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.

PROCEEDINGS OF THE EIGHTH INTERNATIONAL SYMPOSIUM ON LIFE-CYCLE CIVIL ENGINEERING (IALCCE 2023), 2-6 JULY 2023, POLITECNICO DI MILANO, MILAN, ITALY

Life-Cycle of Structures and Infrastructure Systems

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Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

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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National Council of Italian Engineers

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Association of Engineers of the Province of Milan

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American Concrete Institute

AICAP
Italian Association of Reinforced and Prestressed Concrete
Associazione Italiana Calcestruzzo Armato e Precompresso
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fib
The International Federation for Structural Concrete

IABMAS
International Association for Bridge Maintenance And Safety

IABMAS Italy
Italian National Group of IABMAS
International Association for Bridge Maintenance And Safety

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FAZLUR R. KHAN PLENARY LECTURE

Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Net-zero and lightweight steel technologies for the construction sector: Overview and case studies in Italy

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ABSTRACT: The construction industry is responsible for approximately 25% of global emissions, about a third of which are associated with the construction process, being a voracious steel consumer, accounting to 50% of global demand. Given these impacts, there is an urgent need for the construction steel chain to define a realistic decarbonization path. In this context, the paper focuses on a promising technology, the Light-weight Steel Frame (LSF), providing an overview coupled with real applications. LSF and drywall techniques have been shown around the world to result in cost-effective and sustainable buildings under different aspects: fast in construction, seismically resistant, high levels of thermal and acoustic performance, energy efficient, and aesthetic value. The publication also addresses a review of the latest regulations and methodologies for sustainability and carbon neutrality assessment, to clarify challenges and contributions that the steel company can provide to the construction sector in terms of sustainability and circularity.

1 INTRODUCTION

From houses to bridges, hospitals, and skyscrapers, the construction industry is responsible for approximately 37 percent of CO_2 global emissions, about a third of which are associated with the construction process, and for around 34% of total energy consumption (United Nations 2022). Therefore, the reduction of energy consumption and the use of energy from renewable sources in the building sector constitute important measures needed to reduce the European Union's energy dependency and to reach carbon neutrality by 2050, as defined in the European Green Deal, in 2019 (European Commission 2021a). To achieve this ambitious goal, it is urgent to drastically reduce harmful emissions in the construction sector, improve its efficiency and complete its circular transition, which is still struggling to become a consolidated and stable mechanism. For this change to take place, however, it must be conceived not only as an environmental or economic project but as a new cultural project for Europe, capable of triggering a real systemic change with its aesthetics, combining design and sustainability. Sustainable construction is a relatively new subject with which many of those involved in planning and construction are not familiar. It has been covered in numerous publications, but a limited number of them present specific measures for implementing sustainability in the steel building and construction industry.

Light Steel Frame (LSF) solutions are becoming increasingly popular in construction practice in response to the need to work on a heterogeneous and energy-intensive building stock and to meet the new demands of the construction market in a flexible, versatile, industrialized, and sustainable manner. Off-site industrialization, reduced construction time and costs, and aesthetic and performance quality are the strengths of cold-formed profile solutions for the building industry. These technologies provide flexible and aesthetically expressive constructions both from a morphological-architectural point of view and in terms of room adaptability, allowing the design of tailor-made solutions that meet people's needs. This publication aims to review the latest regulations and methodologies for sustainability and carbon neutrality assessment, to clarify

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challenges, opportunities, and prominent contributions that the steel company can provide to the construction sector in terms of sustainability and circularity, thanks to lightweight steel technologies.

After the introduction in section one, 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 sustainability in buildings. Section 3 presents the steel industry's reply to the European New Green Deal, with a focus on LSF solutions as a suitable construction technology to reach the current energy efficiency requirements and targets of the construction sector. Section 4 presents the results of applied research on case studies realized in LSF to verify the level of implementation into the practice of this technology, with a focus on an Italian residential case study. Finally, Section 5 provides conclusions and inputs for improvements and further works in order to complete the framework of challenges and opportunities of the steel construction industry to reach the carbon neutrality target and to realize sustainable buildings.

2 SUSTAINABILITY AND CARBON NEUTRALITY FOR CONSTRUCTION SECTOR

2.1 *Regulations and standards for certification and assessment*

Energy production and consumption significantly impact climate change due to their contribution to atmospheric emissions of CO_2 resulting from fossil fuels. Decarbonization and sustainability have been since decades the key points of the European regulation frameworks, in particular, the reduction of energy demand in buildings through the adoption of an energy efficiency policy is a key pillar of the European Union (EU) climate and energy strategy.

In the European Union (EU), energy production and use is responsible for 80% of all GHG emissions, accounting for about 40% of EU's final energy and 36% of CO_2 emissions, buildings are associated with a significant untapped energy saving potential due to outdated construction practices, use of inefficient systems or appliances and lack of effective technical control systems, even if there are already in the market various passive and active solutions that can limit this energy waste in buildings. (Camarasa et al. 2019).

In the EU, buildings have been an integral part of the EU energy and climate policy for several years. Energy efficiency policies for buildings can take the form of regulatory or control instruments, building codes, consumer information campaigns, and economic or financial incentives.

The "SAVE" Directive (93/76/EEC) of 1993 represents the first major EU policy on energy efficiency. The Directive required the Member States to draw up and implement programs to improve energy efficiency, with the aim to limit CO2 emissions and to promote the rational use of energy. Since 2000 the Commission has published several Energy Efficiency Action Plans laying out its strategic vision and proposing actions such as new policies or strengthened existing measures. In 2006 the European Commission published its second Energy Efficiency Action Plan (Fawcett et al. 2019) with the scope to control and reduce energy demand and to take targeted action on consumption and supply with the intention to save 20% of the annual consumption of primary energy by 2020 compared to baseline energy consumption forecasts for 2020. This objective corresponded to achieving approximately a 1.5% saving per year up to 2020.

The first cohesive European legal act on energy policy in buildings was the Energy Performance of Buildings Directive (EPBD, 2002/91/EC) which introduced a joint energy performance calculation methodology for buildings. Since its adoption, the EPBD has been closely connected with the EU climate targets and has been aligned to reflect their progressive evolution. In this context, the core aim of the directive – to systematically enhance the energy performance of buildings and to increase the level of renovations – has remained unchanged since its introduction.

In 2009 the European Commission presented the recast of the EPBD (2010/31/EC, EPBD Recast) with the aim to strengthen some original EPBD provisions and capture additional energy savings and introduced for the first time the concept of nearly zero energy building (NZEB), defined as a building of very high energy performance, where the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources produced on-site or nearby.

Later, a targeted revision of the EPBD (2018/844/EU, EPBD) was launched as part of the clean energy for all Europeans package and adopted in 2018 (European Parliament 2018). This new

Directive came into force introducing targeted amendments to the previous EPBD version aimed at accelerating the cost-effective renovation of existing buildings, with the aim of a decarbonized building stock by cutting its net CO_2 emissions by at least 55% by 2030, compared to the 1990 levels, and to become climate neutral by 2050. To reach these goals, the EU then adopted a new strategic agenda for 2019-2024, including the European Green Deal (EGD), a package of strategic initiatives. The EGD is the environmental plan of the European Union divided into 116 points, in which all the Member States (MS) declare their commitment to undertake urgent and ambitious interventions to tackle climate change and environmental challenges to limit global warming to 1.5ºC and further biodiversity losses. The main objective of this ambitious climate regulation is the achievement of the legally binding national target of achieving zero emissions by 2050, as well as the 2030 interim target of a 55% reduction in emissions compared to levels of 1990. The EGD is not limited to outlining environmental policy but rather uses environmental protection as a pretext to define and promote attention to a wide range of sectors: from transport to construction and from agriculture to industry (European Commission 2019b).

In this framework, the EU Commission launched in October 2020 the Renovation Wave initiative with the intention to double the European renovation rate of buildings by 2030 and to maintain it in the following years. This strategy highlights several points of intervention with a precise timeline to make existing buildings energy efficient by reducing the consumption of energy and resources, with the use of circular economy approaches, low environmental impact strategies to improve the quality of indoor environmental and air quality, and the buildings' comfort for end users and it can be summarized in the following four main priorities: (i) decarbonization of heating and cooling systems; (ii) tackling energy poverty and inefficiency; (iii) renovation of public buildings such as schools, hospitals and offices; (iv) application of holistic approach throughout the building lifecycle, from project design and financing to completion and subsequent maintenance.

The Renovation Wave strategy aims to reach the target of doubling up the renovation rate of the built environment by 2030, applying existing measures such as energy performance certificates, long-term strategies, financial incentives, and technological innovations but also introducing some new instruments, such as mandatory minimum energy performance standards and the development of a roadmap to 2050 to reduce carbon emissions throughout the buildings' life cycle. In December 2021, the Commission has proposed to align the rules for the energy performance of buildings with the European Green Deal and decarbonize the EU's building stock by 2050 (European Parliament 2021). To achieve this, it is necessary to promote a rapid energy conversion of the building stock, favoring deep renovations and transformation into "nearly zero energy buildings" (nZEB). In the same year, the EC launched, as part of the Green New Deal package, also the New European Bauhaus, to foster spaces for discussion and experimentation around the theme of physical spaces, a creative and interdisciplinary movement to rethink European cities, making them more functional and accessible to all. The program of the new European Bauhaus is divided into three phases: collective design, realization, and dissemination. The first design phase ended in June 2021 with the identification of the first five sites where the program has to be applied, representing the beginning of the second phase of realization. The aim is to make methods and solutions available to designers and the community that can be shared and replicated on a large scale. From January 2023, the third and final phase of Bauhaus will begin, in which space will be given to disseminating and sharing good practices to as wide an audience as possible, including outside Europe.

At the Italian level, the Italy Tomorrow Plan (Piano Nazionale di Ripresa e Resilienza - PNRR) approved in April 2021, foresees reforms and investments to be implemented in the span of the next five years in key sectors. The plan is developed around three strategic axes shared at the European level: digitalization and innovation, ecological transition, and social inclusion, and is divided into 16 components, grouped into 6 missions. Relevance has been set for the construction sector in Component 3 (Energy Efficiency and Renovation of Buildings) of Mission 2 (Green Revolution and Ecological Transition) with which energy efficiency can be strengthened by increasing the efficiency of buildings, which suffers from a building stock more than 60% of which is over 45 years old, both in public and private Italian buildings. The measures included in the PNRR aim to provide a boost to the economy and employment and to promote social resilience by improving comfort, energy saving, and seismic risk prevention of buildings (Sesana 2022a).

2.2 *Methodologies and tools framework*

Besides the regulations, also the tools for the analysis of the sustainability levels of buildings play a fundamental role in their application, as it required particular care to align them. An overview of such instruments is presented in this section, to better understands the methodologies currently in use and the new initiatives with high potential to support the carbon neutrality goal.

The implementation of the regulations outlined in the previous section, especially in relation to buildings, led to the need to define energy-environmental assessment and certification systems as an essential method to improve energy efficiency, minimize energy consumption and enable greater transparency regarding energy use. To provide a complete overview of such methodologies and tools, this subsection focuses on compulsory tools, as required by current regulations, and those that are voluntary or in the process of being defined, for sustainable nZEB design with practical indications and recent updates for their use.

Over the years, the EPBD has employed a diverse set of policy tools, but the most well-known mandatory one for buildings is the energy performance certificate (EPC). The EPC was introduced at the European level by Directive 2010/31/EU and the recent EPBD 2018/844 strengthened the certification system for existing buildings with the inclusion of a mandatory recommendations report listing improvement measures and their priorities (European Parliament 2010).

The Italian version of the EPC, the so-called Attestato di Prestazione Energetica (APE), is considered mainly as an informative document that certificates the energy performance of a building using a rating scale from A4 to G, which provides general recommendations for energy efficiency improvements. If properly drafted, the APE certification could become a powerful market tool for creating demand for energy efficiency in buildings by providing recommendations for cost-effective, time- and cost-optimized improvements (Sesana 2022a).

Complementary to the EPC and structured according to a long-term renovation roadmap outlining intervention measures for the improvement of energy performance based on quality criteria, the Building Renovation Passport (BRP) was introduced for the first time in the revision of Directive 2018/844/EU (Toth et al 2022). The purpose of this tool was then detailed in the Renovation Wave strategy, as a support tool for owners and investors to better understand and plan interventions, providing a clear roadmap for gradual renovation over the lifetime of a building. According to this, the Building Passport can be described as a repository of relevant building-related information covering the physicality, management, financing, valuation and ownership of buildings with the structure defined by two key elements: a data archive part, usually called a logbook, and a renovation roadmap for identifying the actions to be implemented for a deep renovation in terms of time, cost and building technologies to be used.

Alongside experiences with building passports, there have also been initiatives related to establishing digital passports for single material or products in general (Digital Product Passport, DPP). The implementation of such tool could facilitate tracking and tracing materials and compiling information in one unique database. It is supposed to deliver information on the origin, composition, repair, and dismantling options of a product, as well as on its handling at the end of its service life. However, there are several open questions regarding the DPP's final design and its implementation. For instance, any future DPP information requirements should be ideally designed in a way that manufacturers, which are the most important source of product information, and other stakeholders perceive them as an advantage and not as an additional burden, to create business models and intrinsic motivation. Therefore, implementation options for digital product passports need to be evaluated to allow a circular flow of materials through the active engagement of all the actors involved (Sesana 2022a).

An important contribution to the issue of tools and methodologies for construction in the field of efficiency and sustainability has been made by the voluntary environmental assessment and certification developed worldwide over the past twenty years with different approaches: some with prerequisites to gain optional credits in relation to the specific context, others with prescriptive approach or performance-based requirements according to building types. As a result, it can be difficult and time-consuming in terms of time and quality to determine which standards, certifications, and assessment programs are most reliable and applicable to a particular building being various per building types or goals' project. For this reason, the EC within the EGD initiative launched a common framework for assessing the sustainability performance of buildings: Level(S) (European Commission 2019), with the aim to create a common approach based on the integration of current certification tools with a whole life cycle approach. This system relies on existing standards and circularity principles using a limited number of indicators to measure the effects of carbon, materials, water, health, and comfort. Although Level(s) is not a certification scheme, its simple structure aims to facilitate existing schemes to use the same language and facilitate assessment methods and data comparison between projects (Ferrari et al 2022).

3 THE STEEL INDUSTRY REPLIES TO THE EUROPEAN NEW GREEN DEAL

Steel is one of the most important engineering and construction materials. However, the industry now needs to cope with the pressure to reduce its carbon footprint from both environmental and economic perspectives. Currently, the steel industry is among the three biggest producers of carbon dioxide, with emissions being produced by a limited number of locations; steel plants are therefore a good candidate for decarbonization.

For this reason, the European steel industry has set itself the main goal of investing in research and development to rethink its production processes and achieve substantial reductions in emissions to remain competitive and contribute to the achievement of carbon neutrality by 2050.

Steel is a sustainable material, and in some cases, the most sustainable choice, since it is a circular material, being reusable and recyclable repeatedly and allowing a long service life.

In response to the EGD, the more feasible option for the steel sector is to move to a much more circular system by 2050, replacing 30 Mt of the current 92 Mt of primary steel production with secondary production and reducing emissions by 57 Mt CO2 per year by mid-century to meet the targets (EUROFER 2021).

Conceiving steel management as much as possible from a perspective of sustainability and circularity means intervening in the process of production, use, and end-of-life of this material whose properties allow theoretically infinite recycling. However, given this characteristic, a complementary path to increase the level of sustainability of the material is to optimize its use, minimize processing waste, or facilitate the recovery of components to be sent for recycling. It is necessary to rethink on one hand the technologies in use in Europe to produce steel, but at the same time also to encourage the use of scrap, instead of producing a virgin product, with a circular approach. It follows, however, that the efforts required to implement these changes must be supported by all sectors that use steel either as a base material or as a component of other products. The annual volumes recorded in 2019 of the steel demand are distributed percentage-wise between construction and infrastructure (42% of demand), followed by the transportation sector (31%), machinery (16%), and finally a range of other steel products (11%).

Although recycling steel for production not from virgin material is advantageous, particularly in terms of preserving materials and reducing the extraction of raw materials, there is another lower-impact option that is gaining popularity not only in research but also in practice: the reuse of the steel materials and components themselves. From this perspective, the built environment can thus be seen as a veritable bank of materials including the stored energy and carbon emissions in building materials, components, and structures. Their targeted separation and recovery during demolition can avoid the passage of more than 70% of materials from landfills in addition to contributing to the circular economy goals should such materials, components, or structures be reused in new construction. Compared to other recycling options, therefore, it offers additional environmental and economic benefits but often requires higher initial investment costs. Recent research conducted on the technical feasibility of this type of reuse in both quantitative and qualitative terms has confirmed the possibility of achieving the goals that the steel industry has set for itself but has also identified the barriers that currently limit the spread of this practice.

In the case of steel-based structural steelwork and building components, reuse avoids the negative impacts associated with scrap recycling in steel production. Avoided scrap can come from individual fabricated components or entire steel assemblies or steel parts separated by composite elements (McKinsey Global Institute 2022). The market for recycled steel building products is still small because the effort associated with their reconditioning and CE marking often makes the process more expensive than recycling the materials. In addition, reusing individual structural steel components is more difficult because they are generally optimized and manufactured for a specific building project. Therefore, most successful reuse projects are whole building relocations, repairs and renovations or extensions of steel structures, or on-site reuse. The overall benefit of building steel reuse depends on the widespread adoption of this approach in design and construction practices by all stakeholders in the building process. Designers should understand how to incorporate reclaimed materials into new design applications and how to optimize their designs for deconstruction and reuse, while manufacturers should consider reclaimed steelwork as a possible source of materials. Of course, there are also some technical challenges associated with this issue that would require the integrated design to avoid increased deconstruction costs and time.

3.1 *Light steel frame solutions*

The importance of steel in the building construction industry derives from the combination of lightness and loadbearing capacity but also from factors like prefabrication, fast construction time, and 'dry' building site. These aspects, in addition to their lightness and performance, make steel a sustainable building material with great potential for the future. In the last 20 years, Light Steel Frame used as a structural material have become a widely used solution for residential and industrial buildings, especially due to the main advantages that offer in comparison with traditional building materials (Martins et al 2013). The lightness of the system implies the use of less material, facilitates the transportation phase to the construction site, and offers benefits in terms of time construction phase by offering preassembled solutions and demonstrating their great potentialities in terms of circularity. All the main advantages that the technology offers, make LSF the main competitor for traditional structural construction systems (Abou Hamad et al 2019).

In Italy, prefabrication and dry construction are a long tradition in commercial, industrial and public construction, but have been less frequently applied to residential construction, however, recently the benefits of this building technique have opened many interesting opportunities for application in residential buildings. The dry construction system is based on the prefabrication and mechanical assembly of several functional layers made up of elements that are supplied to the worksite certified and ready to be assembled on a light and resistant framework made of steel, wood, and reinforced concrete. In the past, the idea of prefabrication was associated with a limited catalog of building components to combine to form a complete building, characterized by modular rigidity. This aspect was thus seen as a limitation to customization and design creativity and as the reason for the simplicity and seriality of low architectural and technological quality buildings.

Nowadays prefabrication foresees elements manufactured with the precision of industrial production for beams, pillars, uprights, cross-pieces, walls, floors, roofs, unique works or works that can be repeated on a large scale and the architecture/industry nexus, which felt impossible for a long time, has found a real possibility for development. Moreover, the LFS can provide a high level of adaptability to different architectural solutions; high energy and acoustic performance and safety in case of earthquake and fire; industrialization of the system, and the lightness of dry solutions combined with the great durability of steel constructions.

In literature, the LSF is defined as a construction system based on structures composed of cold-formed steel elements, produced by cold-forming or press-bending thin steel sheets (Lawson 1999). The intrinsic characteristics of the construction system, make it competitive compared to traditional systems, this is because the LSF represents a clear point of contact between construction and industry, through the standardization of products, processes, and design. the purely industrial approach of this construction system has proven effective in terms of economic advantages and sustainable performance: compared to traditional construction techniques, the most obvious advantage of LSF is the lightness of the system.

It is estimated that the weight of an LSF building can weigh up to ten times less than a building made with traditional techniques. The physical properties of cold-formed steel make it an exceptionally sustainable material: resilient, durable, and adaptable, steel allows it to operate in a wide range of buildings and environments. For example, its ductility, strength, and lightweight make it a suitable material for construction in windy and seismic locations. The ability to treat steel against corrosion phenomena, for example with zinc coating, provides the material with durability properties that exceed even one hundred years. Steel also does not emit volatile organic compounds and is 100% recyclable, a feature that significantly reduces life cycle costs.

The advantages of the LSF system are not limited to the peculiarities of the production technique and the material; but benefits vary depending on the project site, the complexity of the work, and the quality of the result. In recent years there has been a progressive increase in the number of catalog solutions offered by companies producing cold-formed profiles, and their diffusion is increasing not only for new constructions but also for renovations (Sesana 2022b).

4 AN ITALIAN RESIDENTIAL CASE STUDY WITH LIGHT STEEL FRAME SYSTEM

A study was conducted in 2021, in collaboration with Fondazione Promozione Acciaio (FPA), Italian promotion and communication entity of steel in construction, on a selection of recent mostly residential case studies, mainly located in Italy and some outside the European Union, meeting the above-mentioned regulations and methodologies with LSF solutions.

In this section, one case study in Italy, as representative of the study, is presented as a proof of concept of the LSF feasibility construction and to underline its potentialities in terms of efficiency and sustainability for buildings.

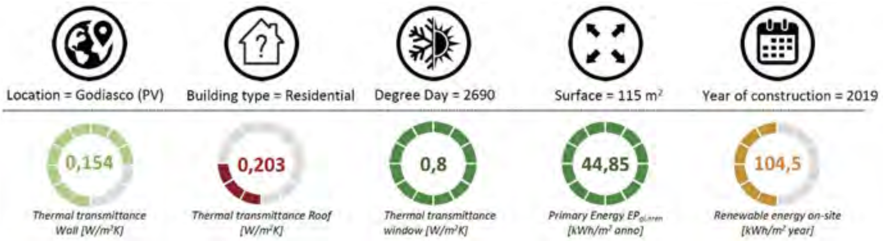

Figure 1. Graphical summary of the main data of the residential case study realized in LSF in Italy.

Slash House is the name of the high-energy-efficient residential building realized in 2019 in Godiasco Salice Terme (PV).

The main data about the location, the climatic context, the year of construction, and geometry are summarized in the first line of the graphical summary (Figure 1), while in the second row, there are represented both the envelope performance in terms of thermal transmittance for wall, roof, and window and the main KPIs for energy (Primary energy and Renewable energy produced on-site). The load-bearing structure is separate from the curtain wall structure: thus the insulating capacity of the walls, curtain wall, and windows and doors was optimized. For the walls, a drywall construction system constituted by C profiles in LSF was used with an outer cladding of reinforced concrete slabs and an inner cladding of gypsum plasterboards. The high-performance envelope is completed with the installation of triple-glazed windows, including the curtain wall, with Argon gas in the double-glazing units and selective low-emissivity treatment. Strategies for optimizing envelope performance include flat roofs with hanging greenery that provide excellent performance in both summer and winter due to the inertia provided by the soil.

In order to achieve nearly zero energy consumption, the system plant foresees efficient summer-winter air conditioning, both in the generation and distribution of heating or cooling fluid, supplemented by mechanical ventilation with heat recovery.

The air-conditioning system is an air-to-air heat pump with internal splits, supplemented by a controlled mechanical ventilation system with total heat recovery and all of the house and system is managed by automatic control.

The house is not connected to the gas grid; electricity is produced by the photovoltaic system composed by 24 modules of about 6 kW, integrated in the roof.

The house, with a total non-renewable primary energy requirement of 44.85 kWh/m^2 per year, reached an energy performance class of A4 and reach its target of nearly-zero energy building covering the overall energy demand with the renewable energy produced on-site.

5 CONCLUSIONS

The paper presents an overview of the major role of the steel construction sector in making sustainable and efficient buildings for the future and reducing the environmental impact of the construction sector in order to achieve the European goal of climate neutrality by 2050.

From the analysis of the presented work, it emerged that despite the effort of the steel industry to adapt their products and building systems to the European goal of carbon neutrality, there is an urgent to identify: (i) the most suitable methodology to design net-zero energy buildings; (ii) commons tools to manage, share and calculate data in a digitalized way; (iii) a common data framework to evaluate the energy performance of the building using the LCA methods.

The LSF solutions implemented in the case study represent a valuable solution to reach the NEB goals thanks to the described potentialities and advantages in comparison with traditional solutions. The LSF systems in fact offer more flexibility compared, for example, to concrete and brick walls and are, therefore, less sensitive to dynamic stress and it is also suited to earthquake-proof designs. The “dry” and “light” aspects, therefore, seem to address all the requirements of modern living, from design to comfort, taking their place in the environment with a light footprint.

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