table 3. Neighbourhood scale protocols considered in the study. Highlighted in grey, protocols chosen for further study concerning circularity criteria.

Sustainability Certification Protocols	Country	Year	N. of circularity indicators	Reference area
BREEAM Communities	UK	2012	1	W
CASBEE for Urban Development	Japan	2024	2	M, WT
DGNB System Districts	Germany	2020	11	M, W, WT, SW
GBC Quartieri	Italy	2015	2	M, WT
HQE Sustainable Urban Planning	France	2021	3	W, WT
ITACA Quartieri	Italy	2016	2	M, WT
LEED Neighborhoods	USA	2018	4	M, W, WT

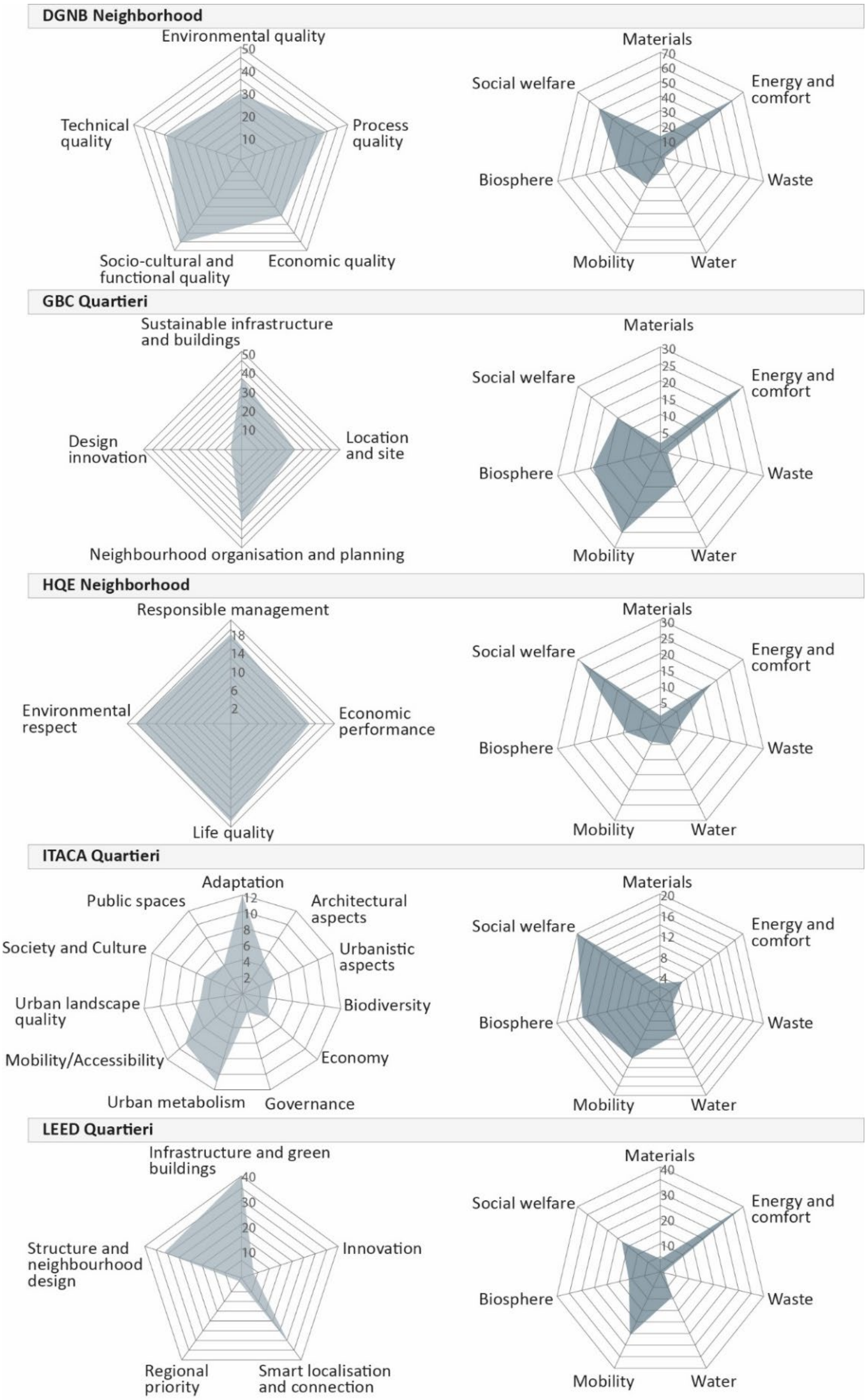

Figure 5. Comparative chart showing the selected 5 neighborhood scale protocols with the weight in terms of number of criteria for each evaluation area in relation to the scheme specific areas (left column) and with reference to the 7 areas established for the integrated framework (right column).

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Indicators pertaining to the area of Waste, specifically oriented to circularity, are present in all examined protocols (12 in all, as shown in Table 4), with the LEED, DGNB and HQE protocols having the largest number of criteria and relative indicators pertaining to Waste. In particular, LEED has the most innovative criteria, including one dedicated specifically to organic waste. The number of criteria in this area are, anyway, limited with respect to other evaluation areas. Indicators pertaining to the area Materials, with a specific focus on circularity, are few and missing in 2 out or 5 protocols (Table 5). These evaluation areas should therefore be much more developed in the integrated framework.

Table 4. Waste circularity related criteria and indicators in the 5 assessed protocols.

	Protocol	Area of evaluation	Criterion	Indicator
1	GBC Quartieri	Infrastructure and Sustainable Buildings	Infrastructure for solid waste management	Reduce the volume of landfilled waste. Promote the correct treatment of hazardous waste
2	HQE Sustainable Urban Planning	Environmental respect	Resources and waste	Prevention of site waste
3	HQE Sustainable Urban Planning	Environmental respect	Resources and waste	Household waste management and activities
4	HQE Sustainable Urban Planning	Environmental respect	Resources and waste	Environmental choice of products, equipment and services
5	DGNB System District	Technical quality	Technical Infrastructure	Waste management
6	DGNB System District	Technical quality	Technical Infrastructure	Waste prevention
7	DGNB System District	Process quality	Quality during use	Waste
8	ITACA Quartieri	Urban metabolism	Accessibility to separate waste collection	Percentage of population within 50 m of recycling bins
9	LEED Neighborhoods	Green infrastructure and buildings	Solid waste management	At least one separate collection point for recyclable materials
10	LEED Neighborhoods	Green infrastructure and buildings	Solid waste management	At least one hazardous waste collection point and a disposal plan
11	LEED Neighborhoods	Green infrastructure and buildings	Solid waste management	At least one organic waste composting station and use plan
12	LEED Neighborhoods	Green infrastructure and buildings	Solid waste management	Recycling bins every 245 m or in each mixed/non-residential block

Table 5. Materials circularity related criteria and indicators in the 5 assessed protocols.

	Protocol	Area of evaluation	Criterion	Indicator
1	GBC Quartieri	Sustainable Infrastructure and Buildings	Building reuse	Building reuse
2	GBC Quartieri	Sustainable Infrastructure and Buildings	Reuse and recycling in infrastructure	At least 30% in mass of materials used made of post + pre consumer recycled content + material recovered on site
3	DGNB System District	Environmental quality	Effects on the global and local environment	Consideration of LCA aspects in planning

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4	DGNB System District	Environmental quality	Effects on the global and local environment	Optimisation of LCA considerations
5	DGNB System District	Economic quality	Life-cycle costs	Circular economy - deconstruction-friendly construction
6	DGNB System District	Technical quality	Technical Infrastructure	Using recyclable materials
7	DGNB System District	Technical quality	Technical Infrastructure	Reuse
8	DGNB System District	Technical quality	Technical Infrastructure	Recycling of recyclable materials
9	LEED Neighborhoods	Green infrastructure and buildings	Building reuse	5 or fewer buildings subject to major renovation, reuse 50% of one of these buildings, based on surface area
10	LEED Neighborhoods	Green infrastructure and buildings	Solid waste management	Recycle, reuse or recover at least 50% of non-hazardous C&D waste
11	LEED Neighborhoods	Green infrastructure and buildings	Recycled and reused infrastructure	At least 50% materials for new infrastructure made of post-consumer recycled content + on-site reused materials + half pre-consumer content

5. Conclusion and next steps

The research results, for the completed steps, have highlighted how existing circularity metrics, at different levels including the building one, provide useful criteria and indicators that can and should be transferred to the neighboorhood scale. Some of these indicators might be kept unvaried in the scale-up, while some others need an adaptation. This seems to be one the most crucial challenges for the ongoing activities of the research (Phase 3). Then, the subsequent step (Phase 4), foreseen for the next year, will see the in-depth study of three pilot cases of circular neighbourhoods in Europe, providing a useful testbed for the integrated assessment framework. Among, these are Bo01 and Augustenborg in Malmö, Sweden, two eco-quartiers dating back to the beginning of 2000, which offer monitoring data that can be used to assess the level of circularity with the developed methodology, and one circular district under development, Nordhavn in Copenhagen, representing the contemporary approach. After data collection, the validation of the developed methodology will be performed in the next year.

The research revealed a high potential in making circularity design and evaluation guidance tools mandatory. Something similar, in Italy, has been experimented, a unique case in Europe, at the building level through the mandatory Green Public Procurement Minimum Environmental Criteria for buildings (since 2016, currently updated by the Ministerial Decree n. 256, 23/06/2022) which, however slow the process may be, by imposing criteria like a minimum recycled content in specific building materials, are proving capable of activating innovation processes at the industrial and product certification level, for example in terms of transparency in communicating recycled content. It was also noted in the policy analysis that there are still very few initiatives with specific impacts, measures and metrics for the neighbourhood scale, which the research aims to stimulate. In this sense, the framework is conceived precisely as a tool for public administrations and designers, seen as targets for the research.

Based on the results illustrated in Par. 4.1, one specific field of interest for the research's future perspectives – that will be one of the focuses in the next steps - pertains to mobility related circularity indicators, since such reference areas is particularly relevant to circular neighbourhoods' development.

Limitations of the study can be identified in the difficulty of managing a very large number of potentially relevant circulators indicators, with reference to the scale of the neighborhood/district, that need to be assessed to ensure a meaningful adaptation from to original scale to the targeted one.

Furthermore, one obstacle can be seen in the complexity of the transfer and implementation of Life Cycle Assessment based indicators to the scale of the neighborhood, considering that even the building scale is still seen as challenging for designers today.

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