# Life-Cycle of Structures and Infrastructure Systems

Editors

Fabio Biondini and Dan M. Frangopol

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# LIFE-CYCLE OF STRUCTURES AND INFRASTRUCTURE SYSTEMS

**Life-Cycle of Structures and Infrastructure Systems** collects the lectures and papers presented at IALCCE 2023 - The Eighth International Symposium on Life-Cycle Civil Engineering held at Politecnico di Milano, Milan, Italy, 2-6 July, 2023. This Open Access Book contains the full papers of 514 contributions, including the Fazlur R. Khan Plenary Lecture, nine Keynote Lectures, and 504 technical papers from 45 countries.

The papers cover recent advances and cutting-edge research in the field of life-cycle civil engineering, including emerging concepts and innovative applications related to life-cycle design, assessment, inspection, monitoring, repair, maintenance, rehabilitation, and management of structures and infrastructure systems under uncertainty. Major topics covered include life-cycle safety, reliability, risk, resilience and sustainability, life-cycle damaging processes, life-cycle design and assessment, life-cycle inspection and monitoring, life-cycle maintenance and management, life-cycle performance of special structures, life-cycle cost of structures and infrastructure systems, and life-cycle-oriented computational tools, among others.

This Open Access Book provides both an up-to-date overview of the field of life-cycle civil engineering and significant contributions to the process of making more rational decisions to mitigate the life-cycle risk and improve the life-cycle reliability, resilience, and sustainability of structures and infrastructure systems exposed to multiple natural and human-made hazards in a changing climate. It will serve as a valuable reference to all concerned with life-cycle of civil engineering systems, including students, researchers, practitioners, consultants, contractors, decision makers, and representatives of managing bodies and public authorities from all branches of civil engineering.

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# Life-Cycle of Structures and Infrastructure Systems


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# Table of contents

*MINI-SYMPOSIA*

**MS1: Component reuse in structures and infrastructures**
*Organizers: O. Iuorio & C. Fivet*



**MS2: Smart condition assessment of railway bridges**
*Organizers: T. Bittencourt, R. Calçada, D. Ribeiro, H. Carvalho, M. Massao & P. Montenegro*

## MS11: Life-cycle asset management and the complexity of socio-environmental-technical transitions

*Organizers: A. Hartmann, M. Hertogh, J. Bakker & H. Roebers*



## MS12: Advanced strengthening and retrofitting solutions for existing concrete structures

*Organizers: N. Randl & E. Rossi*

## MS15: Deconstruction and reuse of steel and lightweight metal structures

*Organizers: M. Kuhnhenne & P. Kamrath*

**MS16: Assessment of existing masonry arch bridge infrastructure**
*Organizers: M. Gilbert, G. Cardani, T. Boothby & D. Coronelli*



**MS17: Recent advance in seismic protection systems: Design, modeling and testing strategies of traditional and innovative solutions**
*Organizers: A. Pavese & M. Furinghetti*

## MS18: Safety and maintenance of masonry arch bridges: diagnostic, monitoring, modelling, risk analysis and retrofit interventions

*Organizers: F. Cannizzaro, N. Cavalagli, C. Chisari, B. Pantò, F. Scozzese, P. Zampieri & M. Zizi*

## SS3: Monitoring of structures for informed decision making

*Organizers: A. Strauss & D.M. Frangopol*



## SS4: Artificial intelligence-based life-cycle management of infrastructure systems

*Organizers: Y. Dong, D.M. Frangopol & X. Lei*

## SS5: Concrete damage assessment using coda waves

*Organizers: C. Gehlen, E. Niederleithinger, J. Timothy & T. Kränkel*



## SS6: Life-cycle redundancy, robustness, and resilience indicators for aging structures and infrastructure systems under multiple hazards

*Organizers: F. Biondini & D.M. Frangopol*



## SS7: Bridge weight-in-motion systems and applications to structural health monitoring

*Organizers: S. Mustafa & D. Cantero*

### SS15: Reinforced concrete-to-concrete interfaces: experiments and modelling

*Organizers: V. Palieraki & S. Cattaneo*



### SS16: Risk-informed life-cycle management of bridges

*Organizers: I. Venanzi, M.P. Limongelli & U. Alibrandi*



### SS17: BIM-based sustainability considerations in infrastructure construction

*Organizer: M. König*

## SS29: Durability and structural assessment of fiber reinforced strengthening materials and strengthened structures

*Organizers: F. Micelli, C. Papanicolaou, B. Ghiassi & M. Leone*



## SS30: Durability of sustainable reinforced concrete for civil engineering structures

*Organizers: M. Carsana & E. Redaelli*



## SS31: Structural health monitoring and asset management of infrastructures

*Organizers: S. AlSanad & J. Parol*

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# Preface

Structures and infrastructure systems need to comply with the continuously increasing demand from societal, political, economic, and environmental needs associated with aging, deterioration processes, and other multiple natural and human-made hazards affecting civil infrastructure facilities. To respond to these needs, civil engineering is undergoing a profound change towards a life-cycle-oriented design and maintenance philosophy where the system performance is considered as time-dependent and the desired levels of target performance are addressed over the entire life-cycle taking into account the effects of aging and deterioration processes, time-variant loadings, and maintenance and repair interventions, among others. This transition is at the heart of civil engineering and is promoting and guiding a considerable amount of research and relevant advances in the fields of modeling, analysis, design, inspection, monitoring, repair, maintenance, and rehabilitation of deteriorating civil engineering systems. To support this process, after a series of International Workshops on Life-Cycle Analysis and Design of Civil Engineering Infrastructure Systems, IALCCE - The International Association for Life Cycle Civil Engineering was created in 2006 (https://www.ialcce.org).

IALCCE covers all aspects of life-cycle assessment, design, maintenance, rehabilitation and monitoring of civil engineering systems. The objective of the Association is to promote international cooperation in the field of life-cycle civil engineering for the purpose of enhancing the welfare of society. Currently, IALCCE includes over 800 individual members from 66 countries and over 30 collective members. Seven International Symposia have been organized since the foundation of IALCCE. The inaugural IALCCE Symposium was held in Varenna, Lake Como, Italy, in June 2008, under the auspices of Politecnico di Milano. Following IALCCE 2008, a series of Symposia have been organized in Taipei, Taiwan (IALCCE 2010), Vienna, Austria (IALCCE 2012), Tokyo, Japan (IALCCE 2014), Delft, The Netherlands (IALCCE 2016), Ghent, Belgium (IALCCE 2018), and Shanghai, China (IALCCE 2020). These events have been very successful, both technically and academically, and IALCCE Symposia have become established events in the field of life-cycle civil engineering. It was therefore considered fruitful to continue this landmark series and celebrate the 15th Anniversary of IALCCE Symposia where they were initiated by bringing together recent advances and cutting-edge research in the field of life-cycle civil engineering and related topics at the Eighth International Symposium on Life-Cycle Civil Engineering (IALCCE 2023), held at Politecnico di Milano, Milan, Italy, 2-6 July, 2023 (https://ialcce2023.org).

IALCCE 2023 has been organized on behalf of IALCCE under the auspices of Politecnico di Milano. The interest of the international civil engineering community in the activities covered by IALCCE has been confirmed by the significant response to the IALCCE2023 call for papers. In fact, over 750 abstracts from more than 50 countries were received by the Symposium Secretariat, and approximately 70% of them were selected for final publication as technical papers and presentation at the Symposium within mini-symposia, special sessions, and general sessions. Contributions presented at IALCCE 2023 cover recent advances and cutting-edge research in the field of life-cycle civil engineering, including emerging concepts and innovative applications related to life-cycle design, assessment, inspection, monitoring, repair, maintenance, rehabilitation, and management of structures and infrastructure systems under uncertainty. Major topics covered include: life-cycle safety, reliability, risk, resilience and sustainability, life-cycle damaging processes (aging of structures, deterioration modeling, durable materials, earthquake and accidental loadings, fatigue and damage, fire and high temperatures, marine and severe environments, structure-environment interaction, global warming and climate change effects), life-cycle assessment and design (design for durability, failure analysis and risk prevention, structural robustness, lifetime structural optimization, long-term performance analysis, performance based design, service life prediction, uncertainty modeling, value of information, life-cycle structural safety, time-variant reliability, functionality and resilience, risk and sustainability), life-cycle monitoring, maintenance, and management (damage identification, field testing and proof loading, health monitoring, inspection and evaluation, robotic and aviation-based techniques, BIM techniques, maintenance strategies, rehabilitation techniques, strengthening and repair, structural integrity, asset management, infrastructure resilience, risk-based prioritization), life-cycle performance of special structures (bridges and viaducts, high-rise buildings, hydraulic structures, off-shore structures, precast systems, roof systems, runway and highway pavements, tunnels and underground structures), life-cycle cost of structures and infrastructure systems (decision making processes, human factors, life-cycle cost models, project management, risk-lifetime analysis and optimization, whole life costing), and life-cycle-oriented computational tools (artificial intelligence methods, evolutionary procedures, heuristic techniques, mathematical optimization, soft-computing methods, survival models and simulation), among others.

*Life-Cycle of Structures and Infrastructure Systems* collects the lectures and papers presented at IALCCE 2023. This Open Access Book contains the full papers of 514 contributions, including the Fazlur R. Khan Plenary Lecture, nine Keynote Lectures, and 504 technical papers from 45 countries. It provides both an up-to-date overview of the field of life-cycle civil engineering and significant contributions to the process of making more rational decisions to mitigate the life-cycle risk and improve the life-cycle safety, reliability, redundancy, robustness, resilience, and sustainability of structures and infrastructure systems exposed to multiple natural and human-made hazards in a changing climate. The Editors hope that this volume will serve as a valuable reference to all concerned with life-cycle of civil engineering systems, including students, researchers, practicioners, consultants, contractors, decision makers, and representatives of managing bodies and public authorities from all branches of civil engineering.

Fabio Biondini and Dan M. Frangopol
Chairs, IALCCE 2023

Milan and Bethlehem, April 2023

# Acknowledgments

The Editors are extremely grateful to all people who contributed to the organization of the IALCCE 2023 Symposium and to the production of this Open Access Book. Particularly, the Editors would like to express their sincere thanks to all the authors for their contributions, to the members of the Steering Committee, International Scientific Committee, and National Advisory Committee for their role in ensuring the highest scientific level of the Symposium, and to the members of the Local Organizing Committee for the time and efforts dedicated to make IALCCE 2023 a successful event.

Moreover, the Editors wish to thank all organizations, institutions, and authorities that offered their patronage. At the institutional level, a special acknowledgment has to be given to the Politecnico di Milano, for organizing and co-sponsoring this Symposium along with the International Association for Life-Cycle Civil Engineering (IALCCE), as well as to the Department of Civil and Environmental Engineering for endorsing and supporting the Symposium organization.

Finally, the Editors wish to express their warmest appreciation to Mattia Anghileri, Adriano D'Iorio, and Francesco Marino, for their effective teamwork and dedication in supporting the editorial activities. Special thanks are due to Andrea Bertoni, Stella Pennini, and Gaia Gorini, who professionally managed the Organizing Secretariat with outstanding expertise, commitment, and enthusiasm, and Marco Guerini for his valuable contribution in designing and developing the Symposium website.

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# Life-cycle assessment of light steel frame buildings: A systematic literature review

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ABSTRACT: Light Steel Frame structures (LSF) have become one of the main competitors of traditional construction systems. The optimized material use, its lightness, and the timesaving in the construction phase, show the potential of this technology to reduce environmental impacts. The purpose of this study is to review and analyse the current literature on the application of the Life Cycle Assessment (LCA) methodology to LSF buildings and identify related gaps. A systematic literature review has been performed to query Web of Science and Scopus databases, highlighting methods, limitations, trends, and tools used to address LCA applied to LSF buildings. Although many efforts have been made to evaluate LSF buildings in comparison with other construction solutions, a gap persists in performing whole LCA. Considering the potential disassembly and reuse offered by LSF and the recyclability of steel, there is a need for future research focusing beyond the end-of-life stage.

## 1 INTRODUCTION

Climate breakdown, resource scarcity, ecological collapse, as well as economic uncertainties make the next years crucial to shape the conversion to a carbon-neutral construction sector. Considering the increasing number of net-zero energy buildings and the consequent optimization of the operational energy emissions, within the next years, the building's embodied energy is likely to become fundamental towards the accomplishment of sustainability goals (Gervásio *et al.* 2010).

The European Green Deal (European Commission 2020) aims to eliminate greenhouse gas emissions through the introduction of circular economy principles in energy-intensive industries (i.e. steel, cement) enhancing the secondary use of materials, components and products (European Commission 2014). In this context, the steel industry plays an important role, since the largest amount of steel produced worldwide is used in construction, material efficiency is necessary. In reducing embodied energy, weight plays an important role (Mateus *et al.* 2013). Therefore, new lightweight building systems such as Light Steel Frame (LSF) have emerged as a promising solution for low-rise buildings.

In the last 20 years, there has been growing interest in LSF both for residential and industrial applications due to the main advantages offered compared to traditional construction techniques (Grubb *et al.* 1999, Abouhamad and Abu-Hamd 2019). LSF is an offsite construction system which relies on the optimization of the shape in favour of the lightness, thus facilitating the transportation and construction phases. Furthermore, the possibility to preassemble the profiles in panels and volumes offers construction time benefits. Moreover, as a dry construction system, it also has a great potential for circularity e recyclability.

Even though there is a general understanding of the cause-and-effect link between a building's environmental performance and its energy needs, the same link is not immediate for embodied

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energy. Hence, is necessary to provide benchmarking values also for the embodied energy (Gervasio *et al.* 2018). In recent years, many researchers have focused on building performance calculation within a life-cycle perspective, investigating and comparing different types of buildings, construction materials, and techniques. Life Cycle Assessment (LCA) is a quantitative approach to measure and analyse products and processes' environmental impacts. According to ISO 14040/44:2006, the LCA methodology usually consists of four main steps: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), (iv) interpretation of results. EN15978 regulates the application of LCA in construction works considering environmental, economic, and social aspects of sustainability.

Besides some review articles have been published concerning LCA applied to LSF buildings, they usually followed the traditional review approach. Therefore, a shared and recognized methodology to perform the review is needed. Considering the growing reputation of offsite construction systems and particularly LSF both in the scientific community and in the construction market as a reliable system in terms of environmental impacts and sustainability assessment (Smith and Quale 2017, Buzatu *et al.* 2020, Tavares, Soares, *et al.* 2021, Thirunavukkarasu *et al.* 2021) the purpose of this work is to give an overview and interpretation of the existent literature.

Through a systematic literature review, the studies on LCA methodology applied to LSF buildings are investigated, understanding methods, highlighting limitations, tools, and trends, thereby enabling practitioners and researchers to gain knowledge on the already researched areas and identifying existent literature gaps. The paper is organized as follows: the second section presents the research questions and the process followed for the systematic literature review. The third section introduces the review of the selected works, highlighting the methodological choices in performing LCA. The paper concludes with a discussion of the main findings in the fourth section, identifying literature gaps and suggesting future research directions.

## 2 METHODOLOGY

This study contributes to the existing literature by synthesising previous scientific works about the application of LCA methodology to LSF buildings through a systematic literature review. Xiao and Watson (2019) recognise the need to perform a systematic literature review to find the current state and gaps of the topic through the breadth and deep analysis of the existing high-quality literature. In this paper, the systematic review follows the methodology found in the literature, which consists of four main steps: the definition of the scope and research questions, the definition of inclusion and exclusion criteria and a synthesis of the findings.

Once the scope of the work has been defined, the authors designed three research questions: 'What are the methodological choices made to perform an LCA of LSF buildings?' and 'What is the environmental performance of LSF buildings?', 'What promising opportunities for future research can be identified?'. To answer the research questions, the authors queried two frequently used databases – Scopus and Web of Science. To gather and analyze a significant and high-quality sample of papers, different spelling (i.e. cold-formed" OR "coldformed" OR "cold formed") and different terms (i.e. cold formed, light steel frame, light gauge) have been used. The search string and the inclusion and exclusion criteria are shown in Table 1.

Table 1. Construction of the search string and criteria used for the articles' selection.

| Search string | Inclusion criteria | Exclusion criteria |
|---|---|---|
| – Keywords: ("cold-formed" OR "cold-formed" OR "cold formed" OR "light steel" OR "LSF" OR "light gauge")<br>– AND ("Life cycle" OR "LCA" OR "Environmental impact")<br>– Search in: title, abstract, keywords<br>– Document type: articles and review articles (Peer-reviewed) | – Articles/review articles investigating the building sector<br>– Articles/review articles investigating environmental LCA of LSF buildings | – Full text not available<br>– Articles not published in peer-reviewed journals<br>– Articles not written in English |

The databases' query was executed on 18 December 2022. The literature identification process retrieved 49 articles from SCOPUS and 42 articles from Web of Science, a total of 91 articles. After removing 34 duplicate articles, 57 articles remained for the abstract screening phase.

Through the abstract reading, the relevance of each article within the search objectives has been evaluated with the inclusion and exclusion criteria. Accordingly, 28 articles were out of scope and related to other disciplines (i.e. metallurgy, chemistry, structural engineering) thus leaving 31 articles for full-text analysis. Once the full-text reading has been completed, the criteria have been applied again: 3 articles were not readable, while 10 articles were investigating LSF buildings but environmental LCA. Since the 10 articles don't meet the criteria, they were not included in the deep review. The remaining 18 articles were analysed to identify the methodological choices made in performing LCA on LSF buildings, considering the first three phases of LCA according to ISO 14040/44:2006. A schematization of the methodology used to narrow down the number of articles from 91 to the final sample of the 18 deeply reviewed papers is presented in Figure 1.

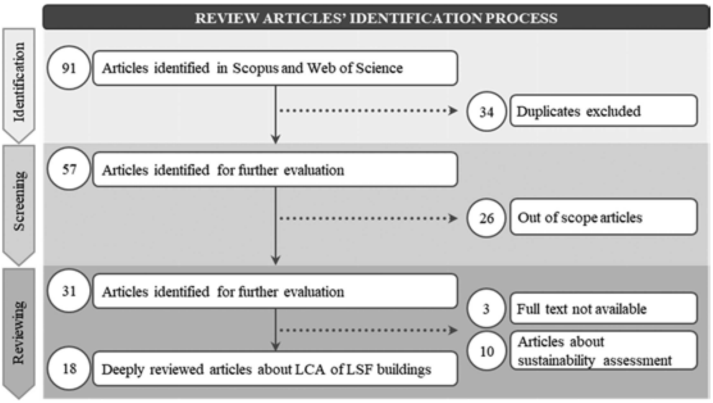


Figure 1. Flow chart for the identification of the reviewed articles according to inclusion/exclusion criteria.

The papers have been analysed to identify methodological choices in performing LCA on LSF buildings to enable researchers and practitioners to gain insights into previously researched areas and identify research gaps. The data have been collected in a comprehensive table divided according to the first three steps of the LCA.

## 3 LIFE CYCLE ASSESSMENT OF LIGHT STEEL FRAME BUILDINGS

With the rapid growth of LCA studies in the building sector, also review papers have been published to summarize the progress. Although, the review articles published concerning LCA applied to LSF buildings follow a traditional reviewing approach. In this section, the results of the systematic literature review of the 28 identified articles are presented to address the search objectives. Among the 28 reviewed articles, 18 works are related to the application of environmental LCA to LSF buildings; the remaining articles are not concerning the specific topic, although they are considered relevant for the reviewed literature body. Within these 10 works identified, Soares et al. (2017) published a traditional literature review highlighting key advantages and drawbacks of LSF in terms of energy efficiency and thermal performance. Many studies focused on Life Cycle Energy Assessment, Gervásio et al. (2010) published a parametric study on different insulation levels of a residential LSF building, confronting operational and embodied energy. The study highlighted that in 16 years the operational energy can overcome the embodied one. On the same page, Santos et al. (2014), focused on the LSF operational energy by optimization of thermal bridges and improvement of thermal inertia, thus addressing "life-cycle design". Other works focused on the calculation of Life Cycle Cost or the adoption of multidimensional methods, acting on the life cycle's risks (Zeynalian *et al.* 2013, Çelik and Kamali 2018, Abouhamad and Abu-Hamd 2019, Sen *et al.* 2021, Noorzai *et al.* 2022). Also considering the structural performances, Lu (2016) and Usefi et al. (2021) addressed the sustainability assessment of LSF.

Considering the 18 articles related to the application of LCA to LSF buildings, the analysis follows the first three main steps of the methodology suggested by ISO 14040/44:2006. The main methodological choices described in the reviewed papers in performing LCA have been synthesized in Table 2. First, the goal and scope definition is presented, highlighting the type of building, the type of study performed, the lifespan, the geographical location, the functional equivalent/unit and the system boundaries. Then, the tools and databases used to create the inventory of input and output flows (LCI) have been highlighted: we found that there isn't a harmonized inventory data collection methodology. Lastly, the choices about the environmental impact assessment (LCIA) are reported. According to this structure, the results are presented in the following paragraph.

### 3.1 *Goal and scope definition in the reviewed literature*

Within the body of reviewed literature, two types of studies have been identified (i) a baseline study (non-comparative) used to assess individual project performances, (ii) a comparative study to compare the environmental performances of different construction systems. On one hand, some methodological choices are shared across the literature, but many others are different and need to be deepened. There is a general agreement on the selection of 50 years lifespan of the building, only one study proposes 90 years. Among the 18 works, the residential building is the most investigated. Considering the building locations, many areas of the world have been covered. Some studies addressed the buildings' environmental impacts in different scenarios and locations (Tavares *et al.* 2019, Tavares, Gregory, *et al.* 2021).

In performing LCA, the definition of the life cycle stages included in the system boundaries is fundamental and can affect the results. According to EN15978, the life cycle stages are: (i) product stage (A1-A3), which includes the provision of materials, products and energy; (ii) construction (A4-A5), which includes transport to the building site and installation; (iii) use (B1-B7) includes also maintenance, repair, replacement, refurbishment and operational energy and water use; (iv) end-of-life (EoL)(C1-C4), includes deconstruction/demolition, transport to waste processing and disposal; (v) benefits and loads beyond the system boundaries (D), this module allows to take into account the net impacts and benefits of reuse, recovery or recycling after demolition.

Considering the non-comparative approach, both a whole case study building and a single component have been analysed. Both Tuca et. al (2012) and Zygomalas and Baniotopoulos (2014) focused on a whole building, one calculating the impact of the maintenance process and the other highlighting the type of environmental impact caused by LSF, which mainly affects natural resources and human health. In the last years, Liu et al. (2022) addressed a new demountable and modular LSF wall, highlighting the environmental impact advantages of a reusable module. Highlighting the benefits associated with recycling and reuse, Abouhamad and Abu-Hamd (2020) included in the analysis also the module D, finding that Global Warming Potential (GWP) is reduced by 15.4% while the embodied primary energy is reduced by 6.22%, accordingly, the environmental impacts of LSF are considerably lower than conventional construction systems. Using the same case study building, Abouhamad and Abu-Hamd (2021) proposed a new framework to facilitate the decision-making process in selecting sustainable design alternatives.

Recycled steel is used in the production of new steel thus, the relevance of module D in steel buildings is confirmed by many comparative studies. Vitale et al. (2018) calculated that LSF has a better environmental performance than reinforced concrete and brick wall buildings, considering the profiles' recovery the performance can increase up to 24%. On the same page, Dani et al. (2022) published a comparative study in New Zealand between LSF and timber frame buildings. Using a cradle-to-cradle approach, the authors showed that when module D is considered, LSF has lower emissions: the difference is 1.69 kg $CO_2$ eq/$m^2$/year.

Many comparative studies showed the environmental advantages of timber frames in different applications and locations when module D is excluded (Gong *et al.* 2012, Rodrigues and Freire 2014, Crafford *et al.* 2017, Li *et al.* 2021). Broadly speaking, the literature agrees on the better environmental performance of LSF among traditional construction systems. For example, some studies highlighted the environmental advantages of LSF when compared to masonry buildings (Iuorio *et al.* 2019, Bianchi *et al.* 2021, de Oliveira Rezende *et al.* 2022).

Table 2. Analysis and synthesis of the reviewed literature.

| N. | Author(s) | Goal and Scope definition: Case study | Type of study | Lifespan | Location | Functional Equivalent/Unit | System Boundaries: P | C | U | EoL | BLC | LCI: Databases | Tools | LCIA: Environmental impacts |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Gong et al. (2012) | R | CS of 3 systems | 50 years | Beijing, China | Building designs, same function and design plan | • | • | • | • | | Ecoinvent; SinoCenter; CAI; data manufacturers/ literature | SimaPro; Designer's simulation Toolkits | PE and $CO_2$ emissions |
| 2 | Tuca et al. (2012) | R | NCS | 50 years | Timisoara, Romania | Whole building | | • | | • | | EU databases | SimaPro | According to Eco-Indicator 99 |
| 3 | Rodrigues and Freire (2014) | R | CS of 3 systems | 50 years | Coimbra, Portugal | 1 $m^2$ of living area over a period of 50 years | | • | • | • | | Tool's database; data from manufacturers and literature | SimaPro 7; Energy Plus | Non-renewable life-cyclePE, CC, OD, TA, FE, ME |
| 4 | Zygomalas and Baniotopoulos (2014) | R | NCS | 50 years | Greece | 1 $m^2$ of living area over a period of 50 years | • | • | • | | | Ecoinvent; ETH-ESU 96; manufacturers' data | - | According to Eco-Indicator 99 and CML 2 baseline 2000 |
| 5 | Crafford et al. (2017) | R | CS of 3 systems | 50 years | Cape Province, South Africa | Quantity of materials required to build the roof | • | | • | • | | Ecoinvent 3.1 | openLCA 1.4.2 | According to CML baseline impact assessment method version 4.4 |
| 6 | Vitale et al. (2018) | R | CS of 2 systems | 50 years | Vaticano, Italy | The total floor area of the building: 130 $m^2$ | • | • | • | • | • | Ecoinvent 3.0.1; data from manufacturers | SimaPro 8.0.2; Epix7 | Respiratory inorganics, Global warming, Non-renewable energy |
| 7 | Johnston et al. (2018) | I | CS of 2 systems | - | Malaysia | - | • | | | | | ICE database; Ecoinvent; manufacturers' data | - | Embodied energy, $CO_2$ emissions |
| 8 | Iuorio et al. (2019) | R | NCS; CS of 2 systems; | 50 years | Naples, Italy | 25$m^2$;1 $m^2$ for the comparison. | • | • | | • | • | Data from SimaPro 7.3; Ecoinvent 3.0.1; EPDs; manufacturers' data | SimaPro 7.3 | GWP, OPD, POCP, AP, EP, NRE |
| 9 | Tavares et al. (2019) | R | CS of 4 systems | - | Different scenarios | One inhabitant (hab); 1 $m^2$ of gross floor area. | • | • | | | | ICE 2.0; Manufacturers' data | - | Embodied energy and greenhouse gas emissions |
| 10 | Abouhamad and Abu-Hamd (2020) | E | NCS | 50 years | Cairo, Egitto | 1 $m^2$ of building area per year | • | • | • | • | • | Tool's database | Athena Impact Estimator v5.04-0100; eQUEST | GWP, AP, OPD, EP, HHP, POCP, PE and fossil fuel consumption |
| 11 | Tavares, Gregory, et al. (2021) | R,O | CS of 4 systems | 30 years | Lisbon, Berlin, Stockholm | $m^2$ of built area; total building stock. | • | • | • | • | | Ecoinvent 3 | - | non-renewable energy and global warming |
| 12 | Tavares, Soares, et al. (2021b) | R | CS of 4 systems | 50 years | Portugal | U-value | • | • | • | • | | Ecoinvent 3; Market data | SimaPro V8.0 | AD, ADFF, GW, OD, PO, AC, EU and Non-renewable energy (NRE) |
| 13 | Li et al. (2021) | R | CS of 5 systems | 50 years | China | kg $CO_2$ eq/$m^2$ | • | | | | | - | - | $CO_2$ emissions |
| 14 | Bianchi et al. (2021) | R | CS of 3 systems | - | Brazil | 1 $m^2$ | • | | | | | Tally database | Autodesk Revit, Tally | GWP, AP, OPD, EP, SFP, PED, NRE, RE |
| 15 | Abouhamad and Abu-Hamd (2021) | E | CS of 3 systems | 50 years | Cairo, Egitto | - | • | • | • | • | • | EPDs | - | Use of non-renewable primary energy resources, GWP |
| 16 | de Oliveira Rezende et al. (2022) | R | CS of 2 systems | - | Brazil | GWP Performance of the whole structural frame | • | • | | | | Ecoinvent 3.6; site observation data; previous know-how | openLCA v.1.7 | GWP |
| 17 | Liu et al. (2022) | M | NCS | - | - | Specimen 90-60-90 | • | • | | • | | Ecoinvent database | Simapro 9.0 | GWP and non-renewable energy |
| 18 | Dani et al. (2022) | R | CS of 2 systems | 90 years | Auckland, New Zeland | kg $CO_2$ eq/$m^2$/year. | • | • | • | • | • | LCAQuick database | LCAQuick V3.4.4 | GWP |

M: Module; R: Residential, I: Industrial, O: Office and E: Educational; CS: Comparative study, NCS: Not Comparative Study; P: Production, C: Construction, U: Use, EoL: End of Life, BLC: Beyond Life Cycle.

Also, the comparison between hot-rolled steel and LSF in a portal frame of industrial buildings performed by Johnston et al. (2018) highlighted the better economic and environmental performances of LSF, which allows 33% of steel savings.

Besides the comparison with different construction materials, the potential of LSF as a prefabricated construction system has been addressed by Tavares, Soares, et al. (2021): prefabricated construction has a lower environmental impact (except for abiotic depletion for LSF) compared to conventional construction systems. The comparative studies analysed, in summary, show that LSF represents a good alternative to traditional construction systems.

### 3.2 *Life cycle inventory in the reviewed literature*

The uncertainty of LCA results occurs also when the inventory phase is performed because of the missing foreground data. Addressing the LCI phase, it must be highlighted the complexity of the data collection of the material flows through the system boundaries. Most of the studies gathered data with the help of well-known databases, such as EcoInvent or databases already included in the LCA tools used to perform the analysis. In some contributions also Environmental Product Declarations (EPDs) have been used as a data source.

Many studies contributed to the LCA literature through primary data collection directly from manufacturers. In performing an LCA, different calculation tools are used to address the environmental impacts. From the literature, it can be observed that in the first publications, the main tool used is SimaPro while in the last years, the increasing sensitivity on the topic allowed the spread of new simplified tools specialized in building applications, often connected with BIM instruments.

### 3.3 *Life cycle impact assessment in the reviewed literature*

In all the studies analysed, the environmental impacts calculated and considered are different. Among others, the entire body of reviewed literature focused on the calculation of the GWP. Although, as many parametric studies highlighted, when performing an LCA it is appropriate to give a complete overview of the performances in all the impact categories, especially in comparative studies. Highlighting a better or worst performance between different materials considering only one specific environmental impact category can lead to misleading conclusions.

## 4 CONCLUSIONS

This systematic literature review has provided an overview of the key methodological choices made by researchers in performing environmental LCA on LSF buildings. In this section, some observations on the reviewed literature are made and research gaps are identified, thus providing guidelines for future research that can contribute to the progress of the scientific debate on the topic. The following propositions mirror the main conclusions of our analysis:

- The review has shown that there is a lot of effort invested in comparative studies. Although, they are not performed considering the same boundary conditions (i.e. different building layouts). In some cases, critical information in goal and scope definition is completely absent;
- The results obtained by different studies are not comparable because they have been conducted with different methodologies, also considering the location. Concerning this, there is a need to develop georeferenced and structured data related to the specific construction system;
- The calculations may vary significantly depending on the data collection, geographical location, scope, and methodology used. These items should not be used to compare results between buildings out of the same scope;
- The comparative studies aim to demonstrate the better environmental performance of a construction technology compared to another. In doing so, some fundamental features of LSF such as recyclability and durability are often not considered;
- In comparative studies, different assets of the system boundaries lead to different results. According to the potential recyclability, further developments are needed to assess the LCA of LSF buildings with a cradle-to-cradle approach which also considers module

D. The potential recyclability of structural elements is fundamental in net-zero buildings since they contain up to 60% of the total embodied energy (Berggren *et al.* 2013). Therefore, the cradle-to-gate analysis should be revised considering also the new European policies on the minimum recycled content;

– Further experimental studies with realistic data and coherent methods are needed to implement and develop reliable and georeferenced benchmarking in different scenarios.

Considering the above, generical statements about the use of specific materials based on not harmonized methodologies and not related to a specific scenario should be revised. Nonetheless, the construction market, asks the scientific community for guidance and comparisons between different construction materials using the right KPIs. In response to this need, the authors are investigating an embryonic project (ARCADIA - ENEA) developed at the Italian level on some material supply chains focused also on the construction of a materials database. In conclusion, the authors want to turn the reader's attention to three main future research directions, LSF durability, its potential use in recladding applications and the need to perform the whole LCA.

Steel durability is rarely considered in comparative studies, especially when steel is compared to wood. In this regard, the authors consider it fundamental to deepen the LCA of LSF through the exploration of different end-of-life scenarios considering that the lifespan of steel is higher than the building's one. The matrix of the scenarios should be recalibrated with meticulous work of sensitivity analysis.

According to the authors' experience, future research in the application of LCA to LSF buildings can be done considering the potential application in buildings' recladding. The authors believe that the application in this context could highlight the LSF benefits among other solutions. Lastly, few studies addressed the potential of LSF also in terms of economic sustainability. Given the advantages of this construction technology, further research is suggested in developing multicriterial methods to perform a whole LCA of LSF, addressing all the various aspects of sustainability.

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# Author Index