Urban Metabolism: Definition of an Integrated Framework to Assess and Plan Cities and Territories

Vanessa Assumma[1](✉) and Francesco Pittau[2]

[1] Interuniversity Department of Regional and Urban Studies and Planning, Politecnico di Torino, Viale Mattioli 39, 10125 Turin, Italy
vanessa.assumma@polito.it

[2] Department of Architecture, Built Environment and Construction Engineering (ABC), Politecnico di Milano, Via Ponzio 31, 20133 Milan, Italy
francesco.pittau@polimi.it

Abstract. The present paper deals with the role of sustainability assessment tools in tackling the increasing complexity and uncertainty of urban and territorial systems. Urban metabolism is ever more under the attention of Decision Makers and policy makers to deal with the current planning challenges, where climate change, environmental quality, social equity and justice, and governance represent very topical issues.

The paper focuses particularly on Life Cycle Assessment (LCA) and the family of Multicriteria Decision Analysis (MCDA) retained as suitable tools to design an integrated framework to envision sustainable, resilient and circular solutions with a multi-scaling approach, ranging from the product to the city and territory levels. This contribution represents a position paper of the authors which defines an integrated framework to explore urban metabolism and support real assessment and planning procedures for cities and territories transformations. This research work is addressed to planners, Decision Makers, technicians and freelances actively involved in planning and assessment procedures for ensuring a better quality of life.

Keywords: Life Cycle Assessment · Multicriteria Decision Analysis · Urban metabolism

1 Introduction

In the ongoing context of climate change, several and different variables, from environmental to economic, from social to political ones, are causing high uncertainty and ambiguity in the planning of sustainable cities and territories. The increasing population and of the quality of life have caused over time a systemic crisis in terms of accessibility to resources and thus causing a potential overcoming of Earth security margins (Rockström et al. 2009). Today, it is widely shared a global awareness about the need of (re)designing

O. Gervasi et al. (Eds.): ICCSA 2022 Workshops, LNCS 13380, pp. 169–182, 2022.
https://doi.org/10.1007/978-3-031-10542-5_12

the planet boundaries and (re)thinking, on the one hand, the use of primary resources, and on the other hand, a new life for secondary materials. The decision-making problems, with particular focus on the urban and building scales, are dealing with important planning challenges. Actors and stakeholders are increasingly given attention to the quality of public and /or private interventions and also to the environmental impact which they could generate to the overall quality of life.

In the international context, many solicitations are counted over the latest years for a route change, spanning from the achievement of the 17 Sustainable Development Goals (SDGs), particularly the SD Goal 11 "Make cities and human settlements inclusive, safe, resilient and sustainable", the SD Goal 12 "Responsible consumption and production", and the SD Goal 13 "Climate Action", to the global reports on climate change (United Nations 2015; IPCC 2019, 2021), until to the 26th United Nation Climate Change Conference held in Glasgow (COP26) where some key issues were fixed to contrast at global warming, such as the creation of international sustainable standards on climate, environmental, social and governance issues (ESG) for businesses and related strategies, as well as the transition towards the net-zero economy (International Financial Reporting Standards - IFRS, 2021). On the one side, the put into practice of these key issues through a cascade adoption until to the local scale is a so urgent need. On the other side, an effort to detect these issues by the class of Decision Makers (DMs) and policy makers into their agendas as spatial interventions is more than ever required today.

Traditional and novel paradigms like sustainability, resiliency, or circularity emphasize the idea that urban systems and territories can be investigated through metabolic filters, since they can be conceived as living and evolving organisms that interact, evolves, adapts and respond across different spatial and temporal scales (Gunderson and Holling 2002). In this way it can be easier to understand their complexity and explore the interdependent relationships between the natural and human spheres. The concept of Urban Metabolism (UM) is not new in literature. It was firstly used to assess both industrialized systems and biological metabolic systems in terms of resource and waste flows from anthropogenic activities (Wolman 1965), influenced by ecological studies (Odum 1983) and was adapted over time and defined today as "the sum total of the technical and socio-economic process that occur in cities, resulting in growth, production of energy and elimination of waste" (Kennedy et al. 2007). UM is a very topical issue today and is interested by high margins of investigation and development. In this context, tools for sustainability assessment can effectively support policy design in the context of urban planning and management, thus promoting the "cradle to cradle" transition.

In light of the above-described context, this contribution represents a position paper of the authors which defines an integrated framework to support real assessment and planning procedures in the exploration of urban metabolism with respect to urban and territorial transformations with the aim to contribute to an extent of the state-of-the-art thinking. Moreover, the framework is finalized to help DMs, policy makers, planners and freelances to design greener and net-zero strategies.

The paper is organized into four sections: Sect. 2 is devoted to the description of the methodology, by focusing on some complex assessment tools for strategic environmental impact assessment; Sect. 3 defines a theoretical framework proposal that combines two specific assessment tools; Sect. 4 discusses the potentialities, the limits and opportunities of development and then concludes the paper with some future perspectives to prosecute this research work.

2 Complex Systems Analysis and Tools

The design of future cities and territories require ever more multidisciplinary and transdisciplinary approaches to tackle their complexity and uncertainty. In this way, planners, and DMs can practice more easily traditional and novel paradigms within government agendas. It is certain that the environment health must be focal more than ever in policy decisions. Several methods and tools are deemed useful in this context to measure impact on the current state of the environment and its components, identifying the most valuable and most critical areas, and to predict possible futures by building alternative transformation scenarios.

Particularly, the paper focuses on two assessment tools which are considered the most suitable to be performed within strategic environmental impact assessment procedures: the Multicriteria Decision Analysis (MCDA) and the Life Cycle Assessment (LCA).

Both the methods can be employed to solve a wide range of complex problems with interdependences, that are often addressed through EIA and SEA procedures. On the one hand, MCDA can help DMs in dealing with uncertainty, subjectivity and multi-stakeholder participation (Linkov et al. 2011; Durbach and Stewart 2012), as well as in selecting the best sustainable solution, and providing a classification of the alternatives to the problem under investigation (Doumpos and Zopounidis 2004).

On the other hand, LCA is retained as a powerful technique for calculating both input and output flow of materials and energy over the course of their life cycle. Moreover, it is gaining importance within business models and, more generally, as decision supporting tool for the transition towards Circular Economy (CE) at various levels (Le Téno and Mareschal 1998; Ghisellini and Ulgiati 2020; Vázquez-Rowe et al. 2021; Hannouf et al. 2021) and addressing the complexity of metabolic processes and systems (Peponi et al. 2022).

The next sub-paragraphs provide an analysis on the concept of urban metabolism and also on both the tools, thus highlighting the strengths and weaknesses as well as potential implementations within integrated frameworks in the context of urban and territorial transformations.

2.1 Urban Metabolism

The UM definition, as stated in part in the introduction (Kennedy et al. 2007; Lucertini and Musco 2020) is intended as technical and socio-economic processes that characterise the cities functions. It can be conceptualized according to six elements: (i) complex system, that is mainly represented by urban and territorial settlements, (ii) material and energy inflows and outflows with respect to the system under investigation; (iii) economic-social interactions which may occur within the system and which are also influenced by outside relations with other systems, (4) economic driving forces that influence the rural-urban boundaries, (iv) inequalities which could be generated by the interactions, and (iv) adaptation and response to promote novel solutions able to rethink existing plans/programs/projects and envision urban planning and management strategies (Lucertini and Musco 2020).

Therefore, UM refers to a given system characterised by human presence, which constantly exchange flows of resources, energy, and information, thus contributing to its growth and development. However, a system must grow for guaranteeing a good functioning and equilibrium. This means that the resources consumption characterized the last century has significantly increased waste production and aggravated unbalances in the environment and its components (e.g. air, water, or soil, among others). This does not necessarily imply the annihilation of living creatures. It means that the metabolic processes of cities and territories have been altered and a recovery is required to ensure the survival and well-being of all living species.

Staring from the assessment of the complexity of metabolic processes associated to urban and territorial contexts, the shift to more sustainable and resilient planning and design models can be effectively supported. The expected result includes strategic guidelines and legislative suggestions, environmental mitigation and compensating initiatives, and best practices for a good Anthropocene (Bennett et al. 2016; Lucertini and Musco 2020).

Several frameworks and tools have been proposed in recent years, with the aim at encouraging beneficial interactions between disciplines and assisting Decision and Policy Makers in conceptualising and implementing as solutions of short-, medium- and long-term.

For example, in the paper (Mostafavi et al. 2014) an Integrated Urban Metabolism Analysis Tool (IUMAT) explores the dynamics occurring in urban and territorial systems from a spatial-temporal perspective and provides overall sustainability based on urban settlements typologies. The coupling of Circular Economy (CE) and Urban Metabolism (UM) in integrated and multidisciplinary frameworks is highly needed for operating in changing urban contexts (see Fig. 1) (Lucertini and Musco 2020).

An interesting conceptual framework is the Economy-Wide Material Flow Analysis (EW-MFA) that employs the Drivers-Pressures-Responses logic (as a simplified version of DPSIR tool) and the system dynamics approach between natural and human sides (Cárdenas-Mamani and Perrotti 2022), or even the combination of life cycle approach with dynamical modelling by considering a nested systems theory to support the improvement of building stocks (Stephan et al. 2022). GIS-based methods play a transversal role in dealing with complex spatial systems. The work (Montealegre et al. 2022) defines a bottom-up strategy to assessing food-energy-water systems (FEW) at district level, taking into account residential and non-residential morphology. The integration of many approaches, such as Life Cycle Thinking (LCT) and Machine Learning for Smart and regenerative urban places (SRUP).

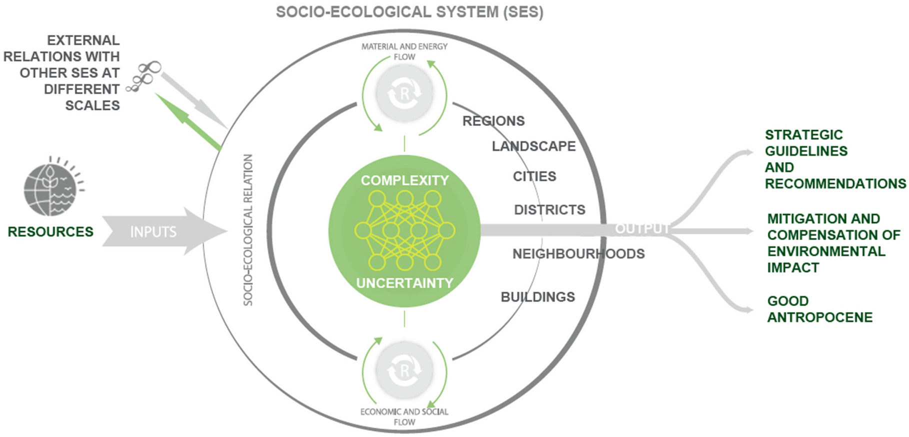

Fig. 1. Representation of urban metabolism with a multi-scale approach. Adapted from (Lucertini and Musco 2020)

2.2 Life Cycle Assessment and Regionalization of Impacts

In developed economies, the production, use, and disposal of goods along a value chain generate impacts and pressure on ecosystems and human wellbeing both at global and regional scale. LCA is a standard methodology for environmental impact accounting able to track the generation of pollutions and resource consumption and assess them from a systems perspective. The main objective of the analysis is identifying strategies for process improvement without shifting burdens along the life cycle. Recent emerging developments in LCA moved from a conventional attributional approach, mostly addressed to product development or company assessment, to a more cohesive approach to support policymakers in environmentally informed decisions or consumers in their responsive choices. Regionalization in LCA is a promising process which makes LCA more consistent for city planning and urban development (Bjorn et al. 2020). On one hand, "top-down" studies of national or transnational economies help to pinpoint crucial areas of consumption and drivers of environmental impacts in sustainable consumption and production, which could not be evaluated with a conventional attributional approach (see Fig. 2). For example, housing, mobility, and food – namely heating and cooling of buildings, car and air travel, and meat and dairy consumption - are responsible for the largest share of most environmental impacts in Europe (Tukker et al. 2008). On the other hand, more detailed "bottom-up" studies of single products or product groups can also help to determine submersed key drivers that may not be linked to the most commonly associated high impacts lifecycle stages (Garnett 2008).

Coupling LCA with material flow analysis (MFA) models is a consolidated approach in literature which allows building future scenarios and predict their environmental consequences and pressure on natural resources at a regional scale (Göswein et al. 2021). However, often the completeness in scope of regional LCA and combined LCA-MFA fails in simplifications and increasing uncertainties (Pittau et al. 2019). Recent studies have highlighted the contribution that system assumptions and value choices can

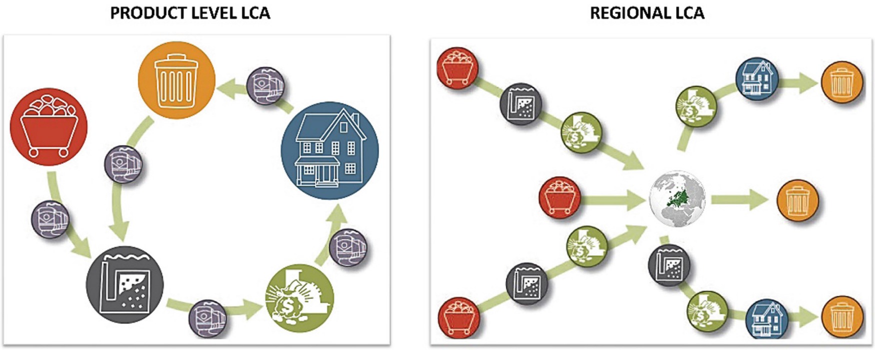

Fig. 2. The expanding nature of LCA from conventional product-based scope to regional-level assessments. Adapted from (Hellweg and Canals 2014)

make to overall uncertainty (De Schryver et al. 2013). Several quantitative uncertainty assessments and robustness analysis are available (Lloyd and Ries 2007) but are rarely implemented in practice (Galimshina et al. 2021). In some cases, rough estimates of input values can be enough to identify supply chain hotspots (Canals et al. 2011), but for other applications, such as product comparisons (Gregory et al. 2013), the demands for more accurate values are higher. LCA practitioners should always attempt to manage the decision-maker's expectations and clarify that LCA is not always a tool to provide a single answer, but rather one that permits comprehensive understanding of a problem and its possible solutions. Other studies have aimed at reducing uncertainties in LCA by mapping and assessing value chains and impacts through a regionalized approach (Yang et al. 2017; Yazdanbakhsh and Lagouin 2019). Regionalized assessments increase the accuracy by considering site-specific production conditions as well as differences in transport and the sensitivity of ecosystems. Impact-assessment methods often need a different geographical resolution, embracing the nature of the impact rather than political boundaries. However, acquiring spatial data constitutes a challenge. Although pilot research software systems are capable of doing this (Steubing et al. 2020), it has yet to be implemented in commercial LCA tools.

2.3 MCDA Within Multidisciplinary and Transdisciplinary Frameworks

Multicriteria Decision Analysis (here and after MCDA) is an umbrella term for techniques that can assist DMs and Policy Makers in solving complex situations characterised by uncertainty. This is the case of spatial problems affecting the environmental system and its key components at all scales, which often imply transformations and consequently impact, direct or indirect, cumulative, and/or synergic, resulting in a loss of natural and socio-economic capital. In this sense, the MCDA expanded its role within planning and environmental assessment procedures (i.e. Environmental Impact Assessment, Strategic Environmental Assessment, or Valuation for Ecological Incidence). The main motivation is that they can simultaneously consider numerous aspects of a decision problem. Second, they can take into consideration the preferences of real actors and stakeholders in a collaborative and transparent manner, which is another fundamental necessity to which public bodies are giving increasing attention (Fig. 3). The employment of MCDA can go beyond the monetary evaluation, such as the Cost-Benefit Analysis (CBA) or the Discount Cash-Flow Analysis (DCFA) and looking at hybrid evaluations to assess urban quality (Oppio and Dell'Ovo 2020), resilience in territorial scenarios (Assumma et al. 2020), the regeneration of critical areas (Bottero et al. 2021a), or even the ecological enhancement for animal species reintroduction (Treves et al. 2020), among others.

In an uncertain context where the policy decisions must consider the environmental impact, it is possible to state that the mentioned tools can be used whether supported by a multidimensional approach, as well as tools capable of addressing final users in the design of environmental mitigation and compensation actions to ensure a better quality of life for both present and next generations. This is a goal that MCDA can achieve.

This paragraph develops an analysis focused directly on the applications relevant in the field and emphasizing their ability or potentialities to be integrated or matched with other environmental assessment tools, such as the Life Cycle Assessment.

Table 1 collects exemplary MCDA applications. The selection was made by searching the Scopus database in March 2022. Specific contributions were selected according to the main scope of this paper and by combining specific keywords such as "multidisciplinary", "transdisciplinary", "decision-making process", "urban planning" and "management". In recent years, there has been an increasing trend in number of contributions that integrate MCDA with other methodologies, ranging from land use planning to landscape ecology, from site localisation to urban regeneration processes, from sustainability to resiliency assessment until circularity. The scope of this selection is to find those applications which highlight MCDA as a powerful tool being applied within multidisciplinary and transdisciplinary frameworks to solve complex spatial problems.

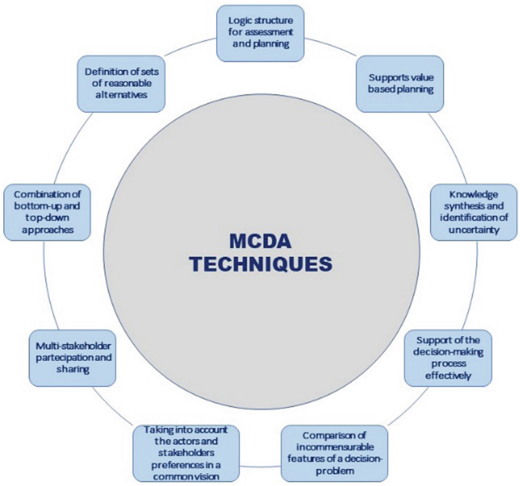

Fig. 3. MCDA techniques benefits from supporting decision-making process. Elaboration from (Marttunen 2010)

Table 1. Collection of exemplary MCDA applications within interdisciplinary and multidisciplinary frameworks

Author and Year	Structure	Field of application
(Miller et al. 2013)	Multicriteria Analysis and Geodesign to integrating livability and sustainability indicators into the overall planning process	Transportation policy and planning
(Evers et al. 2018)	Collaborative Modelling (CM) and MCDA within a Flood Risk Management framework (FRM) to favour the process-driven decision-making	Risk assessment and management
(Bottero et al. 2019)	Integration of A'WOT, DFCA and SROI to design strategies for the rural development of an island by taking into account social, economic, environmental and cultural features	Rural sustainable development
(Bottero et al. 2021.a)	Hybrid evaluation method including STEEP + SWOT Analysis, Stakeholders Analysis, Scenario Building and Multi-Attribute Value Theory to support the identification of the most suitable scenario of urban regeneration for a contaminated sited	Urban regeneration, Industrial Heritage
(Assumma et al. 2021)	Matching of SMARTER Ranking method through a AHP approach with a Lotka-Volterra cooperative model to predict scenarios of territorial resilience in a wine region	Landscape and urban planning
(Dell'Ovo et al. 2021)	GIS and MCDA for exploring the quality of open spaces in the context of COVID-19 pandemics	Urban design
(Vázquez-Rowe et al. 2021)	Coupling of MCDA, CBA and LCA to support the solution of a Building Information Modelling-based problem for a construction project	Education infrastructure

(*continued*)

Table 1. (*continued*)

Author and Year	Structure	Field of application
(Colucci et al. 2022)	Development of a European Interoperable Database for risk assessment of cultural assets. Integration of the SMARTER ranking method and factsheets to calculate a synthetic index of risk to support 3D GIS systems	Risk and Cultural Heritage management
(Voukkali and Zorpas 2022)	Assessment of urban metabolism through SWOT and AHP process	Urban metabolism
(Quagliolo et al. 2023)	Combination of InVEST modeling and A'WOT model to define the most suitable scenario to respond to flood risk in a Man and Biosphere area	Nature-Based Solutions

3 Integrated Evaluation Framework: A Methodological Proposal

Once having analysed the main characteristics of both the LCA and MCDA, it is possible to assert that they are suited for usage as independent tools as well as when integrated within multidisciplinary and transdisciplinary frameworks. In the case when they enter in synergy to solve the same decision problem, can effectively identify the most suitable solution. More in general, this synergy can handle the complexity and unpredictability of Socio-Ecological Systems (SES) (e.g., cities, rural settlements, or regions). Particularly, some specific cases are identified for implementing this synergy for urban revitalization and adaptive reuse (e.g. historic buildings, industrial sites, or villages, or rural accessibility), regeneration, growth, and cohesion (e.g. polluted sites, quarries, or landfills) as new opportunities for spatial planning (Biddau et al. 2020; Cotella and Vitale Brovarone 2021). Their integration can effectively assist DMs, as well as planners, public technicians and freelances for multiple purposes: i) knowledge and assessment studies for intervention site localisation; ii) selection of the best alternative solution; iii) designing the alternatives by considering the material and energy flow; iv) prioritizing winning policy recommendations for plans, programs, and projects, among others. It is provided below a scheme that illustrates the integration of both the tools proposed by the authors as a multi-scale hybrid dynamic model for a multi-scale impact assessment. As shown in Fig. 4, the integrated framework can effectively play the connecting role between planning and assessment procedures. From a practical point of view, the framework can be employed after the screening step (or *ex-ante* phase), once having acquired a comprehensive knowledge of territorial and decisional contexts. Therefore, it can be easily fixed the assessment goal and follow the *in-itinere* phase. The obtained information can be used to define the main criteria better representing the decisional problem and thus to be evaluated by MCDA, according to key actors and stakeholders' preferences, in order to select the best sustainable solution. It should be noted, however, that the solution of a decision problem through MCDA techniques such as Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP) can provide the winning solution, even if the final decision to implement or not that solution is devoted to the DMs, since they detain the political power. Therefore, the evaluator should design the alternative evaluations and criteria selection according to the multidimensionality of a given decision problem, as well as the actors and stakeholders' *desiderata*. The alternatives design should be accompanied by a participatory approach, both bottom-up and top-down, with the purpose of converging towards sustainable policy decisions, including the economic development, social equity and environmental compatibility, and also other relevant components (i.e. technical, administrative-political, and cultural sustainability) (Bottero and Mondini 2009). In the case when the decision problem is explored with the desktop modality, the evaluator's sensitivity, as well as his/her ability to properly identify and blend a variety of driving forces, are required for scenarios building and planning.

In both the cases, the selection of the best solution will help the final users to define strategic and time-oriented recommendations and guidelines.

The LCA contribute to increase the awareness that an individual choice could have an impact on the environment and its components. It can effectively promote the transition towards a circular planning and design, ranging from the local to the regional scales. It can assess a set of alternatives, also complementary to a MCDA evaluation. For example, the alternatives can be contradistinguished using specific materials that can impact on the environment, or that can be recycled and (re)used in their second life in the production cycle. The LCA can address both planning and evaluation processes once the suitable alternative scenario is identified and monitor its performance over time (*ex-post* phase) by considering the material flow analysis and specific indicators.

Considering the scheme of the integrated framework (Fig. 4) we can combine the tools according to a multi-scalar approach, on the one hand, to explore the life and material flow and energy, and on the other hand, to identify the main characteristics of the problem under investigation and the cost-effectiveness ratio of the set of alternative scenarios under investigation.

Particularly, the authors identify some opportunities of employment of this framework. It could be useful in the context of spatial planning and management, for example for the revision of municipal plans, or urban regeneration projects, or even high-impact spatial projects, since these can increase the awareness of final users about the environmental impact entity generated by an intervention, as well as on the sensibilization of secondary material use for closing the cycles. An equitable context of investigation is environmental planning and management, with particular regard to the design and assessment of projects inspired by Nature-Based Solution approach (NBS) (Quagliolo et al. 2023). Last, but not least, the context of sustainable tourism planning could trigger interesting insights in terms of design of circular policies and actions, since projects and interventions developed in tourism destinations impact strongly on the environment, where local communities consensus could not be always reached (Cimnaghi and Mussini 2015; Mandić and Kennell 2021).

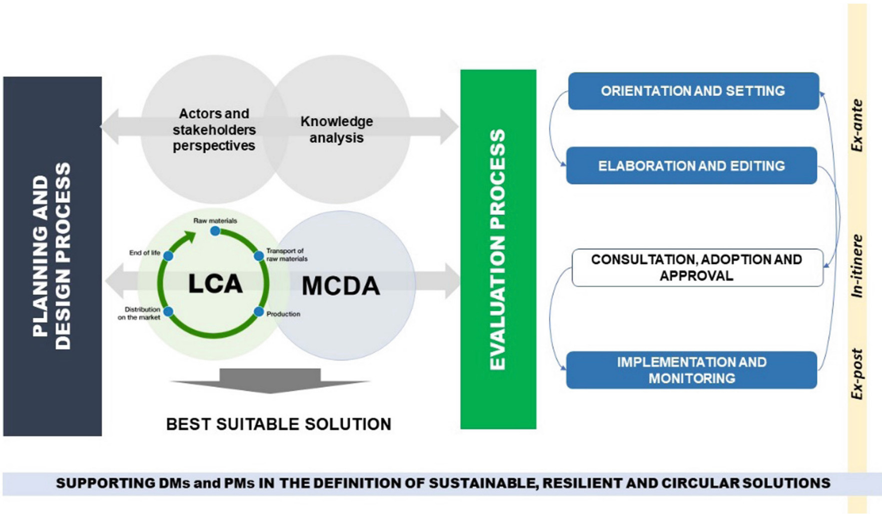

Fig. 4. Definition of the integrated framework combining LCA and MCDA (Own elaboration)

4 Conclusions

The resilient development of the society towards SDGs and the transition to net-zero carbon target by 2050 are challenging objectives which require a specific attention on current planning issues and understanding of complex mechanisms of urban metabolism. Life cycle integrated multi-criteria decision tools are fundamental instruments for sustainability assessment of urban and territorial development due to their ability to tackle the increasing complexity and uncertanties during the evaluation process.

This position paper aimed to identify an integrated framework to explore urban metabolism and define benefits and critical issues of applying integrated Life Cycle Assessment (LCA) and Multicriteria Decision Analysis (MCDA) for decision making. Outcomes from literature were reviewed and suitable tools, with spatial boundaries ranging from building to city/territory levels, discussed to evaluate sustainability, resiliency, and circularity within a multi-scaling approach. Regionalization and accuracy of data are currently the major limits of the integrated framework. Future advances in enhancing regional detail and broadening the assessment to economic and social aspects will make it more relevant for stakeholders involved in planning and assessment procedures.

References

Assumma, V., Bottero, M., Datola, G., et al.: Dynamic models for exploring the resilience in territorial scenarios. Sustain. **12**, 3 (2020). https://doi.org/10.3390/su12010003

Assumma, V., Bottero, M., De Angelis, E., et al.: A decision support system for territorial resilience assessment and planning: An application to the Douro Valley (Portugal). Sci. Total Environ. **756**, 143806 (2021). https://doi.org/10.1016/j.scitotenv.2020.143806

Bennett, E.M., Solan, M., Biggs, R., et al.: Bright spots: Seeds of a good Anthropocene. Front. Ecol. Environ. **14**, 441–448 (2016). https://doi.org/10.1002/fee.1309

Biddau, G.M., Marotta, A., Sanna, G.: Abandoned landscape project design. City, Territ. Archit. **7**, 1–17 (2020). https://doi.org/10.1186/S40410-020-00118-7/FIGURES/13

Bjorn, A., Chandrakumar, C., Boulay, A.M., et al.: Review of life-cycle based methods for absolute environmental sustainability assessment and their applications. Environ. Res. Lett. **15**, 083001 (2020). https://doi.org/10.1088/1748-9326/AB89D7

Bottero, M., Assumma, V., Caprioli, C., Dell'Ovo, M.: Decision making in urban development: The application of a hybrid evaluation method for a critical area in the city of Turin (Italy). Sustain Cities Soc **72**, 103028 (2021). https://doi.org/10.1016/j.scs.2021.103028

Bottero, M., Comino, E., Dell'Anna, F., et al.: Strategic assessment and economic evaluation: The case study of Yanzhou Island (China). Sustain. **11**, 1076 (2019). https://doi.org/10.3390/SU11041076

Bottero, M., Mondini, G.: Valutazione e sostenibilità. Piani, programmi, progetti. CELID, Torino (2009)

Canals, L.M.I., Azapagic, A., Doka, G., et al.: Approaches for addressing life cycle assessment data gaps for bio-based products. J. Ind. Ecol. **15**, 707–725 (2011). https://doi.org/10.1111/J.1530-9290.2011.00369.X

Cárdenas-Mamani, Ú., Perrotti, D.: Understanding the contribution of ecosystem services to urban metabolism assessments: An integrated framework. Ecol. Indic. **136**, 108593 (2022). https://doi.org/10.1016/J.ECOLIND.2022.108593

Cimnaghi, E., Mussini, P.: An application of tourism carrying capacity assessment at two Italian cultural heritage sites. J. Herit. Tour. **10**, 302–313 (2015). https://doi.org/10.1080/1743873X.2014.988158

Colucci, E., Matrone, F., Noardo, F., et al.: Documenting cultural heritage in an INSPIRE-based 3D GIS for risk and vulnerability analysis. J. Cult. Herit. Manag. Sustain. Dev., 1–302022). https://doi.org/10.1108/JCHMSD-04-2021-0068/FULL/HTML

Cotella, G., Vitale Brovarone, E.: Rethinking urbanisation after COVID-19: What role for the EU cohesion policy? Town Plan Rev. **92**, 411–418 (2021). https://doi.org/10.3828/TPR.2020.54

De Schryver, A.M., Humbert, S., Huijbregts, M.A.J.: The influence of value choices in life cycle impact assessment of stressors causing human health damage. Int. J. Life Cycle Assess. **18**, 698–706 (2013). https://doi.org/10.1007/s11367-012-0504-x

Dell'Ovo, M., Dezio, C., Oppio, A.: Bringing values at the center of policies for inner areas regeneration in the Covid-19 age. Territ - Sez Open Access, 43–51 (2021).https://doi.org/10.3280/TR2021-097-SUPPLEMENTOOA12926

Doumpos, M., Zopounidis, C.: A multicriteria classification approach based on pairwise comparisons. Eur. J. Oper. Res. **158**, 378–389 (2004). https://doi.org/10.1016/J.EJOR.2003.06.011

Durbach, I.N., Stewart, T.J.: Modeling uncertainty in multi-criteria decision analysis. Eur. J. Oper. Res. **223**, 1–14 (2012). https://doi.org/10.1016/J.EJOR.2012.04.038

Evers, M., Almoradie, A., de Brito, M.M.: Enhancing flood resilience through collaborative modelling and multi-criteria decision analysis (MCDA). In: Fekete, A., Fiedrich, F. (eds.) Urban Disaster Resilience and Security. TUBS, pp. 221–236. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-68606-6_14

Galimshina, A., Moustapha, M., Hollberg, A., et al.: What is the optimal robust environmental and cost-effective solution for building renovation? Not the usual one. Energy Build. **251**, 111329 (2021). https://doi.org/10.1016/J.ENBUILD.2021.111329

Garnett, T.: Cooking up a storm Food, greenhouse gas emissions and our changing climate Cooking up a storm Food, greenhouse gas emissions and our changing climate Food Climate Research Network (2008)

Ghisellini, P., Ulgiati, S.: Circular economy transition in Italy. Achievements, perspectives and constraints. J. Clean. Prod. **243**, 118360 (2020). https://doi.org/10.1016/J.JCLEPRO.2019.118360

Gregory, J.R., Montalbo, T.M., Kirchain, R.E.: Analyzing uncertainty in a comparative life cycle assessment of hand drying systems. Int. J. Life Cycle Assess **18**, 1605–1617 (2013). https://doi.org/10.1007/s11367-013-0606-0

Göswein, V., Reichmann, J., Habert, G., Pittau, F.: Land availability in Europe for a radical shift toward bio-based construction. Sustain. Cities Soc. **70**, 102929 (2021). https://doi.org/10.1016/J.SCS.2021.102929

Gunderson, L.H., Holling, C.S.: Panarchy: Understanding transformations in systems of humans and nature (2002)

Hannouf, M.B., Assefa, G., Hannouf, M.B., Gates, I.: Cause-effect chains in S-LCA based on DPSIR framework using Markov healthcare model: an application to "working hours" in Canada. Int. J. Life Cycle Assess. **26**, 936–949 (2021). https://doi.org/10.1007/S11367-021-01900-6/FIGURES/7

Hellweg, S., Milà I Canals, L.: Emerging approaches, challenges and opportunities in life cycle assessment. Science **344**, 1109–1113 (2014). https://doi.org/10.1126/SCIENCE.1248361/SUPPL_FILE/HELLWEG-SM.PDF

IFRS - International Financial Reporting Standards. IFRS in your pocket 2021 (2021). https://www.iasplus.com/en/publications/global/ifrs-in-your-pocket/2021/at_download/file/IFRS%20in%20your%20pocket%202021.pdf. Accessed June 2022

IPCC: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change (2019)

IPCC: Summary for Policymakers SPM Summary for Policymakers Drafting Authors (2021). https://doi.org/10.1017/9781009157896.001

Kennedy, C., Cuddihy, J., Engel-Yan, J.: The changing metabolism of cities. J. Ind. Ecol. **11**, 43–59 (2007). https://doi.org/10.1162/JIE.2007.1107

Le Téno, J.F., Mareschal, B.: An interval version of PROMETHEE for the comparison of building products' design with ill-defined data on environmental quality. Eur. J. Oper. Res. **109**, 522–529 (1998). https://doi.org/10.1016/S0377-2217(98)00074-5

Linkov, I., Welle, P., Loney, D., et al.: Use of multicriteria decision analysis to support weight of evidence evaluation. Risk Anal. **31**, 1211–1225 (2011). https://doi.org/10.1111/J.1539-6924.2011.01585.X

Lloyd, S.M., Ries, R.: Characterizing, propagating, and analyzing uncertainty in life-cycle assessment: A survey of quantitative approaches. J. Ind. Ecol. **11**, 161–179 (2007). https://doi.org/10.1162/JIEC.2007.1136

Lucertini, G., Musco, F.: Circular urban metabolism framework. One Earth **2**, 138–142 (2020). https://doi.org/10.1016/J.ONEEAR.2020.02.004

Mandić, A., Kennell, J.: Smart governance for heritage tourism destinations: Contextual factors and destination management organization perspectives. Tour. Manag. Perspect. **39**, 100862 (2021). https://doi.org/10.1016/J.TMP.2021.100862

Marttunen, M.: Description of Multi-Criteria Decision Analysis (MCDA) (2010). http://environment.sal.aalto.fi/MCDA/. Accessed 17 May 2022

Miller, H.J., Witlox, F., Tribby, C.P.: Developing context-sensitive livability indicators for transportation planning: A measurement framework. J. Transp. Geogr. **26**, 51–64 (2013). https://doi.org/10.1016/J.JTRANGEO.2012.08.007

Montealegre, A.L., García-Pérez, S., Guillén-Lambea, S., et al.: GIS-based assessment for the potential of implementation of food-energy-water systems on building rooftops at the urban level. Sci. Total Environ. **803**, 149963 (2022). https://doi.org/10.1016/J.SCITOTENV.2021.149963

Mostafavi, N., Farzinmoghadam, M., Hoque, S.: A framework for integrated urban metabolism analysis tool (IUMAT). Build. Environ. **82**, 702–712 (2014). https://doi.org/10.1016/J.BUILDENV.2014.10.020

Odum, H.T.: Systems Ecology: An Introduction (Environmental Science and Technology: A Wiley-Interscience Series of Texts and Monographs) (9780471652779): Odum, H.T., Books (1983)

Oppio, A., Dell'Ovo, M.: Strategic Environmental Assessment (SEA) and Multi-Criteria Analysis: An Integrated Approach, pp. 47–63 (2020)

Peponi, A., Morgado, P., Kumble, P.: Life cycle thinking and machine learning for urban metabolism assessment and prediction. Sustain. Cities Soc. **80**, 103754 (2022). https://doi.org/10.1016/J.SCS.2022.103754

Pittau, F., Lumia, G., Heeren, N., Iannaccone, G., Habert, G.: Retrofit as a carbon sink: The carbon storage potentials of the EU housing stock. J. Cleaner Prod. **214**(2019), 365–376 (2019). https://www.sciencedirect.com/science/journal/09596526/214/supp/C. https://doi.org/10.1016/j.jclepro.2018.12.304

Quagliolo, C., Assumma, V., Comino, E., et al.: An integrated method to assess flood risk and resilience in the MAB UNESCO Collina Po (Italy). In: Lecture Notes in Networks and Systems (2023, in press)

Rockström, J., Steffen, W., Noone, K., et al.: A safe operating space for humanity. Nat. **461**(7263), 472–475 (2009). https://doi.org/10.1038/461472a

Stephan, A., Crawford, R.H., Bunster, V., et al.: Towards a multiscale framework for modeling and improving the life cycle environmental performance of built stocks. J. Ind. Ecol. (2022). https://doi.org/10.1111/JIEC.13254

Steubing, B., de Koning, D., Haas, A., Mutel, C.L.: The activity browser — An open source LCA software building on top of the brightway framework. Softw. Impacts **3**, 100012 (2020). https://doi.org/10.1016/J.SIMPA.2019.100012

Treves, A., Bottero, M., Caprioli, C., Comino, E.: The reintroduction of Castor fiber in Piedmont (Italy): An integrated SWOT-spatial multicriteria based approach for the analysis of suitability scenarios. Ecol. Indic. **118**, 106748 (2020). https://doi.org/10.1016/J.ECOLIND.2020.106748

Tukker, A., Emmert, S., Charter, M., et al.: Fostering change to sustainable consumption and production: An evidence based view. J. Clean. Prod. **16**, 1218–1225 (2008). https://doi.org/10.1016/J.JCLEPRO.2007.08.015

United Nations: Transforming Our World: the 2030 Agenda for Sustainable Development United Nations United Nations Transforming Our World: the 2030 Agenda for Sustainable Development. A/RES/70/1. United Nations (2015)

Vázquez-Rowe, I., Córdova-Arias, C., Brioso, X., Santa-Cruz, S.: A method to include life cycle assessment results in choosing by advantage (Cba) multicriteria decision analysis. A case study for seismic retrofit in peruvian primary schools. Sustain **13**, 1–18 (2021). https://doi.org/10.3390/su13158139

Voukkali, I., Zorpas, A.A.: Evaluation of urban metabolism assessment methods through SWOT analysis and analytical hierocracy process. Sci. Total Environ. **807**, 150700 (2022). https://doi.org/10.1016/J.SCITOTENV.2021.150700

Wolman, A.: The metabolism of cities. Sci. Am. **213**, 178–190 (1965). https://doi.org/10.1038/scientificamerican0965-178

Yang, Y., Heijungs, R., Brandão, M.: Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA. J. Clean. Prod. **150**, 237–242 (2017). https://doi.org/10.1016/J.JCLEPRO.2017.03.006

Yazdanbakhsh, A., Lagouin, M.: The effect of geographic boundaries on the results of a regional life cycle assessment of using recycled aggregate in concrete. Resour. Conserv. Recycl. **143**, 201–209 (2019). https://doi.org/10.1016/J.RESCONREC.2019.01.002