Life-Cycle Performance of Structures and Infrastructure Systems in Diverse Environments – Li & Frangopol (Eds)

Assessing steel buildings circularity through the synergy of LCA and MFA

M.M. Sesana
University of Brescia, Brescia, Italy

H. Gervasio
University of Coimbra, Coimbra, Portugal

ABSTRACT: The transition of the building sector to a circular economy is thus of primordial importance to mitigate both problems. Material flow analysis (MFA) and life cycle assessment (LCA) are two of the most known and diffuse methodologies to quantify the environmental and economic impacts of the built environment through a circular approach. While there have been advancements over the last decade in the implementation of various circular strategies, the building industry urgently needs to implement more effective recycling and reuse procedures to lower the rate of consumption by applying a circular economy framework, overcoming barriers and limits, such as data quality and availability used in the assessment process. This paper provides a critical review on methodologies to evaluate circularity and sustainability for steel buildings and explores potential synergies between MFA and LCA to define a hybrid (MFA/LCA) methodology for the assessment of the circularity of buildings over the complete life cycle.

1 INTRODUCTION

Globally, the building value chain is responsible for 37% of total carbon emissions. Notably, the construction domain emerges as a substantial consumer of elemental materials and assets, concurrently contributing to more than 36% of the global energy utilization and accounting for 39% of CO_2 emissions arising from energy-related sources (UNEP 2024). Moreover, the building sector value chain involves harder-to-abate industrial sectors such as steel and cement, making its decarbonization even more challenging. As we assess critical priorities in the fight against climate change, the building sector clearly demands immediate attention.

The Global Status Report for Buildings and Construction 2024 (UNEP 2024), which provides an annual snapshot of the progress of the buildings and construction sector on a global scale, underlines that the construction sector accounts for about 21% of global greenhouse gas (GHG) emissions, contributing significantly to global climate change and consequently requesting stronger policies to enhance energy efficiency and address carbon emissions from building materials and construction and to reach the decarbonization target set worldwide. In Europe the New Green Deal stated the goal of net-zero carbon emission buildings for new buildings by 2030 and existing buildings by 2050, coupled with a series of initiatives and frameworks to boost the transition towards a circular and resilient approach for the built environment and to achieve Sustainable Development Goals (SDGs) such as responsible consumption and production. In this context, the implementation of the circular economy is crucial to combat climate change, especially considering steel buildings which are becoming increasingly popular in construction practice in response to the need to meet the new demands of the construction market in a flexible, versatile, industrialized, and sustainable manner. In light of the significant role played by the construction sector in relation to GHG emissions, scholars have extensively examined various facets of this industry from diverse

DOI: 10.1201/9781003595120-169

vantage points. Their objective has been to establish a holistic framework for the construction of buildings with minimal carbon footprints (Serrano-Baena et al. 2023, Seyedabadi et al. 2022, Ylmen et al. 2017, Ascione et al. 2017). Among the robust methodologies for environmental analysis, Life Cycle Assessment (LCA) stands out. LCA involves a comprehensive analysis of distinct stages in a product's lifecycle to ascertain its environmental impact. When employing the LCA methodology to gauge the carbon footprint of a building over its entire lifespan, careful consideration must be given to emissions occurring across pivotal phases of production, construction, operation, and end-of-life. The carbon footprint of the construction phase depends on the type of materials used in the building, the process of the extraction of these materials, how these materials are transported to the building materials factories and then to the construction site, and finally how the building is constructed by using various construction processes (Seyedabadi 2023).

The structural configuration of a building has a profound impact on its embodied carbon emissions. Widely used construction materials on a global scale for constructing a building's structural frame include concrete, steel, and timber (Hansen et al. 2023, Morris et al. 2021, Sesana et al. 2024) emphasize the significance of conducting an early-stage assessment of the embodied carbon in structural systems. This is crucial because employing various retrofitting strategies is more effective than relying on a single specific approach.

The transition towards a circular built environment will require integral changes in the design, supply chain and business model of building components (Balasbaneh et al. 2020).

With the current efforts in striving towards sustainable development both Life Cycle Assessment (LCA) and Material Flow Analysis (MFA) have become extremely popular, worldwide. Both address sustainability aspects, but they are typically applied separately. LCA counts with dedicated tools and databases, while MFA is commonly used to quantify selected mass-based indicators to evaluate the parameters of circular economy.

LCA has emerged as an essential method to evaluate materials' environmental impact. However, is currently used also for assessing other dimensions of Circular Economy (CE), such as the technical, social, system, and functional dimensions.

MFA provides a systematic assessment of flows and stocks within a temporally and spatially defined system, e.g. a city or urban area (Brunner & Rechberger 2004). MFA can be used in both retrospective and prospective analyses of building materials in cities (Augiseau & Barles 2017). An MFA limitation is that emissions embodied in raw materials or products entering the system are not accounted for.

A review of existing literature reveals that noteworthy academic research and publications about both MFA and LCA for steel buildings remain a significant gap in the literature. This paper presents a combination of LCA and MFA, combining and implementing the positive aspects of both assessment methods, to overcome this shortcoming and other barriers of using only each single method derived from a deep critical analysis of both methodologies which led to the definition of a hybrid assessment method which combines MFA and LCA.

After this introduction, the second section sets the scene by discussing the latest regulations and standards for the construction sector in Europe and also providing an overview of methods and tools to assess and evaluate circularity in buildings. Section 3 presents the literature review conducted on MFA and LCA by reporting a review analysis of both methodologies. Finally, section 4 provides conclusions and a description of further developments.

2 GETTING BEYOND ZERO CARBON BUILDING ARCHITECTURE

2.1 *Circular design of buildings*

Considering the framework presented in the previous section, rethinking the building approach to design and implementing best sustainable practices is highly relevant.

Additionally, more than half of the world's population 55% live in cities, and this proportion is expected to increase to 68 percent (two-thirds of the world's population) by 2050 and around 5.5 billion m^2 of buildings are erected worldwide every year, consequently, as the UNEP Executive Director Inger Andersen, said, 'there is no credible path to address climate change without a fundamental shift in the building and construction sector'.

From the European perspective, the process of diagnosing risks and seeking solutions that would help to counteract crisis deepening led to the adoption of a strategy aimed at achieving climate neutrality by 2050 to become the world's first climate-neutral continent. The Directive on the energy performance of buildings and the objectives contained in the European Green Deal also set ambitious targets for the building and construction sector. While the issues of renewable energy generation and low-carbon construction projects are becoming central, the pursuit of making the built environment more sustainable goes far beyond undertaking activities related to technical building infrastructure.

In this context, architectural design attaches importance to, among other things, the pursuit of reducing the scale of manufacture of building materials and thus diminishing negative environmental impacts at an early stage of the construction process. Bernhard & Jørgensen (2006) study has shown that the carbon dioxide emissions from domestic extraction, manufacture, and transport of building materials are approximately twice as high as those from the subsequent use of the buildings. These are significant parameters. The markedly increasing role of recycling and architects' interest in reusing both building materials and other types of waste is therefore not surprising. These issues are important not only due to reducing CO_2 emissions and the consequent energy consumption but also due to the significant challenge that the modern world is facing in terms of the overproduction of waste, its disposal, and its negative impact on the environment. The concept of recycling was introduced in the 20th century. Although the idea of reusing building materials and objects deprived of their original function has accompanied humankind since the earliest times, it was not based on ecological considerations (as it is today), but primarily on economic and sometimes cultural or historical benefits that made the incorporation of fragments of old buildings a symbolic act.

The concept and practice of recycling developed strongly in the 21st century, along with the growing awareness of the environmental crisis. Actions based on the recovery and reuse of construction waste spark growing interest and provoke architects to seek creative solutions.

In circular architecture, it is important to creatively source and use building materials as well as to think, right from the initial stages of a project, about how to reuse components in other buildings, reclaim used products, or use biodegradable materials. The idea of circular architecture is thus more complex and broader than architectural recycling, which is its important component. Researchers from the Institute of Design Research Vienna, who, having conducted a research project within the framework of the New Europe Bauhaus, developed a set of Circular Design Rules (a practical guideline and tool for designers), emphasize that modularity is a very important concept in circular design. A modular design system allows the replacement or addition of independent components, which gives better opportunities for repair, improvement, and expansion and, consequently, extends the useful life of a product.

2.2 *EU regulation framework for zero carbon buildings*

To address the building sector decarbonization path, the EU regulatory framework focuses on the life cycle perspective of emissions shift, utilizing Level(s) framework and EN 15879 as a methodological foundation.

Numerous policies and measures to curb the environmental impacts of the building sector have been implemented or are under preparation. In this paper, we study the construction sector actors' perceptions of the new low-carbon policies and examine how these perceptions differ according to organization type. Ensuring the high-level energy efficiency of new buildings and renovating old buildings is not enough to fully tackle the building sector's greenhouse gas (GHG) emissions.

The EU's path for tackling buildings embodied emissions is dependent on the revision of the Energy Performance of Buildings Directive (EPBD), the methodological development of which calls on the Level(s) framework. It was launched in 2020 (Dodd et al. 2020), and its methodology is based on existing European standards for building life cycle assessment (most relevantly EN 15978, EN 15804, EN 15643).

EU Energy Performance of Buildings Directive recast came into force in April 2024 (Directive EU 2024/1275 2024), with the main goal to substantially reduce greenhouse gas emissions and energy consumption in the EU building sector by 2030 and make it climate-neutral by 2050.

The Directive invites also all the Member States to phase out plans for fossil fuel in buildings by 2035 and sets out tougher emissions targets for buildings undergoing major renovation.

The main key points of the EPBD Recast are summarized in the following bullet list.

- Emissions-reduction targets.
- All new buildings should be zero-emission from 2028, with the deadline for new buildings occupied, operated or owned by public authorities in 2026.
- All new buildings should be equipped with solar technologies by 2028, where technically suitable and economically feasible, while residential buildings undergoing major renovation have until 2032.
- Residential buildings would have to achieve, at a minimum, energy performance class E by 2030, and D by 2033 - on a scale going from A to G, the latter corresponding to the 15% worst-performing buildings in the national stock of a member state. Non-residential and public buildings would have to achieve the same ratings by 2027 and 2030 respectively.
- National renovation plans should include support schemes to facilitate access to grants and funding. Member States need to put in place free-of-charge information points and cost-neutral renovation schemes. Financial measures should provide an important premium for deep renovations, especially of the worst-performing buildings, and targeted grants and subsidies should be made available to vulnerable households.

Parallel to the EPBD revision, various EU Member States are currently creating their own national methods for assessing the impacts of buildings' life cycles (BPIE 2021).

Italy, Switzerland, and Germany have life cycle carbon requirements for public buildings.

Denmark, France, and The Netherlands have national regulations in force that limit the life cycle carbon emissions for a large share of new buildings, and the other two Member States are introducing life cycle carbon regulation with CO_2 limits by 2025 (Finland) and by 2027 (Sweden).

The coordinated development of national building life cycle regulation strategies has the potential to yield substantial benefits at the broader EU level. The success of the initiative will be evidenced by the early actions taken by the forerunners, which will demonstrate the feasibility and acceptability of implementing and enacting a regulation on building carbon footprints.

However, state of the art and state of practice highlight that carbon footprint policies were generally seen as functional, Räihä et al. (2024) in their study remarked that the perceptions varied significantly depending on the respondent's organization type involved in the construction design stage and based on their results, generally seemed more positive about the proposed regulations, whereas advocates (associations and interest groups) were more cautious than the organizations they represented.

In this context, the review of all those findings helps clarify the implementation and development needs of low-carbon policies and methodologies that cover all the spheres of sustainability to assess in a complete way the circularity of the overall building value chain.

3 CIRCULARITY ASSESSMENT METHODS FOR STEEL BUILDINGS

Combining Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) provides a basis for the development of a hybrid approach, able to evaluate related means (material recovery) and performance (protection of human health, biodiversity, and resources).

In this section, both methodologies are presented underlining their ability to evaluate circular economy practices at the building scale but also highlighting their limitations and potentialities to identify the aspects of both methodologies to be considered for their combination with the final scope to develop a unique and hybrid approach.

The two review analyses have been conducted, focusing on research works for steel buildings, but they can be enlarged for other construction technologies.

3.1 *Overview of material flow analysis for steel buildings*

Material Flow Analyses (MFA) are a pertinent tool for evaluating material reduction potentials and providing input for prospective scenarios (Corona et al. 2019, Kullmann et al. 2021). MFA facilitate a comprehensive assessment of material production, material stocks, waste generation and their interrelations (Pauliuk et al. 2015).

Furthermore, multi-factor analysis (MFA) facilitates the examination of potential future scenarios by extrapolating the system (Pauliuk & Hertwich 2016). This approach can be adopted in two distinct ways: inflow-driven, where material stocks and outflows from material inflows and lifetime models are determined, or stock-driven, where material in- and outflows from material stocks are determined (Deng et al. 2023).

MFA applies conservation of mass within a well-defined system boundary to determine the flow of material between the elements of that system. Over the past two decades, MFA has been used to calculate the trade flow of materials between nations (Wang et al. 2007) estimate material stocks (Mueller et al. 2011), and project trends of waste supply (Pauliuk et al. 2013). MFA studies can be classified as top-down if they rely upon nationally collected statistics to form their data set, or bottom-up if the data is gathered by the inventory of the stocks within a system.

A considerable number of research has been dedicated to the analysis of the prospective service-stock-flow nexus of building-related services, including but not limited to comfortable living, education, and workspaces. Those studies, at the national or global level, employing methodologies derived from stock-driven MFA.

Coupling MFA and steel buildings to deeply investigate this circularity assessment method for the selected structural material, literature research gives more than 50 MFA studies results which calculating stocks and flow of steel reveals that date methods provide compelling insights into both the aggregate flow of steel at the global and national scale, as well as determination of steel stocks at a remarkably fine level of spatial resolution.

However, two major gaps were identified in this literature: steel flow has only been disaggregated for a few types of steel, and, where this detail is provided, higher-resolution steel flow has only been assessed for a small set of manufacturing industries.

In most assessments, steel is treated as a single material type, whereas, because of the range of available grades, coatings, and thicknesses, it is in reality a class of many different material types. A few studies have considered various steel grades. Moreover, a higher-resolution MFA, capable of tracking not only flow of steel by grade, but also other material characteristics, such as thickness and coating, in addition to mass, coupled with a detailed assessment of manufacturing processes across industries, could enable the identification of novel opportunities to reduce steel production and to prevent unnecessary recycling and consequent energy use and emissions.

The combination of modelling scrap availability with the actual recycling quantities can allow evaluation of the effectiveness and potential for improvement in the management of steel scrap.

3.2 *Overview of Life Cycle Assessment for steel buildings*

Life Cycle Assessment (LCA) is a systematic and comprehensive methodology used to evaluate the environmental impact of a product, process, or service throughout its entire life cycle.

The process of LCA involves quantifying, measuring, and assessing various environmental factors, such as energy use, resource consumption, emissions, and waste generation. By analyzing the complete life cycle of a product or service, LCA enables professionals to identify areas where efforts can be made to minimize negative effects on the environment, and in which areas the impact of changes will be the greatest.

While the methodology is relevant in any industry, LCA is particularly impactful in architecture and construction. Due to the lifespan of most buildings, and the resources that are expended both to construct and operate them, there is a lot to be gained in selecting the right materials and making optimizations for operational aspects such as energy efficiency and waste management.

The advantage of LCA lies in its ability to analyze the life cycle of a structure, spanning from its conceptualization to its eventual decommissioning. In every phase of a construction project, there are choices to be made that affect the sustainability and total environmental impact of the building throughout its entire lifespan. Choice of materials and the related resource extraction and manufacturing, the construction process itself, operation, maintenance, and eventual end-of-life considerations like recyclability and second-life of materials.

By understanding the nuances of each stage, architects and construction professionals can make informed decisions on sustainability that extend beyond the immediate construction process and have a significant impact on other environmental concerns in the entire life cycle of the building. Materials greatly influence a project's ecological footprint, and selecting the right ones is a pivotal part of sustainable construction. LCA serves as a guiding light in this process, allowing architects to conduct meticulous analysis that grants greater insight into the impacts of each material type and forms the basis for informed decisions on material choice.

Energy efficiency, carbon footprint, and recyclability have all become important considerations. The choice of material can no longer be based on structural integrity and appearance alone but must be made according to their impact on the building's long-term sustainability, balanced against the building's purpose. While the construction phase lays the groundwork for sustainability, a building's operational life presents its own set of challenges and opportunities. In this phase of the building's life cycle, the role of LCA lies in continually analyzing and optimizing energy efficiency. Adopting Life Cycle Assessment marks a paradigm shift in the architect and construction industry, where sustainability is no longer just an afterthought, but an integral part of the entire process. With the insights provided by LCA, architects and construction professionals have a much easier time making informed decisions on sustainability and can strive for greater results than ever before. As industry embraces this transformative methodology, the future of architecture and construction won't just be innovative, but also far more sustainable.

Moreover, LCA contributes to circular economy goals by establishing frameworks for material reuse and recycling, essential components of a circular approach. This methodology also aids in aligning stakeholders across the building ecosystem, fostering collaborative approaches to material use that enhance both sustainability and resource circularity (Sgambaro et al. 2024).

Considering the LCA for the core typology of the manuscript, steel building, in literature various studies confirmed and stated the following lessons learned.

- The high recycling rate of steel construction products within Western Europe: on average, 83% of all steel construction products are recycled at the end of life, 14% are reused, with only 3% landfilled. Although these results are encouraging towards the decarbonization path, greater environmental benefit could be gained by increasing the proportion of products that are reused.
- The importance of accounting for reuse and recycling within LCA methodology has been highlighted and, in recognition of this, Life Cycle Inventory (LCI) data have been disseminated to enable the user of the data to select the most appropriate recycling allocation method for their application. The large variation in LCI data resulting from the recycling allocation method adopted, can cause the non-LCA specialist confusion and cause a lack of confidence in the data generated. European consensus about how to account for the recycling of materials within LCA is badly needed (Sesana et al. 2025).
- Transport movements can represent a potentially significant environmental impact for some products studied. Throughout the entire life cycle of heavy structural steel, for example, transport movements, post steel production, can exceed 1500 km.
- The reluctance and inability of many companies within the steel construction supply chain to collect and make available data for use within this project is an important finding. It is recognized that this supply chain is long and diverse and that the nature of the construction industry is different from more traditional manufacturing industries which have more readily taken on board environmental and life cycle assessment thinking. More work is required within the industry to promote the need for the quantification of environmental impacts and the business benefits that arise through systematic management of whole life cycle impacts.
- Although the environmental impacts of the life cycle phases downstream of steel production have been proven to be relatively small and the high recycling rates observed for most steel construction products, problems in recovering and scrap processing of some products were identified.

3.3 *Synergies between MFA and LCA*

The critical review of MFA and LCA methods shows that further research is needed to improve resource depletion evaluation and that, at the project scale, indicators such as the Material Circularity Indicator (MCI), one of the major circular indicators in use today, limits the overall analysis. MFA provides interesting information complementary to LCA but does not successfully evaluate the environmental performance of circular practices. On the other hand, an LCA is a systematic and comprehensive methodology used to evaluate the environmental impact of a product, process, or service throughout its entire life cycle, but does not provide a clear identification of inputs and outputs.

Hence, the combination of MFA and LCA taking into consideration the respective strengths and opportunities, and overcoming the limitations of each single assessment method, will allow to perform a comprehensive analysis of steel buildings in terms of circularity and environmental assessment, taking into consideration also the potentialities of the material itself.

4 CONCLUSIONS

The results of the critical review on methodologies to evaluate circularity and sustainability for steel buildings underscore the necessity of integrating assessment methodologies that encompass resource levels and environmental sustainability, emphasizing that a myopic focus on resource efficiency can be fallacious. The study underscores the necessity of incorporating environmental assessments during the product development stage to ensure the design of environmentally sustainable and resource-efficient product systems to avoid limiting only energy consumption but embracing a more holistic point of view towards the decarbonization of the sector.

The combination of MFA and LCA is a very promising strategy, and the authors are currently actively involved in the development of such an approach.

REFERENCES

Ascione, F., Bianco, N., De Masi, R.F., Mauro, G.M. & Vanoli, G.P. 2017. Resilience of robust cost-optimal energy retrofit of buildings to global warming: A multi-stage, multi-objective approach. *Energy and Buildings* 153: 150–167.

Augiseau, V. & Barles, S. 2017. Studying construction materials flows and stock: A review. *Resources, Conservation and Recycling* 123: 153–164.

Balasbaneh, A.T. & Ramli. M.Z. 2020. A comparative life cycle assessment (LCA) of concrete and steel-prefabricated prefinished volumetric construction structures in Malaysia. *Environ. Sci. Pollut. Res*. 27 (34): 43186–43201.

Bernhard P. & Jørgensen P. F. 2006. *Byggenæringens CO_2 utslipp. Notat for Byggemiljø - Byggenæringens Miljøsekretæriat*, Oslo: KanEnergi.

BPIE (Buildings Performance Institute Europe) 2021. *Nearly Zero: A review of EU Member State implementation of new build requirements*. Available at: https://www.bpie.eu/publication/nearly-zero-a-review-of-eu-member-state-implementation-of-new-build-requirements

Brunner, P.H. & Rechberger, H. 2004. Methodology of MFA. *Practical Handbook of Material Flow Analysis; Lewis Publishers*: *Boca Raton, FL, USA*, 34–166.

Corona, B., Shen, L., Reike, D., Carreón, J.R. & Worrell, E. 2019. Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling* 151: 104498.

Deng, T., Zhang, Y. & Fu, C. 2023. Modelling dynamic interactions between material flow and stock: A review of dynamic material flow analysis. *Ecological Indicators* 156: 111098.

Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast), available at https://eur-lex.europa.eu/eli/dir/2024/1275/oj/eng

Dodd, N., Donatello, S. & Cordella. M. 2020. Level(s) – *A common EU framework of core sustainability indicators for office and residential buildings*, User Manual 1: Introduction to the Level(s) common framework.EN 15978:2011 - Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.

EN 15804:2012+A2:2019/AC:2021Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products.
EN 15643:2021Sustainability of construction works - Framework for assessment of buildings and civil engineering works.
Hansen, R.N., Hoxha, E., Rasmussen, F.N., Ryberg, M.W., Andersen, C.E. & Birgisdóttir, H. 2023. Enabling rapid prediction of quantities to accelerate LCA for decision support in the early building design. *Journal of Building Engineering* 76: 106974.
Kullmann, F., Markewitz, P., Stolten, D. & Robinius, M. 2021. Combining the worlds of energy systems and material flow analysis: a review. *Energy, Sustainability and Society* 11(1): 13.
Llantoy, N., Chàfer, M. & Cabeza, L. F. 2020. A comparative life cycle assessment (LCA) of different insulation materials for buildings in the continental Mediterranean climate. *Energy and Buildings 225*: 110323.
Morris, F. Allen, S. & Hawkins. F. 2021. On the embodied carbon of structural timber versus steel, and the influence of LCA methodology. *Build. Environ*. 206: 108285.
Müller, D.B., Wang, T. & Duval, B. 2011. Patterns of iron use in societal evolution. *Environmental Science & Technology* 45(1): 182–188.
Pauliuk, S., Milford, R.L., Müller, D.B. & Allwood, J.M. 2013. The steel scrap age. *Environ. Sci. Technol*. 47: 3448–54.
Pauliuk3, S., Majeau-Bettez, G. & Müller, D.B. 2015. A general system structure and accounting framework for socioeconomic metabolism. *Journal of Industrial Ecology* 19(5): 728–741.
Pauliuk, S. & Hertwich, E. G. 2016. Prospective models of society's future metabolism: What industrial ecology has to contribute. *Taking stock of industrial ecology*: 21–43.
Räihä, J., Clarke, S., Sankelo, P., Ruokamo, E. & Kangas, H.L. 2024. The importance of organization type: Construction sector perceptions of low-carbon policies and measures. *Environmental Science & Policy* 151: 103602.
Serrano-Baena, M.M., Ruiz-Díaz, C., Boronat, P.G. & Mercader-Moyano, P. 2023. Optimising LCA in complex buildings with MLCAQ: A BIM-based methodology for automated multi-criteria materials selection. *Energy and Buildings* 294: 113219.
Sesana, M.M., Scrucca, F., Ceruti, F. & Rinaldi, C. 2024. Assessing the mitigation potential of environmental impacts from sustainability strategies on steel construction value chain: a case study on two steel products in Italy. *TEMA* 10(2): 1–11.
Sesana, M.M., Scrucca, F., Ceruti, F. & Rinaldi, C. 2024. Life Cycle Assessment and datasets development of steel construction products for the Italian LCA Database. In *International Conference of Ar. Tec.(Scientific Society of Architectural Engineering)*: 694–707. Cham: Springer Nature Switzerland.
Seyedabadi M.R., Abolhassani S.S. & Eicker U. 2023. District cradle to grave LCA including the development of a localized embodied carbon database and a detailed end-of-life carbon emission workflow. *Journal of Building Engineering*: 107101.
Seyedabadia, M.R., Karrabi, M., Abdollahi, J. & Kazemian, H. 2022. Optimising and investigating the effect of leaf area index, soil depth, and water content on energy conservation and pollutant reduction in green roof systems (case study: Mashhad City). *International Journal of Environmental Technology and Management 25*(5): 351–365.
Seyedabadi, M.R., Karrabi, M. & Nabati, J. 2022. Investigating green roofs' CO 2 sequestration with cold-and drought-tolerant plants (a short-and long-term carbon footprint view). *Environmental Science and Pollution Research*: 1–10.
Seyedabadi, M.R., Eicker, U. & Karimi, S. 2021. Plant selection for green roofs and their impact on carbon sequestration and the building carbon footprint. *Environmental Challenges* 4: 100119.
Sgambaro L, Chiaroni D & Urbinati A, 2024. The design and servitization of products according to the circular economy principles: An ecosystem perspective in the building industry. *Journal of Cleaner Production* 454: 142322.
United Nations Environment Programme 2024. *Emissions Gap Report 2024: No more hot air … please! With a massive gap between rhetoric and reality, countries draft new climate commitments*. Nairobi.
United Nations Environment Programme 2024. *Global Status Report for Buildings and Construction: Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the buildings sector*. Nairobi.
Wang, T., Müller, D. B. & Graedel, T.E. 2007. Forging the anthropogenic iron cycle. *Environmental science & technology* 41(14): 5120–5129.
Ylmén, P., Mjörnell, K., Berlin, J. & Arfvidsson, J. 2017. The influence of secondary effects on global warming and cost optimization of insulation in the building envelope. *Building and Environment* 118: 174–183.
Ylmén, P., Mjörnell, K., Berlin, J. & Arfvidsson, J. 2017. The influence of secondary effects on global warming and cost optimization of insulation in the building envelope. *Building and Environment* 118: 174–183