UNIVERSITY OF MODENA AND REGGIO EMILIA
Department of Sciences and Methods for Engineering

Doctorate School in
INDUSTRIAL INNOVATION ENGINEERING
Curriculum in Engineering Management

Innovative strategies for sustainability of the industrial sector

Candidate:
Eng. Simona Marinelli

Scientific Tutor:
Prof. Eng. Bianca Rimini

XXXIV Period

Alla vita,

capace sempre di sorprendere.

Contents

Sommario

L'industria ha un ruolo centrale da svolgere nella transizione verso la sostenibilità sociale, economica e ambientale guidata dalla Commissione europea e dal Programma delle Nazioni Unite per lo sviluppo.

Nonostante un crescente interesse verso un settore industriale di qualità, affidabile, sostenibile e resiliente, le singole imprese incontrano ancora diverse barriere che ostacolano una transizione conforme ai tre pilastri della sostenibilità. Di solito vengono adottate strategie comuni, ma il raggiungimento degli ambiziosi obiettivi di sostenibilità resta ancora una sfida.

Partendo da una panoramica della letteratura scientifica e delle politiche europee e internazionali, il presente lavoro mette in luce strategie alternative e innovative per promuovere un'industria sostenibile.

Attraverso l'analisi di casi di studio vengono dimostrati i benefici ambientali e il miglioramento del benessere umano, con un focus sulle piccole e medie imprese spesso trascurate rispetto alle grandi aziende energivore. L'obiettivo è l'identificazione di soluzioni praticabili ed efficaci per le industrie che seguono una strategia multi-approccio a più livelli, dimostrando che agire sull'intero settore industriale può contribuire in modo significativo al raggiungimento degli obiettivi di sviluppo sostenibile.

I risultati ottenuti possono aiutare i professionisti e le parti interessate a integrare pratiche sostenibili nel loro modello di gestione.

Abstract

Industry has a central role to play in the social, economic, and environmental sustainability transition driven by the European Commission and by the United Nations Development Programme.

Despite a growing interest in moving towards a quality, reliable, sustainable, and resilient industrial sector, individual firms still encounter several barriers that hamper a transition compliant with the three pillars of sustainability. Common strategies are usually adopted but reaching the ambitious sustainability target levels still remains a challenge. Starting from an overview of the scientific literature and of European and International policies, the present works highlights alternative and innovative strategies for promoting a sustainable industry.

Through the analysis of case studies, environmental benefits and human well-being improvements are demonstrated, with a focus on small and medium-sized enterprises often overlooked compared to energy-intensive and large companies.

The objective is the identification of viable and effective solutions for industries following a multi-approach strategy at several levels, showing that acting on the overall industrial sector can significantly contribute on achieving the Sustainable Development Goals. The obtained results can help practitioners and stakeholders to integrate sustainable practices into their management model.

1. Introduction

Industry is one of the major contributors to the EU final energy consumption and to energy-related carbon dioxide emissions.

Global primary energy consumption is currently growing at its fastest rate and industry accounts for about 25% of the total (**Figure 1**).

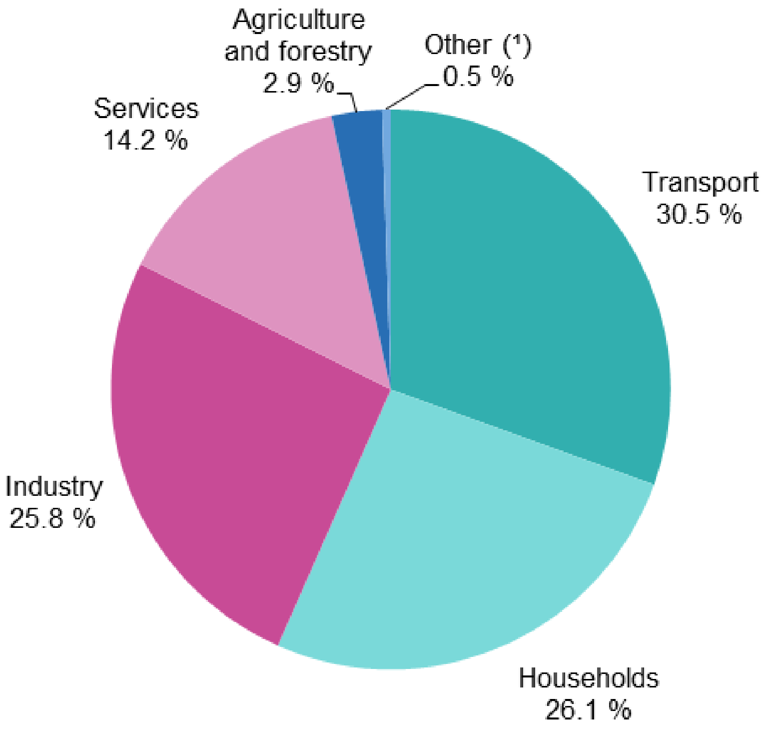


Figure 1. Final energy consumption by sector (Eurostat, available at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Final_energy_consumption_by_sector,_EU-27,_2018_(%25_of_total,_based_on_tonnes_of_oil_equivalent).png, last access: 28.02.2022).

To the primary energy demand corresponds a growing increase in emissions of greenhouse gases released into the atmosphere and in particular of CO_2 emissions (**Figure 2**) of which industry is responsible for about the 36% (Allwood et al., 2010).

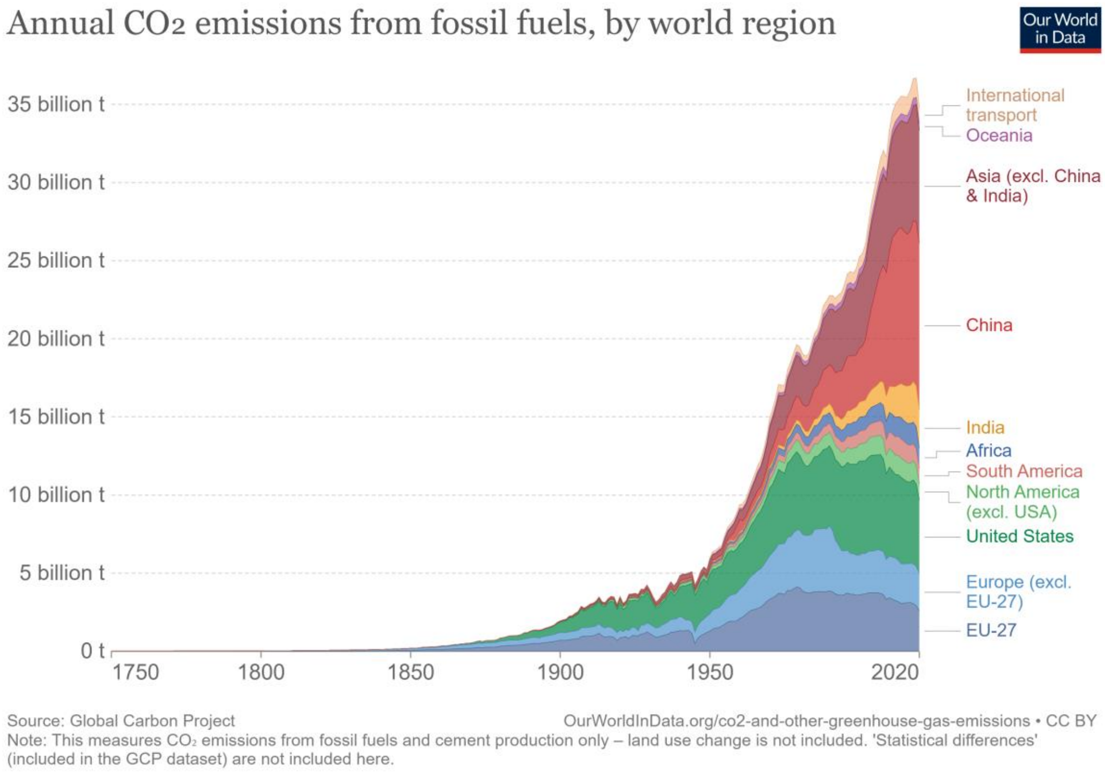


Figure 2. Annual CO_2 emissions from fossil fuels by world region (Global Carbon Project, available at: https://ourworldindata.org/grapher/annual-co-emissions-by-region, last access: 28.02.2022).

Significant benefits will arise from its energy efficiency improvements: the potential for improved energy efficiency is estimated close to 12–17 % (European Commission, 2016). Almost a quarter of Small and Medium Enterprises (SMEs) in Europe already enable the energy transition by offering green products or services (Commission, 2020).

Nevertheless, even though industry has already made considerable efforts in the environmental field, achievement of sustainable industrial development will require further substantial improvements in all three pillars, including in its environmental performance.

Many attempts have been made in order to decarbonize the production processes and the manufacturing operations (Henao et al., 2019; Menghi et al., 2019), largely responsible for the environmental impacts of firms (Augusto de Oliveira et al., 2019). This trend has been largely promoted by the diffusion of Energy Management Systems (EnMSs) and the adoption of regulation and codes as the ISO 50001, aimed at making the productive activities of the industrial sector more efficient in the use of energy leading to the reduction of greenhouse gases emissions (Sousa Lira et al., 2019).

SMEs are normally excluded by EnMSs (Kalantzis and Revoltella, 2019), although in the EU there are 22 million SMEs which represent 99% of all companies (EEFIG, 2015) and in Italy about 50% of Energy Intensive Enterprises are SMEs: 14% of Micro Enterprises, 40% of Small Enterprises and 46% of Medium Enterprises (ENEA, 2020).

Therefore, it’s clear that those of SMEs is a crucial sector for the sustainable development of the industrial sector.

The Eurobarometer (Kuceba and Zawada, 2020) clearly shows that:

- just under two thirds of SMEs across the EU are minimizing waste (65%) and saving energy (63%) in their efforts to become more resource efficient.
- regarding circular economy actions, 42% recycle by reusing material or waste within their company, 25% design products that are easier to maintain, repair or reuse and 21% sell their scrap material to another company.

In addition, crafts and small enterprises typically rely on their local roots and make an essential contribution to local development and social integration, by creating jobs and ensuring the transfer and continuous improvement of specific knowhow, unique traditions and historic and cultural heritage (cr@ftsman project, 2010). In this context, promoting the workers well-being and moving towards a human-centered organization model is a key factor for a sustainable development (Papetti et al., 2020). Taking this into account, a more collaboration-based and place-sensitive policy is required to maximize SME innovation across the variety of European regional contexts (Hervás-Oliver et al., 2021).

Based on this background and starting from the available literature, the present work intends to analyze some of the strategies to the decarbonization of the industrial sector, focusing on SMEs and on specific areas and to demonstrate the validity and the convenience of some strategies with respect to other through the analysis or real case studies.

More in depth, the present work aims to:

(i) surveying industrial strategies to the decarbonization, answering the question “*How manufacturing, supply chain and industrial building design could contribute to the sustainability of the industrial sector?*”

(ii) establishing a framework to set targets concerning climate change, answering the question “*Are new-built industrial facilities aligned with achievement of the 2 °C Paris climate target?*”

2. Implementing sustainability in industry

It has been clear for some time that achieving sustainable industrial development means that business and industry will have to adjust not only production mix but also its structures (European Commission, 1999).

Sustainable industrial development has been incorporated, together with resilient infrastructure and innovation, as Sustainable Development Goal 9 in the 2030 Agenda for Sustainable Development, to demonstrate that industry is not only a driver of development, but also the basis for sustainable economic growth. One of the targets of the Sustainable Development Goal 9 (Target 9.4) considers, by 2030, to upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries acting in accordance with their respective capabilities.

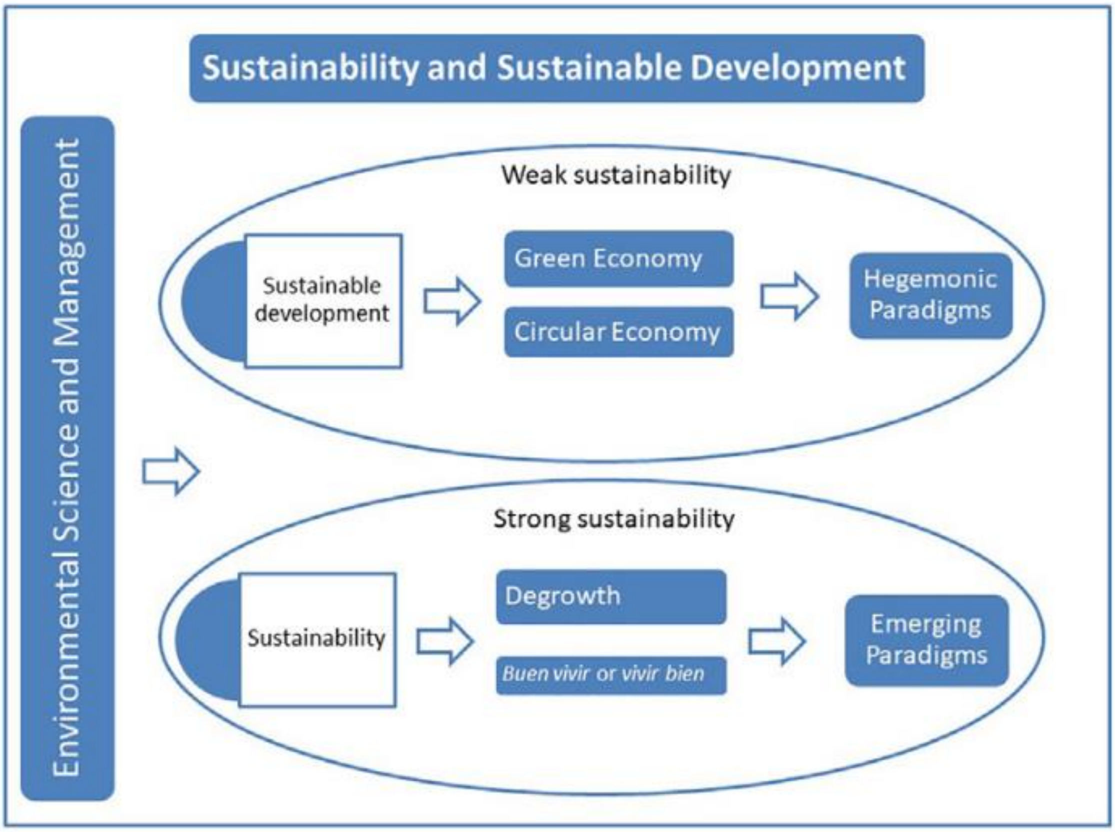


Figure 3. Weak and strong sustainability (Ruggerio, 2021).

Nevertheless, Sustainability Development deals not only with energy and emissions, but includes other relevant issues. In a recent review of principles and definition of sustainability and sustainable development, Ruggierio (Ruggerio, 2021) highlighted that, due to its imprecise definition, there is still a strong criticism of the concept of sustainable development that can be categorized into those which appear to be innovative environmental approaches, but are built upon the same weak foundations as those of sustainable development (e.g., green economy; circular economy; etc.) and those aiming to move towards strong sustainability (welfare and degrowth) (**Figure 3**).

When moving the concept to industry, this translates to satisfy all three dimensions of sustainability: economic; environmental; and social. These three pillars integrate different viewpoints of corporate sustainability such as corporate social responsibility and environmental management (Beltrami et al., 2021) (**Figure 4**).

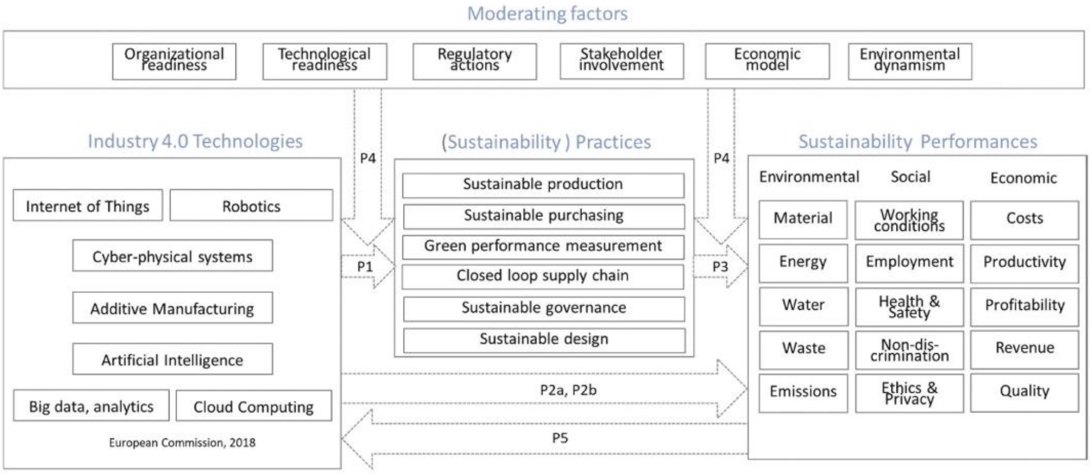


Figure 4. Conceptual framework of a sustainable industry 4.0 (Beltrami et al., 2021).

Authors defined green industry innovation into three categories: green product innovation, green process innovation and finally green management innovation (Gohoungodji et al., 2020). Green product innovation deals with the development of new or significantly improved products in response to environmental concerns. Green process innovation involves modifying manufacturing processes and systems to pro- duce environmental-friendly products. Finally, at the management level, it can be defined as the system that influences the content and nature of the technologies adopted by a company with respect to green initiatives.

Green industry development is a part of green economy, developing mode that can balance the economic growth, social stability and environmental friendliness, aiming for sustainable development (Yuan et al., 2020),

A sustainable industry integrates several aspects, which can be summarized in the macro areas: i) sustainable manufacturing products and process (Guo et al., 2020)(Gao et al., 2022); ii) sustainable supply and value chain (Masi et al., 2017; Sehnem et al., 2019); and iii) sustainable infrastructure and buildings (Espino-Reyes et al., 2020; Shivani Meher et al., 2018) (**Figure 5**). In the following sections the three aspects are addressed separately.

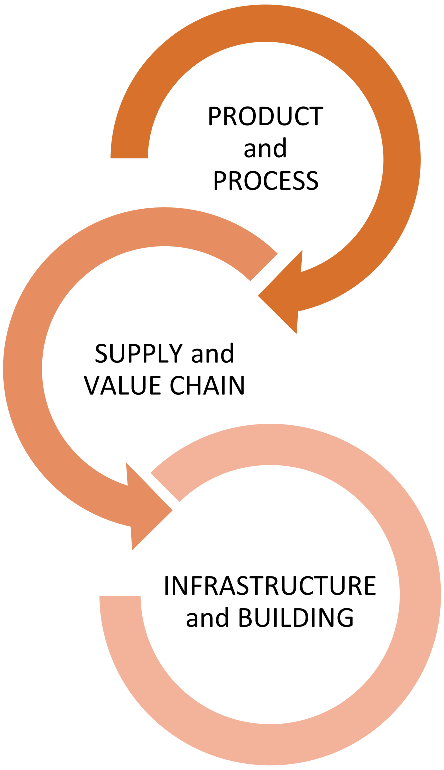


Figure 5. Concept for a sustainable industry (own elaboration).

3. Sustainable manufacturing (product and process)

Several researchers argue that one of the first and most cited or rephrased definition of sustainable manufacturing (SM) is the one proposed by U.S. Department of Commerce in 2008, which quotes as follows "*sustainable manufacturing is the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, is safe for employees, communities, and consumers and is economically sound*" (Moldavska and Welo, 2017).

Nevertheless, over the past few years, innovative definitions have been coined depending on (1) views that researchers see as important when practicing sustainable manufacturing; (2) application domains, e.g., product, process, customer, employees, etc., which are the focus of the actions; and (3) qualities of interest for different domains. The vast majority related SM to the whole product life cycle, starting from the design to the entire manufacturing process until the end-of-life stage (Ching et al., 2022), then to process, community, employees, and customers.

According to many researchers (Haapala et al., 2014; Jawahir et al., 2006; Jayal et al., 2010), a sustainable manufacturing process is significantly affected by six main elements such as (1) environmental impact; (2) manufacturing cost; (3) energy consumption; (4) waste management; (5) operational safety; and (6) personnel health (**Figure 6**).

Figure 6. The six elements of sustainable manufacturing. Own elaboration from (Haapala et al., 2014) and (Jayal et al., 2010).

Among these, the most investigated dimension is the one relative to the energy consumption and related emissions. European surveys of manufacturing activities outlined that several carbon-neutral technologies can be applied, as: Control system for shut down of machines in off-peak periods; Speed regulation; Compressed air contracting; Highly efficient pumps; Low-temperature joining processes; Energy recovery; Bi-/Tri-generation; Waste and Biomass materials for energy (ISI, 2013; Pons et al., 2013); Electrification; Deep geothermal energy; Hydrogen; Technologies for Carbon Capture, Utilization and Storage (CCUS); Circular economy and other process innovations (Bruyn et al., 2020). The choice of the most suitable technology is highly dependent on the type of industry, as highlighted in **Table 1** for some of the main energy-intensive industries.

Table 1. Examples of available technologies for the energy-intensive industries.

Sector	**Technology**	**Actions**	**Reference**

Cement and lime production	Biomass Circular economy Other	Blast furnace on bio- cokes Leveling the kilns Sealing the gaps and holes Insulating the high temperature surfaces Cooperation between lab, mine, and production units Installing the vertical shaft impactors Preventative maintenance (insulation, compressed air system) High-efficiency motors High efficiency fans with variable speed drives Optimization of compressed air systems by reducing leaks Concrete recycling	(Afkhami et al., 2015; Bruyn et al., 2020; Fellaou and Bounahmidi, 2017)
Chemicals, polymers, and fertilizers	Biomass Circular economy Electrification Hydrogen (H_2)	H_2 from biogas Higher quality plastics recycling Naphtha from waste plastic, Reduce fertilizer use Electric boiler H_2 from electrolyze	(Bruyn et al., 2020)
Iron and steel	Circular economy Electrification Biomass	More scrap recycling, replace by wood in construction Electric Arc Furnace, Electrolysis of Iron Ore Blast furnace on biocokes	(Bruyn et al., 2020)
Metal casting	Other	Recovery of heat from flue gases to heat combustion air Control of the air-fuel ratio	(Carabalí et al., 2018)

		Enrichment of combustion air with oxygen Implementation of a cogeneration system by an organic Rankine cycle Self-regenerating or self-regenerating burners that achieve a reduction in fuel consumption by 10–20% compared to furnaces without heat recovery Flameless burners Recovery of heat in the combustion gases for the preheating of the raw material	
Pet food	Other	Harmonic filter installation	(Boharb et al., 2016)
Pulp and paper	Biomass Circular economy Other	Upgrading the equipment of screening/cleaning and bleaching Steam use reduction policy of paper machine and dryer Steam ash blower replacement The motor of causticizing station is switched to an energy-efficient motor-driven system Elimination and upgrading of lime kiln Decreasing the heat used of the dryer by modifying the water evaporation section Process modification of pulp mill for electricity saving Upgrading of the equipment in the boiler and power generation system to increase power generation capacity	(Chen et al., 2012)

		Energy-efficient improvement for vacuum pump	
		Upgrading of the air compressor system	
		Variable frequency drives were applied to the trough-and-paddle mixer for adjustable speed	
		Bio-pulping application for energy saving	
		Waste tires as the derived fuel for the reduction of fuel coal use	
		Pulp and paper mill sludge as the derived fuel for the reduction	
		Upgrading the Economizer in the boiler and power generation system	
Refineries	Biomass	Biofuels	(Bruyn et al., 2020)
	Circular economy	Recycled Carbon Fuels, reduction of demand by electric vehicles	

3.1. Environmental assessment of electrification strategies for industrial sites: the case of an Italian small and medium-sized enterprise

3.1.1. Introduction

An Small and medium-sized enterprise (SME) is defined by the European Commission as one which employs fewer than 250 persons and which has an annual turnover not exceeding €50 million, and/or an annual balance sheet total not exceeding €43 million (European Commission, 2020). SME have a crucial role to play in tackling climate change. First, Europe’s 25 million SMEs represent 99% of European businesses and are the backbone of the EU economy (Hervás-Oliver et al., 2021). Second, they account for approximately 13% of global final energy consumption and related carbon dioxide emissions (Southernwood et al., 2021).

To mitigate CO_2 emission, the utilization of renewable resources is expected to grow with the wide and active implementation of electrified energy systems (Son et al., 2022).

Because electricity will become increasingly decarbonized towards 2050, a recognized potential for energy consumption and related emissions reduction in the manufacturing processes is offered by switching from fossil fuels towards electricity with the electrification of industrial processes supported by the use of combined renewable energy sources (RES), where resources abundance allows to lower the cost of electricity (IEA/OECD; and Philibert, 2017). Indeed, the use of technologies dealing with electrification, is one of the most preferred strategies applied to reduce CO_2 emissions (Bühler et al., 2019). The use of electricity often offers large efficiency benefits as well, for example in the application of heat pumps for low temperature heat. A potential co-benefit is that electrification of industry could help balancing electricity grids by offering flexibility to grid operators. Several commercially available technologies can be implemented to substitute fossil fuels for heat demand: electrode boilers, electrical resistance heating, heat pumps, steam recompression and electric arc furnaces (Bruyn et al., 2020).

Nevertheless, this strategy is not always to be preferred in terms of environmental impact. It is necessary to evaluate case by case using tools that make it possible to estimate the emissions before and after the intervention. Considering a case study involving an Italian SME, the study analyses the potential environmental benefits of alternative electrification strategies. The CO_2 emissions of all the electrification scenarios are calculated and compared with the reference scenario, using the life-cycle assessment (LCA) methodology.

3.1.2. Case study

The case study involves an Italian SME whose main consumptions are electric energy, natural gas and diesel due to activities that can be divided into the following three functional areas: I. Main activities; II: Auxiliary activities; III. General services.

The main energy consumption is the natural gas that accounts for the 57% of the total, used in four industrial furnaces for main activities as drying operations. The remaining consumptions are equally divided into electricity (21%), used firstly for main activities and secondly for general services (as conditioning and lighting) and diesel, used firstly for main activities and secondly for general services (as conditioning and lighting) and diesel (22%) used for auxiliary activities and general services (as internal goods movement) (**Figure 7**).

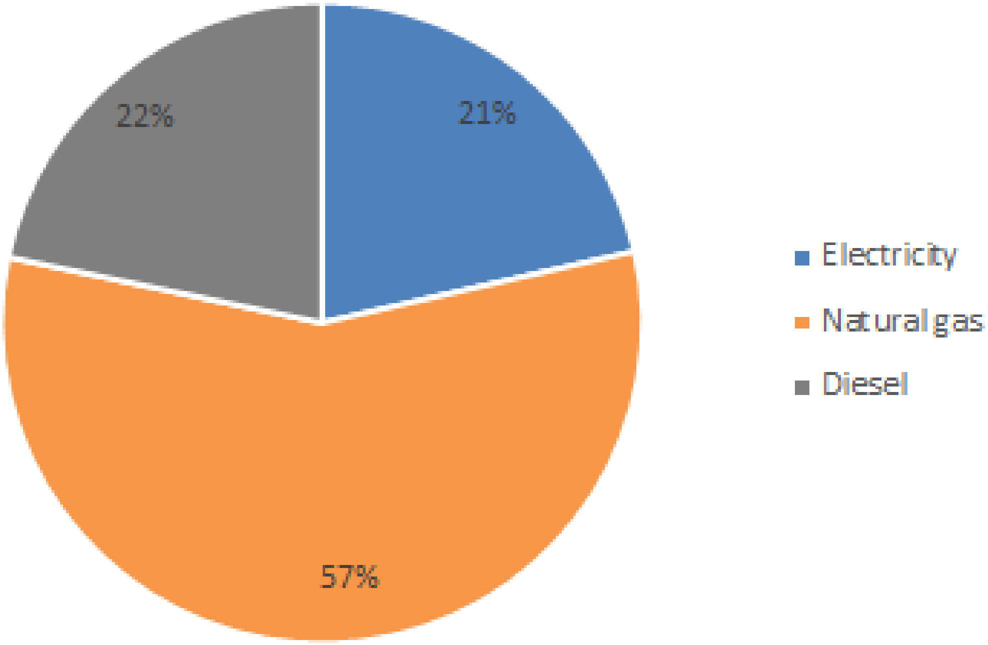


Figure 7. Annual energy consumption for energy vector (own elaboration).

In 2018 the firm involved in the present work, approached an energy audit to uncover the critical issues and plan strategies for improving the energy system. Indeed, between the developed policy tools, the Energy Service Directive (ESD) and later the Energy Efficiency Directive (EED) have advocated energy audits as an essential tool for design energy saving strategies and associated measures and for obtaining related energy cost savings (Kalantzis and Revoltella, 2019).

The study of the consumptions outlined two viable energy reduction strategies:

- reduction of lighting energy consumption by the replacement of obsolete lamps with LED units;

- optimization of auxiliary processes and plants that utilize electric energy by the installation of inverters able to regulate the energy absorption.

The thermal recovery, since the intermittent use of the four furnaces, was not considered an advantageous strategy.

The results of the analysis of the two outlined strategies demonstrated an energy reduction of about 4% against a large investment. By this, the interest to consider a different strategy: the electrification by the replacement of the equipment consuming gas.

3.1.3. Life cycle environmental assessment

In the present study, the standard methodology outlined by ISO 14040 and 14044 (ISO, 2006a, 2006b) is followed to compare the GHG emissions released by the reference scenario with those released by different scenarios: firstly, three scenarios that considers the application of alternative electrification strategies and secondly three scenarios proposed by the mathematical optimization model characterized by the creation of the energy links between firms and the integration of RES.

The functional unit (FU) is the output of the main product of the firm under study (called B1-EII) and the input data is the total energy consumed divided for energy vectors, with a lifespan of 20 years. The life cycle inventory (LCI) includes primary data for energy consumptions and energy datasets from the Ecoinvent database (Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, 2016).

The system boundaries (SB) include all the input of energy and fuels. Raw materials, maintenance operations and wastes are not included, considering that the focus of the assessment is on energy consumptions.

Since the main driver of the strategy is the reduction of CO_2 emissions, for this study is considered the Global Warming Potential (GWP) impact category based on the Intergovernmental Panel on Climate Change (IPCC) assessment method with a 20-year time horizon. The LCA is performed using the SimaPro LCA software.

3.1.4. Electrification strategies

In the specific case, the utilities available to the application of this strategy were only the four industrial furnaces. The electrification of the vehicles used for internal goods movement was not suitable because the vehicle fleet consists mainly of trucks.

For this reason, the evaluation of the electrification was performed for different furnaces electrification scenarios, starting from the reference scenario, corresponding to **Figure 8(a)**:

- Electrification scenario 0 (EL0): all the 4 furnaces are replaced by electric furnaces, corresponding to **Figure 8(b)**;
- Electrification scenario 1 (EL1): the furnace with lower power (furnace A) is replaced by an electric furnace, corresponding to **Figure 8(c)**;
- Electrification scenario 2 (EL2): the furnace with higher power (furnace D) is replaced by an electric furnace, corresponding to **Figure 8(d)**.

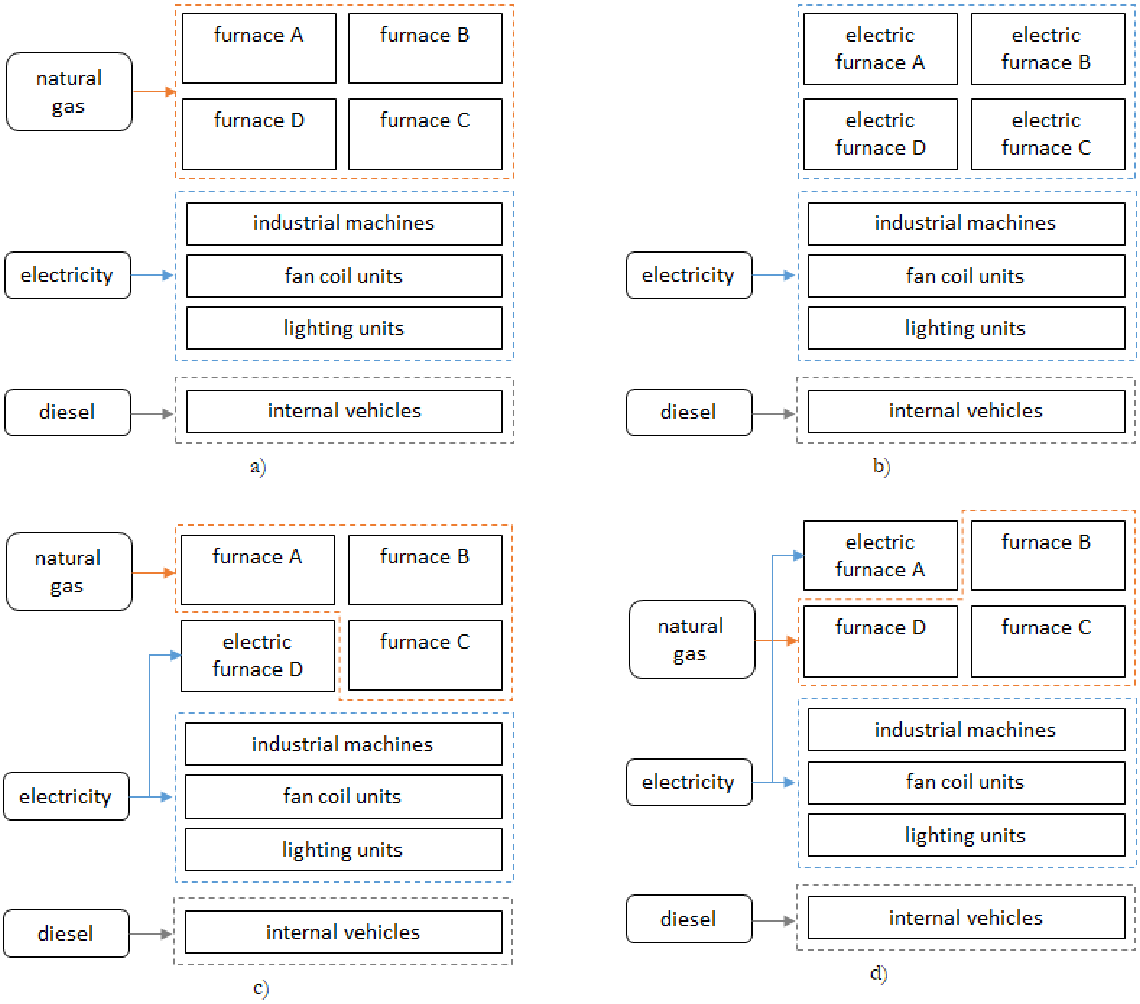


Figure 8. Reference scenario (a) and Electrification scenarios EL0 (b), EL1 (c), EL 2(d) (own elaboration).

All the strategies were considered for an assumed 20-year lifetime, with an estimation of energy consumption year by year on the basis of previous trends.

The CO_2 emissions released by the three different scenarios were calculated with the LCA analysis and compared with the Reference scenario in order to evaluate the environmental burdens.

3.1.5. Results

The environmental impact of the Reference scenario in terms of GWP is equal to 1.1E+08 kg CO_2 eq, due for the 66% to natural gas, for the 28% to electricity and for the remaining 6% to diesel used by vehicles.

With respect to the Reference scenario, the results of the analysis of the three electrification strategies show that the substitution of the four existing furnaces with electric units (Electrification scenario 0) have the potential to increase the CO_2 emissions of the 3%, despite the zeroing of natural gas in input.

An increase of CO_2 emission can be observed also in the other scenarios. An increase of the 0.3% and of the 0.7% can be observed with the substitution of furnace A (Electrification scenario 1) and of furnace D (Electrification scenario 2), respectively (**Figure 9**).

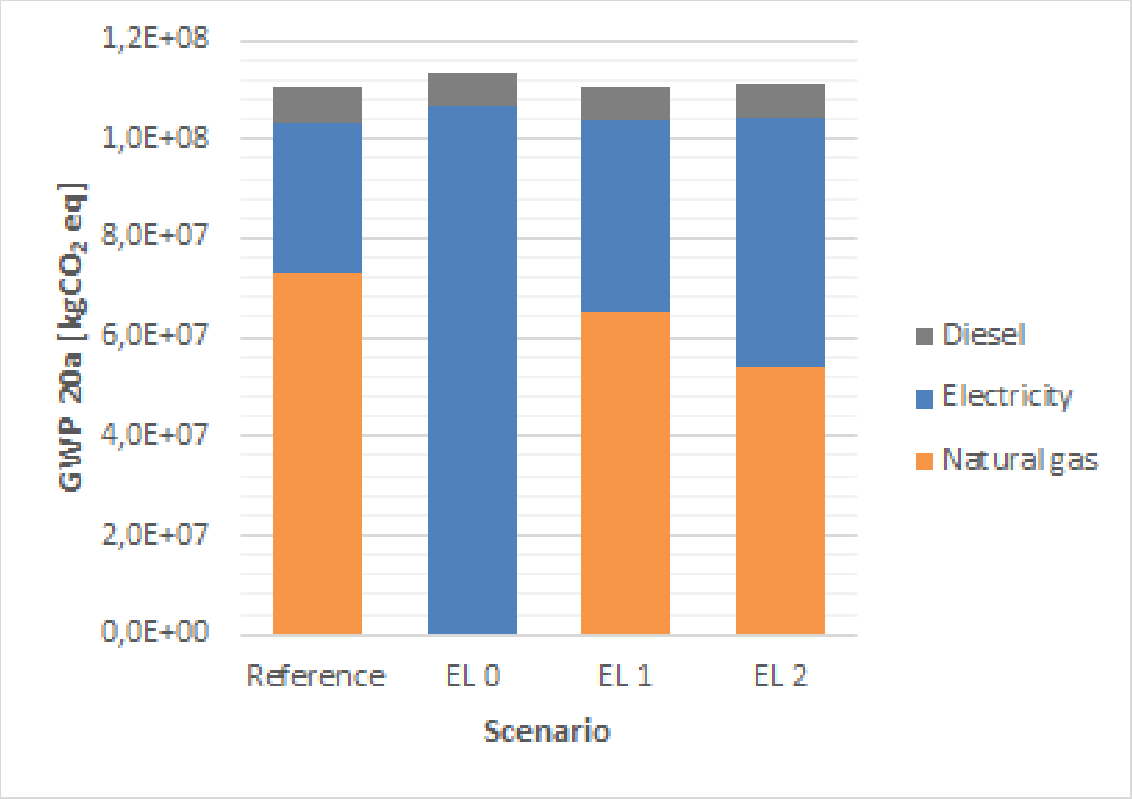


Figure 9. Overview of the electrification scenarios environmental analysis (own elaboration).

3.1.6. Conclusions

This study investigates the potential environmental benefits achieved by means of the integration of electrification strategies into a conventional manufacturing process. The study involved an Italian SME, committed to the environment preservation.

The research aims at supporting firms, energy managers and local authorities in taking decisions regarding energy efficiency and carbon emissions reduction projects.

The environmental analysis of the electrification strategies revealed that, for the electric standard Italian source, the electrification of the main energy intensive equipment (installation of electric furnaces) would not be beneficial in terms of CO_2 emissions.

The research has some several limitations. With regards to the environmental analysis, the study focuses to electricity exchanges, coming from grid or from renewable sources and the system boundaries do not include raw materials, maintenance operations and wastes. This assumption does not permit to quantify a complete environmental impact of a system and, in addition, lead to not consider all the feasible exchanges between involved firms.

4. Sustainable supply chain (SC)

A sustainable industry requires a certain degree of integration and collaboration of the end customers and of all the stakeholders along the supply chain (SC), sharing processes innovation and explaining the adoption of sustainable manufacturing initiatives (Bhatt et al., 2020). Integrating environmental objectives into the management of the operation strategy of the SC deals with a green or sustainable supply chain management (SSCM).

To improve eco-efficiency in the SC looking at a SSCM, several green practices can be adopted (Sellitto et al., 2019) that can be categorized in three main dimensions dealing with (1) innovation; (2) operations; and (3) strategy practices (Sellitto and Hermann, 2016), each of which characterized by categories based on the stage of the supply chain (upstream; internal supply chain; or downstream) as showed in **Figure 10** (Herrmann et al., 2021).

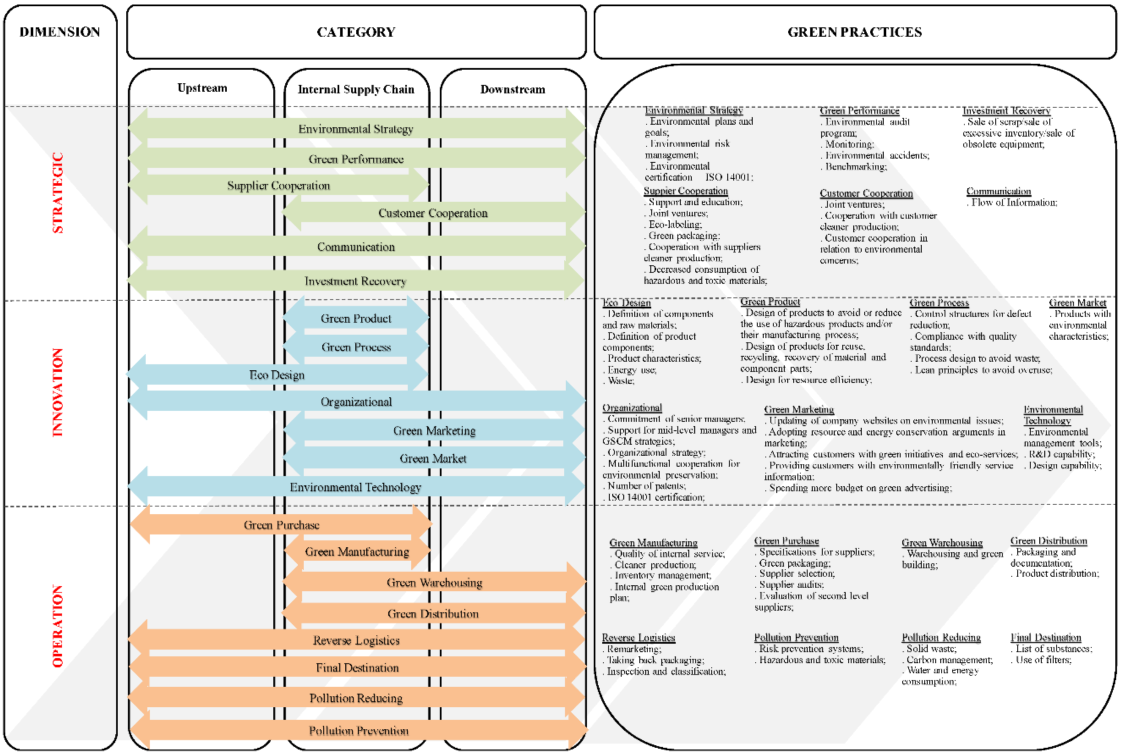


Figure 10. A conceptual framework for green practices in GSCM (Herrmann et al., 2021).

A sustainable supply chain management, achieved by the integration of green practices into the SC demonstrated to have positive impact not only on the environmental dimension, but also on the economic and social ones (Junge and Straube, 2020).

The economic dimension is positively affected by the potential compliance with legislation, the creation of a positive corporate image for the company, and the increased cooperation with SC partners. In addition, green practices as the introduction of products with environmentally friendly features, can contribute to opening up new markets and expanding existing ones. Finally, costs can be reduced through ecological operations related to externalities and information management that act on the selection of raw materials, alternative fuels and on the optimization of logistics and manufacturing activities, which also leads to an increase in reliability and flexibility in industrial processes (Sellitto and Hermann, 2019).

Concerning the social dimension, sustainable SC practices as the blockchain's traceability help through better assurance of human rights as well as fair and safe work practices (Saberi et al., 2019), or as appropriate strategies for direct digital manufacturing, which directly converts digital models to physical objects, can help manufacturers to accumulate sustainability capabilities faster (Holmström et al., 2017).

4.1. The influence of the supply chain on the environmental performance of garment products: a comparing study of two winter jackets diffused in Italian markets

Sustainability is a critical issue in fashion business operations (Choi and Li, 2015) having impacts both on environment and society (Kozlowski et al., 2014; Muthu, 2014). It has been estimated that in 2015, the global textiles and clothing industry was responsible for the consumption of 79 billion m3 of water, 1715 million tons of CO_2 emissions and 92 million tons of waste and by 2030, under a business-as-usual scenario, these numbers would increase by at least 50% (Kerr and Landry, 2017).

To meet the needs for sustainability, fashion companies are competing at different levels, mainly focusing on product design and production processes (Karaosman et al., 2017). Several strategies are used as: the improvement of the slow fashion (Jung and Jin, 2016;

Štefko and Steffek, 2018) as an alternative to the prevalent fast fashion model, even more accused to add criticality to the sustainability challenges associated with the sector (Garcia-Torres et al., 2017; Niinimäki et al., 2020); the use of recycled fibers and materials, as recycled polyester (Shi et al., 2017); the recovery of used fashion products for remanufacturing and converting waste textile into value-added products such as insulation, carpet padding, stuffing for toys and fibers for new clothing (Pensupa, 2020); the sustainable retailing as the e-commerce (S. Yang et al., 2017) or circular design approaches (Butturi et al., 2021).

Fashion brands are exploring alternatives to today's standard materials, with key players focused on more sustainable substitutes that include recently rediscovered and re-engineered old favorites as well as high-tech materials that deliver on aesthetics and function. In last years, the fashion brands, especially those very dependent on polymers, as the footwear industry, moved their interest to bio-based polymers, fully or partially made from biogenic sources such as plants and animals (Babu et al., 2013; Weiss et al., 2012). Of particular interest is the family of bio-based polyamides (PA), thanks to the possibility to be made entirely from renewable inputs such as plant oils or fibers and it can potentially replace synthetic polyamides.

Moving from raw materials, another strategy that can lead to a more sustainable business models is the development of efficient solutions for greener supply chains (Shen, 2014) and logistic flows (Seroka-Stolka, and Ociepa-Kubicka, 2019).

However, despite improvements, green product development performance remains poor in the fashion industry. In fact, the overall adoption of green materials and green products in the fashion market is still relatively limited (Guo et al., 2020) and many sustainable practices are not being widely implemented by luxury brands (Y. Yang et al., 2017). The global fashion industry is extremely energy-consuming, polluting and wasteful and, despite some modest progress, fashion hasn't yet taken its environmental responsibilities seriously enough (Amed et al., 2019).

According to several studies, one of the main drivers to move forwards a sustainable fashion is the consumers' increasing awareness of environment (Shen, 2014).

One way of identifying sustainable produced garments is by utilizing eco-labels (Henninger, 2015), as Environmental Product Declarations (EPD) and EU Ecolabels, defined as declarations able to inform consumers about the environmental impact of the offered products (Yokessa and Marette, 2019). Both declarations aim to enable and support organizations in any country to communicate quantified environmental information on the life cycle of their products in a credible, comparable, and understandable way along the entire supply-chain by using the Life Cycle Assessment (LCA) method.

The present study provides an overview on the environmental sustainability of the fashion sector by combining scientific literature review related to environmental evaluations in the fashion industries and published eco-labels and declarations overview. Secondly, it presents the LCA analysis of the conventional production of a garment by including typical aspects of items diffused in the Italian market. The comparison with the same garment produced with the use of eco-friendly materials and with a shorter and greener supply chain addresses the reader to effects that such choices could involve.

The aim is firstly, to give an overview on the existing eco-labels related to the fashion industry and secondly, to investigate the impact of eco-friendly materials and shorter and greener supply chains on the environmental performance of a garment.

4.1.1. Background and literature review

Several LCA studies have been conducted to evaluate the environmental performance of fashion business operations and products.

Henry et al. (Henry et al., 2015) reviewed several LCA studies related to wool apparel and textiles and quantified the relative contributions of different stages of the complex supply chain across production, processing, manufacture and retail over multiple countries. Van der Velden et al. (van der Velden et al., 2015) presented a LCA of a wearable smart textile device for ambulant medical therapy suggesting various eco-redesign options for environmental improvements. Bech et al. (Bech et al., 2019) investigated the environmental potential of developing a use-oriented PSS business model for Merino wool t-shirts intended for use by the British Ministry of Defence as an alternative to the present supply system based on synthetic t-shirts purchased from sportswear clothing companies.

Although the scientific research helps the industrialists to develop sustainable fashion strategies, still a restrict number of eco-friendly products furnished by an EPD or an EU Ecolabel license are available on the market. An EPD is an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products (EN ISO 14025, 2006) according to Product Category Rules (PCR). As a voluntary declaration of the life-cycle environmental impact, having an EPD for a product does not imply that the declared product is environmentally superior to alternatives.

The EU Ecolabel of Textiles products instead, meets criteria that guarantee limited use of substances harmful to health and environment; reduction in water and air pollution; color resistance to perspiration, washing, wet and dry rubbing and light exposure (European Commission, 2015).

The European EU Ecolabel Clothing and textiles catalogue (http://ec.europa.eu/ecat/ - last access 03.08.2020) counts 53 licenses under the category “Textile products” and only one license under the category “Footware” published in the year 2016 and only one in the year 2017. The licenses are distributed in 17 EU countries with a prevalence in Italy and Norway, with respectively 12 and 10 fashion brands with EU Ecolabel licenses, as shown in **Figure 11**. The companies with a higher number of licenses are an Italian company (288 licenses), producer of home textiles and an UK company (233 licenses), manufacturer of textiles for education, healthcare, transport, office, and hospitals.

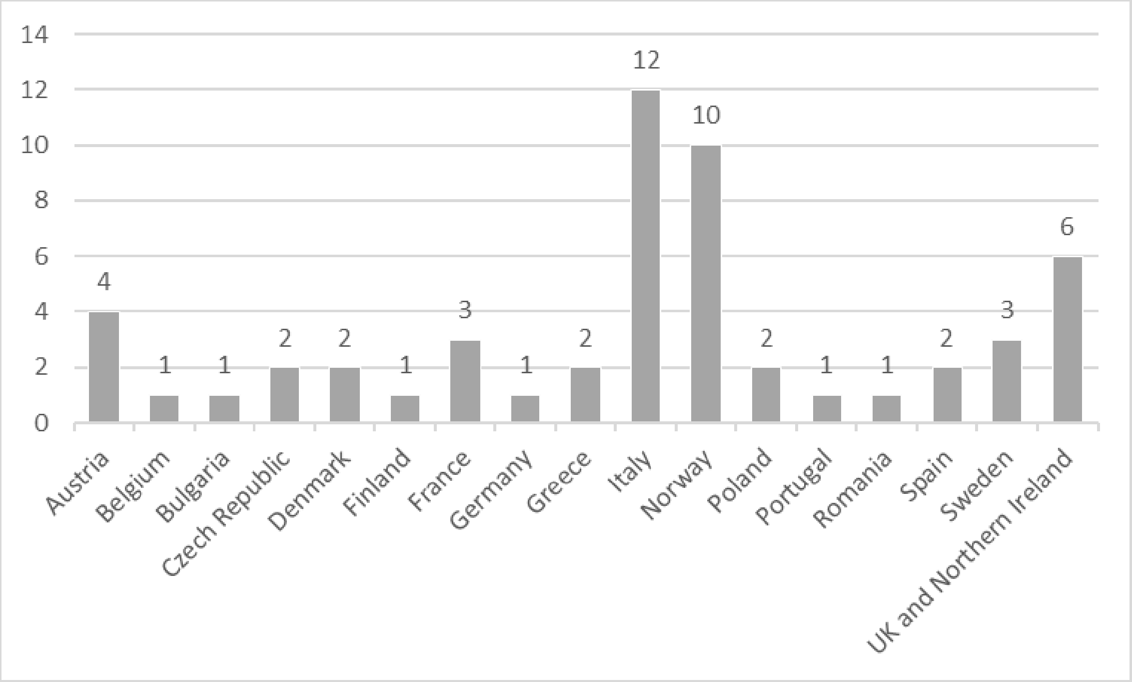


Figure 11. Geographical distribution of companies with EU Ecolabel Clothing licenses.

The European EPD database (https://www.environdec.com/EPD-Search/ - last access: 31.07.2020) lists 80 EPDs under the category "Textiles, footwear & apparel "published mainly from the year 2018, as show in **Figure 12**.

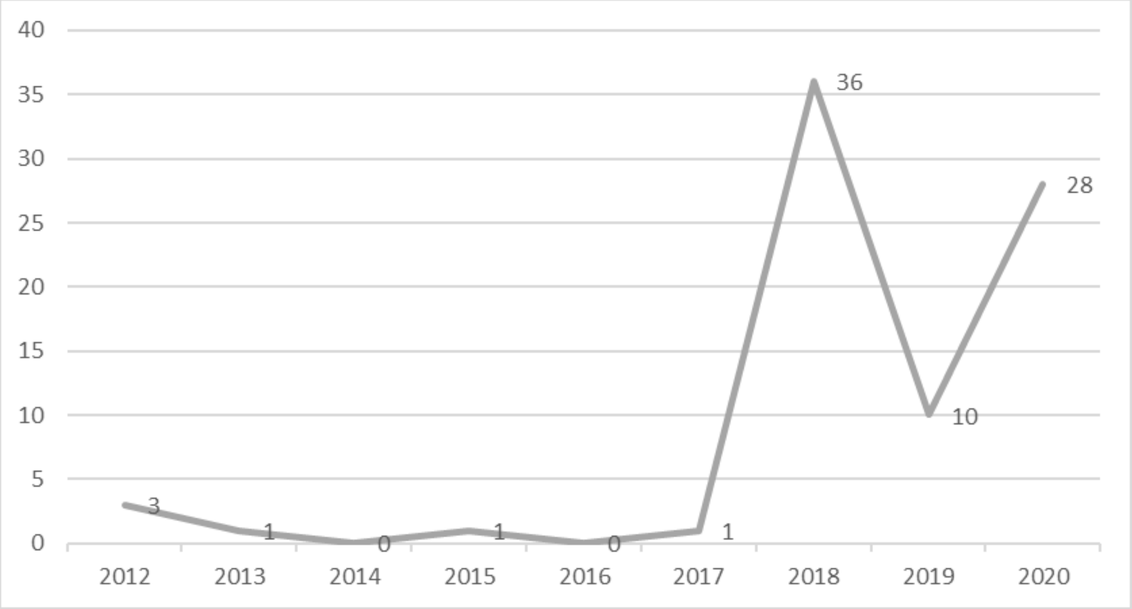


Figure 12. Temporal distribution of EPDs publication.

Italy counts the higher number of companies with products certified by an EPD (6), followed by Turkey (4) and Sweden (3) (**Figure 13**).

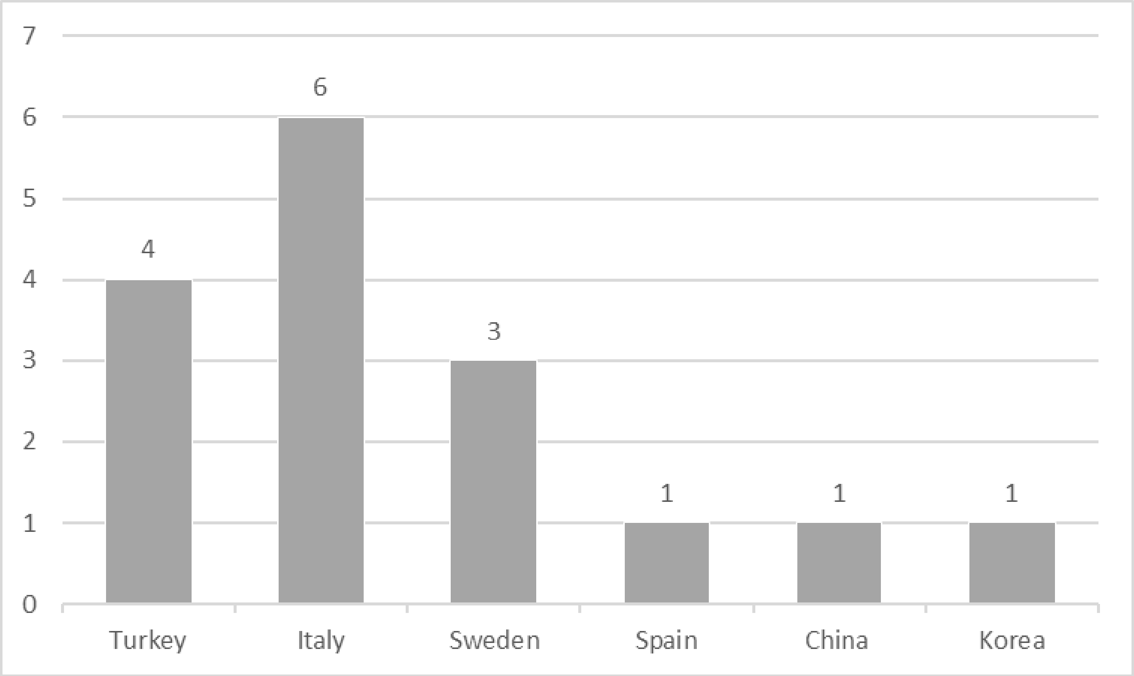


Figure 13. Geographical distribution of companies with EPDs. (own elaboration).

Turkey and Sweden have the higher number of published EPDs with two Turkish companies that published respectively 31 and 17 certificates and a Sweden company that published 12 certificates (**Figure 14**).

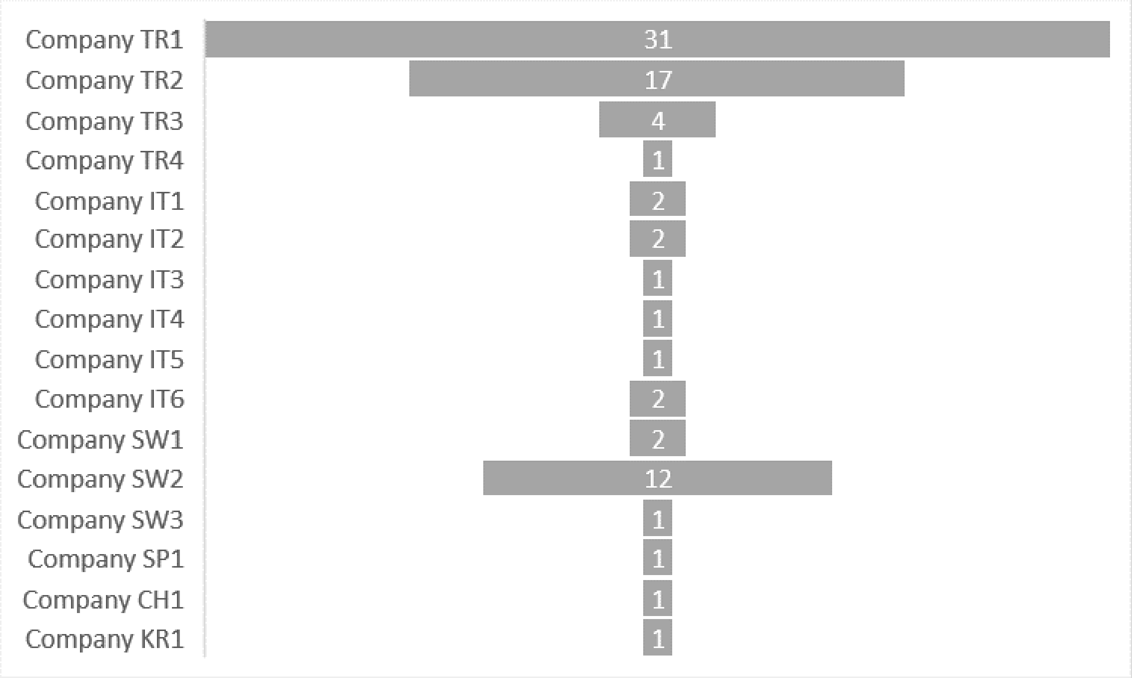


Figure 14. Number of EPDs published for each company (own elaboration).

Regarding the type of products, the most assessed are denim fabric and jeans, followed by cotton yarn and jackets (**Figure 15**).

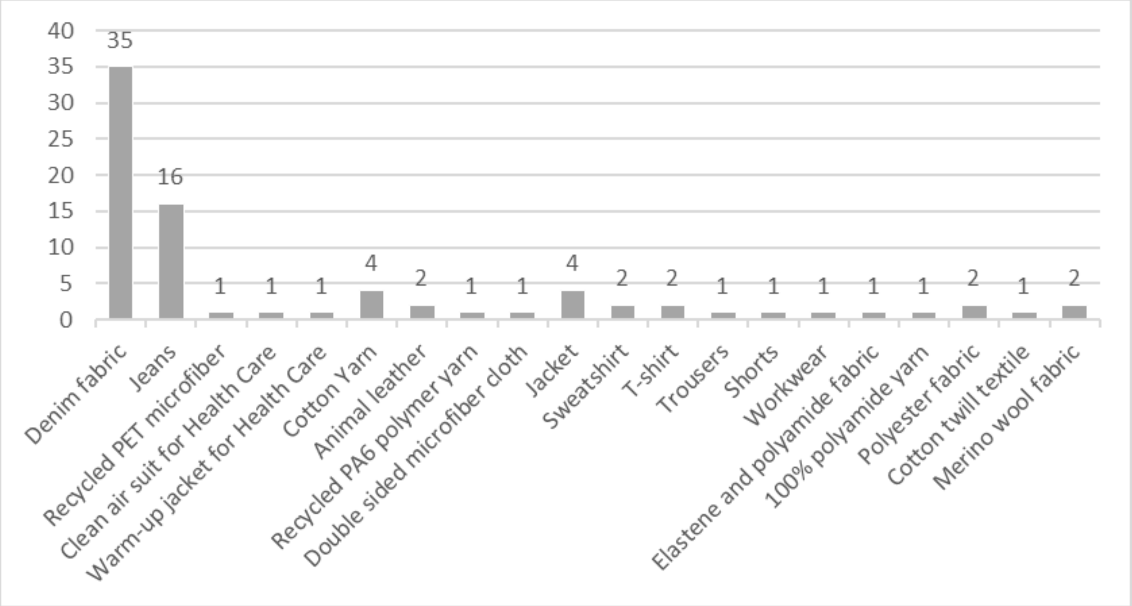


Figure 15. Type of products with EPDs (own elaboration).

Considering the huge number of companies involved in the fashion industry, from component manufacturers to final sellers, results show that there is still a lot of work to do. Obviously, it must be noticed that lots of fashion brands have an available on-line sustainability report where environmental and social issues are analyzed year by year.

4.1.2. Case study

The quantification of the environmental performance of the production of the garment was performed in the context of a case study.

The chosen case study is a winter jacket including characteristics typical of products available on Italian markets (**Figure 16**). Specifically, the item under analysis is characterized by an outer fabric in black nylon and internal padding in goose feather.

Figure 16. The winter jacket chosen as case study (own picture).

The study covered the analysis of the conventional jacket production and of an alternative jacket production, including, precautions typical of available products aiming to reduce environmental impact. Specifically, the alternative jacket production differs from the conventional one from the use of different materials and different suppliers along a shorter supply chain.

The conventional jacket is mainly composed by nylon PA 6 and PA 6.6 and metal, and the supply chain involve European and Asian suppliers. The alternative jacket is mainly composed by polyamide PA 6.10 derived from castor oil, cotton and wool and the supply chain involves more local suppliers, located in Europe.

The production of both the conventional and the alternative jacket does not coincide with the one of an existing company. Rather, it includes processes of an ideal organization, where however have been thought processes available in existing companies.

The aim of the paper is not to focus on a particular item, produced and sold by a specific company, but rather to compare items similar to those produced by a wide range of organizations and so to show the effects of two crucial choices: the selection of raw materials and the selection of local suppliers on the environmental impacts of garments companies.

4.1.3. Environmental assessment method

The environmental analysis has been performed by using the LCA. International standards (ISO, 2006a, 2006b), guidelines (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010) and additional methodological standards were used, including UNI ISO/TS 14067:2014 (ISO, 2013) and the "*Product Category Rules (PCR) 2019:04 for the assessment of the environmental performance of jackets, coats and other similar outdoor garments*" (Classification and Cpc, 2019).

The objective of the study is the evaluation of the environmental impact "of the conventional production of a winter jacket characterized by an outer fabric in black nylon and internal padding in goose feather in comparison with an alternative production of the same garment".

The product under study is a winter garment, called a down jacket, characterized by an outer fabric in black nylon with internal padding designed for the protection from cold.

A functional unit is a measure of the service delivered by the product. For this study, the functional unit (FU) was defined as 1 (one) garment in accordance with the Product Category Rules (PCR), a men's model jacket, size 50. This is to provide a reference to which the inputs and outputs are related to. The interest of the functional unit is to have a reference unit that enables the comparison between two products that provide an equivalent service.

The components of the conventional and the alternative jacket that make-up the FU considered in the study are listed in **Table 2** and **Table 3**.

Table 2. Conventional jacket components included in the study.

Component	%	Material	Tier 1	Tier 2
External fabric	12	PA 6 + PA 6.6	Europe	Europe
Lining	10	PA 6 + PA 6.6	Europe	Europe
Internal padding	38	Goose feathers	Europe	Asia
Snap buttons	13	90% brass + 10% polyethylene	Europe	Europe (assumption)
Zips	15	30% zinc + 70% polyester	Europe	Asia
Elastic cord	< 1	65% polyester + 35% natural rubber	Europe	Asia
Stopper and rings	< 1	Zamak	Europe	Europe (assumption)
Internal labels	< 1	Polyester	Europe	Asia
Eyelets	< 1	Brass	Europe	Europe (assumption)
Washers	< 1	PA 6	Europe	Europe (assumption)
Bias and piping	< 1	PA 6.6	Europe	Europe
Elastic for wrists	2	75% polyester + 25% natural rubber	Europe	Asia (assumption)
Fine rope	< 1	PA 6.6	Europe	Europe
External shield	< 1	Polyester	Europe	Asia

Feathers envelopes	< 1	PA 6	Europe	Asia
Wadding	2	Polyester	Europe	Asia
Yarn	< 1	PA 6	Europe	Asia

Table 3. Alternative jacket components included in the study.

Component	**%**	**Material**	**Tier 1**	**Tier 2**
External fabric	12	PA 6.10	Europe	Europe
Lining	10	PA 6.10	Europe	Europe
Internal padding	38	Goose feathers	Europe	Europe
Snap buttons	13	PA 6.10	Europe	Europe (assumption)
Zips	15	PA 6.10	Europe	Europe
Elastic cord	< 1	65% PA 6.10 + 35% natural rubber	Europe	Europe
Stopper and rings	< 1	PA 6.10	Europe	Europe (assumption)
Internal labels	< 1	Cotton	Europe	Europe
Eyelets	< 1	PA 6.10	Europe	Europe (assumption)
Washers	< 1	PA 6.10	Europe	Europe (assumption)
Bias and piping	< 1	PA 6.10	Europe	Europe
Elastic for wrists	2	Wool	Europe	Europe (assumption)
Fine rope	< 1	PA 6.10	Europe	Europe
External shield	< 1	Wool	Europe	Europe
Feathers envelopes	< 1	85% PA 6.10 + 14% PA 6.6 + 1% polyurethane	Europe	Europe
Wadding	2	50% linen + 30% cotton +20% PLA	Europe	Europe
Yarn	< 1	Cotton	Europe	Europe

Conventionally, a cut-off rule of 1% regarding mass shall apply. However, in the present study all components have been considered because of comparison between different raw materials and suppliers.

Due to lack of sufficient primary data, the following components are excluded from both the analysis: bag to contain and protect the spare buttons; cord contained in the piping; price tag; cellophane bag with which the finished garment is moved to the logistics center; shopper with which the jacket is sold to the customer.

The net weight of the finished garment is almost 1,3 kg. The inventory for the LCA study was carried out during 2019 and has included both primary data collected in collaborating companies and assumptions for data not directly available.

As shown in **Figure 17**, for the evaluation of environmental loads, the process units have been divided into three categories:

1. UPSTREAM: processes relating to the production of material and energy flows entering the borders of the companies producing the individual components of the product being analyzed up to transport to the storage warehouse.
2. CORE: transport of the components to the suppliers designate to assembly the components into the final products.
3. DOWNSTREAM: transport of garments ready for sale to the storage warehouse.

Downstream processes, garment retail use and end-of-life processes are not included in the system boundaries. For the two considered categories, the flows associated with the following processes were excluded from the analysis: packaging of raw materials entering the companies producing the individual components; production plants (e.g.: energy consumption, land consumption, maintenance, etc.) and personnel activities (e.g., transport, etc.); logistics hub (e.g., energy consumption, land consumption, maintenance, etc.) and personnel activities (e.g., transport, etc.).

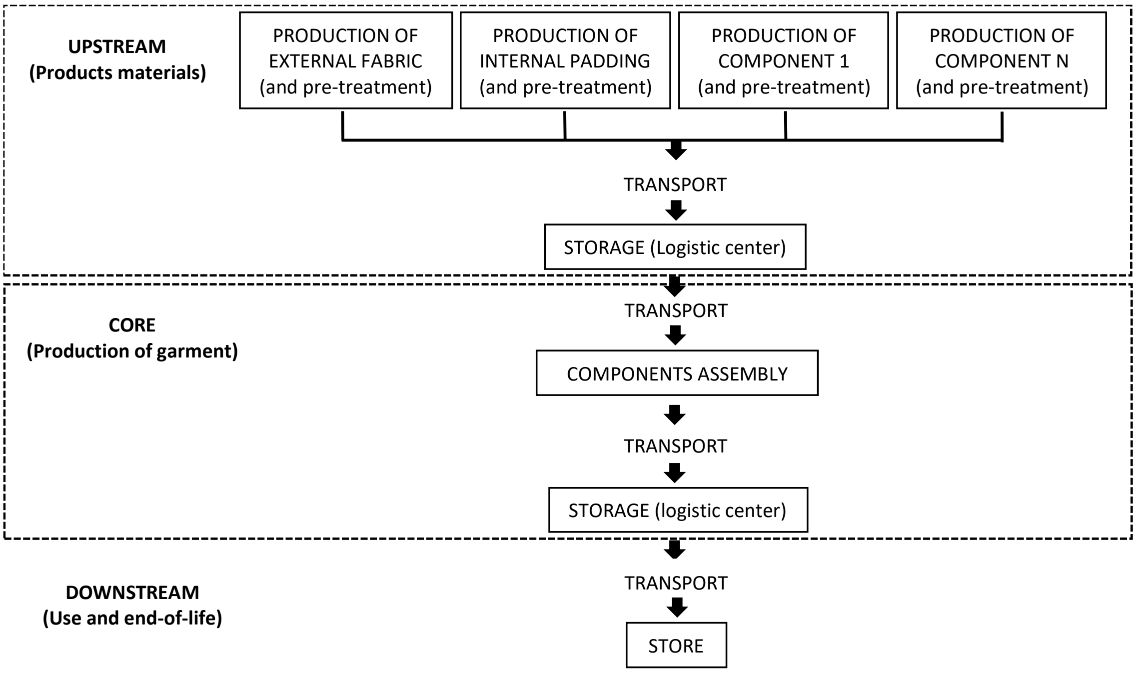


Figure 17. The system boundaries include upstream ad core processes (own elaboration).

All material and resource consumptions were tracked back to the point of raw material extraction, by using both primary data and, in absence of them, secondary data from the literature (Choi et al., 2018; Down et al., 2019; Hottle et al., 2013; Karvinen, 2015; La Rosa et al., 2014; Michael, 2011; Spierling et al., 2018; Venkatachalam et al., 2018; Winnacker and Rieger, 2016) and from the following databases have been used: Ecoinvent V3.4 e V3. (Wernet et al., 2016), Industry data library: PlasticsEurope, ERASM, World Steel V2.0; ELCD V3.2; IDEMAT 2001. LCA was modelled in SmaPro v9.0.

The impact categories considered are the default ones indicated by the PCR 2019:04, calculated with the methods suggested by the same. The default impact categories, their units of measurement and the calculation methods used are listed in **Table 4**. Moreover, the Cumulative Energy Demand (CED) method have been considered to evaluate the energy demand, valued as primary energy during the complete life cycle of the product production and considered one of the most important environmental indicators because of the well-known responsibility of fossil energy demand for global warming and depletion of fossil sources (Huijbregts et al., 2006).

Table 4. Impact categories considered in the study. Adaptation from PCR 2019: 04 Par. 4.9.1.

Impact category	Unit	Calculation method
Acidification potential (AP)	kg SO2 eq.	CML 2001 non-baseline V3.04
Eutrophication potential (EP)	kg PO43- eq.	CML 2001 baseline V3.05
Global warming potential (GWP100)	kg CO2 eq.	CML 2001 baseline V2016
Photochemical oxidant formation potential (POFP)	kg NMVOC eq.	ReCiPe V2016 V1.03
Water Scarcity Footprint (WSF)	m3 H2O eq	AWARE, WULCA V1.02

4.1.4. Results and discussion

The production of the conventional jacket emits a total of 17.89 kg of CO_2eq and 60.07 m^3 WSF and 298.28 MJ of non-renewable primary energy are consumed. The results, listed in **Table 5**, are consistent with previous studies related to the environmental analysis of outdoor jackets.

Table 5. Results of the conventional jacket production.

Impact category	Unit	TOTAL	UPSTREAM	CORE
GWP100	kg CO2 eq	17,89	11,68	6,20
POFP	kg NMVOC eq	0,06	0,04	0,01
WSF	m3 depriv.	60,07	59,16	0,90
AP	kg SO2 eq	0,09	0,07	0,02
EP	kg PO4--- eq	0,03	0,02	0,01
Non-renewable, fossil	MJ	246,87	162,80	84,07
Non-renewable, nuclear	MJ	51,10	36,09	15,01
Non-renewable, biomass	MJ	0,31	0,32	0,00
Renewable, biomass	MJ	9,26	8,46	0,80
Renewable, wind, solar, geo	MJ	5,85	3,40	2,46
Renewable, water	MJ	10,49	5,76	4,73

The production of the alternative jacket instead emits a total of 21.51 kg of CO_2 eq and 15.73 m^3 WSF and 256.21 MJ of non-renewable primary energy are consumed.

Table 6. Results of the alternative jacket production.

Impact category	Unit	TOTAL	UPSTREAM	CORE
GWP100	kg CO2 eq	21,51	17,39	4,13
POFP	kg NMVOC eq	0,04	0,03	0,01
WSF	m3 depriv.	15,73	15,19	0,54
AP	kg SO2 eq	0,07	0,05	0,02
EP	kg PO4--- eq	0,03	0,02	0,01
Non-renewable, fossil	MJ	234,69	178,39	56,30
Non-renewable, nuclear	MJ	21,30	15,63	5,67
Non-renewable, biomass	MJ	0,22	0,22	0,00
Renewable, biomass	MJ	9,06	8,39	0,67
Renewable, wind, solar, geo	MJ	4,09	3,16	0,93
Renewable, water	MJ	6,36	5,02	1,33

The results, listed in **Table 6**, show that the choice of local suppliers has a significant impact on the environmental impacts, mainly for the reduction of transports and for the use of European energy mixes characterized by more renewable energy sources (Centre for Energy-Environment Resources Development (CEERD), Bangkok, 2009).

Moreover, the results confirms recent findings in previous studies that show that polyamides based on bio-renewables outperform purely fossil-based types in some impact categories (Gironi and Piemonte, 2011). However, according to the producer of such materials, if the process conditions are optimized, the values can be lowered even further. Future studies should investigate this point.

To underline is that, with a shorter supply chain, we have been able to obtain more specific data regarding the manufacturing processes. It means that for the analysis of the alternative jacket there are less assumption and more available data with less uncertainty. This is important, not-only in order to perceive a more correct result, but it also useful for the company to have a higher supervision of the supply chain.

4.1.5. Conclusions

The study presents an overview of published eco-labels relative to the fashion sector and an environmental analysis of a jacket typical of those available on Italian markets under two different business model, a conventional one and an alternative one, characterized by the selection of eco-friendly materials and local suppliers.

The research findings have highlighted that still less eco-labels are available on the market making it difficult for a responsible consumer to obtain information. The LCA results showed that the choice of different raw materials and local suppliers have a significant impact on the environmental performance of the total production of a garment.

5. Sustainable industrial building

One of the European's key strategies towards the transition to low-carbon energy systems to meeting global commitments to climate change mitigation, is the decarbonization of the building sector (European Comission, 2011).

Globally, buildings are responsible for 39% of all energy and process-related carbon dioxide emissions. The largest part (18%) is due to scope 2 emissions, i.e., upstream emissions from power generation and commercial heat. This is followed by emissions related to materials and construction (scope 3 or embodied emissions, 11%) and by direct emissions produced in buildings from the burning of fossil fuels for heating and cooking (scope 1, 10%) (United Nations Environment Programme, 2021). It is demonstrated that, with appropriate building design strategies focused on reliably achieving very low energy, the building sector can contribute its share to the 1.5°C goal, both for new-built and refurbishment of the existing building stock (Grove-Smith et al., 2018; Rogelj et al., 2015a).

In this context, the Energy Performance of Buildings Directive (EPBD) introduced the definition of nearly zero-energy building (nZEB) as a building with very high energy performance, where the nearly zero or very low amount of energy required should be extensively covered by renewable sources produced on-site or nearby (European Union, 2010). According to the EPBD, it is required that all new buildings will be nZEB by the end of 2020. However, the main goal of the directive is to increase the renovation rate and move inefficient buildings onto a more sustainable path (Mariottini and Arcipowska, 2015).

The world over, evidence is growing that green buildings bring multiple benefits. They provide some of the most effective means to achieving a range of global goals, such as addressing climate change, creating sustainable and thriving communities, and driving economic growth. Achieving net zero operational and embodied greenhouse gas (GHG) emissions in the built environment is globally recognized as a key strategy to address climate change and achieve the United Nations Sustainable Development Goals (SDGs) (Wen et al., 2020) (**Figure 18**).

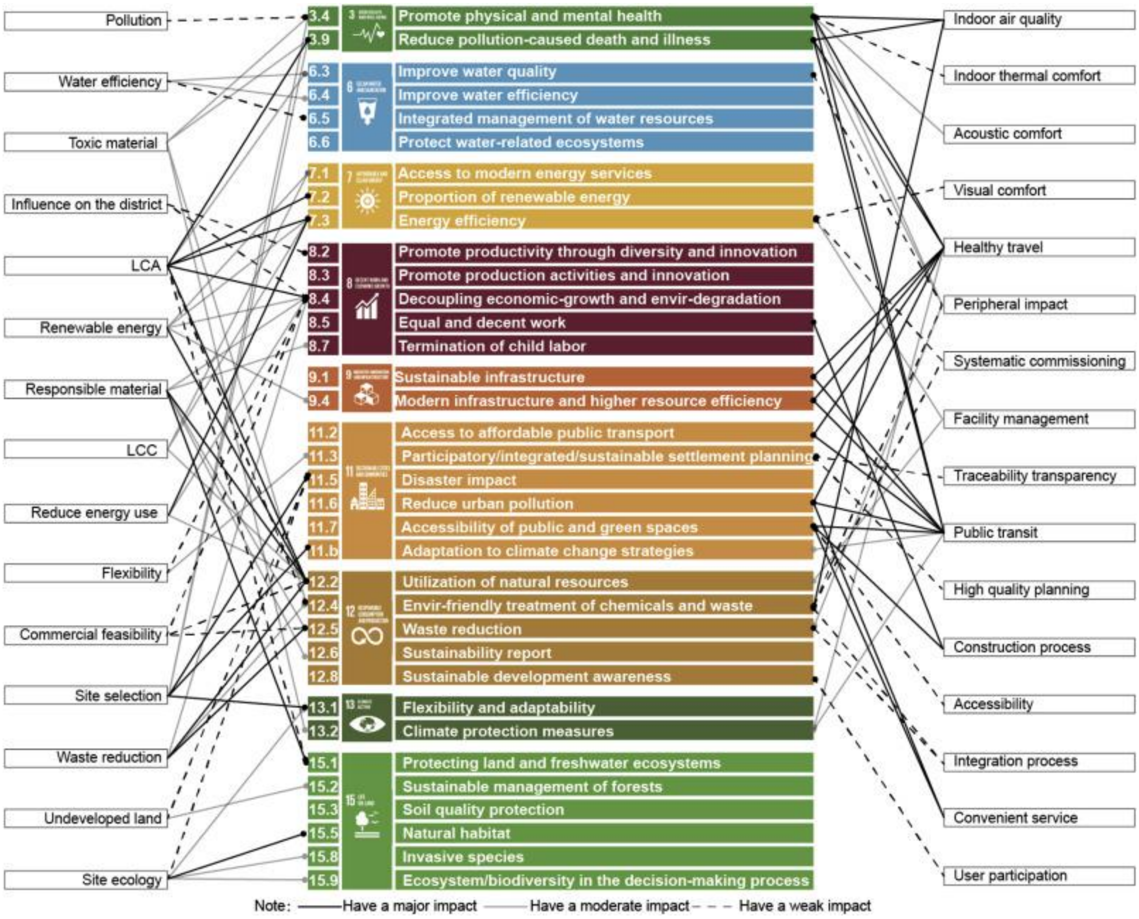


Figure 18. Association of GBRT indicators with the SDGs described in DGNB (Wen et al., 2020).

The U.S. Environmental Protection Agency (EPA) defines a sustainable building as “the practice of maximizing the efficiency with which buildings and their sites use resources—energy, water, and materials—while minimizing building impacts on human health and the environment, throughout the complete building life cycle—from siting, design, and construction to operation, renovation, and reuse” (U.S. Environmental Protection Agency, 2008).

Sustainable buildings are designed to consume less energy, preserve natural resources and offer a cleaner environment when compared to conventional buildings (Yildirim et al., 2020). A sustainable building is a building that, in its design, construction or operation, reduces or eliminates negative impacts, and can create positive impacts, on our climate and natural environment. One of the most important types of benefit green buildings offer is to our climate and the natural environment. Green buildings can not only reduce or eliminate negative impacts on the environment, by using less water, energy, or natural resources, but they can - in many cases - have a positive impact on the environment (at the building or global scales) by generating their own energy or increasing biodiversity. The building sector has the largest potential for significantly reducing greenhouse gas emissions compared to other major emitting sectors (UNEP, 2009). This emissions savings potential is said to be as much as 84 Gt of CO2 by 2050, through direct measures in buildings such as energy efficiency, fuel switching and the use of renewable energy (Global Alliance for Buildings and Construction, 2018). In addition, the building sector has the potential to make energy savings of 50% or more in 2050, in support of limiting global temperature rises to 2°C (above pre-industrial levels) (Larsen et al., 2011)

Besides the preservation of precious natural resources, sustainable buildings improve our quality of life (Das et al., 2016). The sustainability of a building refers to its overall ability to provide a comfortable, healthy, and productive environment over the long term without negatively impacting the environment. The concept of building sustainability deals with the three pillars of sustainability (environmental, economic, and social) therefore, sustainable buildings aren’t just about the planet but take into account also people and profit.

To truly be a sustainable building, this ideology must be conceived and considered at every stage of a building’s life cycle (Giorgi et al., 2018). For example:

- Planning (*Is the building on previously undisturbed land?*)
- Design (*Is the window placement designed for optimal natural lighting?*)
- Construction (*Are the materials used safe for the environment and occupants? Does the construction process conserve natural resources?*)
- Operation and maintenance (*Are energy and water being used efficiently? Is the indoor air quality safe for occupants?*)
- Demolition (*Will waste and disposed materials be handled in an environmentally safe manner?*)

Despite being a challenging ambition influenced by many factors (Gonzalez-Caceres et al., 2020), in recent years a growing attention has been given to improving the energy performance of buildings, mainly focusing on the residential sector (Wei and Skye, 2021).

With regards to the non-residential sector, accounting for 25% of the total stock in Europe, the consideration has tended to focus on the most energy intensive building typologies (BPIE, 2011), such as hospitals, hotels and restaurants (Becchio et al., 2017; Smitt et al., 2021) and educational buildings (Asdrubali et al., 2019; Attia et al., 2020).

Industrial buildings, on the other hand, are seldom studied under an energy retrofit perspective (Gourlis and Kovacic, 2016), with surprising efforts focusing on indoor office environments (Gangolells et al., 2020), while a lack is recognized in terms of analyzing the improvement of the work environment in all the areas that are not used as offices. Industrial buildings are deeply investigated when used for other purposes, e.g., as housing (Valančius et al., 2015) or mixed-uses (Becchio et al., 2015; Opher et al., 2021) or in case of seismic performance improvement (Soydan et al., 2020).

The issues related to design, construction, and operation of industrial buildings have not been comprehensively studied in comparison with residential, educational, medical, and commercial buildings. In recent years, with the advances in technology and methods, it became possible to study these issues more seriously. Generally, criteria for residential or commercial buildings may not always apply to industrial buildings, it is therefore necessary to make certain modifications in models, methods, and approaches to evaluate a proposal of manufacturing buildings, particularly in light industries (Katunský et al., 2017).

Overcoming these difficulties and moving towards a decarbonization of the industrial built environment is of fundamental importance because there is a significant challenge in reducing the environmental impact of the industrial sector against increasing population growth, urbanization, and subsequent new building demand. In Italy, the number of industrial buildings almost doubled between 2014 and 2018 (**Figure 19**), from 11969 m^3 to 30165 m^3 (**Figure 20**), placing significant emphasis on the importance of decarbonizing new industrial building stock. Indeed, it is widely recognized that while energy efficiency is improving building performance per square meter, this is not sufficient to overcome this rapid growth in new floor area (Allen et al., 2022).

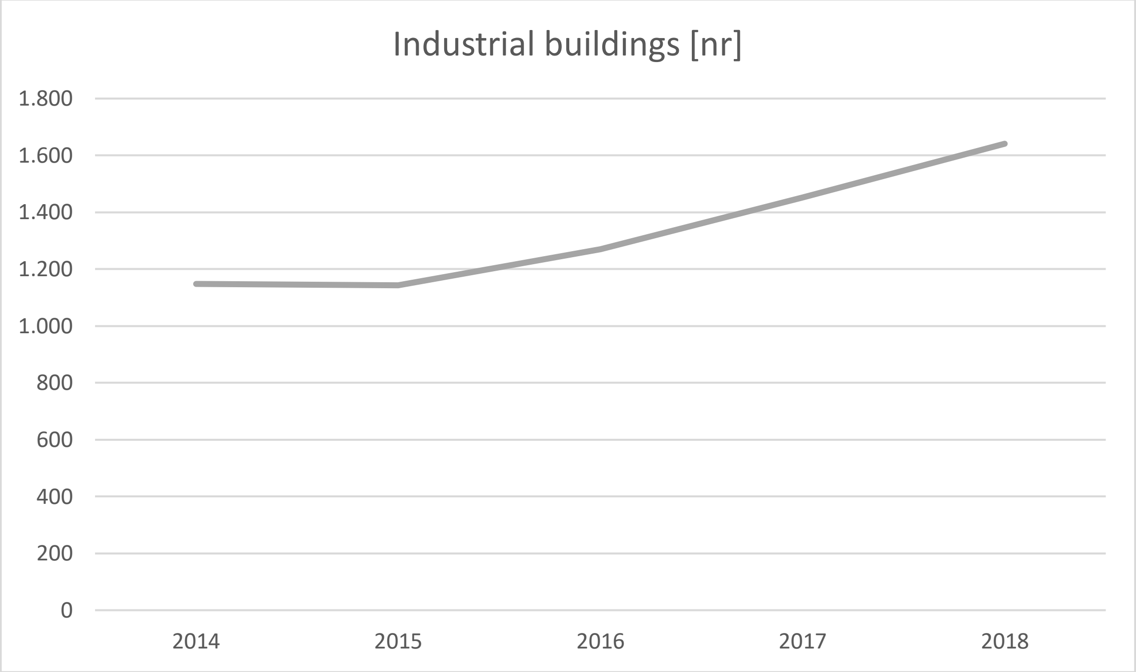


Figure 19. Number of built industrial buildings, 2014-2018. Own elaboration from (ISTAT, 2021).

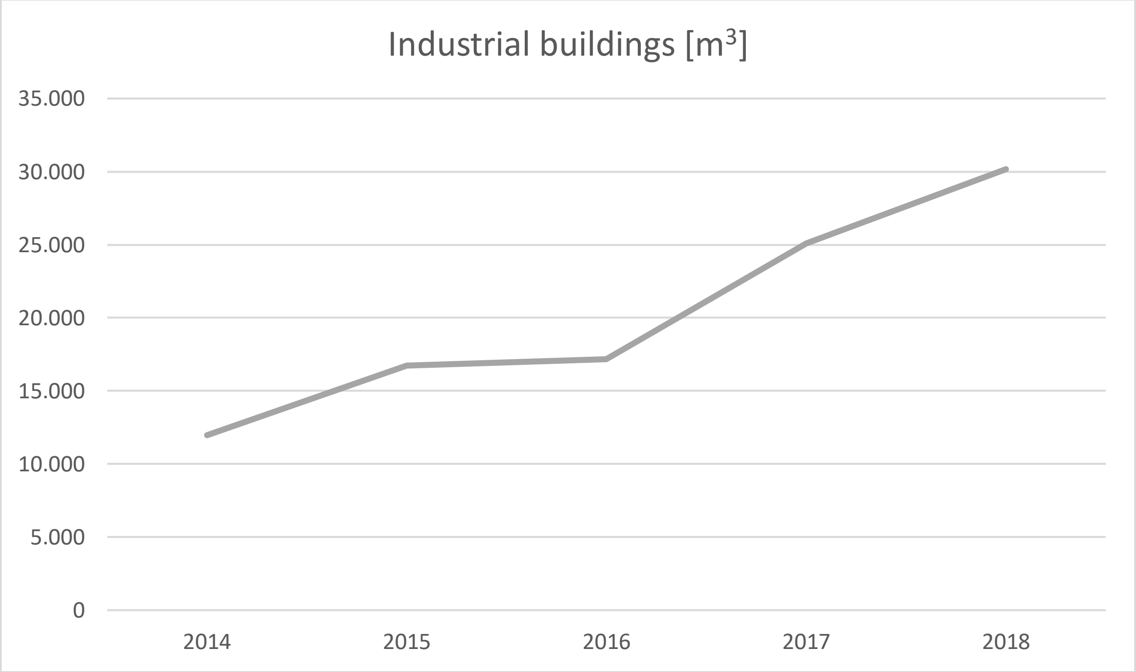


Figure 20. Volume of built industrial buildings, 2014-2018. Own elaboration from (ISTAT, 2021).

Furthermore, buildings used for industrial and craft activities consume on average 40% more energy than residential buildings (250 kWh/m^2 compared to 180 kWh/m^2) (**Figure 21).**

However, it isn't only an energy issue. Industrial buildings are generally energy demanding but also land consuming, and depending on large-scale infrastructure, which makes them an interesting subject: it is believed that energy savings and ecological rethinking can make a real difference in the industrial sector (Weyer and Barагaño, 2014).

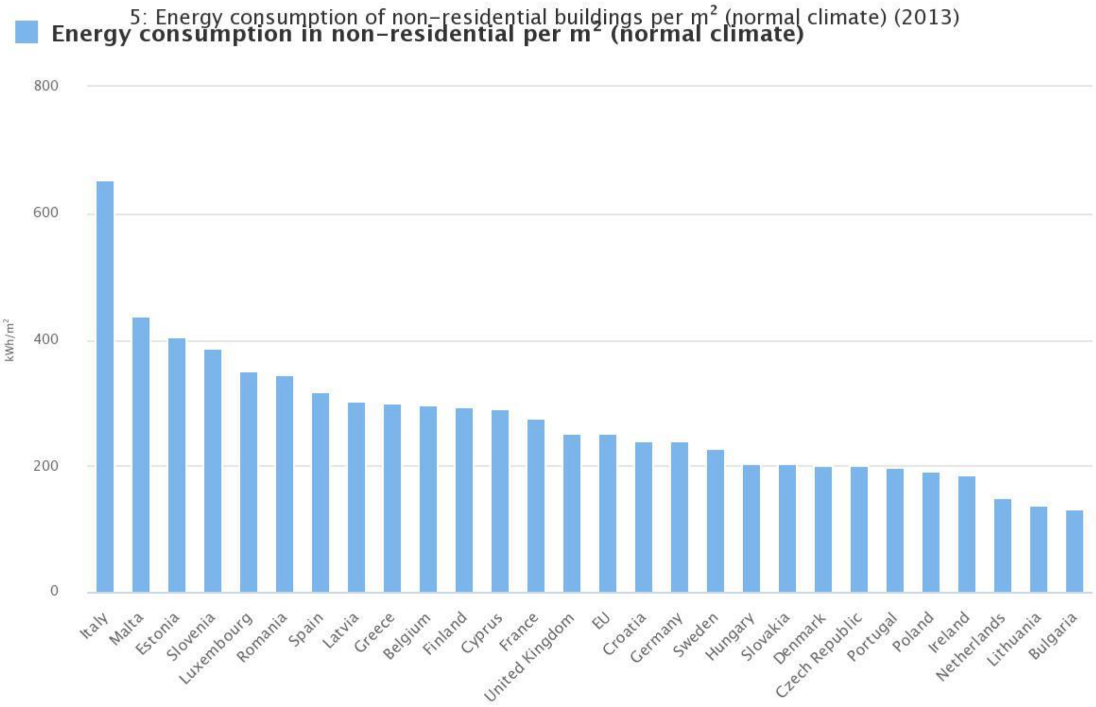


Figure 21. Energy consumption of non-residential buildings per m² (normal climate) (2013). Source: EU Buildings Factsheets. Available online at https://ec.europa.eu/energy/eu-buildings-factsheets_en, last access: 18.02.2022.

5.1. Industrial buildings: an overview

The buildings of the tertiary sector are usually precast structures, typically built as an assembly of monolithic elements: main and secondary beams, square-cross section columns, concrete or sandwich panels as roof and wall elements, ribbon windows and modular windows skylights (Savoia et al., 2017; Yesilyurt et al., 2021).

Unlike other buildings, industrial buildings need a large-scale space plan, considering the large manufacturing equipment and products which they must accommodate. These buildings have a multitude of large open spaces to carry out work a wide envelope compared with the area used. Minimum investment costs and maximum flexibility and expandability of the construction and infrastructure are main goals of industrial facilities (Reisinger and Kovacic, 2021). Due to product individualization and accelerating technological advances in manufacturing, industrial buildings strive for highly flexible building structures to accommodate constantly evolving production processes (Reisinger et al., 2021). Historically, the industrial architecture was dominated by forms and typologies specific to each type of industry. Today, it is more a standardized system of components which can adapt to various uses in an almost one-size-fits all way, as a kind of big box (Brand, 1995; Weyer and Baragaño, 2014) (**Figure 22**). If on the one hand, this approach is useful to facilitate the re-use, on the other hand there is often a lack of quality for its users. A building must always response to the needs and requirements of people, and, in case of an industrial building, to the requirements on workers. In 2020, Deetman et al. (Deetman et al., 2020) declared that modelling highly heterogenous structures as industrial buildings, is challenging and represents an area for further developments.

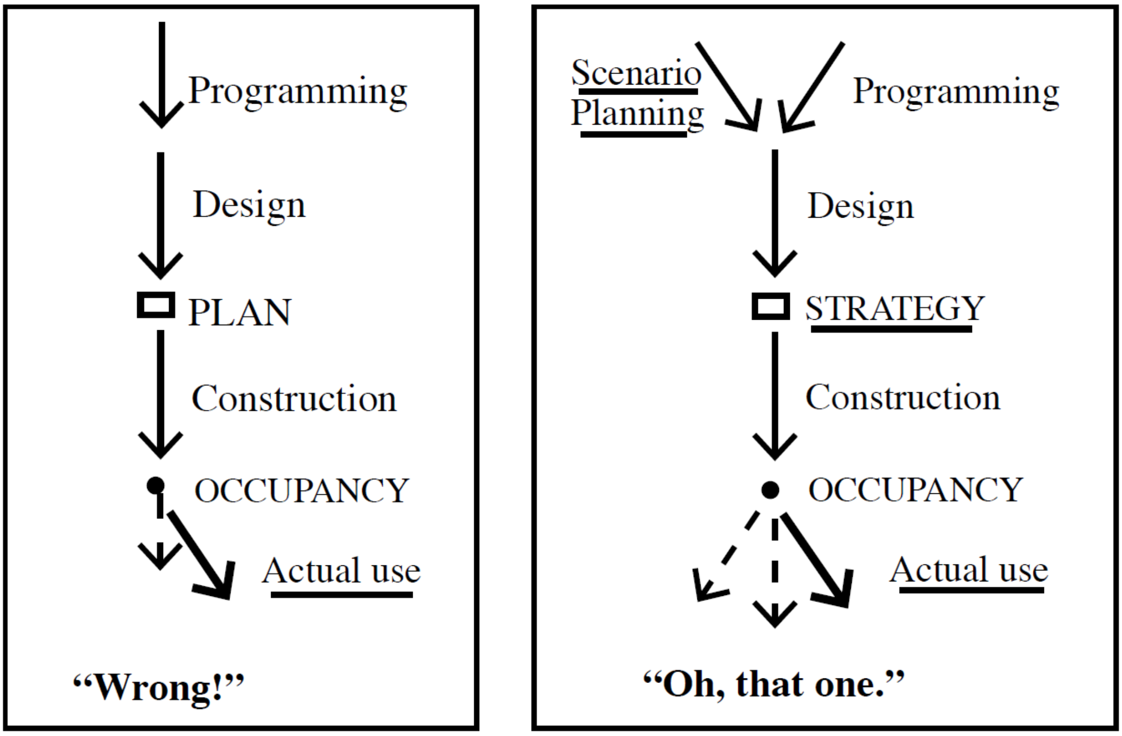


Figure 22. The benefits of Scenario Planning (Brand, 1995).

From the energy performance and the workplaces comfort point of view, the critical issues affecting those kinds of structures are various. They usually need not only winter but also summer air conditioning, in addition to artificial lighting. It is demonstrated that the carbon and energy footprint of typical prefabricated industrial buildings are mainly affected by the energy need for heating and cooling and for lighting (Bonamente et al., 2014).

The problem of air high temperatures inside industrial workplaces occurs particularly during hot sunny days, leading to a proved exposition of workers to thermal stress (Kralikova et al., 2014). Among the different sources of solar heat gain, the heat gain through the roof is one of the predominant, especially for the single-story industrial type buildings with metal roof, affected by the penetration of direct solar heat into the working indoor space, which needs to be cooled for improving working efficiency as well as thermal comfort of the workers (Boobalakrishnan et al., 2021), despite a significant increase in the cooling load. The roof type, indeed, is an important parameter in this building type as it has a close relationship with the building's manufacturing features, as natural lighting and ventilation (Odeleye, 1966).

This means that the building envelope could deeply influence the working environment conditions as much as workstations, like manual and automatic welding stations, oven entrances, assembly stations near hot bath stations, identified as critical because source of high indoor temperature (Morgado et al., 2017).

5.2. Implementing sustainability in industrial buildings

There are a number of features which can make a building sustainable in all steps of the life cycle, starting from the decision phase to the construction; operational; and end-of-life phases (Passoni et al., 2021) (**Figure 23**). These include:

- Efficient use of energy, water, and other resources.
- Use of renewable energy, such as solar energy.
- Pollution and waste reduction measures, and the enabling of re-use and recycling.
- Good indoor environmental air quality.
- Use of materials that are non-toxic, ethical, and sustainable.
- Consideration of the environment in design, construction, and operation.
- Consideration of the quality of life of occupants in design, construction, and operation.
- A design that enables adaptation to a changing environment.

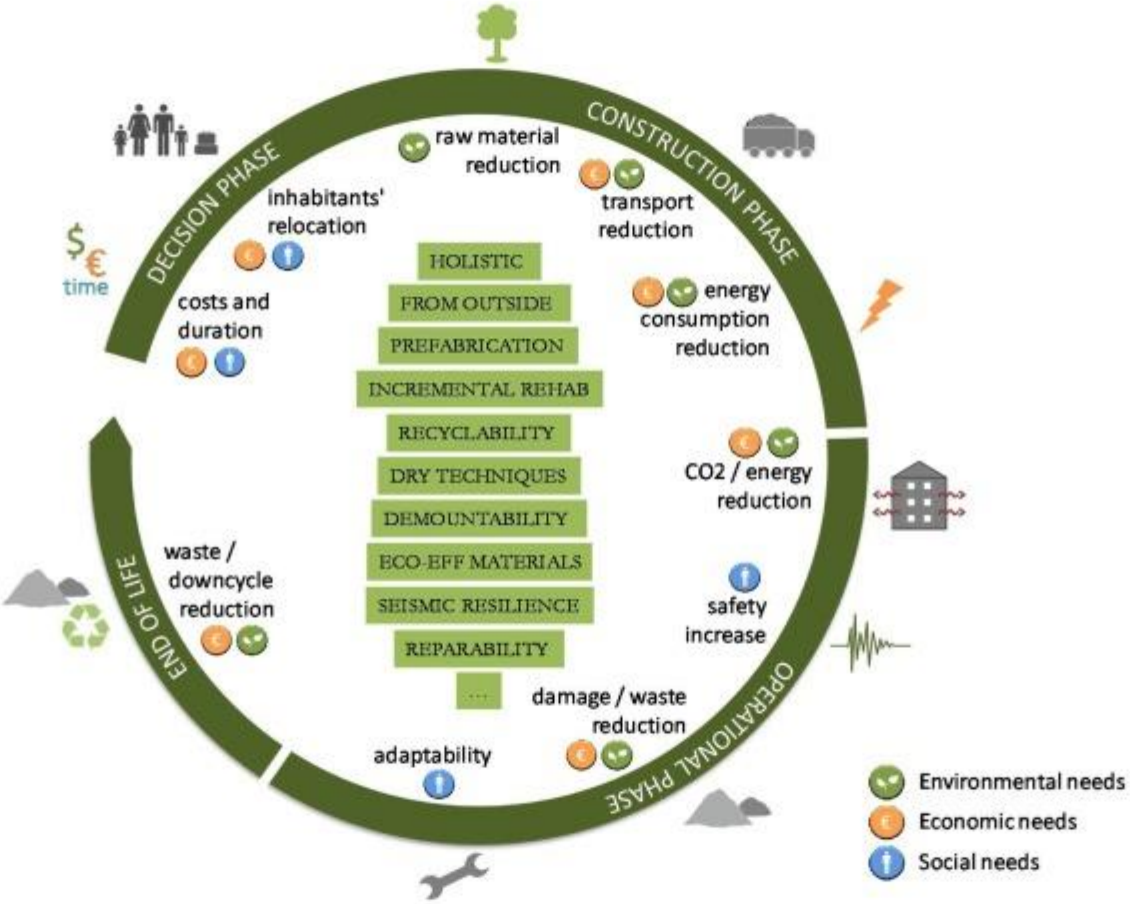


Figure 23. Sustainable Building Renovation (SBR) approach proposed by (Passoni et al., 2021).

Industrial enterprises, nevertheless, tend to focus their efforts on energy intensive processes, therefore the energy retrofitting of the productive buildings they occupy is a scarcely implemented strategy, hindered by several critical issues, despite there may be several positive effects that could result from it. This results in a low number of sustainable and energy efficient tertiary buildings in the whole European Union (**Figure 24**).

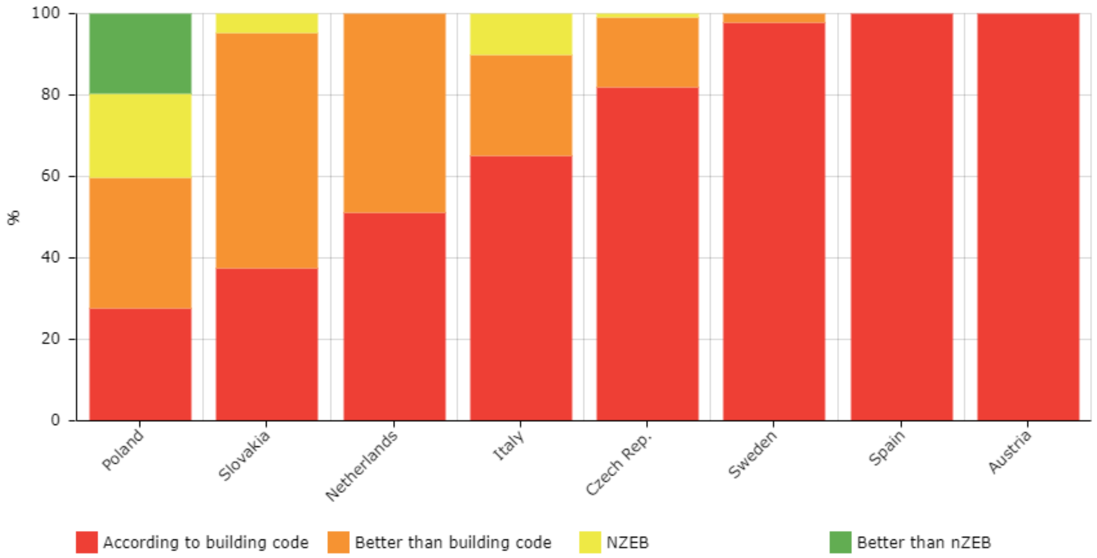


Figure 24. Distribution-of-new-tertiary-buildings-according-to-the-nZEB-radar-graph (https://zebra-monitoring.enerdata.net/overall-building-activities/share-of-new-tertiary-buildings-built-according-to-national-nzeb-definition-or-better-than-nzeb.html#percentage-of-annual-stock-renovated-in-non-residential.html, last access: 03.03.2022.

5.2.1. Barriers

The critical issues could be organizational, technical, economic, or regulatory (**Table 7**).

Table 7. Barriers to the implementation of sustainable strategies in industrial buildings.

Barrier		Source
Technical		
	Lack of data and information	(Blass et al., 2014; Cagno et al., 2015, 2013; Kim and Kang, 2016)
	Ventilation air change rate uncertainty	(Wang et al., 2019) (Ahmed et al., 2020)
	Difficulty in evaluating indoor comfort	(Wang et al., 2016) (Chinese et al., 2011)
	Plant layout modification	(Chinese et al., 2011)
	Thermal bridges and air leakages	(O'Hegarty et al., 2020) (Shin and Kim, 2020) (Choi et al., 2015)
	Lack of adequate and available technologies	(Cagno et al., 2015, 2013)

	Lack of knowledge and awareness	(Cagno et al., 2015, 2013; Walsh and Thornley, 2012)(Gohoungodji et al., 2020)
Economic		
	Investment uncertainty and hidden costs	(Cagno et al., 2015, 2013; Chinese et al., 2011; EEFIG, 2015)
	Energy data requirement	(Kim and Kang, 2016)
	Investment costs	(Cagno et al., 2015, 2013; Trianni et al., 2014b)(Walsh and Thornley, 2012)
	External risks	(Cagno et al., 2015, 2013)
Regulatory		
	Regulatory uncertainty	(Gohoungodji et al., 2020; Malinauskaite et al., 2019; Trianni et al., 2014b)
	Lack of proper regulation	(Cagno et al., 2013)
	Distortion in fiscal policies	(Cagno et al., 2013; Sudhakara Reddy, 2013)

The main difficulties are the technical ones, mainly related to the thermal bridges across the layer of insulation resulting in paths of greater heat loss (O’Hegarty and Kinnane, 2020), caused by the junctions between precast panels and structure elements and the connectors that penetrate the insulation layer (Choi et al., 2015; Shin and Kim, 2020).

Economic barriers have been recognized in relation to the cost of collecting the energy data or installing new energy-efficient equipment (Chinese et al., 2011; EEFIG, 2015). When compared with the simple purchase of energy, those initial costs could not be recognized as a cost savings investment, resulting in a greater obstacle to SMEs (Kim and Kang, 2016).

Several authors highlighted that barriers may also be related to the inappropriateness of legislation regarding technologies (Gohoungodji et al., 2020). The barriers can also be related to the lack of a proper legislation (Cagno et al., 2013; Sudhakara Reddy, 2013) or to the uncertainty on the application of existing regulations due to their complexity (Gohoungodji et al., 2020; Malinauskaite et al., 2019; Trianni et al., 2014b).

5.2.2. Drivers

The drivers can be environmental; economic; and social (**Table 8**).

Table 8. Drivers to the implementation of sustainable strategies in industrial buildings.

Drivers		**Source**
Environmental	Reduction of global final energy consumption	(Southernwood et al., 2021)
	Reduction of global CO_2 emissions	(Southernwood et al., 2021)
	Reduction of embodied and operational carbon	(Gebler et al., 2020; Rodrigues et al., 2018)
	Energy savings	(Weyer and Baragaño, 2014)
Economic		
	Better life-cycle costing	(Edwards and Naboni, 2014; Haddad, 2019)
	Cost savings	(Haddad, 2019)
	Asset value	(Haddad, 2019; Iancu and Moga, 2021)
	Enhanced image for the organization	(Edwards and Naboni, 2014)
	Risk mitigation	(Haddad, 2019; Rödger et al., 2021a)
	Plant layout improvement	(Simson et al., 2016; Weyer and Baragaño, 2014)
Social		
	Lower symptoms of Sick Building Syndrome and improvement of worker's health	(D'Ambrosio Alfano et al., 2014; Parsons, 2000)
	Reduction of thermal loads and improvement of worker's comfort	(Kralikova et al., 2014; Parsons, 2000)
	Improvement of productivity or performance	(Al Horr et al., 2016; Behrer and Park, 2017; D'Ambrosio Alfano et al., 2014; Edwards and Naboni, 2014; Haddad, 2019; Kjellstrom and Crowe, 2011; Nerbass et al., 2017;

		Nunfam et al., 2018; Parsons, 2000; Zander et al., 2017)
	Better social relationships at a building community level	(Edwards and Naboni, 2014)

The benefits deriving from industrial building renovations are various, starting from embodied and operation energy savings, that translates into reduction of global final energy consumption and CO_2 emissions (Gebler et al., 2020; Rodrigues et al., 2018; Southernwood et al., 2021; Weyer and Baragaño, 2014).

Green buildings offer a number of economic or financial benefits, which are relevant to managers and entrepreneurs. These include cost savings on utility bills (through energy and water efficiency); lower construction costs; layout improvement; higher property value for building owners; and job creation (Haddad, 2019).

The high energy performance allows not only to reduce management costs, but also to ameliorate Indoor Environmental Quality (IEQ). Besides improving the conditions of life of workers, the implementation of the best IEQ helps in increasing the market value of the property and, above all, it represents a strong and clear message of the policies that the companies intend to propose on an ethical level ("SMA Solar factory proves its zero carbon green credentials," 2013). IEQ improvements can save \$10-30 billion from reduced symptoms of sick building syndrome and \$20-160 billion from direct impacts on occupant productivity (Fisk, 2000). Moreover, such improvements may represent a useful means to build awareness, and involve employees in energy savings (Fawkes et al., 2016).

Sustainable buildings' benefits go beyond economics and the environment and have been shown to bring positive social impacts too. Many of these benefits are around the health and wellbeing of people who work in sustainable work environments.

Among the many attributes of the work environment, light is one of the most important ones. In recent years, special attention has been given to the impact of natural light on psychological and behavioral influences on workers. A multitude of surveys have indicated also that daylight impacts the health and performance of workers and that worker' health, satisfaction, attention, and consequently performance are improved in the working environment with the help of natural light (Boyce et al., 2003)(Shishegar and Boubekri, 2016) (**Figure 25**).

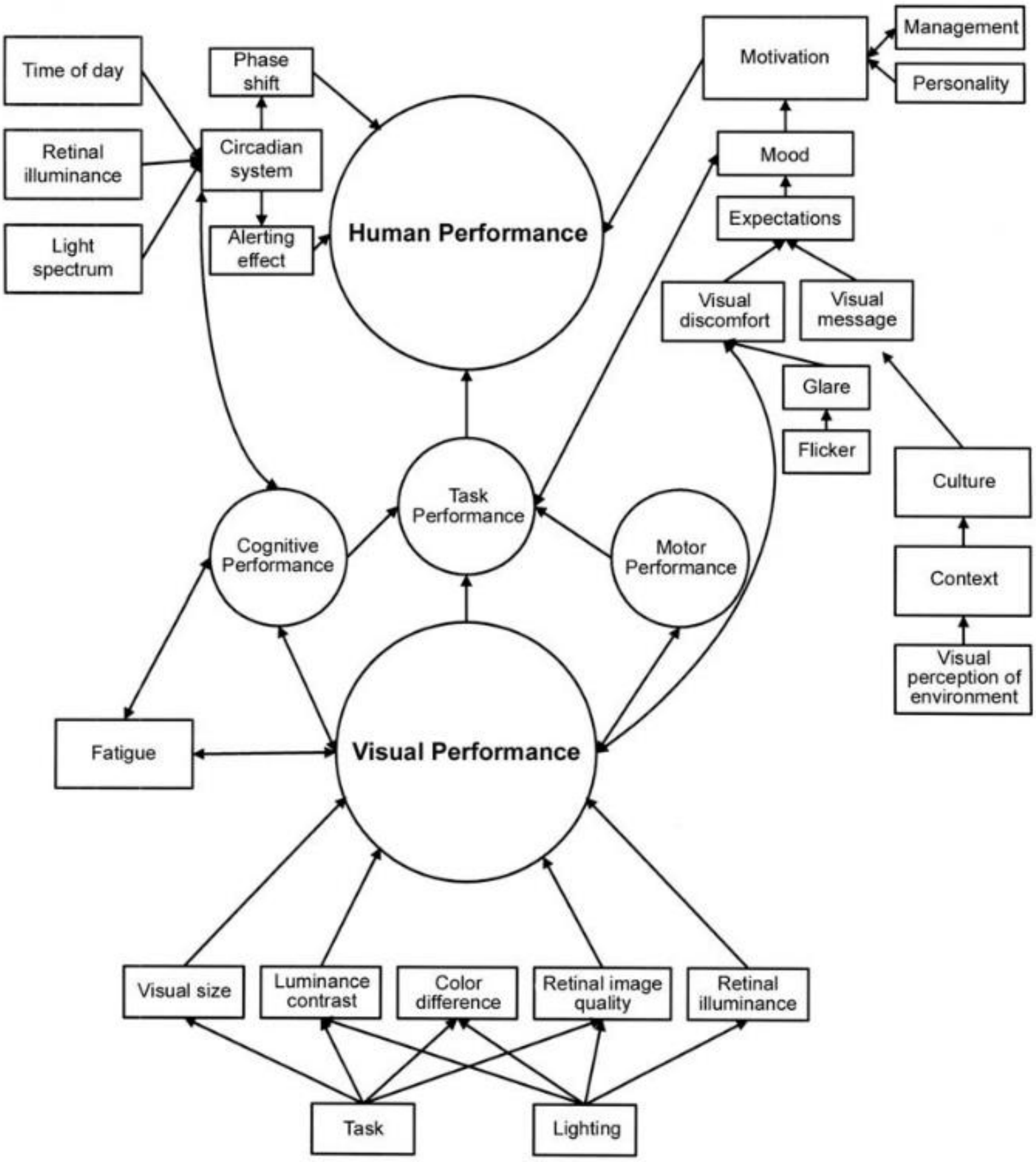


Figure 25. A conceptual framework setting out the routes by which lighting can influence human performance. The arrows indicate the direction of the effects (Boyce et al., 2003).

During working hours in industrial workplaces, workers can be exposed to possible heat and cold risks (Kralikova et al., 2014), in addition to visual risks. It is largely demonstrated that workers who are directly exposed to an unacceptable working environment may have increased health symptoms and decreased productivity (Behrer and Park, 2017; Kjellstrom and Crowe, 2011; Nerbass et al., 2017; Nunfam et al., 2018; Zander et al., 2017). Workers in green, well-ventilated environments record a 101% increase in cognitive scores (Allen et al., 2016). In addition, research suggests that better indoor air quality (low concentrations of CO_2 and pollutants, and high ventilation rates) can lead to improvements in performance of up to 8% (Park and Yoon, 2010).

Furthermore, a sustainable work environment results in human performance and workplace productivity; human health; and financial return on investment (Al Horr et al., 2016) (**Figure 26**).

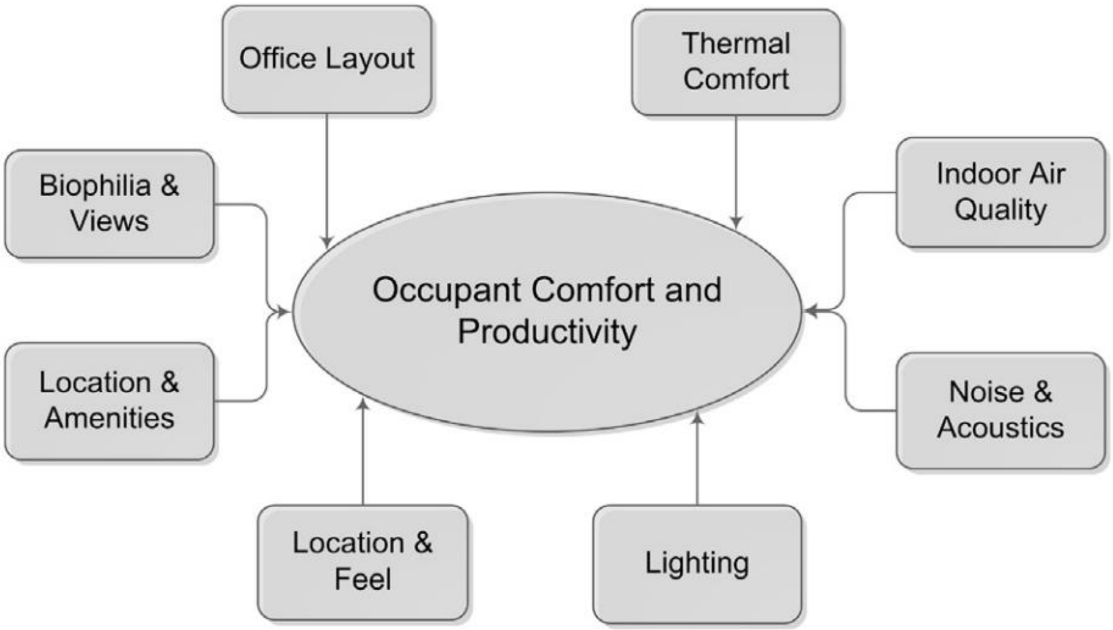


Figure 26. IEQ factors and Occupant Productivity (Al Horr et al., 2016)

5.2.2.1. Indoor environment evaluation in industrial workplaces: the case of the footwear sector.

5.2.2.1.1. Introduction

The Italian footwear industry is a sector of excellence. Comprising 5000 companies, mainly SMEs, and 77 000 employees, it exports 85% of output with an annual turnover of almost EUR 14 billion (Bizzotto, 2017). Italy has always been the undisputed leader among manufacturers of luxury and high-level shoes having a high fashion content. The success of the footwear sector in Italy is linked to the lively entrepreneurial spirit and to the typical structure of the sector, which is part of a supply chain, an operational system consisting of sub-suppliers of raw materials, tanneries, components, accessories, machinery manufacturers, model makers and stylists. This has resulted in a territorial concentration of companies and the formation of shoe manufacturing districts. The leading position of the Italian shoe industry on the international markets is due to the sector's high level of competitiveness based on the superior quality of the product and an elevated capacity for innovation. The characteristics that distinguish Italian production in the footwear sector are: creative talent, innovation of traditional manufacturing methods and skilled labor thanks also to the existence of professional training schools; raw materials, accessories and components that are in the forefront for technology and design; flexibility, thanks to the territorial concentration and size of the companies; a wide range of designs to suit current trends and satisfy customer demands; customer service and the "Made in Italy" image (Assocalzaturifici, 2020).

Therefore, the human contribution to production processes is an added value and the workers well-being is a key factor in guaranteeing quality and productivity.

The present study shows the environmental analysis of the made-to-measure department of an Italian factory that produces shoes for the luxury market, highlighting the most critical point from the microclimate; air quality; and lighting point of view.

5.2.2.1.2. Case study

The method was experimented in an Italian company that produces classic and luxury shoes, especially for men. Handmade workmanship is one of the core elements of distinction from its competitors that allows the distinctive features of the pure Made in Italy remaining unchanged through time. The company's will to monitor and improve the working conditions of its artisans is based on this pillar.

In particular, three hand dyeing workstations of the department of made-to-measure shoes were involved (**Figure 27**). The outcome of the operator's work is a one-of-a-kind shoe, personalized in every single detail and fruit of the human manual ability.

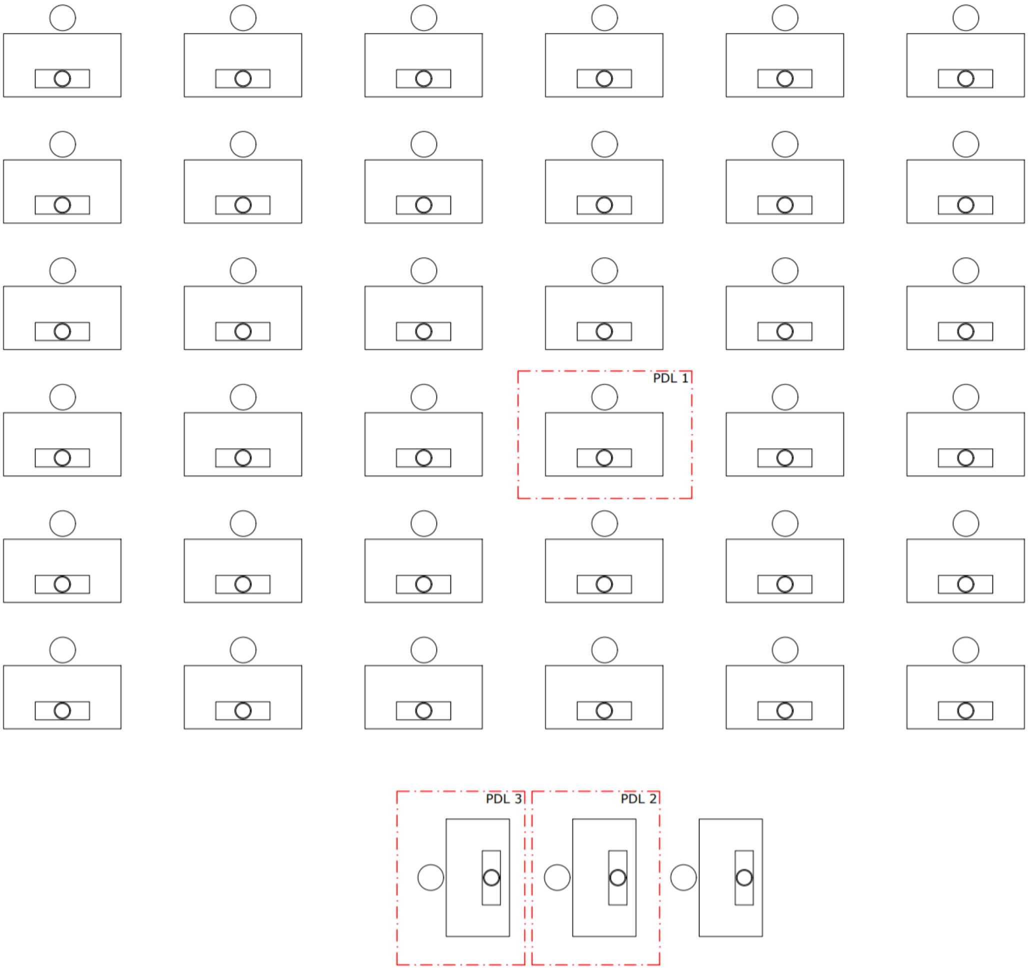


Figure 27. Three analyzed hand dying workstations in the made-to-measure shoes department (own elaboration).

5.2.2.1.3. Methodology and data analysis

The study focuses on microclimate; air quality; and lighting. For each of them, the specific data to be considered and the analysis methodologies are described.

The following environmental parameters are measured by the four sensors of Foobot (https://foobot.io/ - last access: 05.03.2021): CO_2; $PM_{2.5}$; VOCs; temperature; and humidity.

To determine the temperature that guarantees the workers' thermal comfort, according to their clothing and activity, the Fanger method (Fanger, 1970) is used. The air quality is evaluated thanks to the Global Pollution Index (GPI), which is a weighted compound of the different pollutants measured by Foobot. The Foobot application classify the GPI on four levels: great (0-25); sufficient (25-75); and poor (75-100).

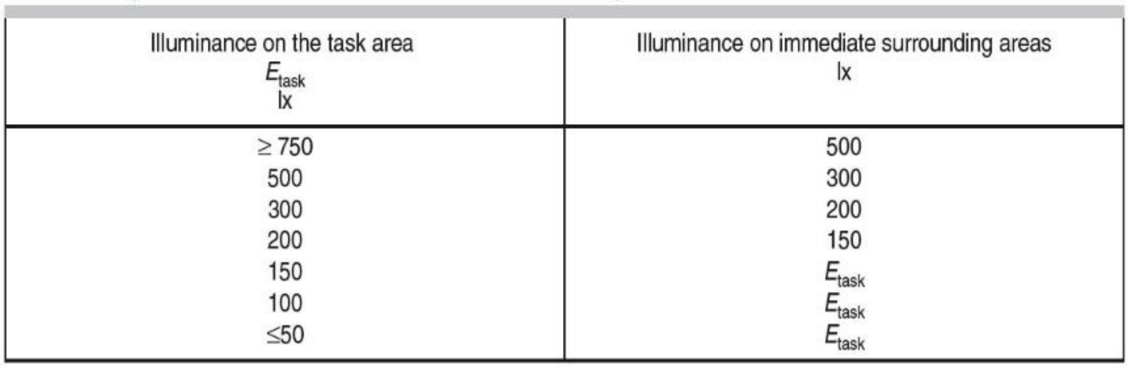
A colorimeter was used to measure the color temperature and lux (**Figure 28**).

Figure 28. Colorimeter (Konica Minolta CL-100). Own picture.

According to the UNI EN 12464-1 and CIE 1931 color space chromaticity diagram, the following three factors are evaluated: average maintained illuminance (Ēm); the color rendering index (CIE Ra) and the illuminance uniformity (Uo).

The average maintained illuminance (Ēm) it is that level of light that must never be reduced in the area of the visual task. The lighting levels are set for the different types of activities and refer to the average state of aging of the lighting system, mainly due to the decay of the flux of the lamps and the fouling of the lighting fixtures and the surrounding surfaces. Within a room there may be different visual tasks that require different levels of illumination in the specific area where they are carried out. The prescribed value is defined by the UNI EN 12464-1 standard. In addition to the illumination of the visual task area, the standard prescribes indications for two other areas: the immediately surrounding area and the background area. The illuminance of the immediate surrounding area is related to the area of the visual task (**Figure 29**) and can be slightly lowered (e.g.

300 lx against 500 lx in the visual task area), while the average illuminance of the area background should be ≥ 1/3 of that of the immediate surrounding area.



Illuminance on the task area E_{task} lx	Illuminance on immediate surrounding areas lx
≥ 750	500
500	300
300	200
200	150
150	E_{task}
100	E_{task}
≤50	E_{task}

Figure 29. Relationship between the illuminances on the immediate surrounding area and the illuminances on the task area (UNI EN 12464-1).

Using the colorimeter, data were measured at regular intervals (approximately every hour) in three different grip points:

1) on the work surface
2) sideways to the worktop
3) behind the operator (between one workstation and another)

with the aim of characterizing the three areas defined by the legislation (**Figure 30**). The light sources position is also considered.

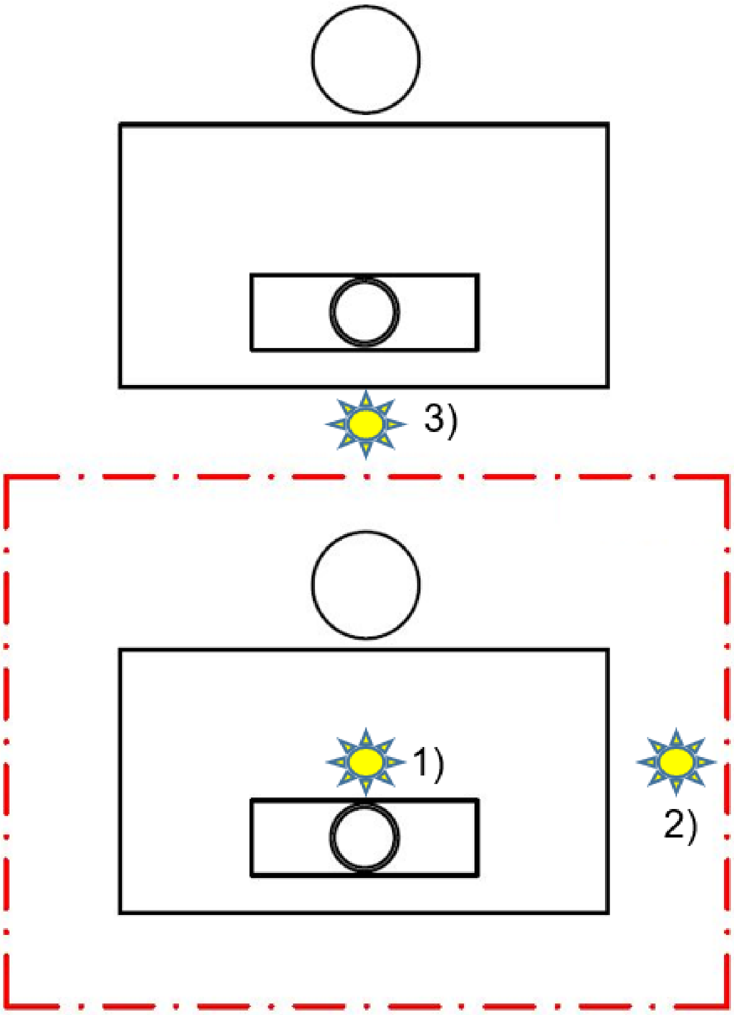


Figure 30. Grip points (own elaboration).

Finally, three operators were interviewed about the perceived wellbeing, their comfort in terms of microclimate; air quality; light; and noise.

5.2.2.1.4. Results

5.2.2.1.4.1. Microclimate

The activity is defined as light-duty (light industry) with MET = 1.6; with workwear CLO = 0.9 according to data of Compendium of Physical Activities (Ainsworth et al., 2011). Using the Fanger method, the well-being condition is estimated at a temperature of 20 °C, with a maximum acceptable variation of ± 4 °C. From the measurements, on the other hand, the average temperature is equal to 25 ° C, oscillating between 23 °C and 27 °C (**Figure 31**).

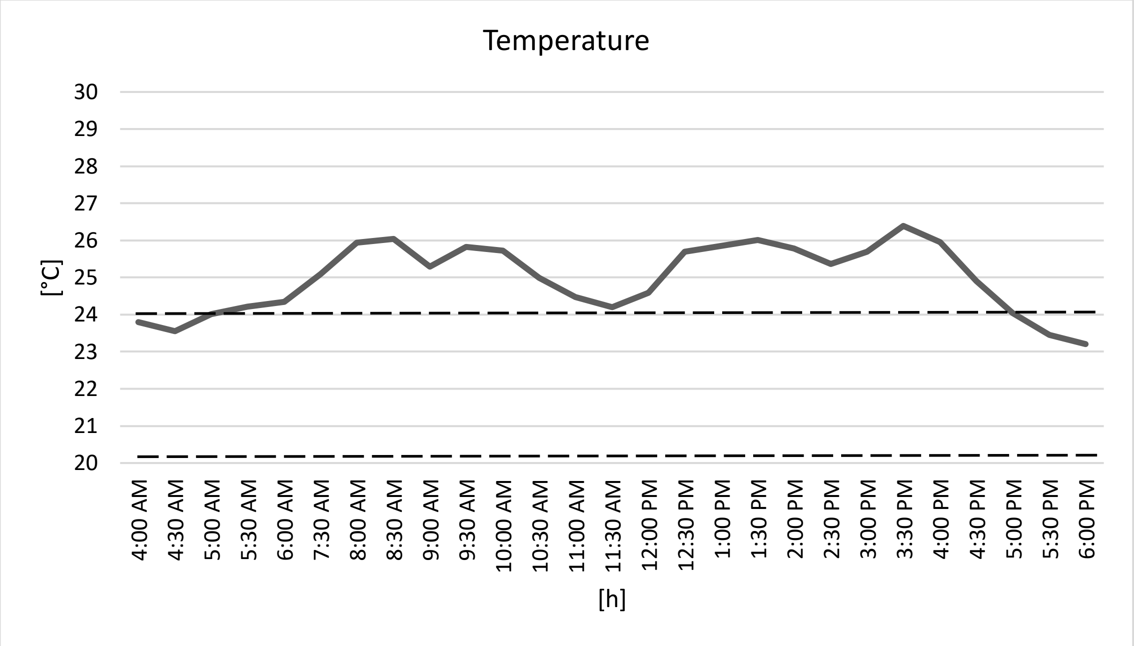


Figure 31. Detected internal temperature (solid line) and indication of the recommended temperature (dashed lines) according to the Fanger method (20 °C ± 4 °C), representative day, 05.06.2019 (own elaboration).

The following graph (**Figure 32**) shows the results of the measurements carried out relating to the relative humidity levels which are within the recommended limits (40% - 60%).

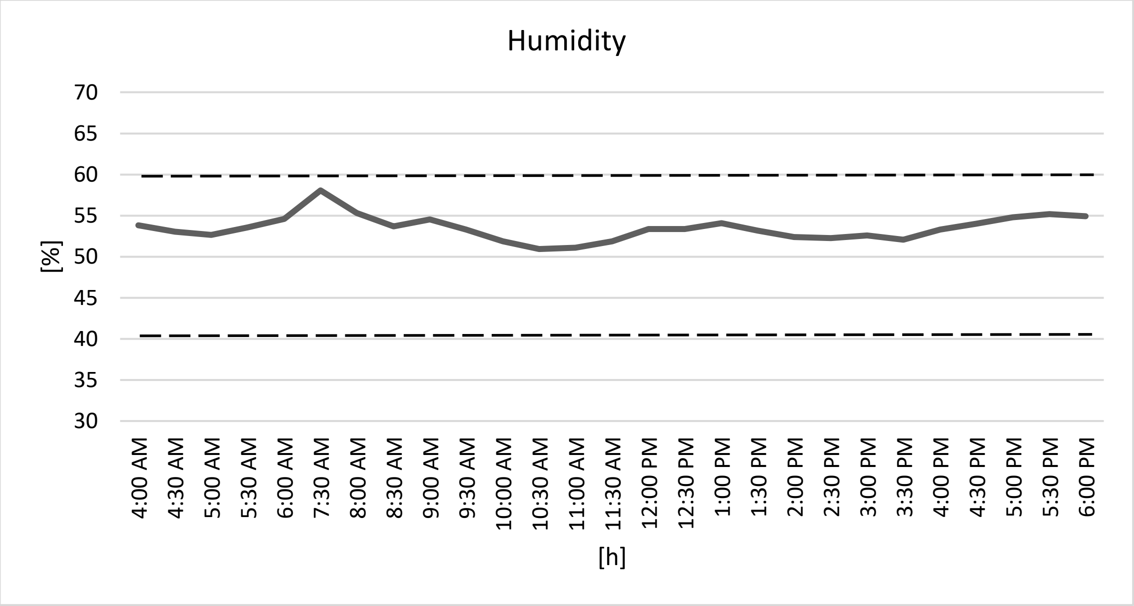


Figure 32. Measured relative humidity (solid line) and indication of the recommended value (40% - 60%) (dashed lines) , representative day, 05.06.2019 (own elaboration).

5.2.2.1.4.2. Air quality

The following graphs show the concentration of the detected pollutants: CO_2 (**Figure 33**); $PM_{2.5}$ (**Figure 34**); and VOCs (**Figure 35**).

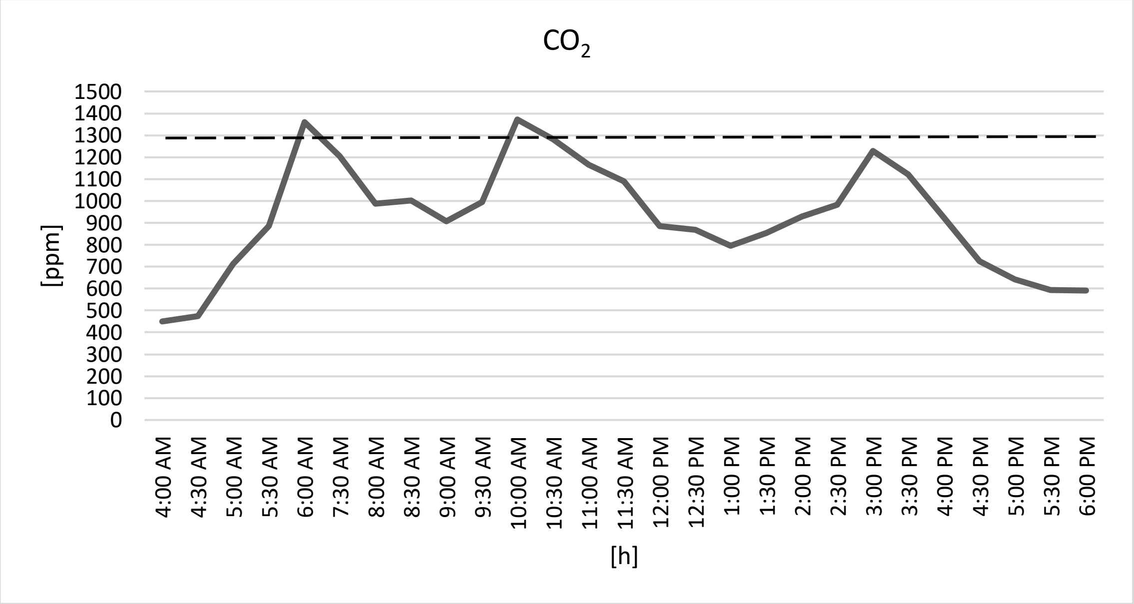


Figure 33. Concentration of CO_2 (own elaboration).

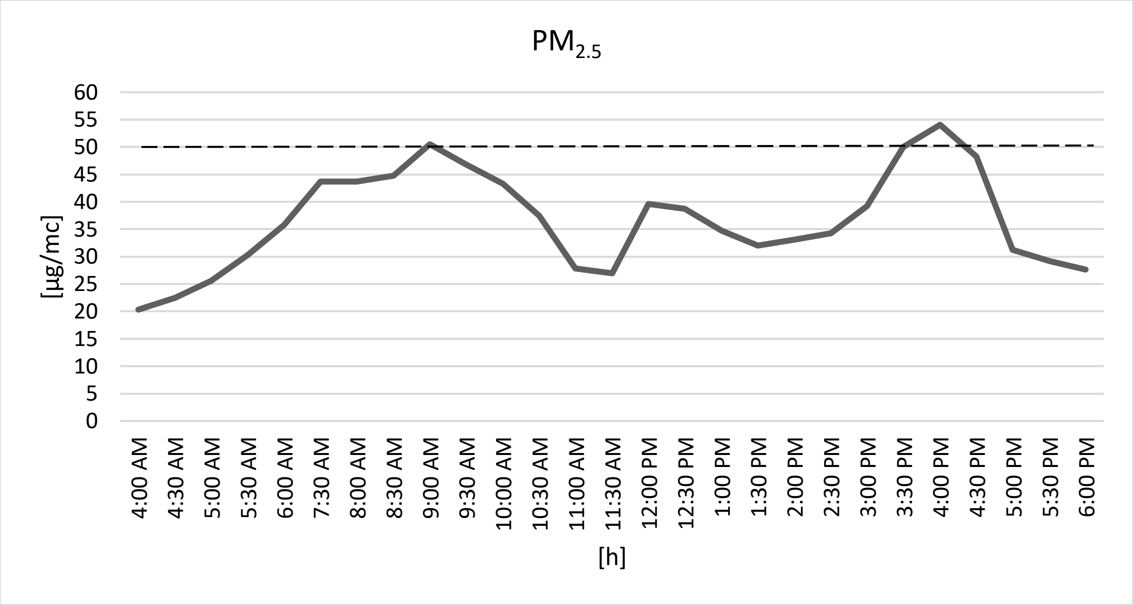


Figure 34. Concentration of $PM_{2.5}$ (own elaboration).

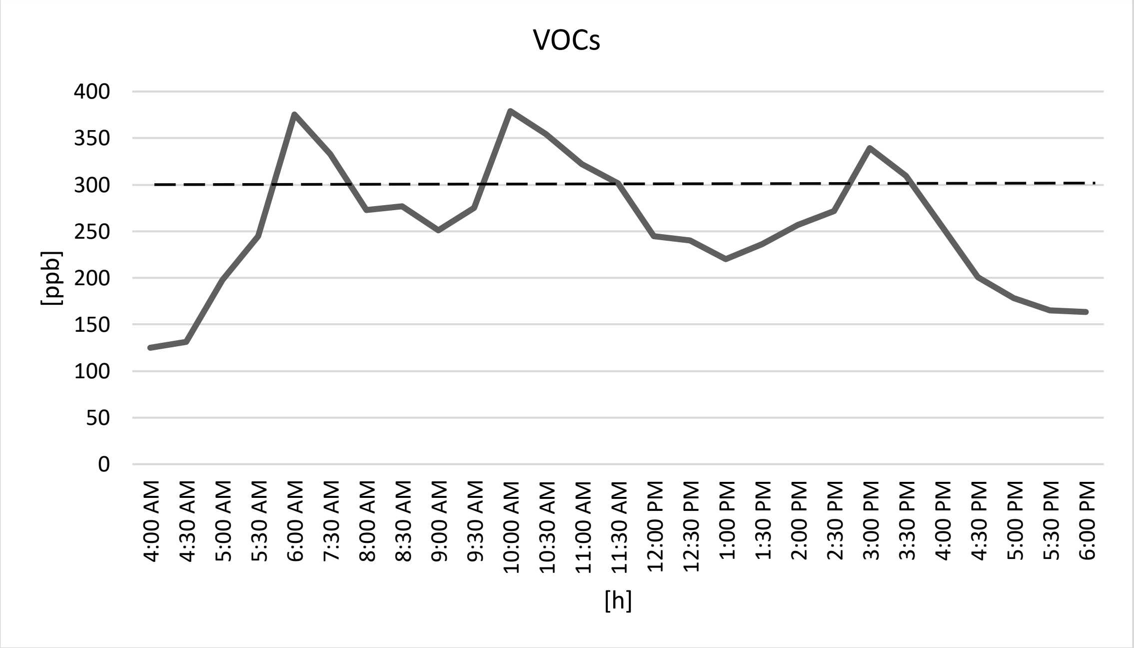


Figure 35. Concentration of VOCs (own elaboration).

The analysis of the graphs shows that the concentration of pollutants is higher than the suggested values. In particular, there is a concentration peak of $PM_{2.5}$ at 16:00 to 16:30 of the afternoon work shift that reaches the value of 55 micrograms/meter and CO_2 and

VOCs concentrations that exceed the recommended levels at three times of the day: at 6:00, 10:00 and 15:00, approximately one hour after the two shifts resumed work.

These concentrations raise the global index which takes values between 50 and 75, indicating sufficient air quality (**Figure 36**).

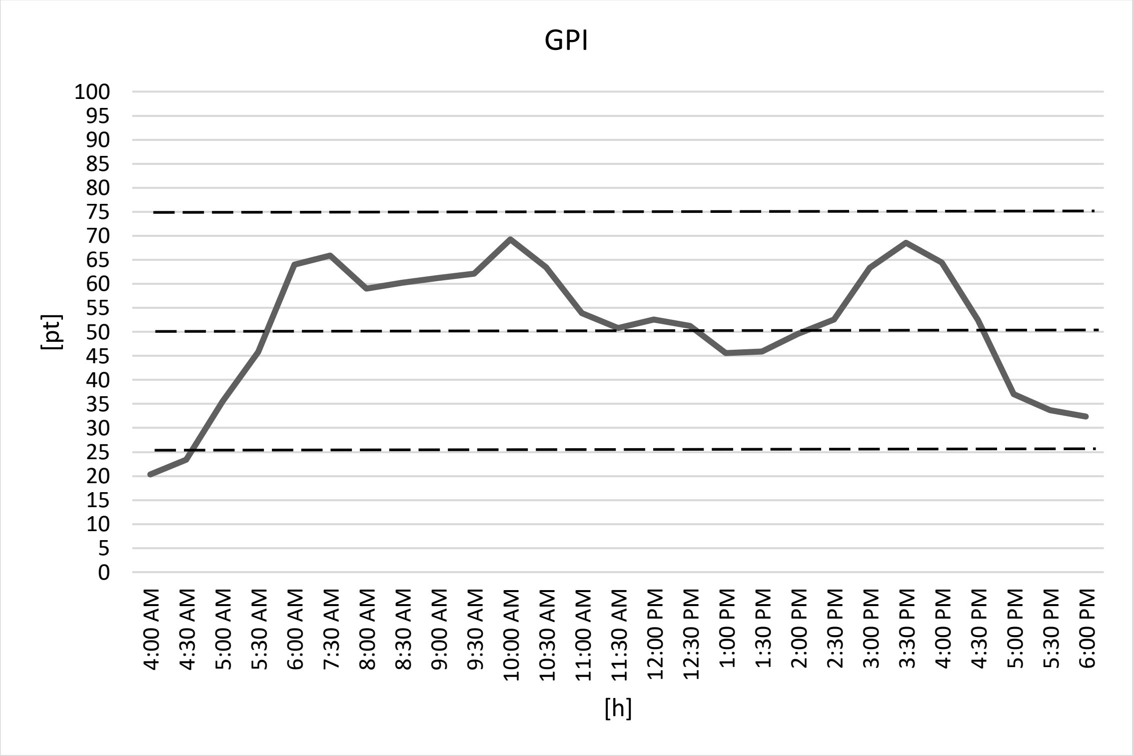


Figure 36. Global Pollutant Index (GPI) (solid line) and reference levels (dashed lines) (own elaboration).

5.2.2.1.4.3. Lighting

In the following graphs results for each workstation are shown, with evidence of the Ēm detected in the task, surrounding, and background areas and the average Ēm.

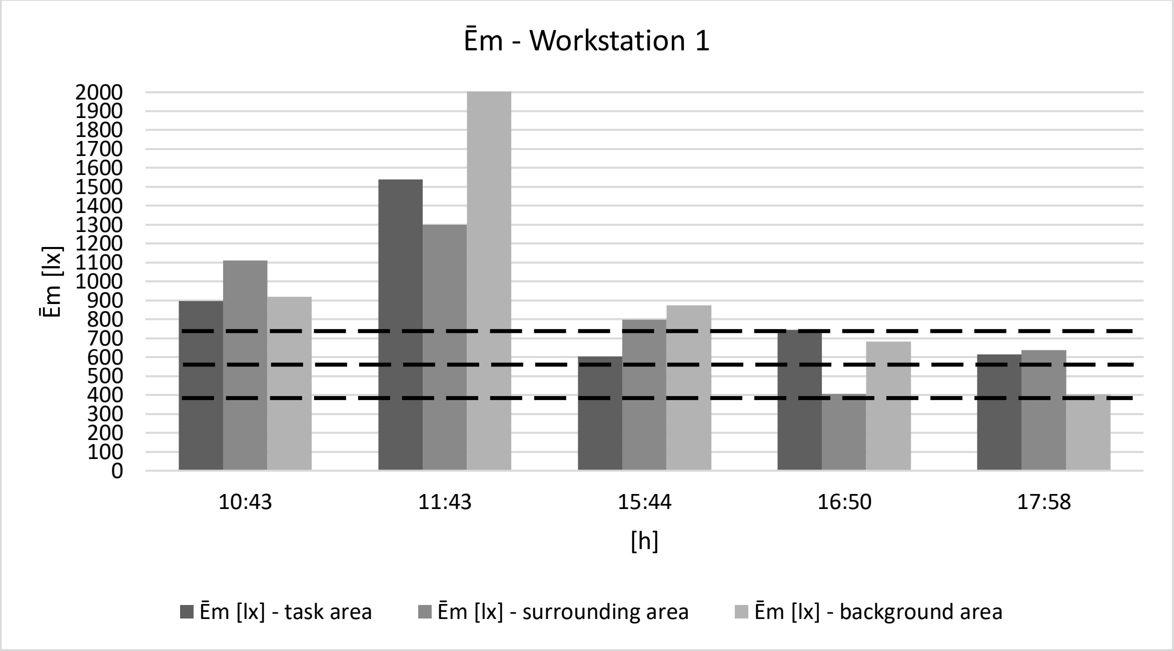


Figure 37. Ēm values for the Workstation 1 (own elaboration).

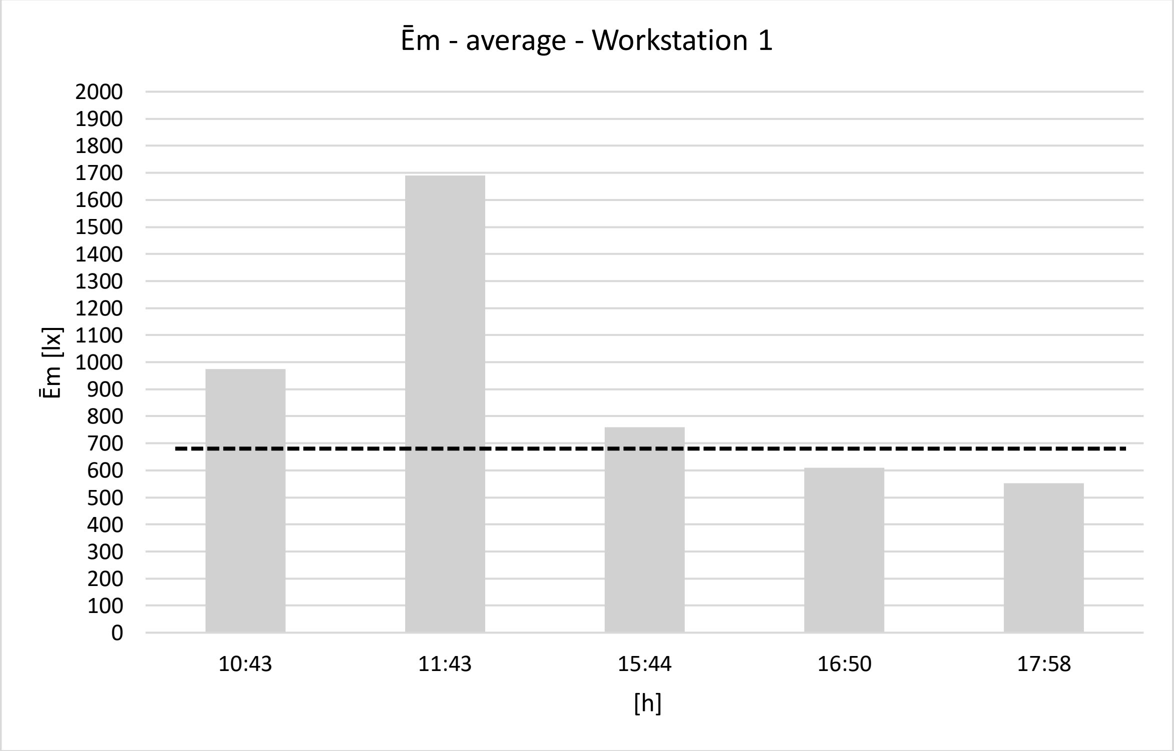


Figure 38. Resulting Ēm for the Workstation 1 (own elaboration).

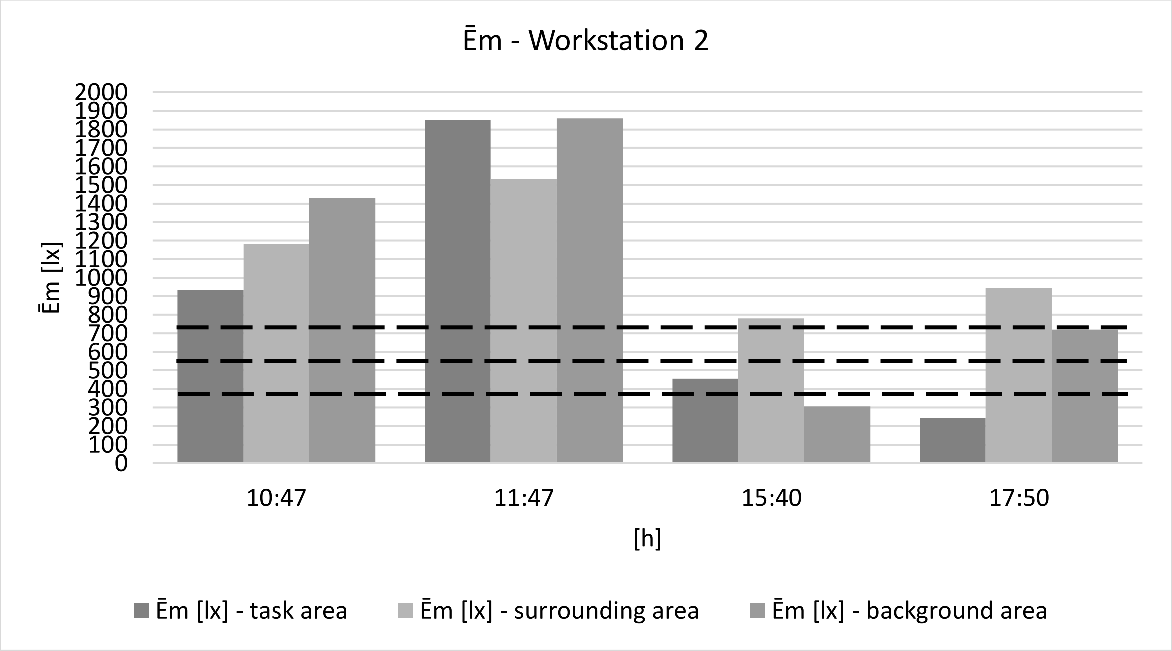


Figure 39. Ēm values for the Workstation 2 (own elaboration)

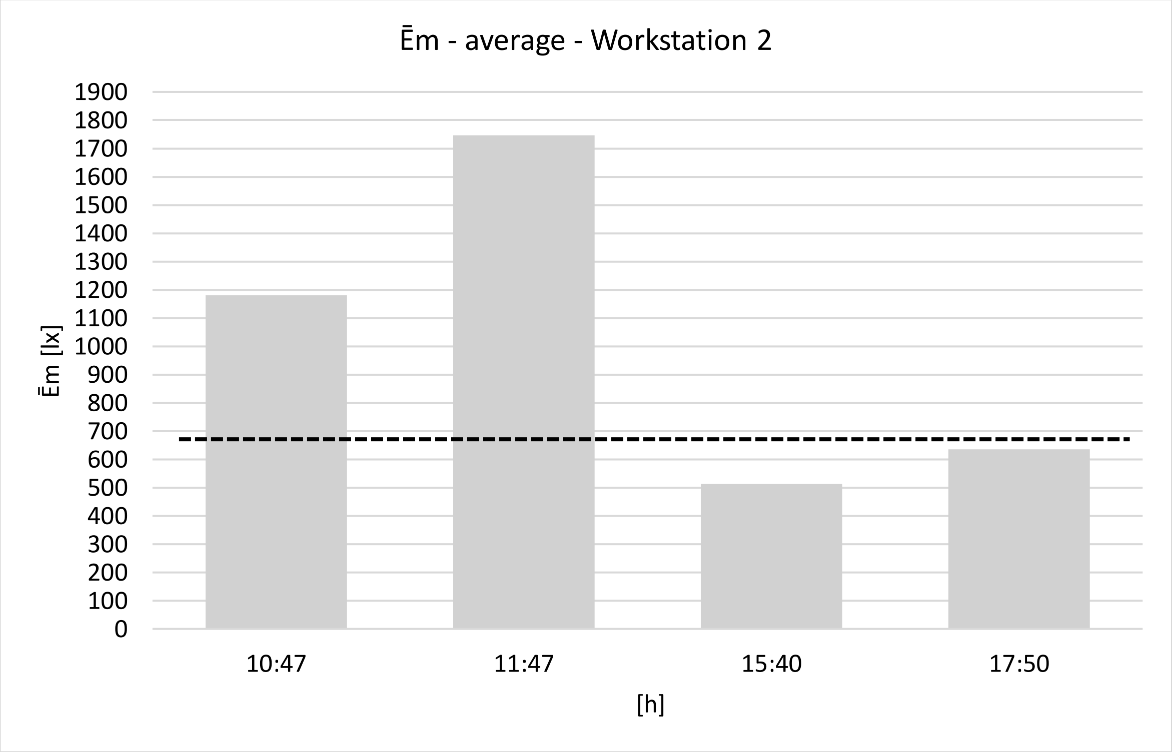


Figure 40. Resulting Ēm for the Workstation 2 (own elaboration).

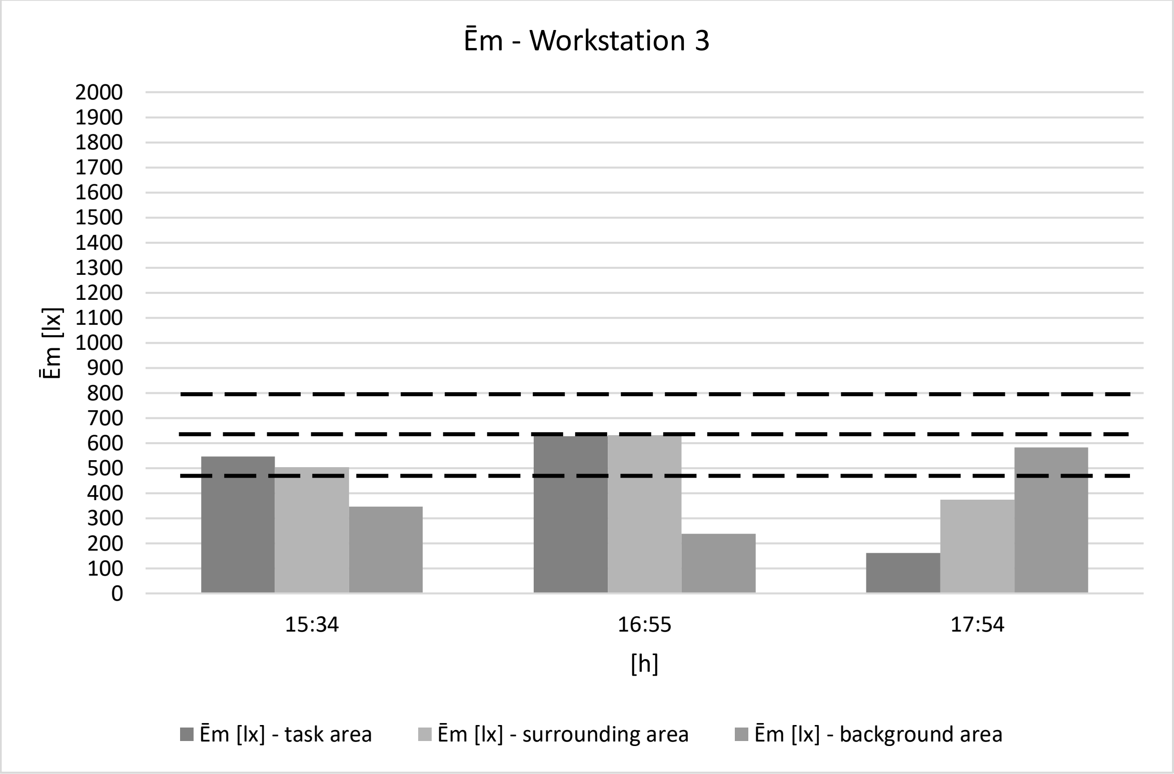


Figure 41. Ēm values for the Workstation 3 (own elaboration).

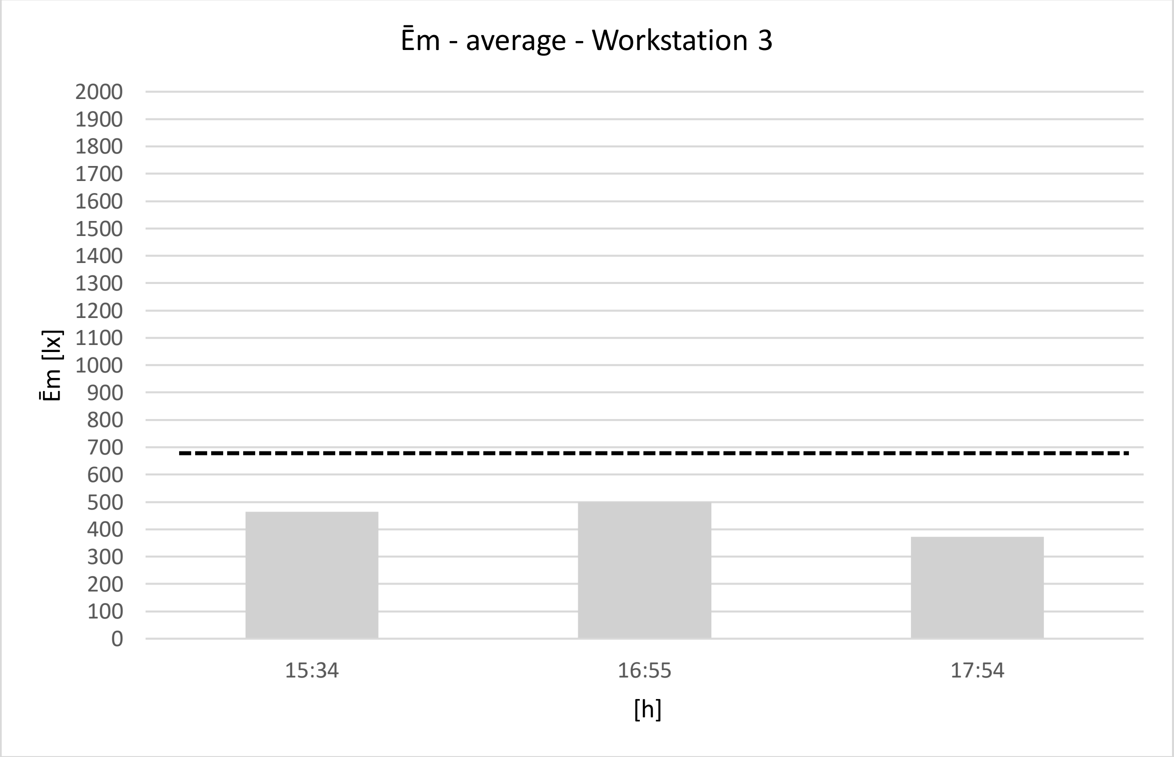


Figure 42. Resulting Ēm for the Workstation 3 (own elaboration).

Lighting data analysis show that the levels of illumination within the visual field are not constant during the period of work shifts, strongly influenced by the natural lighting coming from the skylights present on the roof of the building. Furthermore, in a few hours and for some locations the lighting levels are lower than the levels recommended by the regulations (500 lx). In particular, it is noted that the Workstation 2 and the Workstation 3 are particularly disadvantaged during the afternoon shift (**Figure 38**, **Figure 40**, **Figure 42**).

The lighting levels of the immediate surrounding and background areas are not attenuated compared to the levels of the visual task area; in fact, they are in some cases higher. This is presumably due to the position of the workstations relative to the skylights and the lamps relative to the workstations. They are in fact positioned to the left of the operator, a position which, in addition to not guaranteeing an adequate level of illumination within the work area, is highly disadvantageous for left-handed operators or those who work with the left arm, risking shade themselves (**Figure 37**, **Figure 39**, **Figure 41**).

The level of uniformity U_O is correct, i.e., above the value recommended by the standard (0.60) only in the case of Workstation 1. In all other stations it is lower (**Table 9**).

Table 9. Levels of uniformity U_O.

U_O Workstation 1	U_O Workstation 2	U_O Workstation 3	U_O UNI EN 12464
0.69	0.28	0.28	0.60

For all the analyzed stations, the color coordinates detected are around the values x = 0.35 and y = 0.34, corresponding to a correlated color temperature (T_{CP}) equal to 6000K (**Figure 43**) in compliance with the indications given by the legislation (4000 K $\leq T_{CP} \leq$ 6500).

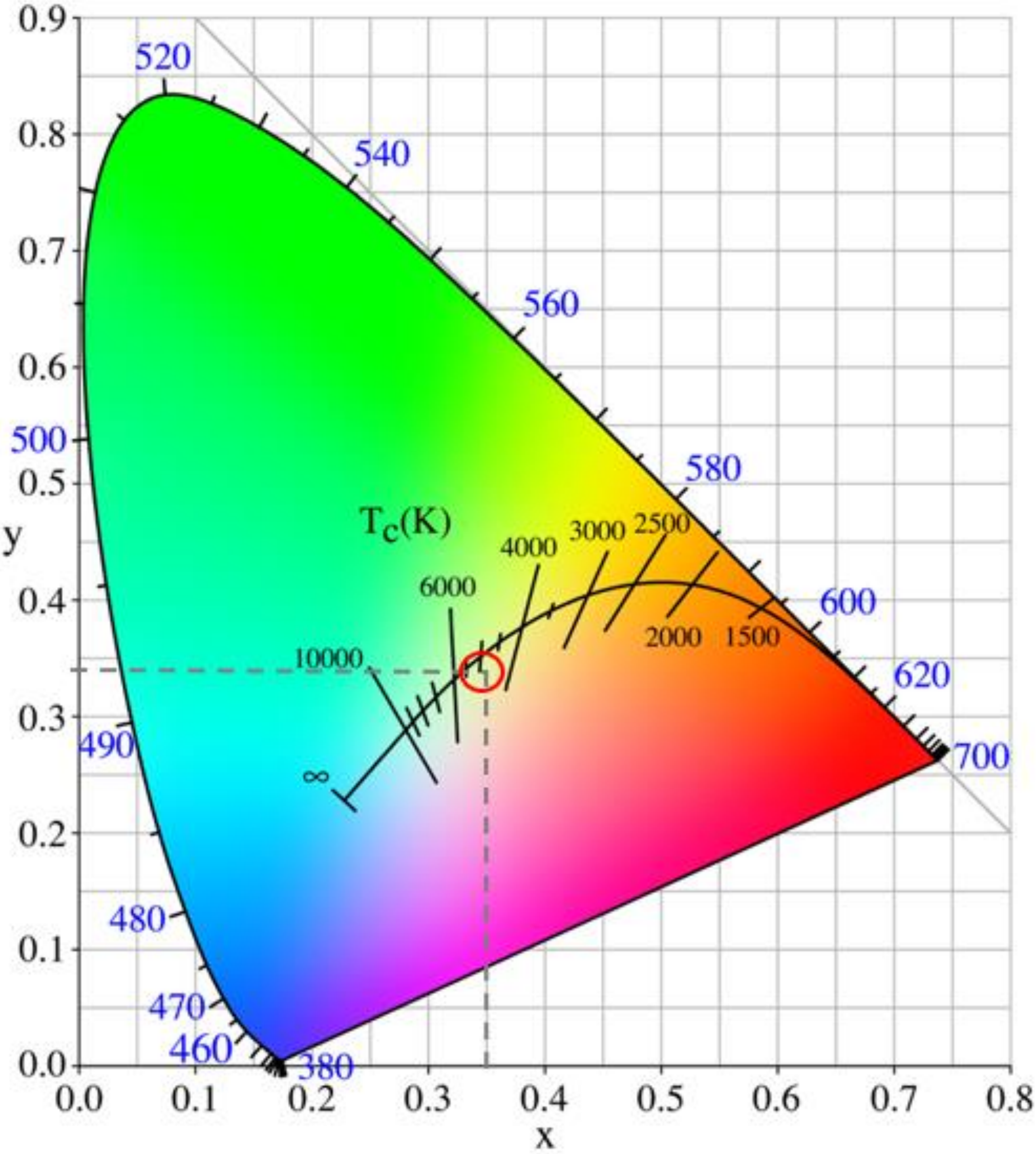


Figure 43. T_{CP} calculation (own elaboration).

Overall, the experimentation was evaluated through an ad hoc questionnaire administered to the workers. According 7- point Likert scale from 1 (strongly disagree) to 7 (strongly agree), it aimed to investigate physical discomfort. **Figure 44** reports the opinions of all three operators involved. In general, the worker’s opinion of thermal and visual comfort agrees with the measurement results. In particular, the temperature of the environment, the air quality, and the lighting causes discomfort to all the operators.

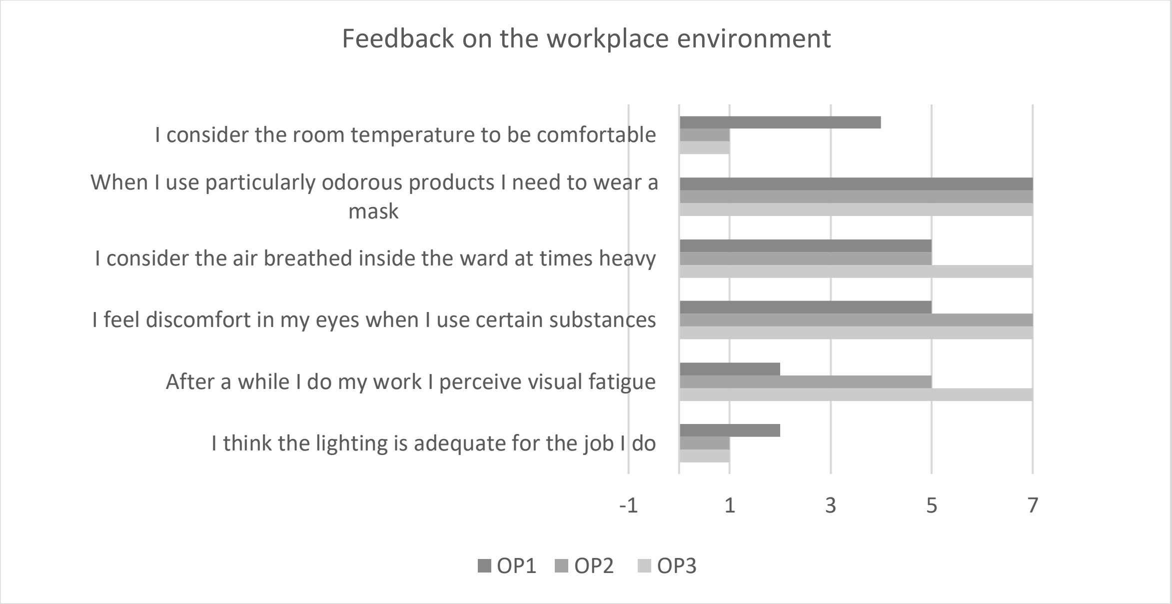


Figure 44. Feedback on the workplace environment (own elaboration based on interviews).

5.2.2.1.5. Conclusions

The study proposes an analysis of a workplace environment in the footwear sector where operators are involved mainly in manual activities and a strong artisan component prevails. The aim was to evaluate the workers wellbeing and to demonstrate that usually old-designed factories do not meet the requirements of the workers causing them a discomfort that can result in illnesses and in a decrease in productivity.

Results demonstrated that the work environment it is not adequate for the task to be done, in terms of temperature, air quality, and lighting.

However, in order to ameliorate the workers well-being, several low-cost solutions could be implemented, without impacting the execution of value-added work. Since the area is equipped with an air conditioning system (for heating and cooling) and a centralized air exchange system, it is proposed to install environmental temperature sensors and detection of pollutant levels in order to to regulate the internal temperature during working hours and to change the air whenever the recommended concentrations of pollutants are exceeded.

To improve the lighting performances, it is suggested a modification of the lighting system with lights positioned in such a way as to obtain:

- a correct level of illumination in the area of the visual field and in the immediate surrounding and background areas;
- a good spatial distribution of light according to the different directions;
- uniformity of lighting levels.

As a first hypothesis, it is assumed to rotate the existing lamps and check the lighting levels. If this solution is not sufficient, the integration of new lighting bodies suitable for the individual lighting requirement and the visual task to be performed is envisaged, installed either on the ceiling or directly on the worktable.

In addition, due to the considerable visual stress to which the operator is subjected due to the type of work that is carried out in the department that requires great attention and precision, and to the constant use of chemicals such as paints, a low-cost solution that could be adopted is to insert a 15-minute break in the morning and afternoon shift, in order to reduce the operator's physical and visual stress.

5.2.3. Energy savings measures

Alongside various management and behavioral strategies that can be implemented for the decarbonization of the industrial sector, such as increasing worker awareness and changing bad habits, or corporate responsibility strategies (Richert, 2017), there are several energy saving measures that could led to a sensitive energy consumption reduction and related emissions (Liu et al., 2014, 2012; Trianni et al., 2014a).

From a preliminary analysis (Marinelli et al., 2021) of the main energy savings measures adopted in industrial factory, and a further in depth analysis, three main areas of intervention are highlighted (**Table 10**):

- Lighting

- Energy systems
- Building envelope

Table 10. Summary of common energy savings measures adopted in industrial buildings.

Energy savings measure		Specific intervention	Source
Lighting			
		Natural lighting	(Katunský et al., 2017; Wang et al., 2019)
		Electric power reduction / Voltage optimization	(Boharb et al., 2016; Simson et al., 2016; Wang et al., 2019)
		Lighting replacement	(Chen et al., 2012)
		Efficient lighting	(Fellaou and Bounahmidi, 2017)
		Intelligent optical control system; integrated dynamic light systems	(Avgoustaki and Xydis, 2021; Katunský et al., 2017; Wang et al., 2019)
Energy			
	HVAC systems		
		Natural ventilation	(Wang et al., 2019)
		Heat pump technology	(Chinese et al., 2011; Wang et al., 2019)
		Energy regulation	(Dongellini et al., 2014)
		Improving the efficiency of boiler	(Chinese et al., 2011; Dongellini et al., 2014; Wang et al., 2019)
		Cooling tower	(Wang et al., 2019)
		Mixed / Hybrid displacement ventilation system	(Caputo and Pelagagge, 2009)
		Optimization of air supply distribution and mechanical ventilation	(Afkhami et al., 2015; Ahmed et al., 2020; Wang et al., 2019)
		Adjustable wind ratio	(Wang et al., 2019)

	Alternative energy		
		Heat recovery (exhaust air heat recovery; boiler heat recovery; compressor waste heat utilization)	(Dongellini et al., 2014; Hasanuzzaman et al., 2012; Wang et al., 2019)
		TES	(Arteconi et al., 2017; Wang et al., 2019)
		GSHP technology	
		RES energy on-site (solar and photo-thermal technology)	(Arteconi et al., 2017; Catalbas et al., 2021; Wang et al., 2019)
		RES energy off-site (connection to off-site RES, industrial and urban energy symbiosis)	(Butturi and Gamberini, 2020; Marinelli et al., 2020)
Building envelope			
		Wall insulation/renovation	(Ahmed et al., 2020; Dongellini et al., 2014; Gustafsson, 2006; Simson et al., 2016; Wang et al., 2019)
		Roof insulation/renovation, cool roof, green roof, coating, membrane	(Ahmed et al., 2020; Boobalakrishnan et al., 2021; Catalbas et al., 2021; Dongellini et al., 2014; Gourlis and Kovacic, 2016; Mastrapostoli et al., 2014; Tian et al., 2021)
		Window renovation	(Dongellini et al., 2014; Gourlis and Kovacic, 2016; Gustafsson, 2006; Simson et al., 2016; Wang et al., 2019)
		Door renovation	(Simson et al., 2016)
		Skylight replacement	(Gourlis and Kovacic, 2016)
		Sun shading system	(Wang et al., 2019)

Note: HVAC= heating ventilation and air conditioning; TES= thermal energy storage; GSHP= ground-source heat pump; RES= renewable energy source.

5.2.3.1. Lighting

Although representing generally a few percentages in the industrial energy consumption, lighting contributes significantly to electrical energy consumption (Worrell, 2010) as well as to the increasing of internal heat gain and the degradation of material and quality of lighting (Boharb et al., 2016).

So, even when lighting is a relatively small part of a plant's energy use, it may be possible to find considerable energy savings from improving natural lighting (Katunský et al., 2017), using more efficient lighting systems as Light Emitting Diode (LED) technologies; reducing electric power (Simson et al., 2016); installing intelligent optical control system (Wang et al., 2019); or implementing and applying fluctuating lighting schemes (Avgoustaki and Xydis, 2021), considering the fact that not all areas of a building are occupied all of the time. Automatic controls and sensors can be deployed to match lighting provision to need.

Furthermore, the importance of industrial lighting can be appreciated both in terms of energy consumption, but also in terms of safety, due to the need to provide adequate visibility so that materials can be transformed into finished products without hazards for the operators executing the tasks (Trianni et al., 2014b). Reducing the lighting levels where there is over lamping and meeting the standard recommendations for lighting levels according to purpose, helps to reduce electricity consumption and meet visual comfort levels. Illumination together with thermal and acoustic, have an impact on human comfort (Dong et al., 2021). Lighting, along with heating and acoustic, is a major element in buildings value and quality that strongly influence comfort, productivity, and health of occupants (Dong et al., 2021; Katunský et al., 2017).

5.2.3.2. HVAC systems

HVAC systems can cover a consistent share of the industrial energy consumption due to their primary role both being submitted to the production processes, but also in providing a comfortable environment to the operators. They should be used to maximize comfort and health condition by controlling humidity, temperature and air quality, with the minimum input of energy.

There are various cost-effective opportunities for the energy saving, as heat pump technologies installation (Chinese et al., 2011; Wang et al., 2019), or improving the energy efficiency of existing equipment as boilers (Chinese et al., 2011; Dongellini et al., 2014; Wang et al., 2019).

The mechanical ventilation also plays an important role for providing fresh air while recovering a big fraction of the ventilation heat otherwise lost by ventilation (Ahmed et al., 2020; Caputo and Pelagagge, 2009; Wang et al., 2019).

5.2.3.3. Alternative energy

According to the EBPD, 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. Various supply-side RE generation technologies are available for NZEBs, depending on the location of RE generation (Pless and Torcellini, 2010)(Feng et al., 2019):

- demand-side, as ground-source heat pumps (Dongellini et al., 2014; Hasanuzzaman et al., 2012; Wang et al., 2019).
- on-site, where all the renewable energies are available on-site and are generated within the building footprint or within the boundary of the building site, as photovoltaic (PV) and solar technologies located on the roof or on adjacent buildings spaces (Arteconi et al., 2017; Catalbas et al., 2021; Wang et al., 2019).
- off-site, when the building uses off-site energy with the connection to grid purchasing energy generated by RES. The renewable sources can be provided from both the urban and the industrial context, as in the case of industrial and urban energy symbiosis (Butturi and Gamberini, 2020; Marinelli et al., 2020; Neves et al., 2020).

5.2.3.4. Building envelope

Improving the building envelope is a primary concern to reach nZEB standards and indoor comfort (Albatayneh, 2021; Woods, 2007).

The most effective strategy of limiting heat loss (or gain) and reducing the energy need, is via the application of (additional) insulation to walls and roofs or the substitution of existing prefabricated panels with more performing components (Ahmed et al., 2020; Dongellini et al., 2014; Simson et al., 2016; Wang et al., 2019).

The cooling load of the metal roof industrial buildings could be reduced with the help of paraffin-based phase changing material (PCM), decrementing the daily average indoor temperature by 5 °C (Boobalakrishnan et al., 2021), or by applying innovative cool coatings (e.g., fluorocarbon, chromotropic and photocatalytic with self-cleaning functionalities, nano-composites, etc.) (Mastrapostoli et al., 2014).

Green roofs is also a largely demonstrated technology able to reduce the thermal gain as well as the heat island effect, and to enhance the hydrology lost habitats (Catalbas et al., 2021).

5.2.4. Sustainable construction materials

The building industry contributes to resource scarcity by consuming vast amounts of natural resources and produces in addition large amounts of waste, both contributing to a considerable portion of the environmental impacts induced by the demands of a growing world population. Manufacturing of most building materials require large amounts of material and energy resources. These materials are nevertheless either downcycled or ends up as waste after demolition. Consequently, the building industry only manages to exploit an insignificant percentage of the building materials’ inherent economic value and durability. Hence, the need for improved resource efficiency will increase parallel to the growing human demands to ensure that future needs. Circular Economy (CE) principles can potentially facilitate minimizing the pending issues emanating from the building industry through recirculation of building materials (Eberhardt et al., 2019).

CE strategies to reduce embodied emissions include: the reuse and recycling of materials; the reduction of resource use; the reduction of construction impacts; a better design; the reduction of end-of-life stage impacts; a green supply chain; the selection of materials (with low carbon, natural or innovative materials) (Allen et al., 2022; Owen et al., 2016).

The last cited strategy, namely, the choice of building materials, affects the extent to which pollutants are generated for the environment at all stages of construction (Mohson et al., 2021) resulting in a high-impact influence on the entire sustainability of buildings.

5.2.5. Green concretes

Concrete is the most widely used construction material next to water (Bhardwaj and Kumar, 2017). This is a mixture of cement, aggregate and water, which are components widely available on the market and at low cost (Ming and Cao, 2020).

According to the Global Cement Report (Cemnet, 2019), the global use of cement in 2019 reached 4.08 billion tons (an increase of 2.8% compared to the previous year). Most of the demand was concentrated in China (about 56%), which strongly influenced the market (+4.9% compared to 2018), followed by India. Excluding these two countries, the global market was unchanged compared to previous years (+0.3% compared to 2018). Aggregates are key elements in concrete, both due to the percentages present (aggregate occupies approximately 65–80 % of the mixture) and because they determine to a good extent the properties of concrete both in a fresh and hardened state. Fibers can be added to the mixture to reinforce the cement matrix (Wang et al., 2000) and to overcome concerns related to the brittleness and poor resistance to crack initiation and growth in cement-based materials (Pakravan and Ozbakkaloglu, 2019).

The increase in global demand for concrete, has led to a consequent build-up in the raw materials necessary for its production. In addition, the demand for green concrete in the construction sector has increased in recent years, encouraged by regulations to reduce the carbon footprint, limit greenhouse gas emissions and reduce limited landfill space (Zhang et al., 2021). For this reason, considerable efforts have been made at international level to support the transition of the infrastructure and construction sector towards approaches capable of respecting the principles of sustainable development, reaching the triple bottom line requirements of sustainability (Goh et al., 2020). This is also important to achieve the Sustainable Development Goals (SDGs) established by *The 2030 Agenda for Sustainable Development* (United Nations, 2018). Among the solutions available to promote the sustainability of the construction sector, the adoption of a circular approach to replace traditional linear paths is a widespread practice (Macarthur, 2020).

The use of by-products and waste materials could play the roles of either supplementary cementitious materials or alternative aggregates (Liew et al., 2017) and it is worldwide considered an approach with high potential to improve the sustainability of both construction and waste management sector (Turk et al., 2015).

A concrete produced by utilizing alternative or recycled waste materials, able to reduce natural resources and energy consumption as well as environmental impact is defined green concrete (Baikerikar, 2014). It is a concept of embracing and integrating environmental considerations in concrete with respect to raw material sourcing, mix and structural design, construction, and maintenance of concrete structures. The potential benefit is double: conservation of natural resources with a consequent low carbon footprint (Dash et al., 2016) and replacement of cement and aggregates with waste materials, thereby helping to reduce the quantities to be disposed of in landfills or incinerators (Shah et al., 2021).

The waste materials that can potentially be used in green concretes are of various kinds and belong to different sectors (**Figure 45**).

Experimental studies on natural fibers, as coir and sisal fibers, evidenced respectively an enhancement in ductile properties and an increasing in strength properties of concrete (Krishna et al., 2018).

In recent years, the recycle of raw wool derived from sheep in the production of concrete is attracting the attention of both research and industry, thanks to economic, technical and environmental advantages (Alyousef et al., 2020). Sheep wool fibers also demonstrated to increase the flexural, tensile, and compressive strength and to reduce the thermal conductivity and the capillarity absorption of concrete. In addition, concrete having sheep wool fibers have better workability, property that makes it suitable for various uses (Wani and ul Rehman Kumar, 2021). Also hemp concrete, a variety of vegetal concrete has been widely researched and is arguably one of the most researched building materials in current times (Jami et al., 2019).

Industrial wastes have long been used in cement mixtures. Recently, fly ash furnished by a paper-pulp industry demonstrated to be a valid substitution of the traditional cementitious materials, as the Ordinary Portland Cement, providing energy and savings (La Scalia et al., 2021).

Some research has begun towards the use of quarry dust, a by-product releases from the cutting and crushing process of stone which is a concentrated material to use as fine aggregates resulting in the reduction of land fill area and in the mitigation of the natural sand scarcity problem (Prakash and Hanumantha Rao, 2017).

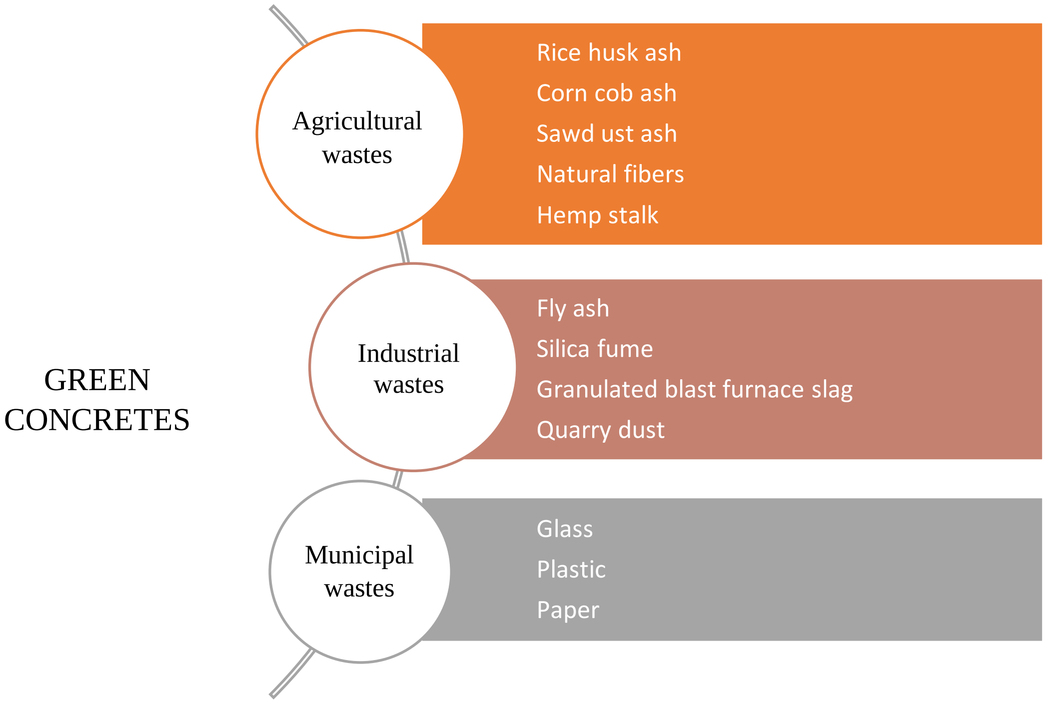


Figure 45. Some of the possible mixable waste materials in green concretes (own elaboration).

Among the different waste materials, plastic and rubbers are widely used in the construction industry (Awoyera and Adesina, 2020). In fact, compared to other waste materials, polymeric aggregates and fibers have several advantages, such as their excellent resistance to chemicals and their durability (Pakravan and Memariyan, 2017; Pakravan and Ozbakkaloglu, 2019). In addition, their use does not result in a loss of quality during the service cycle and, in some cases, improves the overall performance of the product, favoring the development of a large scientific literature that deals with this topic.

5.2.6. Plastic waste in green concretes

The use of recycled plastics in concrete is a practical approach at reducing plastic waste disposal, while improving sustainability in the construction industry (Pelisser et al., 2012).

This approach falls upon the European Strategy for Plastics in a Circular Economy (**Figure 46**) (Hasheminasab et al., 2022), first adopted in January 2018 (Sandanayake et al., 2020). Indeed, re-usage of plastic waste helps reducing dependence on non-renewable fossil fuels for virgin plastics production, curbs CO_2 emissions and eventually promotes cross-linking across the product value chain in a circular economy approach, contributing to a sustainable development of concrete (Liu et al., 2022).

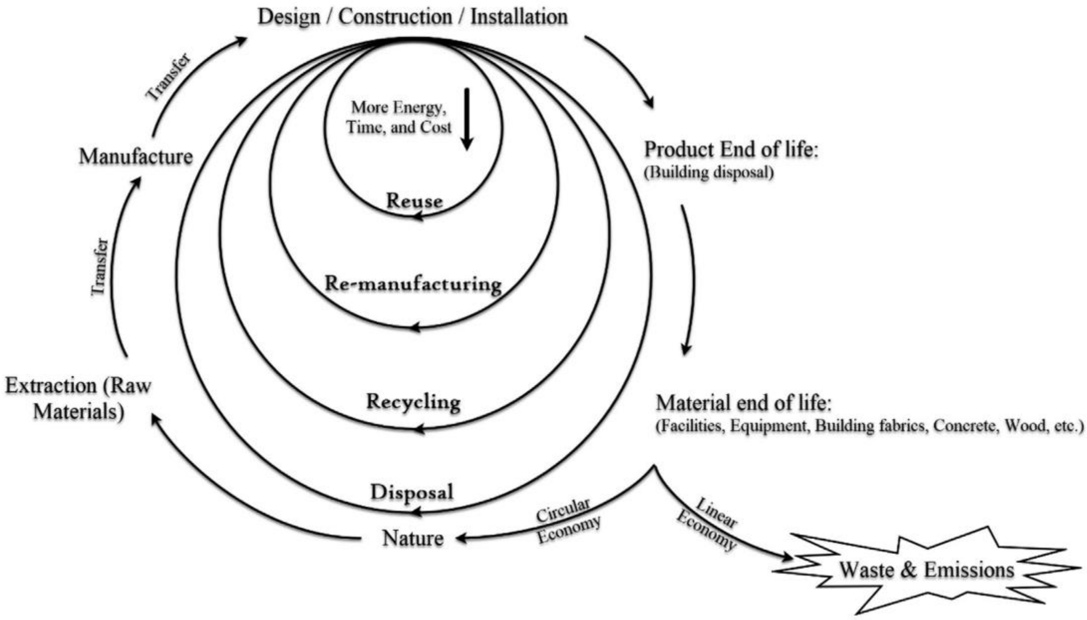


Figure 46. CE model for buildings and construction materials (Hasheminasab et al., 2022).

Against this background, in last years a high number of scientific studies and literature reviews have been published related to the recycling of plastic and rubber waste. Despite this interest, there are still critical and open issues. Previous works have mainly focused on properties of plastic waste in green concretes, leaving out important environmental issues, as discussed in the following sections.

5.2.6.1. Literature overview

One of the first review paper was published in 2008 by Siddique et al. (Siddique et al., 2008), while most of the other articles, representing the 84% of the total), are concentrated in recent years, in particular from 2016 onwards (**Figure 47**).

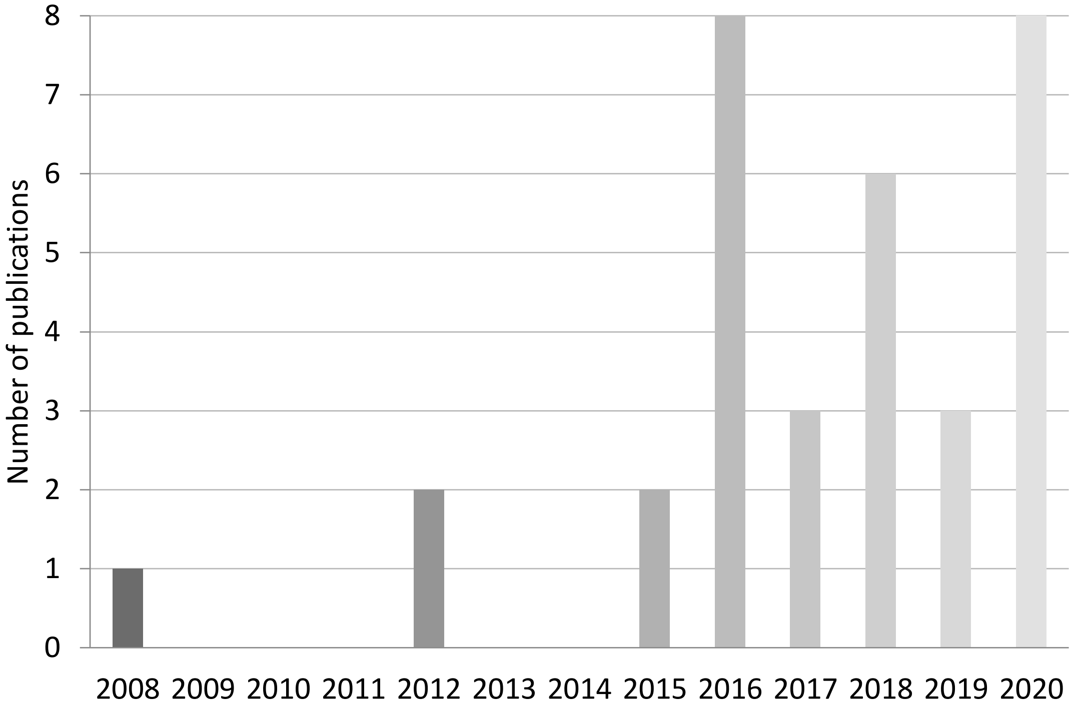


Figure 47. Number of publications per year (own elaboration).

The selected literature reviews are published in 17 different journals, with a strong concentration in Construction and Building Materials (about 35% of the articles analyzed). The rest are distributed almost homogeneously among all the other journals. **Figure 48** provides an overview of this situation, where the “other” category includes 12 different journals, each with one publication selected.

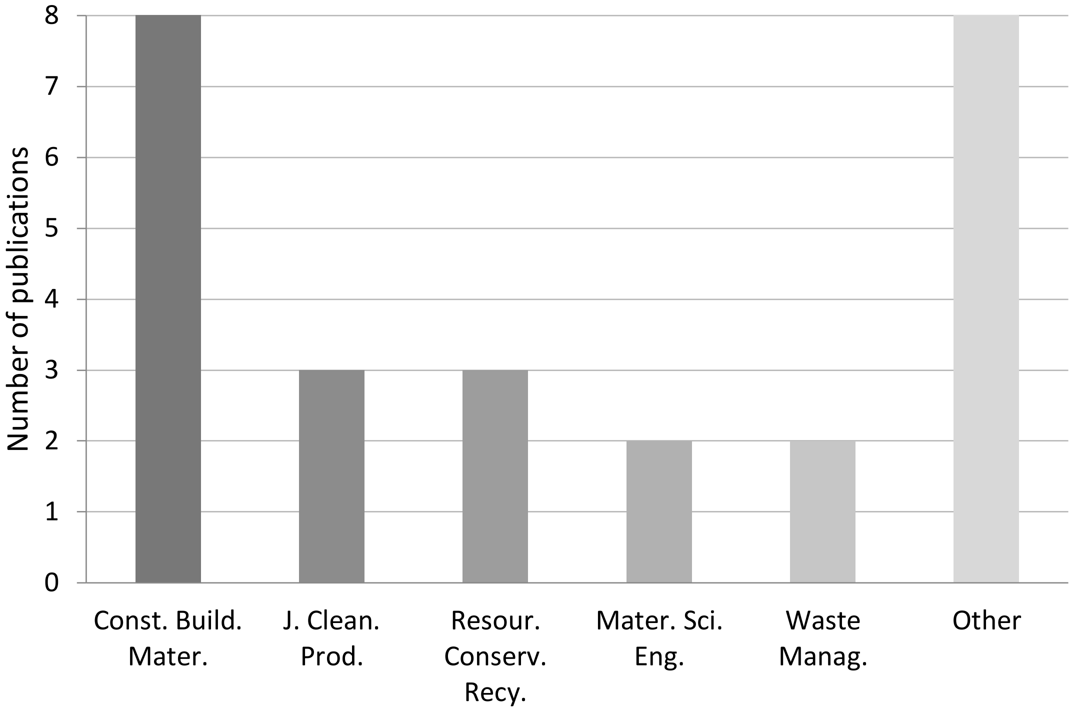


Figure 48. Number on publications per journal (own elaboration).

The geographical distribution (**Figure 49**) involves 15 different countries, with a strong concentration in Asia and Europe. This evidence is in line with statistics related to: i) the total plastic waste generation by country, which shows that China produces the largest quantity of plastics (nearly 60 million tons per year); ii) mismanaged plastic waste, indicating that India most inadequately disposes plastic waste (Geyer et al., 2017).

Figure 49. Geographical distribution of studies divided by reference areas (own elaboration).

Each review analyses a significant number of research papers. (Merli et al., 2020) and (Pakravan and Ozbakkaloglu, 2019) analyze 194 and 159 articles, respectively. (Roychand et al., 2020) present the findings from 100 research studies published in the last 30 years on tyre rubber concrete. (Chowdhury et al., 2018) and (Babafemi et al., 2018) focus on the descriptions of fewer articles (8 and 10, respectively). On average, about 60 papers are evaluated by each review.

5.2.6.2. Category analysis

The category analysis defines the plastics studied to be used in concrete and cement mortar, specifying type (PE; HDPE; LDPE; PET; PP; PVC; PVA; PS; EPS; HIPS; GFRP; PUR; ABS; PC; PMMA; MM; PA; PO; E-plastic); origin of waste; dimensions of the used samples (A; B; C; D); as well as their applications (**Table 11**).

Almeshal et al. (Almeshal et al., 2020) provide a very broad picture of the plastics used in concrete and cement mortar, analyzing 12 different types. This study, which analyses 103 papers, describes the use of recycled plastic aggregate as fine aggregate in cementitious composites and its impact on physical and mechanical properties, and durability. Also, the benchmark described by Mercante et al. (Mercante et al., 2018) is very comprehensive, with 10 types described. These outcomes derive from the analysis of 45 review papers referring to the addition of recycled plastic to concrete and mortar. The results clearly show that PET represents the type of plastic most studied in the literature: 78% of the authors analysis describe its use as a material added to cement and mortar. PP, rubber and tires follow, described by 50% of the authors analyzed.

Several authors focused their review on the mix in concrete and cement mortar of PET in the form of aggregates (Saikia and De Brito, 2012) and fibers (Jandiyal et al., 2016; Rostami et al., 2020) or both dimensions (Gao et al., 2019; Gu and Ozbakkaloglu, 2016), highlighting the different properties of the final products. PET and PP are widely used thanks to their numerous possible applications, such as packaging for liquids and for food products (e.g., crisps or ice cream). In the case of rubber and tires, Mohajerani et al. (Mohajerani et al., 2020) and Roychand et al. (Roychand et al., 2020) report that 1.5 billion waste tires are generated annually and identify the sectors of civil and geotechnical engineering as key sectors of use.

The dimensions of the plastic samples that are used in concrete and cement mortar, according to Novotny et al. (Novotny et al., 2019), can be divided into four categories, as shown below:

A. Dust: size up to 1 mm

B. Flakes: size of 1–10 mm

C. Pellets: size of 10–25 mm

D. Fibers: length of 25–50 mm

Fibers represent the dimensional structure most frequently analyzed and described in the review articles selected by this study, with approximately 78% of the authors analyzing them. Among polymer fibers, PP fibers have attracted the most research attention, because of their lower cost and simple processing compared with those of PE and PVA fibers (Pakravan and Ozbakkaloglu, 2019).

Dust follows, although with almost halved percentages (about 43%). It is evident that the two extreme categories (fine plastics and larger fragments) represent the forms of greatest interest.

Several studies (Alfahdawi et al., 2016; Alhasanat et al., 2016; Almeshal et al., 2020; Faraj et al., 2020; Novotny et al., 2019; Pakravan and Ozbakkaloglu, 2019; Sharma and Bansal, 2016; Siddique et al., 2008) describe the use of plastics across all possible identified dimensions.

Finally, from the point of view of their possible applications, concrete admixture represents the main use. According to these authors, a polymeric waste concrete potentially has several practical applications, such as concrete paving blocks and hydraulic structures, thanks to a higher abrasion resistance than conventional concrete (Gao et al., 2019; Saikia and De Brito, 2012).

Other authors also describe further possible uses in the construction and infrastructure sector, for example within the mixture that forms asphalt (Merli et al., 2020) and in bricks (Meng et al., 2018; Mercante et al., 2018). The possible applications indicated by many authors are not very thorough or precise, indicating their application for a wide range of uses relating to the construction and infrastructure sector.

When specified, the main source of plastic waste comes from the food industry, mainly beverage and food containers, followed by bags and other household plastics. Only two of the selected reviews (Babafemi et al., 2018) and (Vishwakarma and Ramachandran, 2018) consider the plastic deriving from electric and electronic waste (e-plastic).

Table 11. Results of the category analysis.

Nr	Reference	Plastic types	Waste sources	Dimensions	Applications
1	(Alfahdawi et al., 2016)	PP, PET	bottles, bags, unspecified	A, B, C, D	lightweight concrete
2	(Alhasanat et al., 2016)	PE, LDPE, PP, PET	bags, unspecified	A, B, C, D	self-compacted concrete
3	(Almeshal et al., 2020)	HDPE,	bottles, beverage	A, B, C, D	concrete,

		LDPE, PET, PP, PVC, PS, EPS, HIPS, ABS, PC, MM, rubber	containers, food containers, other household plastics		lightweight concrete, mortar
4	(Babafemi et al., 2018)	PET, e-plastic	bottles, electronic industry, unspecified	A, B, C	concrete, mortar
5	(Chowdhury et al., 2018)	PET, PVC	bottles, beverage containers	A, D	admixture to concrete
6	(Dam et al., 2016)	virgin plastic, LDPE, HDPE	packaging, electronic industry, automobile residues	C, D	admixture to concrete, asphalt
7	(Faraj et al., 2020)	PET, PVC, HDPE, GFRP, PUR, PC, PE, PP, PVA	bottles, bags, boxes, unspecified	A, B, C, D	self-compacting mortar and concrete, self-compacting lightweight concrete, self-compacting high-strength concrete
8	(Gao et al., 2019)	PET	unspecified	D	unsaturated polyester resin concrete
9	(Gu and Ozbakkaloglu, 2016)	PET	bottles	D	admixture to concrete
10	(Jandiyal et al., 2016)	PET	bottles	D	admixture to concrete
11	(Kamaruddin et al., 2017)	HDPE, PET, PVC, EPS, GFRP, virgin plastic	bottles, beverage containers, food containers, other household plastics	A, B, D	admixture to concrete
12	(Li et al., 2020)	PET, EPS,	bags, unspecified	A, B, C	admixture to

		PP, PO, PS, PE, rubber			concrete
13	(Liew et al., 2017)	PP, rubber	unspecified	D	Fiber-reinforced mortar
14	(Meng et al., 2018)	PET, unspecified	unspecified	B, C (unspecified)	concrete blocks
15	(Mercante et al., 2018)	HDPE, LDPE, PET, PP, PVC, PS, PUR, MM, PA, rubber	unspecified	B, D	mortar and concrete composites, bricks, panels, subfloors
16	(Merli et al., 2020)	PE, PET, PP, PUR, PA, rubber	plastic bottles, tyres, textile industry, bag manufacturing	D	asphalt, fibre-reinforced concrete, concrete, lightweight concrete, mortar
17	(Mohajerani et al., 2020)	rubber	tyres	A, B, C	admixture to concrete
18	(Mukhopadhyay and Khatana, 2015)	PA, PET, PP, PUR	unspecified	D	admixture to concrete
19	(Novotny et al., 2019)	PE, HDPE, PET, PP, PVC	bottles, rubbish bags	A, B, C, D	admixture to concrete
20	(Pacheco-Torgal et al., 2012)	rubber, PET	bottles, tyres	A, B, C, D	admixture to concrete
21	(Pakravan and Memariyan, 2017)	PA, PET, PP, PVA, PUR	unspecified	D	admixture to concrete
22	(Pakravan and Ozbakkaloglu, 2019)	PP, PE, PVA	unspecified	A, B, C, D	fibre-reinforced cementitious composites
23	(Rostami et al., 2020)	PET	beverage containers, soft	D	admixture

			drink bottles		to concrete
24	(Roychand et al., 2020)	rubber	tyres	A, B, C	admixture to concrete
25	(Saikia and De Brito, 2012)	PET	bottles	B, C	cement mortar and concrete
26	(Sharma and Bansal, 2016)	PE, PET	bottles, unspecified	A, B, C, D	admixture to concrete, concrete blocks
27	(Siddique et al., 2008)	virgin plastic, LDPE, HDPE, PET, PP, PC, PVC, PS, ABS	electric and electronic equipment, automobile residues, packaging, unspecified	A, B, C, D	admixture to concrete
28	(Thakare et al., 2020)	rubber, PET	plastic bags, bottles, unspecified	D	incorporation in self-compacting cementitious mixes (SCM) (mortar and concrete)
29	(Tavakoli et al., 2018)	PET, rubber	tyres and bottles	A, B	admixture to concrete
30	(Tiwari et al., 2016)	PET, rubber	and bottles	A, D	admixture to concrete
31	(Thomas and Gupta, 2016)	rubber	tyres	A, B, C	admixture to cement concrete
32	(Vishwakarma and Ramachandran, 2018)	plastic waste, rubber, e-plastic	tyres and bags and plastic bottles, electronic industry	A, B, C, D	admixture to concrete
33	(Yin et al., 2015)	PP, HDPE, PET	bottlers, unspecified	D	admixture to concrete

Legend: PE, Polyethylene; HDPE, High-density polyethylene; LDPE, Low-density polyethylene; PET, Polyethylene terephthalate; PP, Polypropylene; PVC, Polyvinyl chloride; PVA, Polyvinyl alcohol; PS, Polystyrene; EPS, Expanded polystyrene; HIPS, High-impact polystyrene; GFRP, Glass fibre reinforced plastic; PUR, Polyurethane; ABS, Acrylonitrile butadiene styrene; PC, Polycarbonate; PMMA, Poly(methyl methacrylate) acrylic; MM, Melamine; PA, Polyamide; PO, Polyolefins; E-plastic, plastic from electric and electronic wastes; A, Dust (up to 1 mm); B, Flakes (1–10 mm); C, Pellets (10–25 mm); D, Fibres (length of 25–50 mm).·

5.2.6.3. Stated properties

Between all the physical and mechanical properties characterizing concrete and cement mortar, 25 have been identified as the main investigated by authors of the review studies **Figure 50**).

Among the physical properties, the workability is the most frequently analyzed followed by the dry density, while among the mechanical properties the compressive and split tensile strength are the most frequently investigated (analyzed by 21 and 22 authors, respectively), followed by the flexural strength and the elastic modulus (Young’s modulus) (18 and 16 articles, respectively).

Many others are physical and mechanical properties of less interest to authors, covered in very few studies. Alkali resistance, roughness, spalling and deflection are some examples. Among the reviewed review papers, the paper by Rostami et al. (Rostami et al., 2020) is the article that analyses the largest number of properties (16 shared between physical and mechanical properties), followed by Almeshal et al. (Almeshal et al., 2020) and Mercante et al. (Mercante et al., 2018) with 15 properties investigated and, finally, by Novotny et al. (Novotny et al., 2019) with 12 properties. Many other authors have preferred to focus on a few properties, analyzing in detail the effect of plastics and rubbers on the characteristics of concrete and cement mortar. In fact, 13 papers analyze fewer than five properties, focusing mainly on compressive and flexural strength and on workability.

It is evident from the literature that most of the studied properties have different results depending on several variables, such as type, size, proportion, and recycling and treatment methods of waste materials used. Some properties, however, seem not to be influenced at all by the cited variables, or influenced only partially, such as fresh and dry densities, which decrease with the increase in plastic and rubber content because the specific gravity of plastic and rubber is significantly lower than that of conventional aggregates or fibers (Li et al., 2020; Roychand et al., 2020; Siddique et al., 2008).

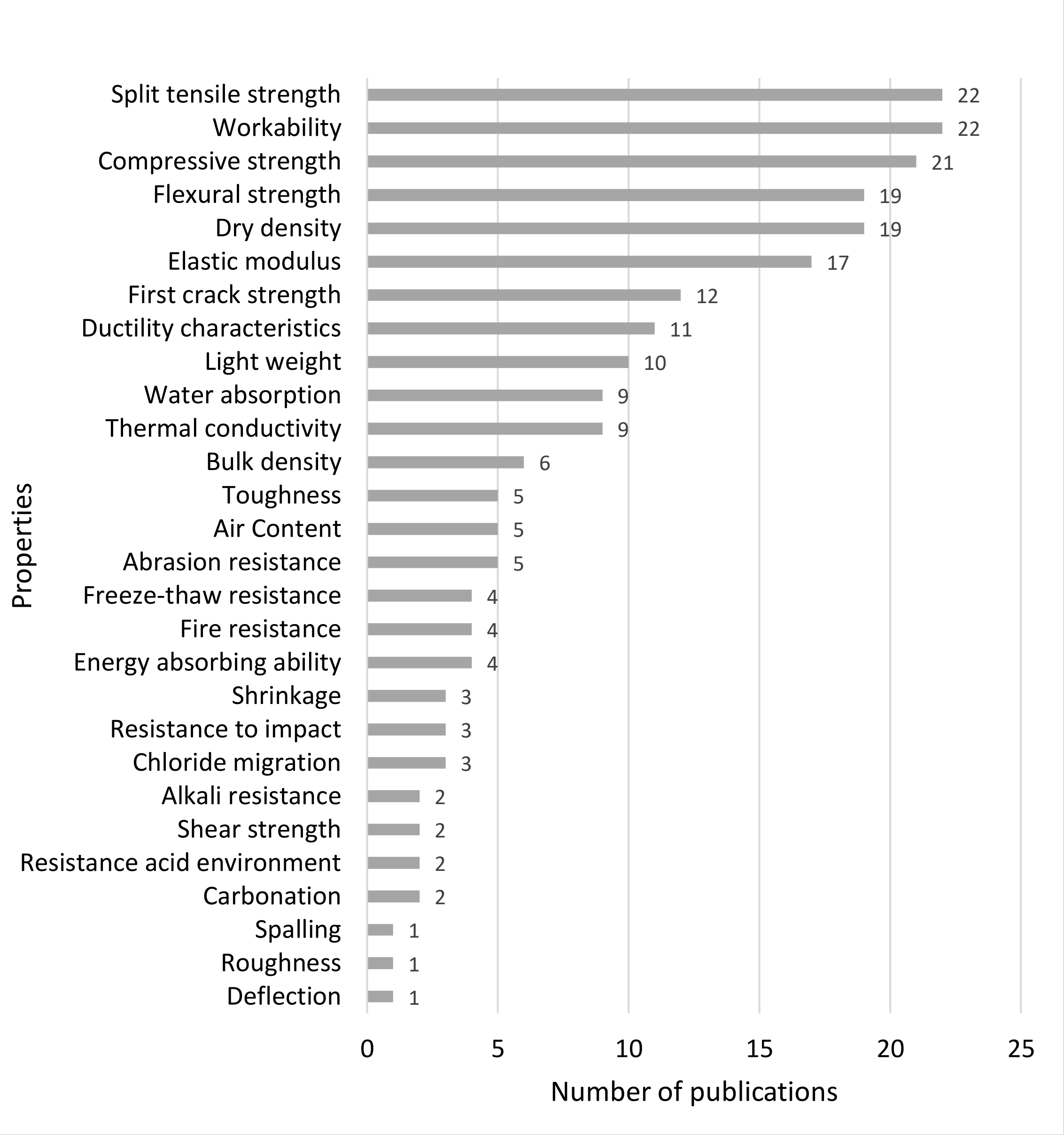


Figure 50. Physical and mechanical properties analyzed by authors of the selected reviews (own elaboration).

Researchers demonstrated that the thermal conductivity always decreases in concrete and cement mortar containing plastic and rubber waste material, leading consequently to better thermal insulation properties than conventional concrete, which can be used to control heat loss from buildings during winter and heat gain during summer (Alfahdawi et al., 2016; Babafemi et al., 2018; Li et al., 2020; Pacheco-Torgal et al., 2012; Saikia and De Brito, 2012). The critical issues related to the main properties influenced by the previously cited variables are discussed in the following section.

5.2.6.4. Critical aspects

Among the numerous properties analyzed, workability strongly characterizes fresh cement mortar. Workability of concrete is defined as the ease with which concrete can be mixed, transported, placed and finished without segregation and it is measured through slump tests, the K-test and the inverted slump cone test for fiber-reinforced concrete (Siddique et al., 2008). Research findings show conflicting performances of cement and mortar concrete workability under the influence of polymeric waste aggregates and fibers in the mixture. According to the review conducted by Pacheco-Torgal et al. (Pacheco-Torgal et al., 2012), the workability is mainly dependent on the characteristics and on the treatments of the aggregate, while according to Babafemi et al. (Babafemi et al., 2018), it is mainly influenced by the particle shape, size, roughness, water-cement ratio and amount of cement paste. According to the study conducted by Alhasanat et al. (Alhasanat et al., 2016), the workability increases with the addition of fine recycled plastic aggregates, while it decreases with the addition of fibres and coarse aggregates. Pakravan et al. (Pakravan and Ozbakkaloglu, 2019), based on analysis of the reports in the literature related to the influence of PP, PE and PVA fibers, concluded that workability is not very sensitive to the type of fiber.

Among the mechanical properties, the compressive strength presents ambiguous indications among the authors analyzed. Compressive strength is the ability of a material to support and resist pressure until it breaks. It is another property described by the authors analyzed with conflicting performances in respect to specific characteristics of the composition of cement and mortar concrete. The results available in the bibliography show that the use of alternative materials in the composition of concrete mixes determines a general tendency for the compressive strength of the material to deteriorate, with a marked dependence on the substitution level of fine plastic aggregate (S_{pa}), the shapes (uniform or non-uniform materials), the material used (plastic or rubber) and the water-to-cement ratio (w/c). Almeshal et al. (Almeshal et al., 2020) studied the relationship between S_{pa} and compressive strength, highlighting the general inverse relationship between the two aspects. The results presented by Pakravan and Memariyan (Pakravan and Memariyan, 2017) also confirm that a reduction in compressive strength is observed with the incorporation of PP fibers in concrete at any dosage. The non-uniform behavior among authors is summarized in the study by Alfahdawi et al. (Alfahdawi et al., 2016), which reports the bibliographic evidence of the effect of plastic ratio substitution on compressive strength in mixes, highlighting the conditions that determine a reduction in compressive strength and those that determine an increase. Gu and Ozbakkaloglu (Gu and Ozbakkaloglu, 2016), in their review, confirm the general trend towards a progressive reduction in compressive strength, indicating that non-uniformly shaped PA decreases more significantly than that of concrete containing uniformly shaped PA. This study also reports that, using PF with a high ultimate tensile strength, there is a significant improvement in the compressive strength compared to the use of fibers with a low ultimate tensile strength. Novotny et al. (Novotny et al., 2019) emphasize that concrete containing plastic fibers up to 1% have a higher compressive strength, which decreases at 1.5% of plastic fiber content. The ratio of fiber length to fiber diameter is reported as a relevant parameter in defining properties. Using rubber as an alternative material, Mohajerani et al. (Mohajerani et al., 2020) report a significant reduction in concrete compressive strength with an increase in rubber content. This behavior is also confirmed by the studies analyzed by Roychand et al. (Roychand et al., 2020), who also identified an author who showed a contradictory result.

Linked with the compressive strength, often the split tensile strength and flexural tensile strength are also used by authors for determining strength. Compressive and tensile strength are closely linked, and display similar behavior (Mercante et al., 2018). Jandiyal et al. (Jandiyal et al., 2016) state that split and flexural tensile strength improved with an increase in fiber content, in particular up to a replacement level of 0.1%. With long fibers, flexural strength is greater than using smaller ones. In the same study, bibliographic cases are reported in which these properties have an opposite trend. Also, Novotny et al. (Novotny et al., 2019) confirm these results. Pacheco-Torgal et al. (Pacheco-Torgal et al., 2012) correlate these performances with the characteristics and the treatments of the aggregate.

For the elastic modulus, many studies have not reported significant variations when alternative materials are used (Mukhopadhyay and Khatana, 2015), although disagreements are attributed to different aspects, such as the type, the shape, the dosage, the w/c ratio and the porosity (Faraj et al., 2020; Gu and Ozbakkaloglu, 2016; Mercante et al., 2018)

Water absorption is one of the physical properties that present performances that are still much discussed among the authors in the literature, with aspects and situations still being studied in depth. Almeshal et al. (Almeshal et al., 2020) report that water absorption increases when the replacement ratio of sand with plastic also increases. This is due to the increase in the porosity of the cementitious matrix. In fact, the increase in water absorption is influenced by the increase in the size of plastic/rubber particles, the content of aggregate and fibers, and the w/c ratio. In studying the collected papers, the authors also identified divergent experiences, where the water absorption decreases. For Jandiyal et al. (Jandiyal et al., 2016), this property decreased up to 1% of the fiber content. Increasing behavior is also confirmed by Rostami et al. (Rostami et al., 2020). The effect of the shape of the materials was analyzed in the paper by Li et al. (Li et al., 2020), where it is described that lamellar and angulated plastic aggregates cause higher water absorption in concrete than the corresponding spherical and regular ones. This study also analyzed the effect of rubber, which shows a general tendency to have a negative impact on the water absorption of concrete by increasing the content of rubber. Also, for this material, threshold values are highlighted, below which the water absorption tends to decrease, and then increase after exceeding a specific content.

5.2.6.5. Open issues

5.2.6.5.1. Environmental performances

Studies are available on the environmental performances of plastic recycling techniques, reporting that mechanical recycling (e.g. melting and grinding) provides a higher net positive environmental impact than recovery of energy (incineration) or landfilling

(Saikia and De Brito, 2012; Sharma and Bansal, 2016). For example, Jandiyal et al. (Jandiyal et al., 2016) report that recycling one pound of PET reduces energy use and greenhouse gas emission by 84% and 71%, respectively. It is important to underline that the construction industry (with traditional materials) puts a lot of pressure on the environment, in terms of both the use of resources and the production of waste (Merli et al., 2020).

However, according to the reviewed literature, no reports are available on environmental analyses, such as LCA based on material flow analysis of plastic waste concrete.

Several authors highlight the need to conduct environmental evaluations related to plastic waste concrete (Li et al., 2020; Mohajerani et al., 2020; Saikia and De Brito, 2012) considering the whole life cycle of the final product, such as long-term environmental exposure (Liew et al., 2017) or waste treatment techniques (Thakare et al., 2020). Some mechanical properties and performances, such as the workability, of rubber and plastic concrete are influenced by the fact that wastes were previously submitted to a treatment (Roychand et al., 2020). Pacheco-Torgal et al. Pacheco-Torgal et al. (Pacheco-Torgal et al., 2012) highlight the need to study whether these treatments have an environmental impact that shadows the ecological benefits of using rubber and plastic wastes. Comparisons have been made between recycled plastic and steel fibers, considering only the production phase, showing that plastic fibers offer significant environmental benefits over traditional steel reinforcements, reducing carbon dioxide emissions during the production and the extraction of raw materials (Yin et al., 2015).

5.2.6.5.2. Cost savings and impacts on the supply chain

Practical applications of polymeric waste in concrete and cement mortar involve economic issues.

Many authors declare that the use of plastic and rubber waste reduces the cost of the final products compared to the use of conventional raw materials (Dam et al., 2016). According to Pakravan et al. (Pakravan and Ozbakkaloglu, 2019) and to the studies reviewed by Yin et al. (Yin et al., 2015), plastic fibers have a significantly low cost compared to steel mainly for two reasons: i) they need a lower quantity of plastic fiber to achieve the same degree of reinforcement in a concrete footpath of same area; ii) they require less labor time and expense to prepare the plastic fibers that can be directly mixed with concrete, eliminating the need for preparation of steel. However, no studies are available on detailed economic analyses of plastic or rubber waste-based concrete and cement mortar, to the best of the analyzed authors' knowledge. Liew et al. (Liew et al., 2017) describe some quantitative information on possible economic savings, but without going into too many details.

Moreover, Saikia and De Brito (Saikia and De Brito, 2012) suggest conducting a life cycle cost (LCC) analysis in order to investigate cost issues related not only to the production of cement composites containing various types of plastic waste such as aggregate, filler or fibers containing plastic waste aggregates, but also cost implications related to the recycling of the new products at the end of the service life. Other authors, meanwhile, identify a potential cost increase, especially during the manufacturing processes. (Roychand et al., 2020) state in their review that the cost of processing and shredding scrap tyres involves labour, power, and equipment, and that the smaller the particle size, the higher the cost associated with its production.

5.2.6.5.3. Long-term health implications

A key aspect to be addressed when evaluating the possible degree of pollution related to plastic waste construction products is the potential leaching of toxic constituents from plastic waste construction products (Butturi et al., 2020).

In fact, as demonstrated by several authors, the majority of the plastics contain toxic organic and inorganic chemical constituents such as lead, cadmium, chromium, mercury, bromine, tin, antimony, bisphenol A and chloro-ethane monomer (Kousaiti et al., 2020; Rajmohan et al., 2019; Sánchez, 2020; Verma et al., 2016). In regard to the use of such materials in cement and mortar concrete, only Saikia and De Brito (Saikia and De Brito, 2012) underline the need to consider the long-term health implications, highlighting a study that reports that the formation of some organic compounds after prolonged curing of PET fibers in simulated cement pore fluid could initiate the alkaline hydrolysis of PET. Also Roychand *et al.* (Roychand et al., 2020) conclude their review on the mechanical properties of waste tire rubber concrete by pointing out that some concerns still need to be investigated, such as the high flammability and resultant release of noxious gases from rubber particles when exposed to fire.

5.2.6.5.4. Influence of recycling techniques and treatment methods

From the analysis of the selected review, it emerges that recycling techniques and treatment methods have an influence on:

- properties of the final products;
- environmental performances;
- cost savings.

Siddique et al. (Siddique et al., 2008) investigated the main different plastic recycling techniques, namely mechanical recycling, chemical modification and thermal reprocessing, concluding that: i) mechanical recycling leads to high-quality recycled materials; ii) feedstock recycling has a greater flexibility in terms of composition and is more tolerant to impurities than mechanical recycling, although it is capital-intensive and requires very large quantities of used plastic for reprocessing to be economically viable; iii) thermal reprocessing can be applied only to some types of plastics: for example, it could not be applied to thermosets (such as cross-linked polyesters) because they cannot soften at high temperatures without degrading.

Moreover, thermal reprocessing cannot be repeated indefinitely since repeated processes may eventually adversely affect the plastic properties. Roychand et al. (Roychand et al., 2020) explored the effect of 20 different rubber treatment methods on the mechanical properties of rubber concrete, demonstrating that treatment methods, such as water washing, water soaking and precoating of rubber with cement paste, could influence the workability, the modulus of elasticity and the abrasion resistance.

5.2.6.6. Conclusions and prospects for development

In conclusion, the potential addition of polymeric waste materials, such as plastic and rubber, to concrete and cement mortar is a widespread practice to replace natural aggregates, promoting the development of circular economy solutions, supporting the transition towards greater economic and environmental sustainability of the construction sector.

From the study of the widespread literature available in this field, the following conclusions to be highlighted:

- The addition of polymeric wastes in concrete and cement mortar is a viable way to reduce the amount of landfilled and incinerated waste and to reduce the extraction of raw materials.
- Waste polymeric materials can improve some physical and mechanical properties of fresh and hardened composites.
- The physical and mechanical properties of polymeric waste concrete and cement mortar are strictly dependent on several parameters, such as type; size; shape; amount; and treatment of the waste polymeric materials.

Despite this, critical aspects remain open, and the following recommendations for further research proposals are also suggested:

- Environment LCA studies should be conducted to evaluate the feasibility of the use of polymeric wastes as an eco-friendly substitute for conventional materials considering all the life cycle stages, particularly the treatment of waste materials and the end of life.
- Economic evaluations should always be conducted when waste material needs treatment before being added to a new product.
- Health and risk implications of polymeric waste concrete and cement mortar should be evaluated during the application and in particular conditions, such as toxic emissions in use or under high temperatures as in the case of fire.

5.2.7. Environmental assessment analysis of a concrete reinforced with synthetic fibers obtained from recycling end-of-life sport pitches

5.2.7.1. Case study

The present work focuses on fully recycled polyolefins synthetic fibers as dispersed reinforcement in Fiber Reinforced Cement Composites (FRCCs). Fibers are directly obtained from processing disposed artificial turf carpets (ATC) aimed at paving sport facilities (**Figure 52**).

Figure 51. Artificial turf carpet (https://sabbiediparma.com/, last access: 06.03.2022).

Demonstrated the mechanical performance (Signorini and Volpini, 2021), in this study the LCA is adopted to evaluate the environmental impact of fibers reuse against fibers manufacturing from either virgin materials or plastic waste. It clearly appears that fibers reuse brings a double environmental benefit: on the one side, it decreases the need for new plastics and, on the other, it reduces plastic waste, whose traditional disposal technique, through incineration, entails a considerable footprint.

5.2.7.2. Goal and scope definition, system boundary and life cycle inventory

The aim of the present LCA study is to assess the environmental impacts related to the recovery of the PE-PP fibers from artificial turf carpets and the recycle into a cementitious matrix (FRC).

The set functional unit (FU) is 1 kg of PE-PP fibers (**Figure 52**). It means that all input and outputs are expressed per 1 kg of PE-PP fiber product, ready to be dispersed in the cementitious matrix. This reference flow allows to easily multiply the environmental profiles with the quantity of fibers relevant to each specific application. Impacts related to the production of the other constituent materials (i.e., Portland cement, gypsum, and blended materials) and to the building process itself (i.e., construction, maintenance and dismantling) is outside the scope of the analysis, as it is assumed that it would take place regardless of the recycling process. Indeed, other materials and processes remain practically unaffected by the choice of the reinforcement phase: the single pre-mixed ordinary Portland cementitious (OPC) mortar would be the same, the FRC would be adopted for the same application and the building processes are similar, independently of the mix design. Therefore, the simplified method herein adopted is considered to be a good and reliable approximation at this specific stage, also in line with previous studies (Yina et al., 2016).

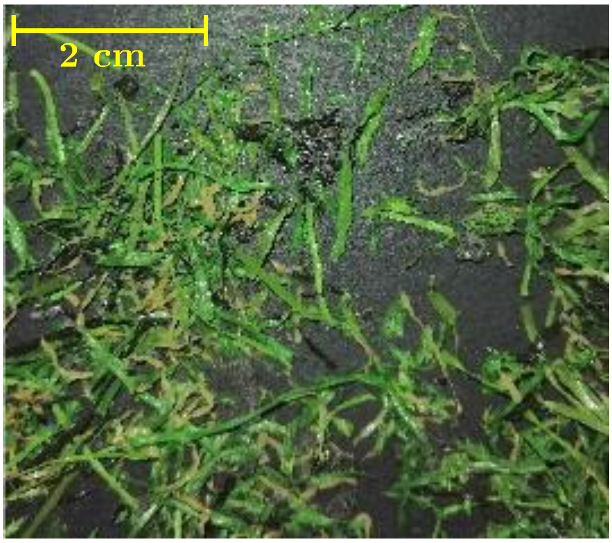


Figure 52. PE-PP fibers obtained from recycling disposed artificial turf carpets (Signorini and Volpini, 2021).

A diagram of the process required in the recovery of PE-PP fibers from artificial turf carpet is shown in **Figure 53**. The artificial turf carpets are collected and transported to the processing center, where a mechanical sorting is used to wash and separate out the components. The transport distance is on average 300 km.

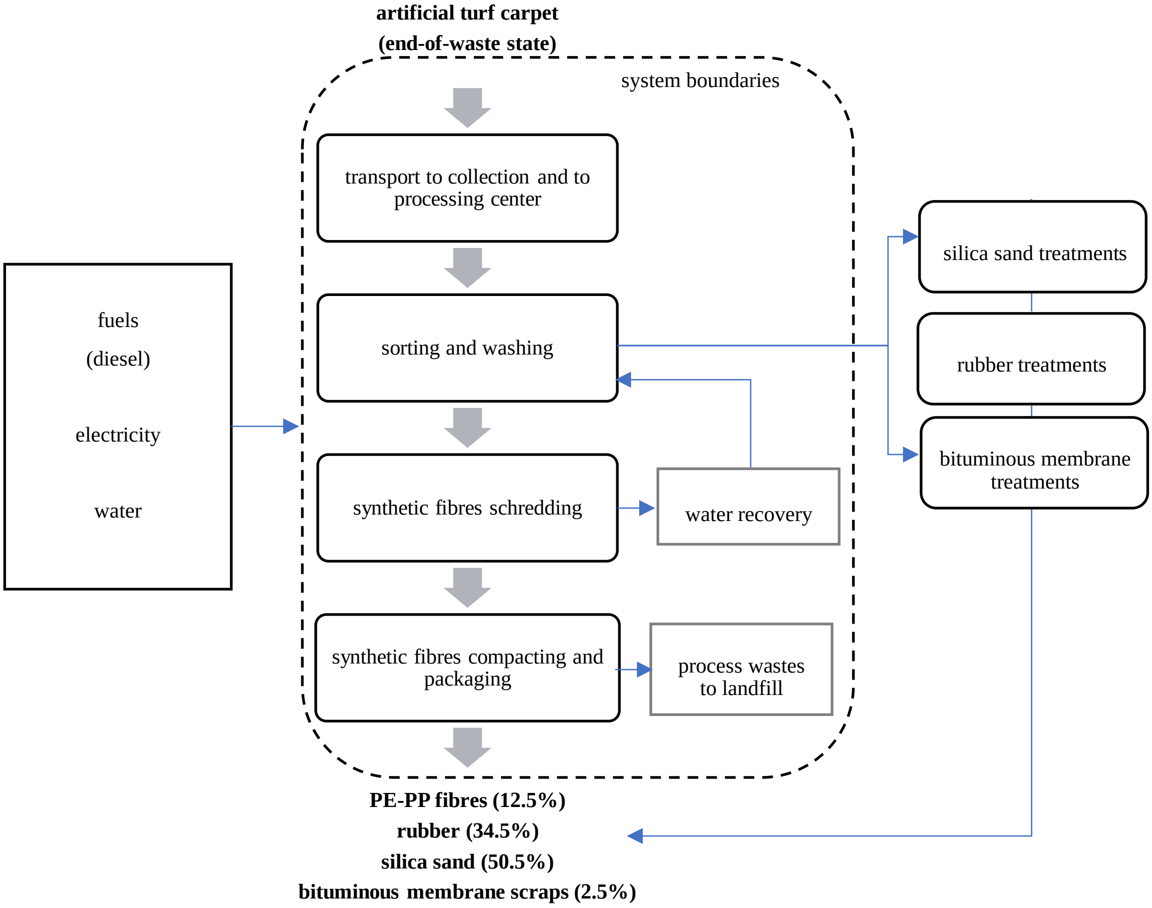


Figure 53. Flow sheet of the production of recycled PP-PE fibers from an artificial turf carpet (own elaboration).

Generally, an artificial turf carpet has a weight of 25 kg/m^2 and the materials that are recovered are: synthetic fibers (12.5%), bituminous membrane (2.5%), sand (50.5%) and rubber (34.5%) (**Figure 54**).

Figure 54. Bituminous membrane, sand and rubber recovered by artificial turf carpets(https://sabbiediparma.com/, last access: 06.03.2022).

The machine uses water to clean the synthetic surface. The machine has a performance of 300 kg/h. The plant is set up with a closed cycle system with recovery and purification of process water, without drain. During the cleaning operations, there is a loss of water retained by the capillary tensions as a percentage of the 7% of the total washed material. Process water is first conveyed to a collection system and subsequently in a purifier for its recovery and further reuse. The sludge is subsequently disposed of as waste. After drying, the PE-PP fibers are shredded, compacted and packed into big bags. The machine has a performance of 1000 kg/h. Processes related to the treatments necessary to recover the other materials, such as bituminous membrane, sand and rubber are not included in the system boundaries. The impacts related to the collecting processes and to the sorting and washing are accounted only for the 12.5% (mass allocation).

In the study, primary data are used, collected directly via on-site investigations and via face-to-face, telephone and email communications with an Italian company that deals with this activity. Data are relative to the collection and the treatment of artificial turf carpets in the year 2019. Background data, such as electricity and waste treatments, was taken from the Ecoinvent database version 3.5.

5.2.7.3. Environmental impact assessment

The LCIA is the estimation of indicators of the environmental pressures in terms of e.g., climate change, summer smog, resource depletion, acidification, human health effects, etc. associated with the environmental interventions attributable to the life cycle of a product. The software SimaPro 9.0 has been used for the LCIA.

The impact categories include global warming potential (GWP), acidification potential (AP) (kg SO_2 eq), eutrophication potential (EP) (kg $PO4^{3-}$ eq), photochemical oxidant formation potential (POFP) (kg NMVOC eq), abiotic depletion potential – elements (ADP elements) (kg Sb eq), abiotic depletion potential – fossil fuels (ADP fossil fuels) (MJ), water scarcity footprint (WSF). The impacts categories have been selected according to the Product Category Rule (PCR 2019:14), referring to the EN 15804 for construction products and services, in order to easily compare the environmental profile with products on the market and to pave the way to potential future environmental declarations, even more necessary in the construction sector (Passer et al., 2015). GWP (kg CO_2 eq) has been calculated based on the database of 100-year greenhouse gas emissions reported by the Intergovernmental Panel on Climate Change method (Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, 2013). AP (kg SO_2 eq) is based on CML 2001 non-baseline method (Heijungs et al., 1992), while EP (kg $PO4^{3-}$ eq), ADP elements (kg Sb eq), ADP fossil fuels (MJ) are based on CML 2001 baseline method (Heijungs et al., 1992). POFP (kg NO_x eq) is based on Recipe 2008 method (Huijbregts et al., 2017) and, finally, WSF (m^3 H_2O eq) is based on AWARE method (Huijbregts et al., 2017).

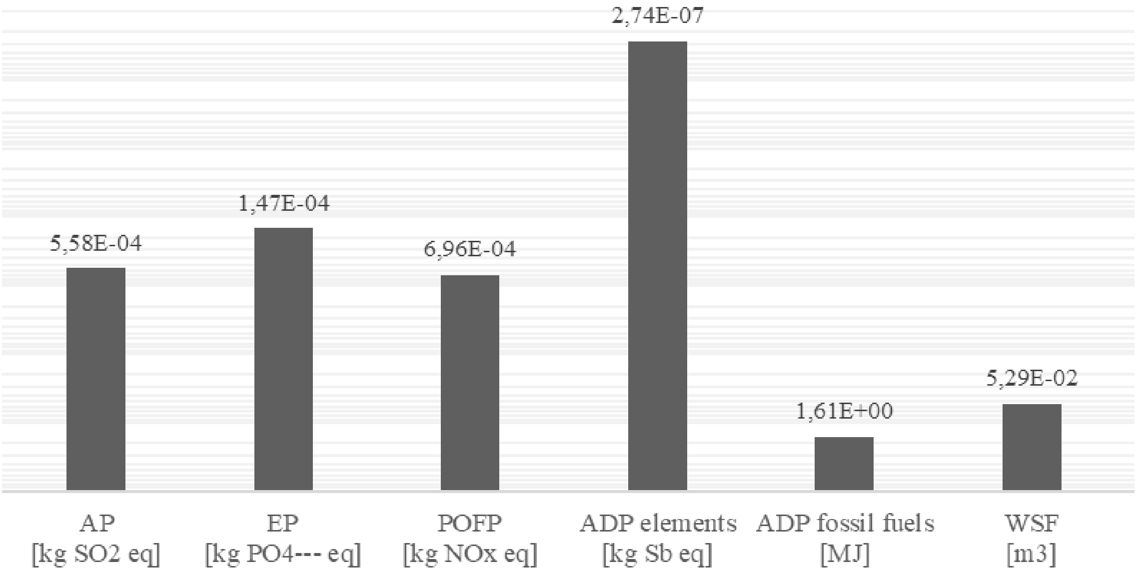


Figure 55. LCIA result to produce 1 kg of recycled PE-PP fibers (own elaboration).

Figure 55 shows the estimated environmental impact induced by producing 1 kg of recycled PE-PP fibers from disposed AT carpets. As it can be seen, fibers recycling results in little environmental impact for the selected categories. Indeed, to produce 1 kg of fibers, the industrial plant produces 0.117 kg CO2 eq, 0.000147 kg of kg PO43- eq, 1.61 MJ of ADP fossil fuels and 0.0529 m^3 H2O eq, considering the most impactful categories.

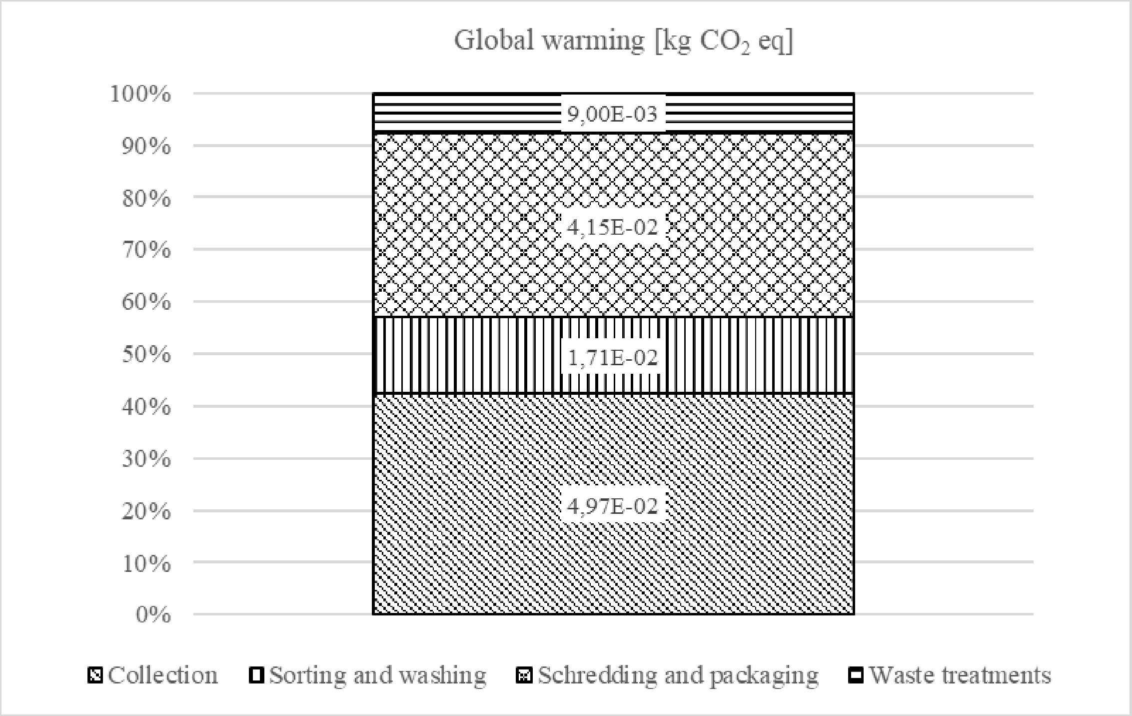


Figure 56. Contribution of the major processes to the overall impacts within the Global warming impact category (own elaboration).

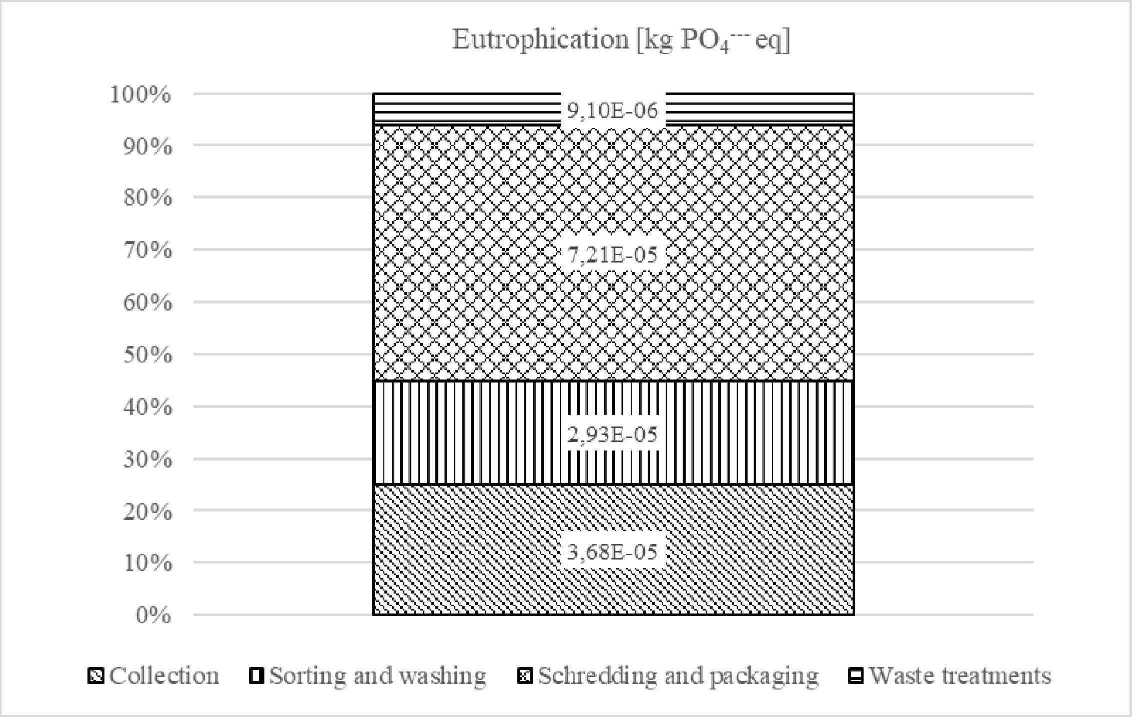


Figure 57. Contribution of the major processes to the overall impacts within the Eutrophication impact category (own elaboration).

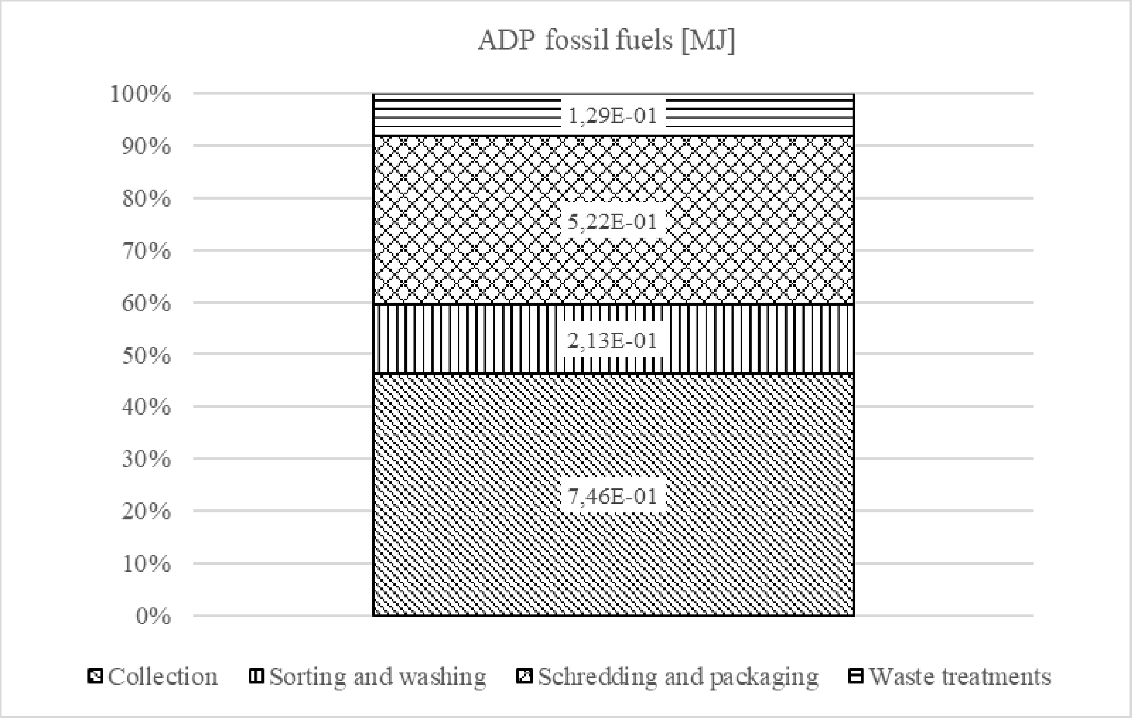


Figure 58. Contribution of the major processes to the overall impacts within the ADP fossil fuels impact category (own elaboration).

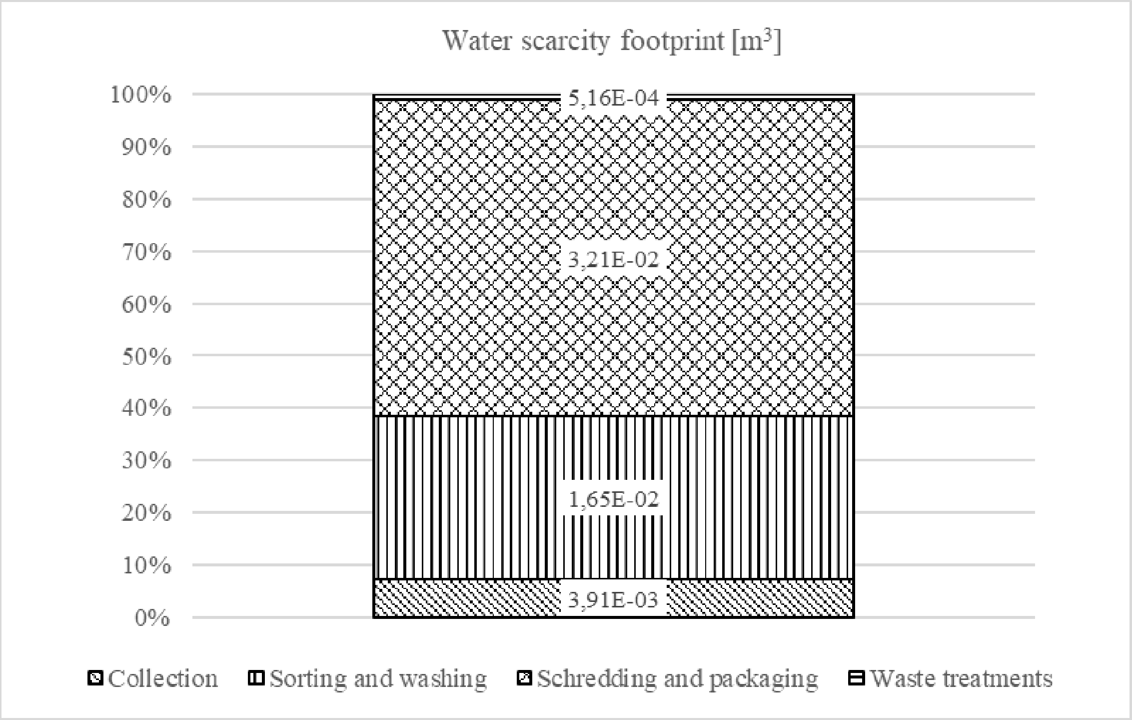


Figure 59. Contribution of the major processes to the overall impacts within the Water scarcity footprint impact category (own elaboration).

Figure 56 to **Figure 59** lays out the contribution of the major processes to the overall impacts within each impact category. As can be seen, GWP and ADP fossil fuels are dominated by the transport to collection and to the processing center, because of the diesel consumption by the lorry used to transport the artificial turf carpets. EP and WSF are dominated by shredding and packaging processes, mainly due to the electricity used by the plant. However, also the washing and sorting processes are also significant, mainly in WSF due to the water consumption used to clean the carpets.

The results demonstrate that the production of PE-PP fibers from the recovery of plastics from artificial turf carpets can save almost the 94 % of kg CO_2 eq emitted in the production of fibers from industrial and domestic recycled plastics and the 99 % of kg CO_2 eq emitted in the production of fibers form virgin PP granulates. Indeed, the environmental benefit is mainly due to the absence of several impactful processes needed to re-compound generic recycled plastic waste and subsequent extrusion for fiber production. A specific comparison that brings similar results is possible with, for example, the commercial product emesh®, for which impact data are available from The International EPD® System.

5.2.7.4. Conclusions

In conclusion, the study demonstrates that recycling PE-PP fibers from AT carpets offers very substantial environmental benefits over virgin fibers and, most interestingly, also over fibers recycled from general plastic waste. This significant advantage is obtained because carpet recycling immediately provides workable fibers as opposed to plastic granulates which require further impactful processing.

It is concluded that adopting synthetic fibers obtained from disposed AT carpets in the FRC technology is a viable and efficient strategy for the construction sector to decrease its large environmental impact and move a step in the direction of the circular economy.

6. A science-based framework to setting climate targets for industrial facilities

A recent examination of EU countries approaches towards building sector decarbonization both in terms of consistency regarding the definition of ‘nZEB’ as laid out in the Energy Performance of Buildings Directive (EPBD), and in terms of overall ambition levels suggest that decarbonization in new buildings in the EU is happening too slowly and inconsistently (BPIE, 2022). Against this backdrop, a series of targets and strategies are emerging for the decarbonization of the built environment, covering both operational and embodied emissions. The particular importance of assessing GHG emissions associated to the building stock and of setting environmental benchmarks has been recognized early (Hollberg et al., 2019).

Despite this interest, few studies have benchmarked their results against broader national sustainable development targets such as those contained in the SDGs (Allen et al., 2022), and, to the best of the author’s knowledge, there are no studies that have attempted to define an approach for setting climate targets for industrial buildings using a whole life cycle perspective. Existing studies have mainly focused on residential buildings (Schmidt et al., 2020).

In that context, the final section of the present work aims to introduce an integrated whole life cycle and science-based approach for setting the climate target for existing, refurbished, and future industrial facilities in any country over a specified time period.

The main aim is to answer the following research question “*Are new-built industrial facilities aligned with achievement of the 2 °C Paris climate target?*”

6.1. Environmental benchmarks for industrial buildings

Benchmarking is the process of comparing differences in performance between similar processes (Energy and Benchmarking, 1999). When dealing with environmental impacts, it is an important tool to help identify potential savings. Benchmarking studies can be influential in the setting of policies, regulations, and targets. The benchmarking process can be useful in highlighting where improvements can be made and in the case of temporal benchmarking identify the need for, or effectiveness of, maintenance work.

In general, and more in detail in the industrial context, benchmarks can be produced through top-down approaches, using annually reported energy-use and production data or bottom-up approaches, using plant level energy-audit and production data (Rogers et al., 2018).

Regarding the industrial sector, previous work has only focused on energy performances of manufacturing systems (Boyd et al., 2008), production processes (Benedetti et al., 2018; Ke et al., 2013; Rogers et al., 2018) and industrial plants (Salvatori et al., 2018).

However, in the light of what has been stated in the previous paragraphs of the present thesis, in order to decarbonize the industrial sector in an eccentric and efficient way, it is necessary to look at the problem as a whole, according to a life cycle approach.

With the introduction of certifications on the environmental sustainability of buildings, as the EN 15804 and the EN 15978, the LCA methodology has become an integral part of sustainability analyzes in buildings (**Figure 60**).

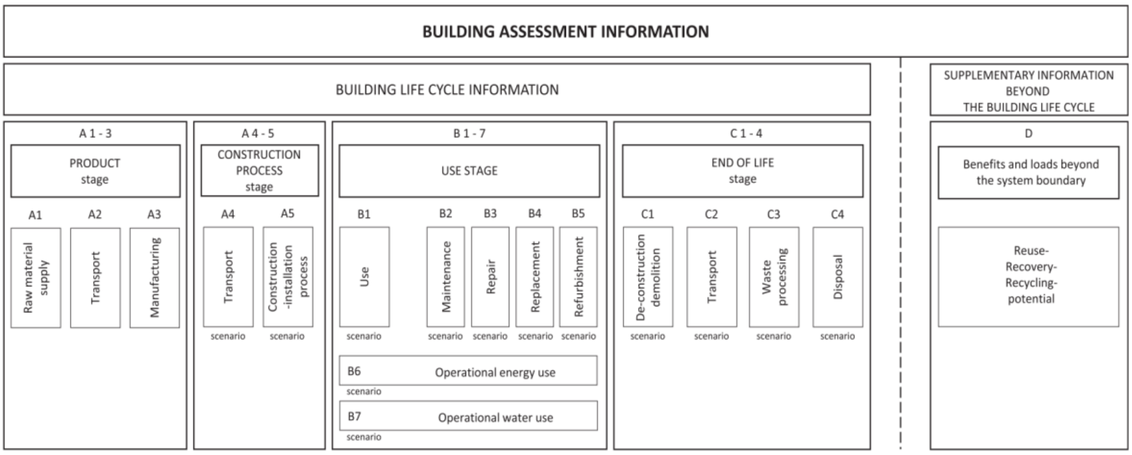


Figure 60. Display of modular information for the different stages of building assessment (EN 15978).

Despite several studies related to residential and office buildings (Röck et al., 2020), the life cycle performance of an entire factory has not yet gained much attention or is studied primarily with the focus on embodied carbon and energy (Rodrigues et al., 2018), process phase (Lunetto et al., 2021), energy performances of production processes (Rödger et al., 2021b), process lines (Jacquemin et al., 2012), or by evaluating efficiency increases of production systems (Mawson and Hughes, 2019). A complete decarbonization process, instead, needs the combination of several optimization strategies as increases in energy and material efficiency, renewable energy, green chemistry, circular resource flows and changes in building design and process equipment, as demonstrated by Gebler et al. (Gebler et al., 2020) in their LCA of an automotive factory.

Regarding the building and the overall infrastructure environmental performances of industrial sites, to the author´s knowledge, they have been scarcely investigated.

A comparative study relating to different structural systems and materials for the construction of an industrial building (bauforumstahl e. V., 2015) has shown that, even with the same functionality, becomes evident as a project based on a steel structure, when light and efficient, it is beneficial. It's not just about small amounts of material for a given structural item (in the specific case, the frame of a single-elevation building) but also of fewer pillars, smaller foundations, or minor transports to the construction site, etc. Another advantage of steel is its special "Cradle to Cradle"): after the dismantling of a building, construction steel can be directly reused or recycled, to allow its use again as a building material, saving in this way natural resources.

6.1.1.1. Relative or absolute values and rating systems

A review of the literature highlighted that several rating systems are available and have been largely accepted and widely used in the building sector (Bernardi et al., 2017; Bida et al., 2018) across the world (**Table 12**) and, some of them, includes specific sections for the industrial context.

Table 12. Green Building Rating Systems across the world.

Country	Green Building Rating System	Year of Initiation
Australia	Green Star	2003
Austria	EnergieAusweis	2009
Brazil	LEED Brazil	2010
Canada	LEED Canada	2000
Czech Republic	SBToolCZ	2005

China	GBAS	2006
	HKBEAM (Hong Kong)	2009
Finland	PromisE	1998
France	HQE	1996
Germany	DNGB	2007
	Passive House Protocol	1991
India	Indian Green Building Council	2007
Indonesia	Indonesian Green Building Council	2009
Italy	Itaca	2000
	CasaClima	2002
Japan	CASBEE	2004
Korea	KGBC	2000
Malaysia	Green Building Index	2008
Mexico	LEED Mexico	2000
Netherlands	BREEAM Netherlands	1990
New Zealand	Green Star NZ	2005
Portugal	Lider A	2005
Singapore	Green Mark	2005
South Africa	Green Star SA	2007
Switzerland	Minergie	1994
United Arab Emirate	Estidama	2009
United Kingdom	BREEAM	1990
United States	LEED	1993
	ENERGY STAR	

6.1.1.1.1. CasaClima

CasaClima is a certificate introduced in 2002 which certifies the energy performance, sustainability, and quality of a building. The certificate first evaluates the efficiency of the envelope, that is, the energy quality of the design aspects that reduce energy waste. The overall efficiency of the envelope quality and the quality of the plant engineering choices is also analyzed. Finally, environmental sustainability is assessed, which expresses the building's eco-compatibility by promoting the use of materials with low energy consumption and a limited environmental impact.

A certificate for offices and industrial buildings, called CasaClima Work & Life, has been introduced recently. The CasaClima Work & Life guidelines aim to standardize the methods of calculation, execution and control related to the CasaClima Work & Life certification. The Protocol is applied to buildings destined for offices and company headquarters. CasaClima certification Work & Life can be requested for both new buildings and existing buildings for which they are intended redevelopment, modernization, or expansion interventions. In the case of expansion, the certification must be required for the entire structure, i.e., for both the existing part and the newly built portion. This also applies if the buildings are physically separate but attributable to the same company structure. The certificate and the CasaClima Work & Life tags are issued for the entire building complex.

6.1.1.1.2. Itaca

The ITACA Protocol, is an Italian tool for assessing the level of energy and environmental sustainability of buildings that allows to verify the performance of a building with reference to energy and water consumption, to the quality of the materials used in construction process, to the site selection and design, taking into consideration environmental, human health.

The Protocol guarantees the objectivity of the evaluation using indicators and verification methods compliant with the technical standards and national laws of reference and can be used for different purposes in relation to its different use: it is a tool to support planning for professionals, control and guidance for the public administration, support choice for the consumer, enhancement of an investment for financial operators. Its use is pursuant to specific regulations (ITACA, 2019). In the last in the latest update there is a section relating to non-residential buildings, in which aspects such as infrastructures, services and accessibility are added.

It refers to the SBTool, a generic framework for rating the sustainable performance of buildings and projects developed by the International Initiative for a Sustainable Built Environment (iiSBE) (https://www.iisbe.org/sbmethod - last access: 06.03.2022).

6.1.1.1.2.1. BREEAM

The BREEAM (Building Research Establishment Environmental Assessment Method) certification is one of the first tools created for assessing the sustainability of buildings. Each building category to be analyzed contains a set of parameters. For example, for the quality of indoor environments, reference is made to air quality, lighting quality and acoustic control and, where it is more appropriate, sub-parameters are introduced for greater detail. The certification takes place through the verification carried out by certifiers authorized by the BRE (British Research Establishment). It is a six-level (gradually more restrictive) assessment system, which a building can reach based on the results obtained within nine sustainability criteria (management, health, and well-being; energy consumption with related CO_2 emissions; consumption and emissions during transport; water consumption; environmental impact of materials; waste management and land use; ecological assessment of the site; air and water pollution) (https://www.breeam.com/ - last access: 06.03.2022).

The BREEAM Industrial methodology is used to assess the environmental impact of the development and construction of storage and distribution centers, light industrial units, and factories and workshops in the following circumstances:

- Speculative: speculatively developed buildings with an unknown end occupier.
- Fitted Out: buildings that are being designed and fitted out for a known end occupier, or the end occupier is unknown, but the operational area is being fitted out.

Several industries located all over the world received the BREEAM certification (https://www.breeam.com/case-studies/filter/ - last access: 06.03.2022).

6.1.1.1.2.1.1. ENERGY STAR

Energy Star is a is a voluntary government/industry partnership that offers information to businesses and consumers on energy-efficient solutions. Designed to identify and promote energy-efficient products as basic pollution prevention opportunities, the Energy

Star label was extended beyond its role in identifying energy efficient products to identifying energy-efficient production (Boyd, 2017).

The certification is available for homes; commercial buildings; and industrial plants. The U.S. Environmental Protection Agency (EPA) distinguishes the best performing plants within an industry with ENERGY STAR certification. Select manufacturing plants located in the U.S. and its territories and Canada can earn ENERGY STAR certification and display the ENERGY STAR similar to those seen on appliances and electronics in the marketplace. Manufacturing plants must achieve an ENERGY STAR score of 75 or higher using an industry-specific ENERGY STAR Energy Performance Indicator (EPI). In the U.S. EPIs, EPA’s benchmarking tools for industrial plants, measure a plant’s energy performance and compare it to that of similar plants nationwide, generating an ENERGY STAR score on a scale of 1 to 100. Certified plants are awarded a congratulatory letter to the company’s CEO, a certificate of achievement, decals for identifying the plant’s certification, the option to obtain and display flags/banners/plaques, and a listing in EPA’s ENERGY STAR certified plant registry (https://www.energystar.gov/industrial_plants?s=mega – last access: 06.03.2022).

6.1.1.1.2.1.2. LEED

It is a voluntary certification system on building sustainability based on a set of prerequisites and credits. The fulfillment of the prerequisites is mandatory (in cases where you choose to join the LEED certification) for all projects. The credit system, on the other hand, is optional and gives rise to the assignment of points within certain broad categories (sustainability of the site, efficient management of water, energy and atmosphere, materials and resources, quality of the internal environments, innovation in planning, regional priorities). Based on the score obtained, a building can thus obtain certification:

- Certificate (40-49 points)
- Silver (50-59 points)
- Gold (60-79 points)
- Platinum (80-110 points)

Green buildings achieving the LEED certification in the US and other countries have been shown to consume 25% less energy and 11% less water, than non-green buildings (USGBC, 2022).

6.2. Aim and approach

In that context, building upon the previous work of benchmarking approaches, this study introduces a preliminary integrated LCA-and science-based approach to calculate the climate target for both existing and future industrial buildings in any country over a specified period, which also provides a breakdown of this climate target into individual life cycle stages.

It is difficult to generalize the discourse on production and manufacturing processes: industrial plants and related consumptions and emissions are specific to each sector. The service/auxiliary facility systems an industrial building is equipped with are instead of the same type for each sector and all with the sole purpose of guaranteeing the safety and comfort of the occupants. For this reason, this work is focused on industrial buildings and leaves out the aspects of product and manufacturing processes. Furthermore, an industrial building often changes its use, therefore the production plants can change, but the service plants are always the same. At most they can be enhanced and modified based on the number of occupants and on types of activities that are carried out within them. Reference is made to lighting systems that must be designed according to directives that guarantee adequate levels of illumination based on the specific activity to be carried out.

The scope of the study includes both embodied and operational impacts. It applies a scenario analysis incorporating different levels of climate ambition, including the shift to renewable energy sources and the replacing of carbon-intensive materials.

The procedure for calculating the climate target for industrial buildings follows the procedure described in (Chandrakumar et al., 2020) and provides the following steps:

1) Determine the maximum acceptable amount of GHG emissions that can be emitted globally while respecting the chosen global climate target during a specific time period (referred to as the global carbon budget).

2) Assign a share of the global carbon budget to a country based on population projections.
3) Assign a share of the country's carbon budget to the country's building construction sector based on the relative contribution of the sector to the country's total climate impact in a chosen reference year (or period).
4) Calculate the climate target for industrial buildings by assigning the construction sector's carbon budget to the different building types based on the LCA climate impact of each building type and the projected number of those buildings, both pre-existing, refurbished, and new-built stock, in the chosen time period. This means that, for example, buildings constructed in 2030 will only include 20 years of utilization if the chosen period extends to 2050.

The proposed framework is shown in **Figure 61** and considers all the steps required to obtain the results, as well as the scenario assumptions.

6.2.1. Global climate target and carbon budget

The framework intends to be useful for reaching the 2 °C global climate target, i.e., the maximum amount of GHG emissions that can be emitted and still limit average global warming to below 2 ℃ above pre-industrial levels according to the Intergovernmental Panel on Climate Change (IPCC) findings and indications (IPCC, 2021). The chosen global climate target can be translated into a global carbon budget ($GtCO_2eq$) for the period of 2018–2050, using the approach proposed by Rogelj et al. (Rogelj et al., 2015b).

The global carbon budget can be retrieved using data from the Global Carbon Project (https://www.globalcarbonproject.org/carbonbudget/ - last access: 09.03.2022) or data calculated by the IPCC in the AR6 report

6.2.2. Impact calculation of industrial buildings

The weighted average climate impact of industrial building is calculated using LCA methodology, following the EN 15978 standard. The calculation is needed both for the existing and for the new-build building stock. Also refurbished buildings needs to be considered. The functional unit (FU) is defined as the 'construction and occupation of 1 m² of built area of an industrial building over its reference service life", the most consensual unit in literature studies on building and construction'. The service life is set according to the technical legislation of the country. In Italy, the service life of a building destinated to craft and production activities is ≥ 50 years (NTC, 2018).

Inventory data for existing and new-built constructions are categorized according to a modular structure into the following life cycle stages: product (A1-A3), construction process (A4-A5), maintenance (B2), repair (B3) and replacement (B4), operational energy use (B6), operational water use (B7), end-of-life (C1-C4), and benefits and loads beyond the system boundary (D). The refurbished (B5) life cycle stage is included in the inventory data for refurbished construction.

6.2.2.1. Embodied and Operational impacts

The product stage considers the embodied GHG emissions of materials used in the overall construction. For the construction process stage, the GHG emissions associated with activities such as transportation, assembly and energy for the construction machinery are included. Similarly, for the maintenance and replacement stages, the GHG emissions associated with activities such as painting, and replacement are considered.

The GHG emissions related to the energy consumption (appliances, lighting, water heating and space conditioning) are calculated at the operational energy use stage. Likewise, for the operational water use stage, the GHG emissions associated with energy consumption for getting water in/out of the building (pumping and treatment) is considered. For the end-of-life stage, the GHG emissions of the demolition activities of the building are considered. Finally, the GHG emissions (or benefits) associated with reuse, recovery or recycling of construction materials which substitute for primary production are considered in benefits and loads beyond the system boundary. The operational energy demand is based on the simulated energy use in the industrial buildings, in order to maintain an internal temperature of between 19°C and 26°C (for health reasons) as well as to provide hot water, lighting and plug loads (e.g., computers etc.).

6.2.3. Climate target and carbon budget of industrial building stock

Climate impact results (KgCO_2eq/m^2) calculated for pre-existing; refurbished; and new-built stocks, are the basis for the share of the carbon budget available for the industrial building sector for 2018-2050. Subsequently, the climate targets for 1 m^2 floor area for individual life cycle stages is determined (separately for pre-existing and new- built) by dividing the available carbon budget for each life cycle stage by the associated total gross floor area of the whole buildings.

A total building stock (m^2) need to be calculated, adding up the existing building stock and the projections related to the refurbishment of pre-existing buildings and those built ex-novo from 2018 to 2050.

Finally, the climate targets for individual pre-existing; refurbished; and new-built industrial buildings are derived by multiplying the climate targets for individual life cycle stages with the respective gross floor areas at each of those stages. The results are summed to give the total climate targets for individual pre-existing; refurbished; and new-built detached houses.

6.2.4. Scenario framework and sensitive analysis

In addition to the scenario as usual (Scenario 1), two alternative scenarios are modelled, describing moderate (Scenario 2) and high (Scenario 3) decarbonization ambitions (**Table 13**) reaching the 2050 targets, strictly reliant on policy settings driving energy transition, and strongly influenced by general assumptions as: electricity mix; temperature and climate change; resources demand; and energy demand.

In addition, several built environment assumptions are considered, in order to conduct sensitivity analysis to model future changes.

The effect of changes on manufacturing of construction materials is included in the scenario framework. Although the annual emissions related to the energy mix reduces its intensity in GHG emission, the aspect is considered when calculating impacts in the production of construction materials and in the operational energy stage.

Table 13. Scenario framework.

Scenario Framework			
Scenarios	Scenario 1: As usual	Scenario 2: Moderate ambition	Scenario 3: High ambition
General assumptions	Energy mix mainly from fossil fuels High temperature and climate change High resources demand High energy demand	Energy mix from fossil fuels and RES Low temperature and climate change Low resources demand Low energy demand	Energy mix mainly from RES Very low temperature and climate change Very low resources demand Very low energy demand
Built environment assumptions	Natural resources Secondary raw materials Material and energy symbiosis Renewable energy sources		
Policy settings	Slower transition	Rapid transition	100% transition

The simulation of the energy demand in the operational phase, it’s strictly dependent to the used energy mix and to variation in temperature and climate change. Those aspects are included in the framework scenario. In addition, factors such as government policy on climate change, energy efficiency regulations, construction sector policy and building code requirements on insulation, and environmentally conscious consumers influence the operational energy demand. Therefore, the GHG emissions related to the operational energy use have to be quantified considering different mixed renewables scenario for each year during the period 2018-2050.

6.3. Conclusions

The framework developed in this study represents a methodological approach to explore coherent pathways to net zero emissions in the industrial built environment sector by 2050. The proposed framework can support:

- researchers investigating the sustainability issues of industrial buildings and, in general, of the industrial sector’s sustainability,
- managers who intend to integrate sustainable strategies in their business management,
- skilled practitioners designing improved industrial buildings and facilities,
- LCA specialists involved in the built environment assessment.

Future research will focus on the application of the proposed framework to the Italian industrial context and will consider also economic and social issues.

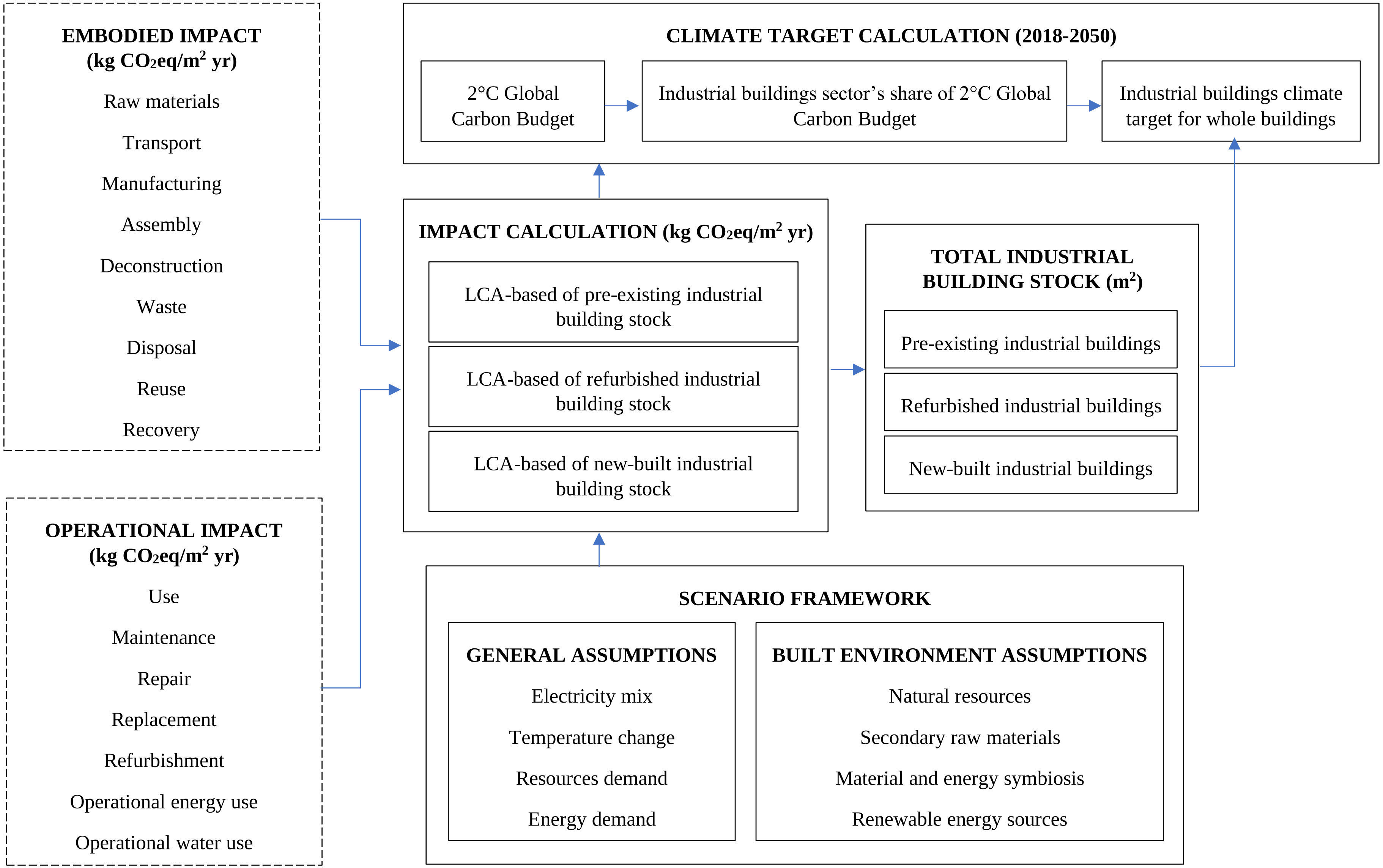


Figure 61. The proposed framework to calculate a climate target for industrial buildings (own elaboration).

Appendix 1: The Life Cycle Assessment (LCA) methodology

Since in almost all the case studies discussed in the present thesis was used the Life Cycle Assessment (LCA) methodology to measure potential environmental damages or advantages, it is considered appropriate to include an in-depth information appendix to define and describe the methodology.

LCA is a technique used worldwide to evaluate all the environmental impacts linked to the different steps of the product life cycle, from raw material extraction, processing and production right through to the use phase and disposal, according to the international standards ISO 14040 and ISO 14044 (ISO, 2006a, 2006b); and to guidelines (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

ISO states that LCA methodology is able to i) identify opportunities to improve the environmental performance of products at various points in their life cycle; ii) inform decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign); iii) the selection of relevant indicators of environmental performance, including measurement techniques; and iv) marketing (e.g. implementing an ecolabelling scheme, making an environmental claim, or producing an environmental product declaration).

According to the European Commission, LCA provide the best framework for assessing the potential environmental impacts or benefits currently available, as well as a helpful tool to identify trade-offs and areas for achieving improvements by taking into account the full life cycle of a product, a process or a service (European Commission, 2003).

LCA is structured in four phases (**Figure 62**):

1. goal and scope definition
2. inventory analysis
3. impact assessment
4. interpretation

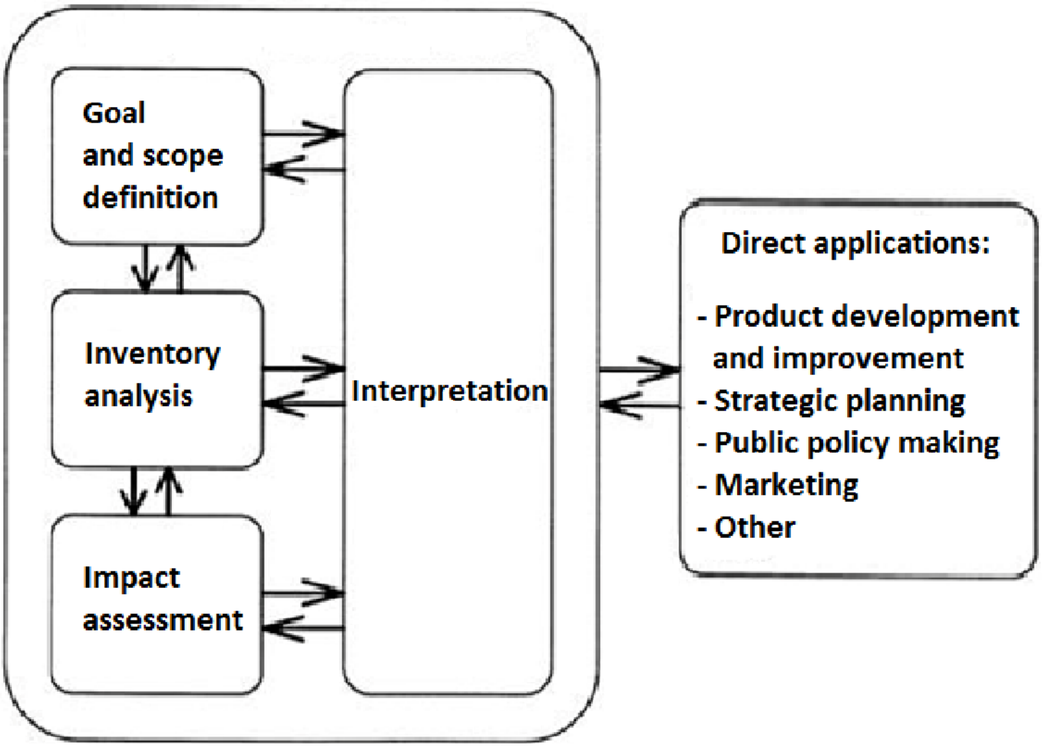


Figure 62. Stage of a Life Cycle Assessment (ISO 14040 and ISO 14044).

1. Goal and scope definition

The definition of the goal and scope of an LCA depends on the analyzed system and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA. In defining the goal of an LCA, the following items shall be unambiguously stated: the intended application, the reasons for carrying out the study, the intended audience, whether the results are intended to be used in comparative assertions intended to be disclosed to the public. The scope of the study must clearly describe the analyzed system (product, process, service), the function of the product system, the functional unit, the system boundary, the allocation procedure, the data quality, the methodology applied, and finally, the necessary assumptions, and restrictions.

The functional unit (FU) defines what is studied and plays a reference role to which the input and output data must be normalized in a mathematical sense. The functional unit must be clearly defined and measurable. The system boundaries determine which life cycle steps and processes are included and which are excluded within the LCA. Here, the level of detail to which the LCA shall be performed is explained. The system boundaries definition can be helped from a flow diagram use, which specifies the typologies and amounts of input (materials, resources, energies) and output (emissions, waste materials).

The allocation procedure carries out the allocation of all inputs and outputs to the different products according to clearly stated procedures that shall be documented and explained together with the allocation procedure. The data quality shows its ability to satisfy stated requirements, such as time-related coverage, geographical coverage, technology coverage, measure of the variability of the data, completeness, representativeness, consistency, reproducibility, sources of the data, uncertainty of the information. The methodology applied indicates the LCIA methods shall be adopted to perform the impacts assessment. The assumptions and restrictions made shall be clearly stated and explained in the first LCA phase.

2. Life cycle inventory

Life Cycle Inventory (LCI) is the second phase of LCA and is an inventory of input/output data with regard to the system being studied. It involves the collection of the data necessary to meet the goals of the defined study. The LCI represents the core of LCA, the collection and use of complete and reliable data and the availability of clear explanations of applied assumptions, advantages and disadvantages, as well as caveats to satisfy transparency, acceptability and credibility criteria for such analyses. The qualitative and quantitative data for inclusion in the inventory shall be collected for each process represented in the analyzed LCA and included within the system boundary. The collected data, acquired from several reporting locations and published references, shall be measured in order to reach uniform and consistent understanding of the product systems to be modelled.

ISO 14044 (ISO 2006,b) suggests that the measures to take into consideration are:

- drawing unspecific process flow diagrams that outline all the unit processes to be modelled, including their interrelationships;

- describing each unit process in detail with respect to factors influencing inputs and outputs;
- listing of flows and relevant data for operating conditions associated with each unit process;
- developing a list that specifies the units used;
- describing the data collection and calculation techniques needed for all data;
- providing instructions to clearly document any special cases, irregularities or other items associated with the data provided.

4. Life cycle impact assessment

The third phase of LCA is the life cycle impact assessment (LCIA). LCIA aim at providing additional information to help assess a product system's LCI results so as to better understand their environmental significance. It shall be determined some parameters such as impact categories, damage categories and characterization models are included within the LCA study. LCIA is different from other techniques, such as environmental performance evaluation, environmental impact assessment and risk assessment, since it is a relative approach based on a functional unit. The LCIA phase shall be carefully planned to achieve the goal and scope of an LCA study. The LCIA and all others LCA phases shall be coordinated with each other in order to take into account possible shortcomings, such as the quality of the LCI data; the system boundary and data cut-off decisions have been sufficiently reviewed to ensure the availability of LCI results necessary to calculate indicator results for the LCIA and the environmental relevance of the LCIA results is decreased due to the LCI functional unit calculation, system wide averaging, aggregation and allocation (ISO 14044, 2006).

Hence, the LCIA phase is a collection of environmental effect indicators which come out from different impact categories, which together represent the LCIA profile for the analyzed system. Traditionally, as in many other environmental assessments, LCIA uses linear modeling and takes the effects of the substances into account, but not their background concentrations and the geographical dependency on fate. The method aggregates the environmental consequences over release points in time, release locations and substances (chemicals). This allows calculating potential impact scores, which reflect contributions to environmental burdens).

There is consensus (ISO 2006,b) in distinguishing the four stages of the impact assessment: classification, characterization, normalization and weighting. The first two stages are mandatory elements, whereas the latter two are optional ones.

4.1. Mandatory elements of LCIA

The LCIA phase shall include the following mandatory elements:

- **Classification:** assignment of LCI results to impact categories should consider the following: a) assignment of LCI results that are exclusive to one impact category; b) identification of LCI results that relate to more than one impact category, including: distinction between parallel mechanisms (e.g. SO_2 is apportioned between the impact categories of human health and acidification), and assignment to serial mechanisms (e.g. NO_x can be classified to contribute to both ground-level ozone formation and acidification).
- **Characterization:** the calculation of indicator results involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category. This conversion uses characterization factors. The outcome of the calculation is a numerical indicator result. The method of calculating indicator results shall be identified and documented, including the value-choices and assumptions used.

4.1. Optional elements of LCIA

Normalization and weighting are optional steps under ISO 14044:2006 to support the interpretation of the impact profile and are steps towards a fully aggregated result. These phases may also be used to define the quantitative cut-off rules and to check the achieved degree of completeness of the data set inventory.

- **Normalization:** calculation of the magnitude of indicator resulted from characterization phase; the indicator results for the different midpoint level impact categories or endpoint level damages are expressed relative to a common reference, by dividing the indicator results by the respective reference value. As reference values typically the impact or damage results of the total annual territorial elementary flows in a country, region, or continent, or globally (or per average citizen, i.e., per capita) are used. For midpoint level results the normalization basis is the overall potential impact, calculated from the annual inventory of elementary flows. For endpoint level results the normalization basis is the overall damage to the areas of protection (JRC-IES, 2010a).

- **Weighting:** adapting and aggregating indicator results across impact categories using numerical factors based on value-choices; data prior to weighting should remain available; In weighting, the indicator results for the different impact categories or damages are each multiplied by a specific weighting factor, that is intended to reflect the relative relevance of the different impact categories (midpoint) and damage category (endpoints) among each other. The identification of a suitable weighting set shall be done, justified, and documented during the initial scope phase of the study and in line with its goal, especially the intended applications and target audience.

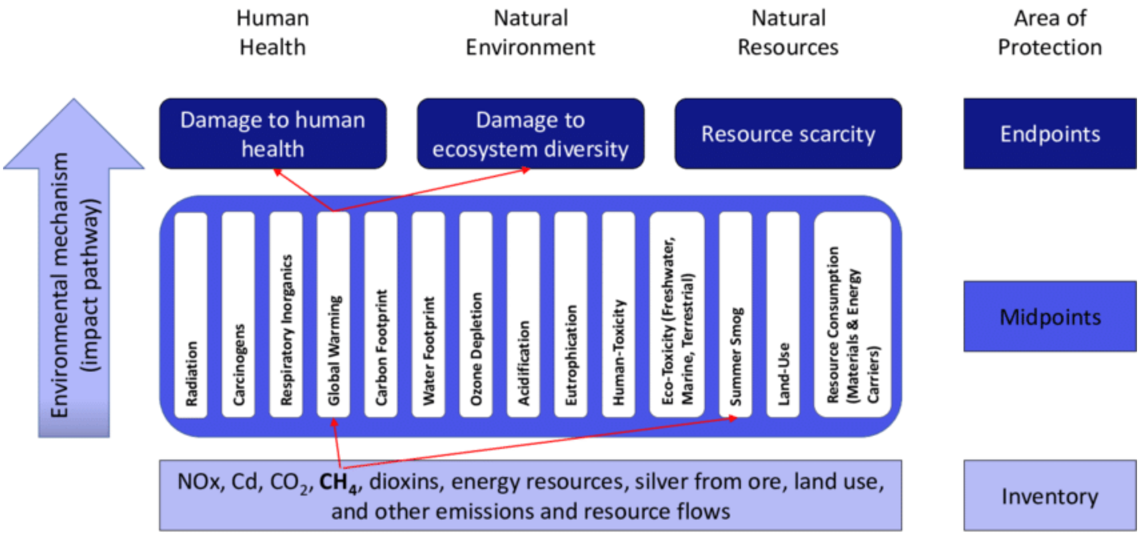


Figure 63. Life cycle impact assessment - Schematic steps from inventory to category endpoints (Masoni and Zamagni, 2011).

The LCIA covers both toxic and non-toxic impact categories. Some example of non-toxic impact categories is climate change, acidification, resource depletion. In contrast, carcinogens, human toxicity and ecotoxicity represent the toxic impact categories. Furthermore, the impact categories are distinguished in midpoint or endpoint.

The distinction among midpoint or endpoint categories is based on the point in which the indicator is chosen along the impact pathway. Characterization at midpoint level models the impact using an indicator located somewhere along (but before the end of) the environmental impact pathway of a substance. Characterization at the endpoint level requires modelling all the way to the impact on the entities described by the Area of Protection i.e. on Human Health, on the Natural Environment and on Natural Resources (**Figure 45**).

5. Interpretation

The life cycle interpretation phase comprises several elements as follows:

- identification of the significant issues based on the results of the LCI and LCIA phases of LCA;
- an evaluation that considers completeness, sensitivity and consistency checks;
- conclusions, limitations, and recommendations.

The interpretation should reflect the fact that LCIA results i) are based on a relative approach, ii) indicate potential environmental effects, iii) do not predict actual impacts on category endpoints, the exceeding of thresholds or safety margins or risks. The findings of this interpretation may take the form of conclusions and recommendations to decision-makers, consistent with the goal and scope of the study. Life cycle interpretation is also intended to provide a readily understandable, complete and consistent presentation of the results of an LCA and can involve the iterative process of reviewing and revising the scope of the LCA, as well as the nature and quality of the data collected in a way which is consistent with the defined goal. Finally, the findings of the life cycle interpretation should reflect the results of the evaluation element.

References

Afkhami, B., Akbarian, B., Beheshti A., N., Kakaee, A.H., Shabani, B., 2015. Energy consumption assessment in a cement production plant. Sustain. Energy Technol. Assessments 10, 84–89. https://doi.org/10.1016/j.seta.2015.03.003

Ahmed, T., Fung, A.S., Kumar, R., 2020. Energy benchmarking and ventilation related energy saving potentials for SMEs in Greater Toronto Area. J. Clean. Prod. 246, 118961. https://doi.org/10.1016/j.jclepro.2019.118961

Ainsworth, B.E., Haskell, W.L., Herrmann, S.D., Meckes, N., Bassett, D.R., Tudor-Locke, C., Greer, J.L., Vezina, J., Whitt-Glover, M.C., Leon, A.S., 2011. 2011 compendium of physical activities: A second update of codes and MET values. Med. Sci. Sports Exerc. 43, 1575–1581. https://doi.org/10.1249/MSS.0b013e31821ece12

Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M., Elsarrag, E., 2016. Occupant productivity and office indoor environment quality: A review of the literature. Build. Environ. 105, 369–389. https://doi.org/10.1016/j.buildenv.2016.06.001

Albatayneh, A., 2021. Optimising the parameters of a building envelope in the east mediterranean Saharan, cool climate Zone. Buildings 11, 1–23. https://doi.org/10.3390/buildings11020043

Alfahdawi, I.H., Osman, S.A., Hamid, R., Al-Hadithi, A.I., 2016. Utilizing waste plastic polypropylene and polyethylene terephthalate as alternative aggregates to produce lightweight concrete: A review. J. Eng. Sci. Technol. 11, 1165–1173.

Alhasanat, M.B.A., Al Qadi, A.N.S., Haddad, M., Al-Eas, A., Yaseen, A., 2016. The Addition of Plastic Waste in Self- Compacted Concrete : a Critical Review the Addition of Plastic Waste in Self-Compacted. Int. J. Curr. Res. 8, 33240–33244.

Allen, C., Oldfield, P., Teh, S.H., Wiedmann, T., Langdon, S., Yu, M., Yang, J., 2022. Modelling ambitious climate mitigation pathways for Australia’s built environment. Sustain. Cities Soc. 77, 103554. https://doi.org/10.1016/j.scs.2021.103554

Allen, J.G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., Spengler, J.D., 2016. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: A controlled exposure study of green and conventional office environments. Environ. Health Perspect. 124, 805–812. https://doi.org/10.1289/ehp.1510037

Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for achieving a 50% cut in industrial carbon emissions by 2050. Environ. Sci. Technol. 44, 1888–1894. https://doi.org/10.1021/es902909k

Almeshal, I., Tayeh, B.A., Alyousef, R., Alabduljabbar, H., Mustafa Mohamed, A., Alaskar, A., 2020. Use of recycled plastic as fine aggregate in cementitious composites: A review. Constr. Build. Mater. 253, 119146. https://doi.org/10.1016/j.conbuildmat.2020.119146

Alyousef, R., Alabduljabbar, H., Mohammadhosseini, H., Mohamed, A.M., Siddika, A., Alrshoudi, F., Alaskar, A., 2020. Utilization of sheep wool as potential fibrous materials in the production of concrete composites. J. Build. Eng. 30, 101216. https://doi.org/10.1016/j.jobe.2020.101216

Amed, I., Berg, A., Balchandani, A., Hedrich, S., Rölkens, F., Young, R., Poojara, S., 2019. The state of fashion 2020, McKinsey&Company and The Business of Fashion.

Arteconi, A., Ciarrocchi, E., Pan, Q., Carducci, F., Comodi, G., Polonara, F., Wang, R., 2017. Thermal energy storage coupled with PV panels for demand side management of industrial building cooling loads. Appl. Energy 185, 1984–1993. https://doi.org/10.1016/j.apenergy.2016.01.025

Asdrubali, F., Ballarini, I., Corrado, V., Evangelisti, L., Grazieschi, G., Guattari, C., 2019. Energy and environmental payback times for an NZEB retrofit. Build. Environ. 147, 461–472. https://doi.org/10.1016/j.buildenv.2018.10.047

Assocalzaturifici, 2020. The Italian footwear sector 2020 - Highlights & notes.

Attia, S., Shadmanfar, N., Ricci, F., 2020. Developing two benchmark models for nearly zero energy schools. Appl. Energy 263, 114614. https://doi.org/10.1016/j.apenergy.2020.114614

Augusto de Oliveira, J., Lopes Silva, D.A., Devós Ganga, G.M., Filho, M.G., Ferreira, A.A., Esposto, K.F., Ometto, A.R., 2019. Cleaner Production practices, motivators and performance in the Brazilian industrial companies. J. Clean. Prod. 231, 359–369. https://doi.org/10.1016/j.jclepro.2019.05.013

Avgoustaki, D.D., Xydis, G., 2021. Energy cost reduction by shifting electricity demand in indoor vertical farms with artificial lighting. Biosyst. Eng. 211, 219–229. https://doi.org/10.1016/j.biosystemseng.2021.09.006

Awoyera, P.O., Adesina, A., 2020. Plastic wastes to construction products: Status, limitations and future perspective. Case Stud. Constr. Mater. https://doi.org/10.1016/j.cscm.2020.e00330

Babafemi, A.J., Šavija, B., Paul, S.C., Anggraini, V., 2018. Engineering properties of concrete with waste recycled plastic: A review. Sustain. 10. https://doi.org/10.3390/su10113875

Babu, R.P., O'Connor, K., Seeram, R., 2013. Current progress on bio-based polymers and their future trends. Prog. Biomater. https://doi.org/10.1186/2194-0517-2-8

Baikerikar, A., 2014. A Review on Green Concrete. J. Emerg. Technol. Innov. Res. 1, 472–474.

bauforumstahl e. V., 2015. Ökobilanzieller Vergleich von Hallen unterschiedlicher Bauweisen.

Becchio, C., Corgnati, S.P., Vio, M., Crespi, G., Prendin, L., Magagnini, M., 2017. HVAC solutions for energy retrofitted hotel in Mediterranean area. Energy Procedia 133, 145–157. https://doi.org/10.1016/j.egypro.2017.09.380

Becchio, C., Ferrando, D.G., Fregonara, E., Milani, N., Quercia, C., Serra, V., 2015. The cost optimal methodology for evaluating the energy retrofit of an ex-industrial building in Turin. Energy Procedia 78, 1039–1044. https://doi.org/10.1016/j.egypro.2015.11.057

Bech, N.M., Birkved, M., Charnley, F., Kjaer, L.L., Pigosso, D.C.A., Hauschild, M.Z., McAloone, T.C., Moreno, M., 2019. Evaluating the environmental performance of a product/service-system business model for Merino Wool Next-to-Skin Garments: The case of Armadillo Merino®. Sustain. https://doi.org/10.3390/su11205854

Behrer, A.P., Park, J., 2017. Will We Adapt? Temperature, Labor and Adaptation to Climate Change. Work. Pap. 39p.

Beltrami, M., Orzes, G., Sarkis, J., Sartor, M., 2021. Industry 4.0 and sustainability: Towards conceptualization and theory. J. Clean. Prod. 312, 127733. https://doi.org/10.1016/j.jclepro.2021.127733

Benedetti, M., Bonfa, F., Bertini, I., Introna, V., Ubertini, S., 2018. Explorative study on Compressed Air Systems' energy efficiency in production and use: First steps towards the creation of a benchmarking system for large and energy-intensive industrial firms. Appl. Energy 227, 436–448. https://doi.org/10.1016/j.apenergy.2017.07.100

Bernardi, E., Carlucci, S., Cornaro, C., Bohne, R.A., 2017. An analysis of the most adopted rating systems for assessing the environmental impact of buildings. Sustain. 9, 1–27. https://doi.org/10.3390/su9071226

Bhardwaj, B., Kumar, P., 2017. Waste foundry sand in concrete: A review. Constr. Build. Mater. https://doi.org/10.1016/j.conbuildmat.2017.09.010

Bhatt, Y., Ghuman, K., Dhir, A., 2020. Sustainable manufacturing. Bibliometrics and content analysis. J. Clean. Prod. 260, 120988. https://doi.org/10.1016/j.jclepro.2020.120988

Bida, S.M., Nora, F., Abdul, A., Jaafar, M.S., Hejazi, F., Nabilah, A.B., Star, G., 2018. Advances in Precast Concrete Sandwich Panels toward Energy Efficient Structural Buildings. Preprints 2018100147. https://doi.org/10.20944/preprints201810.0147.v1

Bizzotto, M., 2017. Italian footwear sector and "Made in Italy" goods: manufacturers' associations call for mandatory indication of origin to protect Italian excellence.

Blass, V., Corbett, C.J., Delmas, M.A., Muthulingam, S., 2014. Top management and the adoption of energy efficiency practices: Evidence from small and medium-sized manufacturing firms in the US. Energy 65, 560–571. https://doi.org/10.1016/j.energy.2013.11.030

Boharb, A., Allouhi, A., Saidur, R., Kousksou, T., Jamil, A., Mourad, Y., Benbassou, A., 2016. Auditing and analysis of energy consumption of an industrial site in Morocco. Energy 101, 332–342. https://doi.org/10.1016/j.energy.2016.02.035

Bonamente, E., Merico, M.C., Rinaldi, S., Pignatta, G., Pisello, A.L., Cotana, F., Nicolini, A., 2014. Environmental impact of industrial prefabricated buildings: Carbon and Energy Footprint analysis based on an LCA approach. Energy Procedia 61, 2841–2844. https://doi.org/10.1016/j.egypro.2014.12.319

Boobalakrishnan, P., Manoj Kumar, P., Balaji, G., Jenaris, D.S., Kaarthik, S., Jaya Prakash Babu, M., Karthhik, K., 2021. Thermal management of metal roof building using phase change material (PCM). Mater. Today Proc. https://doi.org/10.1016/j.matpr.2021.05.012

Boyce, P., Hunter, C., Howlett, O., 2003. The Benefits of Daylight through Windows Sponsored by : Capturing the Daylight Dividend Program The Benefits of Daylight through Windows 1–88.

Boyd, G., Dutrow, E., Tunnessen, W., 2008. The evolution of the ENERGY STAR® energy performance indicator for benchmarking industrial plant manufacturing energy use. J. Clean. Prod. 16, 709–715. https://doi.org/10.1016/j.jclepro.2007.02.024

Boyd, G.A., 2017. Comparing the statistical distributions of energy efficiency in manufacturing: meta-analysis of 24 Case studies to develop industry-specific energy performance indicators (EPI). Energy Effic. 10, 217–238. https://doi.org/10.1007/s12053-016-9450-y

BPIE, 2022. Ready for carbon neutral by 2050? Assessing ambition levels in new building standards across the EU.

BPIE, 2011. Europe ' s buildings under the microscope, Buildings Performance Institute Europe, Buildings Performance Institute Europe (BPIE).

Brand, S., 1995. How Buildings Learn: What Happens After They're Built.

Bruyn, S. De, Jongsma, C., Kampman, B., Görlach, B., Thie, J., 2020. Energy-intensive industries – Challenges and opportunities in energy transition. Luxembourg.

Bühler, F., Zühlsdorf, B., Nguyen, T. Van, Elmegaard, B., 2019. A comparative assessment of electrification strategies for industrial sites: Case of milk powder production. Appl. Energy 250, 1383–1401. https://doi.org/10.1016/j.apenergy.2019.05.071

Butturi, M.A., Barbi, S., Marinelli, S., Montorsi, M., Gamberini, R., 2021. Circular design options for wearables integrated sportswear to be employed in adverse outdoor conditions. Proc. Summer Sch. Fr. Turco.

Butturi, M.A., Gamberini, R., 2020. Urban-industrial symbiosis to support sustainable energy transition. Int. J. Energy Prod. Manag. 5, 355–366. https://doi.org/10.2495/EQ-V5-N4-355-366

Butturi, M.A., Marinelli, S., Gamberini, R., Rimini, B., 2020. Ecotoxicity of Plastics from Informal Waste Electric and Electronic Treatment and Recycling. Toxics 8, 99. https://doi.org/10.3390/toxics8040099

Cagno, E., Trianni, A., Abeelen, C., Worrell, E., Miggiano, F., 2015. Barriers and drivers for energy efficiency: Different perspectives from an exploratory study in the Netherlands. Energy Convers. Manag. 102, 26–38. https://doi.org/10.1016/j.enconman.2015.04.018

Cagno, E., Worrell, E., Trianni, A., Pugliese, G., 2013. A novel approach for barriers to industrial energy efficiency. Renew. Sustain. Energy Rev. 19, 290–308. https://doi.org/10.1016/j.rser.2012.11.007

Caputo, A.C., Pelagagge, P.M., 2009. Upgrading mixed ventilation systems in industrial conditioning. Appl. Therm. Eng. 29, 3204–3211. https://doi.org/10.1016/j.applthermaleng.2009.04.025

Carabalí, D.M., Forero, C.R., Cadavid, Y., 2018. Energy diagnosis and structuring an energy saving proposal for the metal casting industry: An experience in Colombia. Appl. Therm. Eng. 137, 767–773. https://doi.org/10.1016/j.applthermaleng.2018.04.012

Catalbas, M.C., Kocak, B., Yenipınar, B., 2021. Analysis of photovoltaic-green roofs in OSTIM industrial zone. Int. J. Hydrogen Energy 46, 14844–14856. https://doi.org/10.1016/j.ijhydene.2021.01.205

Cemnet, 2019. The Global Cement Report^{TM} - 13th Edition. Int. Cem. Rev.

Centre for Energy-Environment Resources Development (CEERD), Bangkok, T., 2009. Analysis of the Energy Trends in the European Union & Asia To 2030.

Chandrakumar, C., McLaren, S.J., Dowdell, D., Jaques, R., 2020. A science-based approach to setting climate targets for buildings: The case of a New Zealand detached house. Build. Environ. 169, 106560. https://doi.org/10.1016/j.buildenv.2019.106560

Chen, H.W., Hsu, C.H., Hong, G.B., 2012. The case study of energy flow analysis and strategy in pulp and paper industry. Energy Policy 43, 448–455. https://doi.org/10.1016/j.enpol.2012.01.037

Chinese, D., Nardin, G., Saro, O., 2011. Multi-criteria analysis for the selection of space heating systems in an industrial building. Energy 36, 556–565. https://doi.org/10.1016/j.energy.2010.10.005

Choi, B., Yoo, S., Park, S. Il, 2018. Carbon footprint of packaging films made from LDPE, PLA, and PLA/PBAT blends in South Korea. Sustain. https://doi.org/10.3390/su10072369

Choi, K.B., Choi, W.C., Feo, L., Jang, S.J., Yun, H. Do, 2015. In-plane shear behavior of insulated precast concrete sandwich panels reinforced with corrugated GFRP shear connectors. Compos. Part B Eng. 79, 419–429. https://doi.org/10.1016/j.compositesb.2015.04.056

Choi, T.M., Li, Y., 2015. Sustainability in fashion business operations. Sustain. https://doi.org/10.3390/su71115400

Chowdhury, T.U., Mahi, M.A., Haque, K.A., Mostafizur Rahman, M., 2018. A review on the use of polyethylene terephthalate (PET) as aggregates in concrete. Malaysian J. Sci. 37, 118–136. https://doi.org/10.22452/mjs.vol37no2.4

Classification, P.C., Cpc, U.N., 2019. JACKETS , COATS AND OTHER SIMILAR OUTDOOR 1–32.

Commission, E., 2020. Science for Environment Policy FUTURE BRIEF : Eco-Innovation in SMEs. https://doi.org/10.2779/077211

cr@ftsman project, 2010. Report on the Situation of Craftsmanship in Europe.

D’Ambrosio Alfano, F.R., Olesen, B.W., Palella, B.I., Riccio, G., 2014. Thermal comfort: Design and assessment for energy saving. Energy Build. 81, 326–336. https://doi.org/10.1016/j.enbuild.2014.06.033

Dam, A., Choudhury, S.R., Dey, A., 2016. A Review of the Use of Solid Waste Materials in Concrete Mix. J. Basic Appl. Eng. Res. 3, 948–954.

Das, R., Saha, S., Das, S., 2016. Green Building an Environment- Friendly Concept for Building Sector. Int. Res. J. Eng. Technol. 03, 1092–1100.

Dash, M.K., Patro, S.K., Rath, A.K., 2016. Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete – A review. Int. J. Sustain. Built Environ. 5, 484–516. https://doi.org/10.1016/j.ijsbe.2016.04.006

Dong, X., Wu, Y., Chen, X., Li, H., Cao, B., Zhang, X., Yan, X., Li, Z., Long, Y., Li, X., 2021. Effect of thermal, acoustic, and lighting environment in underground space on human comfort and work efficiency: A review. Sci. Total Environ. 786, 147537. https://doi.org/10.1016/j.scitotenv.2021.147537

Dongellini, M., Marinosci, C., Morini, G.L., 2014. Energy audit of an industrial site : a case study. Energy Procedia 45, 424–433. https://doi.org/10.1016/j.egypro.2014.01.046

Down, I., Bureau, F., Sustainability, L.T., Severinghaus, S., Bernstein, P., Hamilton, M., 2019. Experts in Product Stewardship Life Cycle Assessment of Down Fill Material 1–46.

Eberhardt, L.C.M., Birgisdottir, H., Birkved, M., 2019. Potential of Circular Economy in Sustainable Buildings. IOP Conf. Ser. Mater. Sci. Eng. 471. https://doi.org/10.1088/1757-899X/471/9/092051

Edwards, B.W., Naboni, E., 2014. Green Buildings Pay, Design, Productivity and Ecology - Third

Edition. Routledge.

EEFIG, 2015. Energy Efficiency – the first fuel for the EU Economy.

EN ISO 14025, 2006. Environmental labels and declarations - Type III environmental declarations - Principles and procedures. Eur. Stand.

ENEA, 2020. RAPPORTO ANNUALE EFFICIENZA ENERGETICA 2020.

Energy, I., Benchmarking, U., 1999. Essentials of Benchmarking 771–781.

Espino-Reyes, C.A., Ortega-Avila, N., Rodriguez-Muñoz, N.A., 2020. Energy savings on an industrial building in different climate zones: Envelope analysis and PV system implementation. Sustain. 12. https://doi.org/10.3390/su12041391

European Comission, 2011. A Roadmap for moving to a competitive low carbon economy in 2050. Office of Publications of the European Commission, Brussels., Brussels, 13.4.2011 COM(2011) 206 final.

European Commission, 2020. An SME Strategy for a sustainable and digital Europe. Office of Publications of the European Commission, Brussels, Brussels, 10.3.2020 COM(2020) 103 final.

European Commission, 2016. A Study on Energy Efficiency in Enterprises: Energy Audits and Energy Management Systems - Report on the fulfilment of obligations upon large enterprises, the encouragement of small- and medium-sized companies and on good-practice.

European Commission, 2015. Establishing the ecological criteria for the award of the EU Ecolabel for growing media, soil improvers and mulch (2015/2099/EU). Off. J. Eur. Union.

European Commission, 2003. Communication COM (2003:302) - Integrated Product Policy - Building on Environmental Life-Cycle Thinking. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52001DC0068.

European Commission, 1999. Commission Staff Working Paper on Sustainable Industrial Development, SEC(1999) 1729. Brussels, 25.10.1999.

European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010. International Reference Life Cycle Data System (ILCD) Handbook -- General guide for Life Cycle Assessment -- Detailed guidance, Constraints. Luxembourg. https://doi.org/10.2788/38479

European Union, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Off. J. Eur. Union 153, 13–35.

Fanger, P.O., 1970. Thermal comfort. Analysis and applications in environmental engineering. Therm. Comf. Anal. Appl. Environ. Eng.

Faraj, R.H., Hama Ali, H.F., Sherwani, A.F.H., Hassan, B.R., Karim, H., 2020. Use of recycled plastic in self-compacting concrete: A comprehensive review on fresh and mechanical properties. J. Build. Eng. 30, 101283. https://doi.org/10.1016/j.jobe.2020.101283

Fellaou, S., Bounahmidi, T., 2017. Evaluation of energy efficiency opportunities of a typical Moroccan cement plant: Part I. Energy analysis. Appl. Therm. Eng. 115, 1161–1172.

https://doi.org/10.1016/j.applthermaleng.2017.01.010

Feng, W., Zhang, Q., Ji, H., Wang, R., Zhou, N., Ye, Q., Hao, B., Li, Y., Luo, D., Lau, S.S.Y., 2019. A review of net zero energy buildings in hot and humid climates: Experience learned from 34 case study buildings. Renew. Sustain. Energy Rev. 114, 109303. https://doi.org/10.1016/j.rser.2019.109303

Fisk, W., 2000. Health and productivity gains from better indoor environments and their relationship with building energy efficiency. Annu. Rev. Energy Env. 25, 537–566. https://doi.org/10.1146/annurev.energy.25.1.537

Gangolells, M., Gaspar, K., Casals, M., Ferré-Bigorra, J., Forcada, N., Macarulla, M., 2020. Life-cycle environmental and cost-effective energy retrofitting solutions for office stock. Sustain. Cities Soc. 61, 102319. https://doi.org/10.1016/j.scs.2020.102319

Gao, M., Wang, Q., Wang, N., Ma, Z., Li, L., 2022. Application of green design and manufacturing in mechanical engineering: Education, scientific research, and practice. Sustain. 14. https://doi.org/10.3390/su14010237

Gao, Y., romero, P., Zhang, H., Huang, M., Lai, F., 2019. Unsaturated polyester resin concrete: A review. Constr. Build. Mater. 228, 116709. https://doi.org/10.1016/j.conbuildmat.2019.116709

Garcia-Torres, S., Rey-Garcia, M., Albareda-Vivo, L., 2017. Effective disclosure in the fast-fashion industry: From sustainability reporting to action. Sustain. https://doi.org/10.3390/su9122256

Gebler, M., Cerdas, J.F., Thiede, S., Herrmann, C., 2020. Life cycle assessment of an automotive factory: Identifying challenges for the decarbonization of automotive production – A case study. J. Clean. Prod. 270, 122330. https://doi.org/10.1016/j.jclepro.2020.122330

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. https://doi.org/10.1126/sciadv.1700782

Giorgi, S., Lavagna, M., Campioli, A., 2018. Life Cycle Assessment of building end of life. Politecnico di Milano, ABC Department.

Gironi, F., Piemonte, V., 2011. Bioplastics and petroleum-based plastics: Strengths and weaknesses. Energy Sources, Part A Recover. Util. Environ. Eff. https://doi.org/10.1080/15567030903436830

Goh, C.S., Chong, H.Y., Jack, L., Mohd Faris, A.F., 2020. Revisiting triple bottom line within the context of sustainable construction: A systematic review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2019.119884

Gohoungodji, P., N'Dri, A.B., Latulippe, J.M., Matos, A.L.B., 2020. What is stopping the automotive industry from going green? A systematic review of barriers to green innovation in the automotive industry. J. Clean. Prod. 277, 123524. https://doi.org/10.1016/j.jclepro.2020.123524

Gonzalez-Caceres, A., Lassen, A.K., Nielsen, T.R., 2020. Barriers and challenges of the recommendation list of measures under the EPBD scheme: A critical review. Energy Build. 223, 110065. https://doi.org/10.1016/j.enbuild.2020.110065

Gourlis, G., Kovacic, I., 2016. A study on building performance analysis for energy retrofit of existing industrial facilities. Appl. Energy 184, 1389–1399.

https://doi.org/10.1016/j.apenergy.2016.03.104

Grove-Smith, J., Aydin, V., Feist, W., Schnieders, J., Thomas, S., 2018. Standards and policies for very high energy efficiency in the urban building sector towards reaching the 1.5°C target. Curr. Opin. Environ. Sustain. 30, 103–114. https://doi.org/10.1016/j.cosust.2018.04.006

Gu, L., Ozbakkaloglu, T., 2016. Use of recycled plastics in concrete: A critical review. Waste Manag. 51, 19–42. https://doi.org/10.1016/j.wasman.2016.03.005

Guo, S., Choi, T.M., Shen, B., 2020. Green product development under competition: A study of the fashion apparel industry. Eur. J. Oper. Res. 280, 523–538. https://doi.org/10.1016/j.ejor.2019.07.050

Gustafsson, S.I., 2006. Refurbishment of industrial buildings. Energy Convers. Manag. 47, 2223–2239. https://doi.org/10.1016/j.enconman.2005.12.011

Haapala, K.R., Zhao, F., Camelio, J., Sutherland, J.W., 2014. MSEC2011-50300 0–21.

Haddad, Z., 2019. The business case for green building. AEE World Energy Eng. Congr. 2019 4529–4551. https://doi.org/10.4324/9780080942315-10

Hasanuzzaman, M., Rahim, N.A., Hosenuzzaman, M., Saidur, R., Mahbubul, I.M., Rashid, M.M., 2012. Energy savings in the combustion based process heating in industrial sector. Renew. Sustain. Energy Rev. 16, 4527–4536. https://doi.org/10.1016/j.rser.2012.05.027

Hasheminasab, H., Hashemkhani Zolfani, S., Kharrazi, M., Streimikiene, D., 2022. Combination of sustainability and circular economy to develop a cleaner building industry. Energy Build. 258, 111838. https://doi.org/10.1016/j.enbuild.2022.111838

Heijungs, R., Guinée, J.B., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wegener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., Duin, R. van, Goede, H.P. de, 1992. Environmental life cycle assessment of products: guide and backgrounds (Part 1). Inst. Environ. Sci. Leiden Univ.

Henao, R., Sarache, W., Gómez, I., 2019. Lean manufacturing and sustainable performance: Trends and future challenges. J. Clean. Prod. 208, 99–116. https://doi.org/10.1016/j.jclepro.2018.10.116

Henninger, C.E., 2015. Traceability the new eco-label in the slow-fashion industry?-Consumer perceptions and micro-organisations responses. Sustain. 7, 6011–6032. https://doi.org/10.3390/su7056011

Henry, B.K., Russell, S.J., Ledgard, S.F., Gollnow, S., Wiedemann, S.G., Nebel, B., Maslen, D., Swan, P., 2015. LCA of wool textiles and clothing, Handbook of Life Cycle Assessment (LCA) of Textiles and Clothing. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100169-1.00010-1

Herrmann, F.F., Barbosa-Povoa, A.P., Butturi, M.A., Marinelli, S., Sellitto, M.A., 2021. Green Supply Chain Management: Conceptual Framework and Models for Analysis. Sustainability 13, 8127. https://doi.org/10.3390/su13158127

Hervás-Oliver, J.-L., Parrilli, M.D., Rodríguez-Pose, A., Sempere-Ripoll, F., 2021. The drivers of SME innovation in the regions of the EU. Res. Policy 50, 104316. https://doi.org/10.1016/j.respol.2021.104316

Hollberg, A., Lützkendorf, T., Habert, G., 2019. Top-down or bottom-up? – How environmental benchmarks can support the design process. Build. Environ. 153, 148–157. https://doi.org/10.1016/j.buildenv.2019.02.026

Holmström, J., Liotta, G., Chaudhuri, A., 2017. Sustainability outcomes through direct digital manufacturing-based operational practices: A design theory approach. J. Clean. Prod. 167, 951–961. https://doi.org/10.1016/j.jclepro.2017.03.092

Hottle, T.A., Bilec, M.M., Landis, A.E., 2013. Sustainability assessments of bio-based polymers. Polym. Degrad. Stab. 98, 1898–1907. https://doi.org/10.1016/j.polymdegradstab.2013.06.016

Huijbregts, M.A.J., Rombouts, L.J.A., Hellweg, S., Frischknecht, R., Hendriks, A.J., Van De Meent, D., Ragas, A.M.I., Reijnders, L., Struijs, J., 2006. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? Environ. Sci. Technol. https://doi.org/10.1021/es051689g

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-016-1246-y

Iancu, I.E., Moga, L., 2021. Thermo-energetic assessment of industrial buildings. IOP Conf. Ser. Mater. Sci. Eng. 1138, 012024. https://doi.org/10.1088/1757-899x/1138/1/012024

IEA/OECD;, Philibert, C., 2017. Renewable Energy for Industry: From green energy to green materials and fuels. IEA Insight Ser. 2017. https://doi.org/10.1111/j.1365-2990.2010.01130.x

IPCC, 2021. Technical Summary. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Climate Change 2021: The Physical Science Basis.

ISO, 2013. ISO 14067:2013 Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification and communication. Int. Organ. Stand.

ISO, 2006a. ISO 14040. Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization, Geneva, Switzerland. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-011-0297-3

ISO, 2006b. ISO 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-011-0297-3

ISTAT, 2021. Annuario statistico italiano 2021.

ITACA, 2019. UNI/PdR 13.0:2019 - Sostenibilità ambientale nelle costruzioni - Strumenti operativi per la valutazione della sostenibilità - Inquadramento generale e principi metodologici.

Jacquemin, L., Pontalier, P.Y., Sablayrolles, C., 2012. Life cycle assessment (LCA) applied to the process industry: A review. Int. J. Life Cycle Assess. 17, 1028–1041. https://doi.org/10.1007/s11367-012-0432-9

Jami, T., Karade, S.R., Singh, L.P., 2019. A review of the properties of hemp concrete for green building applications. J. Clean. Prod. 239, 117852.

https://doi.org/10.1016/j.jclepro.2019.117852

Jandiyal, A., Salhotra, S., Sharma, R., Nazir, U., 2016. A review on using fibers made from waste PET bottles in concrete. Int. J. Civ. Eng. Technol. 7, 553–564.

Jawahir, I.S., Dillon, O.W., Rouch, K.E., Joshi, K.J., Venkatachalam, A., Jaafar, I.H., 2006. Total life-cycle considerations in product design for sustainability: A framework for comprehensive evaluation. Proc. TMT 2006 1–10.

Jayal, A.D., Badurdeen, F., Dillon, O.W., Jawahir, I.S., 2010. Sustainable manufacturing: Modeling and optimization challenges at the product, process and system levels. CIRP J. Manuf. Sci. Technol. 2, 144–152. https://doi.org/10.1016/j.cirpj.2010.03.006

Jung, S., Jin, B., 2016. Sustainable development of slow fashion businesses: Customer value approach. Sustain. 8. https://doi.org/10.3390/su8060540

Junge, A.L., Straube, F., 2020. Sustainable supply chains - Digital transformation technologies' impact on the social and environmental dimension. Procedia Manuf. 43, 736–742. https://doi.org/10.1016/j.promfg.2020.02.110

K, P.P., Isaac S, R.R., Author, C., 2016. Microbial Degradation of Plastic Waste: A Review. J Pharm Chem Biol Sci.

Kalantzis, F., Revoltella, D., 2019. Do energy audits help SMEs to realize energy-efficiency opportunities? Energy Econ. 83, 229–239. https://doi.org/10.1016/j.eneco.2019.07.005

Kamaruddin, M.A., Abdullah, M.M.A., Zawawi, M.H., Zainol, M.R.R.A., 2017. Potential use of plastic waste as construction materials: Recent progress and future prospect. IOP Conf. Ser. Mater. Sci. Eng. 267. https://doi.org/10.1088/1757-899X/267/1/012011

Karaosman, H., Morales-Alonso, G., Brun, A., 2017. From a systematic literature review to a classification framework: Sustainability integration in fashion operations. Sustain. https://doi.org/10.3390/su9010030

Karvinen, H., 2015. Heikki Karvinen.

Katunský, D., Dolníková, E., Doroudiani, S., 2017. Integrated Lighting Efficiency Analysis in Large Industrial Buildings to Enhance Indoor Environmental Quality. Buildings 7, 47. https://doi.org/10.3390/buildings7020047

Ke, J., Price, L., McNeil, M., Khanna, N.Z., Zhou, N., 2013. Analysis and practices of energy benchmarking for industry from the perspective of systems engineering. Energy 54, 32–44. https://doi.org/10.1016/j.energy.2013.03.018

Kerr, J., Landry, J., 2017. Pulse of the fashion industry. Glob. Fash. Agenda Bost. Consult. Gr. 11.

Kim, H.Y., Kang, H.J., 2016. A study on development of a cost optimal and energy saving building model: Focused on industrial building. Energies 9. https://doi.org/10.3390/en9030181

Kjellstrom, T., Crowe, J., 2011. Climate Change, Workplace Heat Exposure, and Occupational Health and Productivity in Central America, International Journal of Occupational and Environmental Health. https://doi.org/10.1179/107735211799041931

Kousaiti, A., Hahladakis, J.N., Savvilotidou, V., Pivnenko, K., Tyrovola, K., Xekoukoulotakis, N., Astrup, T.F., Gidarakos, E., 2020. Assessment of tetrabromobisphenol-A (TBBPA) content in plastic waste recovered from WEEE. J. Hazard. Mater. 390, 121641. https://doi.org/10.1016/j.jhazmat.2019.121641

Kozlowski, A., Bardecki, M., Searcy, C., 2014. Environmental Impacts in the Fashion Industry. J. Corp. Citizsh. https://doi.org/10.9774/gleaf.4700.2012.sp.00004

Kralikova, R., Sokolova, H., Wessely, E., 2014. Thermal environment evaluation according to indices in industrial workplaces. Procedia Eng. 69, 158–167. https://doi.org/10.1016/j.proeng.2014.02.216

Krishna, N.K., Prasanth, M., Gowtham, R., Karthic, S., Mini, K.M., 2018. Enhancement of properties of concrete using natural fibers, in: Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2018.10.173

Kuceba, R., Zawada, M., 2020. Scientific and Business Networks as a Stimulator of Eco-Innovations Diffusion in Small and Micro-Enterprises. Eur. Res. Stud. J. XXIII, 790–802. https://doi.org/10.35808/ersj/1793

La Rosa, A.D., Recca, G., Summerscales, J., Latteri, A., Cozzo, G., Cicala, G., 2014. Bio-based versus traditional polymer composites. A life cycle assessment perspective. J. Clean. Prod. 74, 135–144. https://doi.org/10.1016/j.jclepro.2014.03.017

La Scalia, G., Saeli, M., Adelfio, L., Micale, R., 2021. From lab to industry: Scaling up green geopolymeric mortars manufacturing towards circular economy. J. Clean. Prod. 316, 128164. https://doi.org/10.1016/j.jclepro.2021.128164

Li, X., Ling, T.C., Hung Mo, K., 2020. Functions and impacts of plastic/rubber wastes as eco-friendly aggregate in concrete – A review. Constr. Build. Mater. 240, 117869. https://doi.org/10.1016/j.conbuildmat.2019.117869

Liew, K.M., Sojobi, A.O., Zhang, L.W., 2017. Green concrete: Prospects and challenges. Constr. Build. Mater. https://doi.org/10.1016/j.conbuildmat.2017.09.008

Liu, T., Nafees, A., khan, S., Javed, M.F., Aslam, F., Alabduljabbar, H., Xiong, J.J., Ijaz Khan, M., Malik, M.Y., 2022. Comparative study of mechanical properties between irradiated and regular plastic waste as a replacement of cement and fine aggregate for manufacturing of green concrete. Ain Shams Eng. J. 13, 101563. https://doi.org/10.1016/j.asej.2021.08.006

Liu, X., Niu, D., Bao, C., Suk, S., Shishime, T., 2012. A survey study of energy saving activities of industrial companies in Taicang, China. J. Clean. Prod. 26, 79–89. https://doi.org/10.1016/j.jclepro.2011.12.030

Liu, X., Yamamoto, R., Suk, S., 2014. A survey analysis of energy saving activities of industrial companies in Hyogo, Japan. J. Clean. Prod. 66, 288–300. https://doi.org/10.1016/j.jclepro.2013.10.011

Lunetto, V., Priarone, P.C., Kara, S., Settineri, L., 2021. A comparative LCA method for environmentally friendly manufacturing: Additive manufacturing versus Machining case. Procedia CIRP 98, 406–411. https://doi.org/10.1016/j.procir.2021.01.125

Macarthur, E., 2020. Towards the circular economy - Economic and Business Rationale for an Accelerated transition. Ellen Macarthur Found. Rethink Futur.

Malinauskaite, J., Jouhara, H., Ahmad, L., Milani, M., Montorsi, L., Venturelli, M., 2019. Energy efficiency in industry: EU and national policies in Italy and the UK. Energy 172, 255–269.

https://doi.org/10.1016/j.energy.2019.01.130

Marinelli, S., Butturi, M.A., Rimini, B., Gamberini, R., Marinello, S., 2020. Evaluating the environmental benefit of energy symbiosis networks in eco-industrial parks. IFAC-PapersOnLine 53, 13082–13087. https://doi.org/10.1016/j.ifacol.2020.12.2260

Marinelli, S., Gamberini, R., Rimini, B., Nesi, F., 2021. Implementing the Nearly Zero-Energy Buildings (nZEBs) Notion in Industrial Facilities. WIT Trans. Ecol. Environ. 254, 151–161. https://doi.org/10.2495/esus210141

Mariottini, F., Arcipowska, A., 2015. Nearly Zero Energy Buildings definitions across Europe.

Masi, D., Day, S., Godsell, J., 2017. Supply chain configurations in the circular economy: A systematic literature review. Sustain. 9. https://doi.org/10.3390/su9091602

Masoni, P., Zamagni, A., 2011. Guidance Document for performing LCAs on Fuel Cells and Hydrogen Technologies (Hyguide) 139.

Mastrapostoli, E., Karlessi, T., Pantazaras, A., Kolokotsa, D., Gobakis, K., Santamouris, M., 2014. On the cooling potential of cool roofs in cold climates: Use of cool fluorocarbon coatings to enhance the optical properties and the energy performance of industrial buildings. Energy Build. 69, 417–425. https://doi.org/10.1016/j.enbuild.2013.10.024

Mawson, V.J., Hughes, B.R., 2019. The development of modelling tools to improve energy efficiency in manufacturing processes and systems. J. Manuf. Syst. 51, 95–105. https://doi.org/10.1016/j.jmsy.2019.04.008

Meng, Y., Ling, T.C., Mo, K.H., 2018. Recycling of wastes for value-added applications in concrete blocks: An overview. Resour. Conserv. Recycl. 138, 298–312. https://doi.org/10.1016/j.resconrec.2018.07.029

Menghi, R., Papetti, A., Germani, M., Marconi, M., 2019. Energy efficiency of manufacturing systems: A review of energy assessment methods and tools. J. Clean. Prod. 240, 118276. https://doi.org/10.1016/j.jclepro.2019.118276

Mercante, I., Alejandrino, C., Ojeda, J.P., Chini, J., Maroto, C., Fajardo, N., 2018. Mortar and concrete composites with recycled plastic: A review. Sci. Technol. Mater. 30, 69–79. https://doi.org/10.1016/j.stmat.2018.11.003

Merli, R., Preziosi, M., Acampora, A., Lucchetti, M.C., Petrucci, E., 2020. Recycled fibers in reinforced concrete: A systematic literature review. J. Clean. Prod. 248. https://doi.org/10.1016/j.jclepro.2019.119207

Michael, D., 2011. Life Cycle Assessment : Australian Duck Meat Value Chain. 7th Aust. Conf. Life Cycle Assess.

Ming, X., Cao, M., 2020. Development of eco-efficient cementitious composites with high fire resistance and self-healing abilities-a review. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2020.105017

Mohajerani, A., Burnett, L., Smith, J. V., Markovski, S., Rodwell, G., Rahman, M.T., Kurmus, H., Mirzababaei, M., Arulrajah, A., Horpibulsuk, S., Maghool, F., 2020. Recycling waste rubber tyres in construction materials and associated environmental considerations: A review. Resour. Conserv. Recycl. 155, 104679. https://doi.org/10.1016/j.resconrec.2020.104679

Mohson, Z.H., Ismael, Z.A., Shalal, S.S., 2021. Comparison between smart and traditional building materials to achieve sustainability. Period. Eng. Nat. Sci. 9, 808–822. https://doi.org/10.21533/pen.v9i3.2283

Moldavska, A., Welo, T., 2017. The concept of sustainable manufacturing and its definitions: A content-analysis based literature review. J. Clean. Prod. 166, 744–755. https://doi.org/10.1016/j.jclepro.2017.08.006

Morgado, M., Talaia, M., Teixeira, L., 2017. A new simplified model for evaluating thermal environment and thermal sensation: An approach to avoid occupational disorders. Int. J. Ind. Ergon. 60, 3–13. https://doi.org/10.1016/j.ergon.2015.11.001

Mukhopadhyay, S., Khatana, S., 2015. A review on the use of fibers in reinforced cementitious concrete. J. Ind. Text. 45, 239–264. https://doi.org/10.1177/1528083714529806

Muthu, S.S., 2014. Assessing the Environmental Impact of Textiles and the Clothing Supply Chain, Assessing the Environmental Impact of Textiles and the Clothing Supply Chain. https://doi.org/10.1533/9781782421122

Nerbass, F.B., Pecoits-Filho, R., Clark, W.F., Sontrop, J.M., McIntyre, C.W., Moist, L., 2017. Occupational Heat Stress and Kidney Health: From Farms to Factories. Kidney Int. Reports 2, 998–1008. https://doi.org/10.1016/j.ekir.2017.08.012

Neves, A., Godina, R., Azevedo, S.G., Matias, J.C.O., 2020. Carbon Dioxide Recovery through Industrial and Urban Symbiosis. ICITM 2020 - 2020 9th Int. Conf. Ind. Technol. Manag. 171–175. https://doi.org/10.1109/ICITM48982.2020.9080405

Niinimäki, K., Peters, G., Dahlbo, H., Perry, P., Rissanen, T., Gwilt, A., 2020. The environmental price of fast fashion. Nat. Rev. Earth Environ. https://doi.org/10.1038/s43017-020-0039-9

Novotny, R., Sal, J., Ctibor, M., 2019. Environmental use of waste materials as admixtures in concrete. IOP Conf. Ser. Mater. Sci. Eng. 603. https://doi.org/10.1088/1757-899X/603/5/052101

NTC, I.M. of I. and, 2018. Norme Tecniche per le Costruzioni. DM 17/1/2018. Gazz. Uff. della Repubb. Ital. 1–198.

Nunfam, V.F., Adusei-Asante, K., Van Etten, E.J., Oosthuizen, J., Frimpong, K., 2018. Social impacts of occupational heat stress and adaptation strategies of workers: A narrative synthesis of the literature. Sci. Total Environ. 643, 1542–1552. https://doi.org/10.1016/j.scitotenv.2018.06.255

O'Hegarty, R., Kinnane, O., 2020. Review of precast concrete sandwich panels and their innovations. Constr. Build. Mater. 233, 117145. https://doi.org/10.1016/j.conbuildmat.2019.117145

O'Hegarty, R., Reilly, A., West, R., Kinnane, O., 2020. Thermal investigation of thin precast concrete sandwich panels. J. Build. Eng. 27, 100937. https://doi.org/10.1016/j.jobe.2019.100937

Odeleye, O.A., 1966. Design considerations in industrial architecture. New York.

Opher, T., Duhamel, M., Posen, I.D., Panesar, D.K., Brugmann, R., Roy, A., Zizzo, R., Sequeira, L., Anvari, A., MacLean, H.L., 2021. Life cycle GHG assessment of a building restoration: Case study of a heritage industrial building in Toronto, Canada. J. Clean. Prod. 279, 123819. https://doi.org/10.1016/j.jclepro.2020.123819

Owen, A., Killip, G., Morgan, E., 2016. Supply chain dynamics in the UK construction industry and their impact on energy consumption in homes. ECEEE Summer Study Proc. 613–622.

Pacheco-Torgal, F., Ding, Y., Jalali, S., 2012. Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): An overview. Constr. Build. Mater. 30, 714–724. https://doi.org/10.1016/j.conbuildmat.2011.11.047

Pakravan, H.R., Memariyan, F., 2017. Modification of Low-surface Energy Fibers used as Reinforcement in Cementitious Composites: A Review. Polym. - Plast. Technol. Eng. 56, 227–239. https://doi.org/10.1080/03602559.2016.1233266

Pakravan, H.R., Ozbakkaloglu, T., 2019. Synthetic fibers for cementitious composites: A critical and in-depth review of recent advances. Constr. Build. Mater. 207, 491–518. https://doi.org/10.1016/j.conbuildmat.2019.02.078

Papetti, A., Rossi, M., Menghi, R., Germani, M., 2020. Human-centered design for improving the workplace in the footwear sector. Procedia CIRP 91, 295–300. https://doi.org/10.1016/j.procir.2020.02.179

Park, J., Yoon, C., 2010. The effects of outdoor air supply rate on work performance during 8-h work period. Indoor Air 21, 284–290. https://doi.org/10.1111/j.1600-0668.2010.00700.x

Parsons, K.C., 2000. Environmental ergonomics: A review of principles, methods and models. Appl. Ergon. 31, 581–594. https://doi.org/10.1016/S0003-6870(00)00044-2

Passer, A., Lasvaux, S., Allacker, K., De Lathauwer, D., Spirinckx, C., Wittstock, B., Kellenberger, D., Gschösser, F., Wall, J., Wallbaum, H., 2015. Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-015-0926-3

Passoni, C., Marini, A., Belleri, A., Menna, C., 2021. Redefining the concept of sustainable renovation of buildings: State of the art and an LCT-based design framework. Sustain. Cities Soc. 64, 102519. https://doi.org/10.1016/j.scs.2020.102519

Pelisser, F., Montedo, O.R.K., Gleize, P.J.P., Roman, H.R., 2012. Mechanical properties of recycled PET fibers in concrete. Mater. Res. 15, 679–686. https://doi.org/10.1590/S1516-14392012005000088

Pensupa, N., 2020. Recycling of end-of-life clothes, in: Sustainable Technologies for Fashion and Textiles. https://doi.org/10.1016/b978-0-08-102867-4.00012-8

Pless, S., Torcellini, P., 2010. Net-Zero Energy Buildings : A Classification System Based on Renewable Energy Supply Options. Contract 1–14.

Prakash, K.S., Hanumantha Rao, C., 2017. Strength Characteristics of Quarry Dust in Replacement of Sand. IOP Conf. Ser. Mater. Sci. Eng. 225, 012074. https://doi.org/10.1088/1757-899x/225/1/012074

Rajmohan, K.V.S., Ramya, C., Raja Viswanathan, M., Varjani, S., 2019. Plastic pollutants: effective waste management for pollution control and abatement. Curr. Opin. Environ. Sci. Heal. https://doi.org/10.1016/j.coesh.2019.08.006

Reisinger, J., Knoll, M., Kovacic, I., 2021. Design space exploration for flexibility assessment and decision making support in integrated industrial building design, Optimization and Engineering. Springer US. https://doi.org/10.1007/s11081-021-09614-2

Reisinger, J., Kovacic, I., 2021. A parametric design technique to connect production planning and structural Framework proposal for automated generation of production layout scenarios : A parametric design technique to connect production planning and structural industrial building design.

Richert, M., 2017. An energy management framework tailor-made for SMEs: Case study of a German car company. J. Clean. Prod. 164, 221–229. https://doi.org/10.1016/j.jclepro.2017.06.139

Röck, M., Saade, M.R.M., Balouktsi, M., Rasmussen, F.N., Birgisdottir, H., Frischknecht, R., Habert, G., Lützkendorf, T., Passer, A., 2020. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Appl. Energy 258, 114107. https://doi.org/10.1016/j.apenergy.2019.114107

Rödger, J.M., Beier, J., Schönemann, M., Schulze, C., Thiede, S., Bey, N., Herrmann, C., Hauschild, M.Z., 2021a. Combining Life Cycle Assessment and Manufacturing System Simulation: Evaluating Dynamic Impacts from Renewable Energy Supply on Product-Specific Environmental Footprints. Int. J. Precis. Eng. Manuf. - Green Technol. 8, 1007–1026. https://doi.org/10.1007/s40684-020-00229-z

Rödger, J.M., Beier, J., Schönemann, M., Schulze, C., Thiede, S., Bey, N., Herrmann, C., Hauschild, M.Z., 2021b. Combining Life Cycle Assessment and Manufacturing System Simulation: Evaluating Dynamic Impacts from Renewable Energy Supply on Product-Specific Environmental Footprints. Int. J. Precis. Eng. Manuf. - Green Technol. https://doi.org/10.1007/s40684-020-00229-z

Rodrigues, V., Martins, A.A., Nunes, M.I., Quintas, A., Mata, T.M., Caetano, N.S., 2018. LCA of constructing an industrial building: Focus on embodied carbon and energy. Energy Procedia 153, 420–425. https://doi.org/10.1016/j.egypro.2018.10.018

Rogelj, J., Luderer, G., Pietzcker, R.C., Kriegler, E., Schaeffer, M., Krey, V., Riahi, K., 2015a. Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nat. Clim. Chang. 5, 519–527. https://doi.org/10.1038/nclimate2572

Rogelj, J., Luderer, G., Pietzcker, R.C., Kriegler, E., Schaeffer, M., Krey, V., Riahi, K., 2015b. Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nat. Clim. Chang. 5, 519–527. https://doi.org/10.1038/nclimate2572

Rogers, J.G., Cooper, S.J., Norman, J.B., 2018. Uses of industrial energy benchmarking with reference to the pulp and paper industries. Renew. Sustain. Energy Rev. 95, 23–37. https://doi.org/10.1016/j.rser.2018.06.019

Rostami, R., Zarrebini, M., Mandegari, M., Mostofinejad, D., Abtahi, S.M., 2020. A review on performance of polyester fibers in alkaline and cementitious composites environments. Constr. Build. Mater. 241, 117998. https://doi.org/10.1016/j.conbuildmat.2020.117998

Roychand, R., Gravina, R.J., Zhuge, Y., Ma, X., Youssf, O., Mills, J.E., 2020. A comprehensive review on the mechanical properties of waste tire rubber concrete. Constr. Build. Mater. https://doi.org/10.1016/j.conbuildmat.2019.117651

Ruggerio, C.A., 2021. Sustainability and sustainable development: A review of principles and definitions. Sci. Total Environ. 786, 147481. https://doi.org/10.1016/j.scitotenv.2021.147481

Saberi, S., Kouhizadeh, M., Sarkis, J., Shen, L., 2019. Blockchain technology and its relationships to sustainable supply chain management. Int. J. Prod. Res. 57, 2117–2135. https://doi.org/10.1080/00207543.2018.1533261

Saikia, N., De Brito, J., 2012. Use of plastic waste as aggregate in cement mortar and concrete preparation: A review. Constr. Build. Mater. 34, 385–401. https://doi.org/10.1016/j.conbuildmat.2012.02.066

Salvatori, S., Benedetti, M., Bonfà, F., Introna, V., Ubertini, S., 2018. Inter-sectorial benchmarking of compressed air generation energy performance: Methodology based on real data gathering in large and energy-intensive industrial firms. Appl. Energy 217, 266–280. https://doi.org/10.1016/j.apenergy.2018.02.139

Sánchez, C., 2020. Fungal potential for the degradation of petroleum-based polymers: An overview of macro- and microplastics biodegradation. Biotechnol. Adv. https://doi.org/10.1016/j.biotechadv.2019.107501

Sandanayake, M., Bouras, Y., Haigh, R., Vrcelj, Z., 2020. Current sustainable trends of using waste materials in concrete—a decade review. Sustain. 12, 1–38. https://doi.org/10.3390/su12229622

Savoia, M., Buratti, N., Vincenzi, L., 2017. Damage and collapses in industrial precast buildings after the 2012 Emilia earthquake. Eng. Struct. 137, 162–180. https://doi.org/10.1016/j.engstruct.2017.01.059

Schmidt, M., Crawford, R.H., Warren-Myers, G., 2020. Quantifying Australia's life cycle greenhouse gas emissions for new homes. Energy Build. 224, 110287. https://doi.org/10.1016/j.enbuild.2020.110287

Sehnem, S., Chiappetta Jabbour, C.J., Farias Pereira, S.C., de Sousa Jabbour, A.B.L., 2019. Improving sustainable supply chains performance through operational excellence: circular economy approach. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2019.05.021

Sellitto, M.A., Hermann, F.F., 2019. Influence of Green Practices on Organizational Competitiveness: A Study of the Electrical and Electronics Industry. EMJ - Eng. Manag. J. 31, 98–112. https://doi.org/10.1080/10429247.2018.1522220

Sellitto, M.A., Hermann, F.F., 2016. Prioritization of green practices in GSCM: Case study with companies of the peach industry. Gest. e Prod. 23, 871–886. https://doi.org/10.1590/0104-530X2516-15

Sellitto, M.A., Hermann, F.F., Blezs, A.E., Barbosa-Póvoa, A.P., 2019. Describing and organizing green practices in the context of Green Supply Chain Management: Case studies. Resour. Conserv. Recycl. 145, 1–10. https://doi.org/10.1016/j.resconrec.2019.02.013

Seroka-Stolka, O., Ociepa-Kubicka, A., 2019. Green logistics and circular economy. Transp. Res. Procedia 39, 471–479. https://doi.org/10.1016/j.trpro.2019.06.049

Shah, S.N., Mo, K.H., Yap, S.P., Yang, J., Ling, T.C., 2021. Lightweight foamed concrete as a promising avenue for incorporating waste materials: A review. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2020.105103

Sharma, R., Bansal, P.P., 2016. Use of different forms of waste plastic in concrete - A review. J. Clean. Prod. 112, 473–482. https://doi.org/10.1016/j.jclepro.2015.08.042

Shen, B., 2014. Sustainable fashion supply chain: Lessons from H&M. Sustain.

https://doi.org/10.3390/su6096236

Shi, X., Qian, Y., Dong, C., 2017. Economic and environmental performance of fashion supply Chain: The joint effect of power structure and sustainable investment. Sustain. https://doi.org/10.3390/su9060961

Shin, D.H., Kim, H.J., 2020. Composite effects of shear connectors used for lightweight-foamed-concrete sandwich wall panels. J. Build. Eng. 29, 101108. https://doi.org/10.1016/j.jobe.2019.101108

Shishegar, N., Boubekri, M., 2016. Natural Light and Productivity: Analyzing the Impacts of Daylighting on Students' and Workers' Health and Alertness. Int. J. Adv. Chem. Eng. Biol. Sci. 3. https://doi.org/10.15242/ijacebs.ae0416104

Shivani Meher, Ruchita Nar, Sadichha Jagadale , Gautami Kalal, Viren Chandanshive, 2018. Design of Industrial Warehouse. Int. J. Eng. Res. V7, 302–306. https://doi.org/10.17577/ijertv7is020170

Siddique, R., Khatib, J., Kaur, I., 2008. Use of recycled plastic in concrete: A review. Waste Manag. 28, 1835–1852. https://doi.org/10.1016/j.wasman.2007.09.011

Signorini, C., Volpini, V., 2021. Mechanical performance of fiber reinforced cement composites including fully-recycled plastic fibers. Fibers 9, 1–15. https://doi.org/10.3390/fib9030016

Simson, R., Fadejev, J., Kurnitski, J., Kesti, J., Lautso, P., 2016. Assessment of Retrofit Measures for Industrial Halls: Energy Efficiency and Renovation Budget Estimation, in: Energy Procedia. https://doi.org/10.1016/j.egypro.2016.09.114

Smitt, S., Tolstorebrov, I., Gullo, P., Pardiñas, A., Hafner, A., 2021. Energy use and retrofitting potential of heat pumps in cold climate hotels. J. Clean. Prod. 298. https://doi.org/10.1016/j.jclepro.2021.126799

Son, H., Kim, M., Kim, J.K., 2022. Sustainable process integration of electrification technologies with industrial energy systems. Energy 239, 122060. https://doi.org/10.1016/j.energy.2021.122060

Sousa Lira, J.M., Salgado, E.G., Beijo, L.A., 2019. Which factors does the diffusion of ISO 50001 in different regions of the world is influenced? J. Clean. Prod. 226, 759–767. https://doi.org/10.1016/j.jclepro.2019.04.127

Southernwood, J., Papagiannis, G.K., Güemes, E.L., Sileni, L., 2021. Energy Efficiency Solutions for Small and Medium-Sized Enterprises. Proceedings 65, 19. https://doi.org/10.3390/proceedings2020065019

Soydan, C., Yüksel, E., İrtem, E., 2020. Seismic performance improvement of single-storey precast reinforced concrete industrial buildings in use. Soil Dyn. Earthq. Eng. 135, 106167. https://doi.org/10.1016/j.soildyn.2020.106167

Spierling, S., Knüpffer, E., Behnsen, H., Mudersbach, M., Krieg, H., Springer, S., Albrecht, S., Herrmann, C., Endres, H.J., 2018. Bio-based plastics - A review of environmental, social and economic impact assessments. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2018.03.014

Štefko, R., Steffek, V., 2018. Key issues in Slow Fashion: Current challenges and future perspectives. Sustain. https://doi.org/10.3390/su10072270

Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V.B. and P.M.M. (eds. ., 2013. IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Sudhakara Reddy, B., 2013. Barriers and drivers to energy efficiency - A new taxonomical approach. Energy Convers. Manag. 74, 403–416. https://doi.org/10.1016/j.enconman.2013.06.040

Tavakoli, D., Hashempour, M., Heidari, A., 2018. Use of waste materials in concrete: A review. Pertanika J. Sci. Technol. 26, 499–522.

Thakare, A.A., Singh, A., Gupta, V., Siddique, S., Chaudhary, S., 2020. Sustainable development of self-compacting cementitious mixes using waste originated fibers: A review. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2020.105250

Thomas, B.S., Gupta, R.C., 2016. A comprehensive review on the applications of waste tire rubber in cement concrete. Renew. Sustain. Energy Rev. 54, 1323–1333. https://doi.org/10.1016/j.rser.2015.10.092

Tian, G., Fan, Y., Wang, H., Zheng, H., Gao, M., Liu, J., Liu, C., 2021. Studies on the thermal optical properties and solar heat gain of thin membrane structure industrial building. Sol. Energy 213, 81–90. https://doi.org/10.1016/j.solener.2020.10.083

Tiwari, A., Singh, S., Nagar, R., 2016. Feasibility assessment for partial replacement of fine aggregate to attain cleaner production perspective in concrete: A review. J. Clean. Prod. 135, 490–507. https://doi.org/10.1016/j.jclepro.2016.06.130

Trianni, A., Cagno, E., De Donatis, A., 2014a. A framework to characterize energy efficiency measures. Appl. Energy 118, 207–220. https://doi.org/10.1016/j.apenergy.2013.12.042

Trianni, A., Cagno, E., Farnè, S., 2014b. An empirical investigation of barriers, drivers and practices for energy efficiency in primary metals manufacturing SMEs. Energy Procedia 61, 1252–1255. https://doi.org/10.1016/j.egypro.2014.11.1071

Turk, J., Cotič, Z., Mladenovič, A., Šajna, A., 2015. Environmental evaluation of green concretes versus conventional concrete by means of LCA. Waste Manag. 45, 194–205. https://doi.org/10.1016/j.wasman.2015.06.035

U.S. Environmental Protection Agency, 2008. EPA’s Green Building Strategy EPA-100-F-08-073.

United Nations, 2018. The Sustainable Development Agenda - United Nations Sustainable Development. About.

USGBC, 2022. Advancing Resilience at USGBC.

Valančius, K., Motuziene, V., Paulauskaite, S., 2015. Redeveloping industrial buildings for residential use: Energy and thermal comfort aspects. Energy Sustain. Dev. 29, 38–46. https://doi.org/10.1016/j.esd.2015.09.004

van der Velden, N.M., Kuusk, K., Köhler, A.R., 2015. Life cycle assessment and eco-design of smart textiles: The importance of material selection demonstrated through e-textile product redesign. Mater. Des. 84, 313–324. https://doi.org/10.1016/j.matdes.2015.06.129

Venkatachalam, V., Spierling, S., Horn, R., Endres, H.J., 2018. LCA and Eco-design:

Consequential and Attributional Approaches for Bio-based Plastics. Procedia CIRP 69, 579–584. https://doi.org/10.1016/j.procir.2017.11.086

Verma, R., Vinoda, K.S., Papireddy, M., Gowda, A.N.S., 2016. Toxic Pollutants from Plastic Waste- A Review. Procedia Environ. Sci. https://doi.org/10.1016/j.proenv.2016.07.069

Vishwakarma, V., Ramachandran, D., 2018. Green Concrete mix using solid waste and nanoparticles as alternatives – A review. Constr. Build. Mater. 162, 96–103. https://doi.org/10.1016/j.conbuildmat.2017.11.174

Walsh, C., Thornley, P., 2012. Barriers to improving energy efficiency within the process industries with a focus on low grade heat utilisation. J. Clean. Prod. 23, 138–146. https://doi.org/10.1016/j.jclepro.2011.10.038

Wang, Q., Hu, Y.J., Hao, J., Lv, N., Li, T.Y., Tang, B.J., 2019. Exploring the influences of green industrial building on the energy consumption of industrial enterprises: A case study of Chinese cigarette manufactures. J. Clean. Prod. 231, 370–385. https://doi.org/10.1016/j.jclepro.2019.05.136

Wang, Y., Gao, J., Xing, X., Liu, Y., Meng, X., 2016. Measurement and evaluation of indoor thermal environment in a naturally ventilated industrial building with high temperature heat sources. Build. Environ. 96, 35–45. https://doi.org/10.1016/j.buildenv.2015.11.014

Wang, Y., Wu, H.C., Li, V.C., 2000. Concrete Reinforcement with Recycled Fibers. J. Mater. Civ. Eng. https://doi.org/10.1061/(asce)0899-1561(2000)12:4(314)

Wani, I.A., ul Rehman Kumar, R., 2021. Experimental investigation on using sheep wool as fiber reinforcement in concrete giving increment in overall strength. Mater. Today Proc. 45, 4405–4409. https://doi.org/10.1016/j.matpr.2020.11.938

Wei, W., Skye, H.M., 2021. Residential net-zero energy buildings: Review and perspective. Renew. Sustain. Energy Rev. 142, 110859. https://doi.org/10.1016/j.rser.2021.110859

Weiss, M., Haufe, J., Carus, M., Brandão, M., Bringezu, S., Hermann, B., Patel, M.K., 2012. A Review of the Environmental Impacts of Biobased Materials. J. Ind. Ecol. https://doi.org/10.1111/j.1530-9290.2012.00468.x

Wen, B., Musa, S.N., Onn, C.C., Ramesh, S., Liang, L., Wang, W., Ma, K., 2020. The role and contribution of green buildings on sustainable development goals. Build. Environ. 185, 107091. https://doi.org/10.1016/j.buildenv.2020.107091

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. Ecoinvent Version 3. Int. J. Life Cycle Assess.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. https://doi.org/10.1007/s11367-016-1087-8

Weyer, J., Baragaño, S., 2014. Industrial Building Planning and Design. Design Media Publishing Limited.

Winnacker, M., Rieger, B., 2016. Biobased Polyamides: Recent Advances in Basic and Applied Research. Macromol. Rapid Commun. https://doi.org/10.1002/marc.201600181

Woods, T., 2007. Improving the building envelope to meet the challenges of new research and regulation. Therm. Perform. Exter. Envel. Whole Build.

Worrell, E., 2010. Managing Your Energy An ENERGY STAR ® Guide for Identifying Energy Savings in Manufacturing Plants. Environ. Prot.

Yang, S., Song, Y., Tong, S., 2017. Sustainable retailing in the fashion industry: A systematic literature review. Sustain. https://doi.org/10.3390/su9071266

Yang, Y., Han, H., Lee, P.K.C., 2017. An exploratory study of the mechanism of sustainable value creation in the luxury fashion industry. Sustain. https://doi.org/10.3390/su9040483

Yesilyurt, A., Zulfikar, A.C., Tuzun, C., 2021. Seismic vulnerability assessment of precast RC industrial buildings in Turkey. Soil Dyn. Earthq. Eng. 141, 106539. https://doi.org/10.1016/j.soildyn.2020.106539

Yildirim, N., Erdonmez, F., Ozen, E., Avci, E., Yeniocak, M., Acar, M., Dalkılıç, B., Ergün, M., 2020. Fire-retardant bioproducts for green buildings, in: Bio-Based Materials and Biotechnologies for Eco-Efficient Construction. pp. 67–79. https://doi.org/10.1016/B978-0-12-819481-2.00004-0

Yin, S., Tuladhar, R., Shi, F., Combe, M., Collister, T., Sivakugan, N., 2015. Use of macro plastic fibres in concrete: A review. Constr. Build. Mater. 93, 180–188. https://doi.org/10.1016/j.conbuildmat.2015.05.105

Yina, S., Tuladhar, R., Sheehan, M., Combe, M., Collister, T., 2016. A life cycle assessment of recycled polypropylene fibre in concrete footpaths. J. Clean. Prod. 112, 2231–2242. https://doi.org/10.1016/j.jclepro.2015.09.073

Yokessa, M., Marette, S., 2019. A review of eco-labels and their economic impact. Int. Rev. Environ. Resour. Econ. https://doi.org/10.1561/101.00000107

Yuan, Q., Yang, D., Yang, F., Luken, R., Saieed, A., Wang, K., 2020. Green industry development in China: An index based assessment from perspectives of both current performance and historical effort. J. Clean. Prod. 250, 119457. https://doi.org/10.1016/j.jclepro.2019.119457

Zander, K.K., Moss, S.A., Garnett, S.T., 2017. Drivers of self-reported heat stress in the Australian labour force. Environ. Res. 152, 272–279. https://doi.org/10.1016/j.envres.2016.10.029

Zhang, J., Ouyang, Y., Ballesteros-Pérez, P., Li, H., Philbin, S.P., Li, Z., Skitmore, M., 2021. Understanding the impact of environmental regulations on green technology innovation efficiency in the construction industry. Sustain. Cities Soc. 65. https://doi.org/10.1016/j.scs.2020.102647

Research outputs

The following list collects all the research outputs produced throughout the doctoral period by the candidate, both those strictly relating to relevant topics to thesis work, and those referred to the further research projects which the candidate has participated during the doctoral program, divided by peer-reviewed publications and scientific contributions to national and international conferences. In **Table 14** is presented an overview of the peer-reviewed research outputs, with a detail of the research topics addressed by the candidate and the inclusion of the last submitted contributions.

Peer-reviewed publications

1. Marinelli, S., Lolli, F., Gamberini, R., Rimini, B., 2019. Life Cycle Thinking (LCT) applied to residential heat pump systems: A critical review. Energy Build. https://doi.org/10.1016/j.enbuild.2018.12.035
2. Marinelli, S., Lolli, F., Butturi, M.A., Rimini, B., Gamberini, R., 2020. Environmental performance analysis of a dual-source heat pump system. Energy Build. 223, 110180. https://doi.org/10.1016/j.enbuild.2020.110180
3. Marinelli, S., Butturi, M.A., Lolli, F., Rimini, B., Gamberini, R., 2020. Data on the environmental performance analysis of a dual-source heat pump system. Data Br. 31, 105919. https://doi.org/10.1016/j.dib.2020.105919
4. Marinelli, S., Butturi, M.A., Rimini, B., Gamberini, R., Marinello, S., 2020. Evaluating the environmental benefit of energy symbiosis networks in eco-industrial parks. IFAC-PapersOnLine 53, 13082–13087. https://doi.org/10.1016/j.ifacol.2020.12.2260
5. Marinelli, S., Butturi, M.A., Balugani, E., Lolli, F., Rimini, B., 2020. Environmental benefits of the industrial energy symbiosis approach integrating renewable energy sources. XXV Summer School “Francesco Turco” – Industrial Systems Engineering, Conference Proceedings
6. Sellitto, M.A., Murakami, F.K., Butturi, M.A., Marinelli, S., Kadel, J.N., Rimini, B., 2020. Barriers, drivers, and relationships in industrial symbiotic initiatives of two steelmaking plants Sustain. Prod. Consum. 26, 443–454. https://doi.org/10.1016/j.spc.2020.09.016
7. Butturi, M.A., Marinelli, S., Gamberini, R., Rimini, B., 2020. Ecotoxicity of Plastics from Informal Waste Electric and Electronic Treatment and Recycling. Toxics 8, 99. https://doi.org/10.3390/toxics8040099

8. Barbi, S., Barbieri, F., Marinelli, S., Rimini, B., Merchiori, S., Larwa, B., Bottarelli, M., Montorsi, M., 2021. Phase change material-sand mixtures for distributed latent heat thermal energy storage: Interaction and performance analysis. Renew. Energy 169, 1066–1076. https://doi.org/10.1016/j.renene.2021.01.088
9. Lolli, F., Coruzzolo, A.M., Alessandro, G., Balugani, E., Butturi, M.A., Marinello, S., Marinelli, S., 2021. The Dynamic, Individual and Integrated Risk Assessment: A Multi-criteria Approach Using Big Data 207–215. https://doi.org/10.1007/978-3-030-80288-2_25
10. Marinelli, S., Butturi, M.A., Rimini, B., Gamberini, R., Sellitto, M.A., 2021. Estimating the Circularity Performance of an Emerging Industrial Symbiosis Network: The Case of Recycled Plastic Fibers in Reinforced Concrete. Sustainability 13, 10257. https://doi.org/10.3390/su131810257
11. Herrmann, F.F., Barbosa-Povoa, A.P., Butturi, M.A., Marinelli, S., Sellitto, M.A., 2021. Green Supply Chain Management: Conceptual Framework and Models for Analysis. Sustainability 13, 8127. https://doi.org/10.3390/su13158127
12. Butturi, M.A.; Barbi, S.; Marinelli, S.; Montorsi, M.; Gamberini, R., 2021. Circular design options for wearables integrated sportswear to be employed in adverse outdoor conditions. XXVI Summer School “Francesco Turco” – Industrial Systems Engineering, Conference Proceedings
13. Marinelli, S., Gamberini, R., Rimini, B., Nesi, F., 2021. Implementing the Nearly Zero-Energy Buildings Notion in Industrial Facilities. WIT Trans. Ecol. Environ. 254, 151–161. https://doi.org/10.2495/esus210141
14. Barbi, S.; Barbieri, F.; Marinelli, S.; Rimini, B.; Merchiori, S.; Bottarelli, M.; Montorsi, M. Phase Change Material Evolution in Thermal Energy Storage Systems for the Building Sector, with a Focus on Ground-Coupled Heat Pumps. Polymers 2022, 14, 620. https:// doi.org/10.3390/polym14030620
15. Signorini, C., Marinelli, S., Volpini, V., Nobili, A., Radi, E., Rimini, B., 2022. Performance of concrete reinforced with synthetic fibres obtained from recycling end-of-life sport pitches. J. Build. Eng. 53, 104522. https://doi.org/10.1016/j.jobe.2022.104522

Scientific contributions to national and international conferences

1. Marinelli, S., Butturi, M.A., Rimini, B., Gamberini, R., Marinello, S. Evaluating the environmental benefit of energy symbiosis networks in eco-industrial parks, 21st International Federation Automatic Control (IFAC) World Congress, July 2020, online event
2. Marinelli, S., Butturi, M.A., Balugani, E., Lolli, F., Rimini, B. Environmental benefits of the industrial energy symbiosis approach integrating renewable energy

sources, XXV Summer School “Francesco Turco” – Industrial Systems Engineering, September 2020, online event

3. Marinelli, S., Butturi, M.A., Rimini, B., Gamberini, R. Circularity performances of the production of a cement mortar reinforced with recycled synthetic fibers, Engineered Materials for Sustainable Structures (EM4SS’21), April 2021, online event
4. Lolli, F., Coruzzolo, A.M., Alessandro, G., Balugani, E., Butturi, M.A., Marinello, S., Marinelli, S. The dynamic integrated and individual risk assessment: a novel big data approach, (International Conference on Applied Human Factors and Ergonomics) AHFE Conference, July 2021, online event
5. Butturi, M.A., Barbi, S., Marinelli, S., Montorsi, M., Gamberini, R. Circular design options for wearables integrated sportswear to be employed in adverse outdoor conditions, XXVI Summer School “Francesco Turco” – Industrial Systems Engineering, September 2021, online event
6. Marinelli, S., Gamberini, R., Rimini, B., Nesi, F. Implementing the nearly zero-energy buildings (nZEBs) notion in industrial facilities, Energy and Sustainability 2021, October 2021, online event
7. Marinelli, S., Butturi, M.A., Rimini, B., Gamberini, R. Estimating the Circularity Performance of an Emerging Industrial Symbiosis Network: The Case of Recycled Plastic Fibers in Reinforced Concrete, Poster in Engineered Materials for Sustainable Structures (EM4SS’21) dissemination event, September 2021, Reggio Emilia
8. Marinelli, S. Implementing the nearly zero-energy buildings notion in industrial facilities, Invited Panellist with HER presentation at the Wessex Institute of technology (WIT) Winter Webinar: Energy and Sustainability in the Built Environment, February 2022, online event

Table 14. Overview of the peer-reviewed research outputs, with the inclusion of the last submitted contributions.

#	Authors	Title	Keywords / Research topics	Year	Type
1	Marinelli, S.; Lolli, F.; Gamberini, R.; Rimini, B.	Life Cycle Thinking (LCT) applied to residential heat pump systems: A critical review	heat pump; life cycle; renewable energy; review; sustainability	2019	Journal Article
2	Marinelli, S.; Lolli, F.; Butturi, M.A.; Rimini, B.; Gamberini, R.	Environmental performance analysis of a dual-source heat pump system	dual-source heat pump; life cycle assessment; environmental impact; energy; building	2020	Journal Article
3	Marinelli, S.; Lolli, F.; Butturi, M.A.; Rimini, B.; Gamberini, R.	Data on the environmental performance analysis of a dual-source heat pump system	dual-source heat pump; life cycle assessment; environmental impact; energy consumption; renewable energy	2020	Journal Article
4	Marinelli, S.; Butturi, M.A.; Rimini, B.; Gamberini, R.; Marinello, S.	Evaluating the environmental benefit of energy symbiosis networks in eco-industrial parks	decision making; energy dependence; energy management system; environment; industrial production systems; integration; models; performance analysis; renewable energy systems	2020	Journal Article
5	Marinelli, S.; Butturi, M.A.; Balugani, E.; Lolli, F.; Rimini, B.	Environmental benefits of the industrial energy symbiosis approach integrating renewable energy sources	energy intensive industry; industrial symbiosis; life-cycle assessment; multi-objective optimization; renewable energy	2020	Conference Proceedings
6	Sellitto, M.A.; Murakami, F.K.; Butturi, M.A.; Marinelli, S.; Kadel, N. Jr.; Rimini, B.	Barriers, drivers, and relationships in industrial symbiosis of a network of Brazilian manufacturing companies	industrial symbiosis; reverse logistics; clusters; solid waste; energy recovery; slag; mill scale	2020	Journal Article
7	Butturi, M.A.; Marinelli, S.;	Ecotoxicity of Plastics from Informal Waste	e-plastics; toxicity; flame retardants; informal	2020	Journal Article

	Gamberini, R.; Rimini, B.	Electric and Electronic Treatment and Recycling	WEEE treatment; LCA; USEtox		
8	Barbi, S.; Barbieri, F.; Marinelli, S.; Rimini, B.; Merchiori, S.; Larwa, B.; Bottarelli, M.; Montorsi, M.	Phase change material-sand mixtures for distributed latent heat thermal energy storage: Interaction and performance analysis	energy storage; backfilling sand; flat-panel ground heat exchanger; paraffin; n-octadecane; building	2021	Journal Article
9	Lolli, F.; Coruzzolo, A.M.; Alessandro, G.; Balugani, E.; Butturi, M.A.; Marinello, S.; Marinelli, S.	The Dynamic, Individual and Integrated Risk Assessment: A Multi-criteria Approach Using Big Data	occupational health and safety; risk assessment; wireless sensor network; multi-criteria decision making; big data.	2021	Conference Proceedings
10	Marinelli, S.; Butturi, M.A.; Rimini, B.; Gamberini, R.; Sellitto, M.A.	Estimating the Circularity Performance of an Emerging Industrial Symbiosis Network: The Case of Recycled Plastic Fibers in Reinforced Concrete	sustainable construction material; fiber-reinforced concrete; recycled aggregate; circular economy; industrial symbiosis	2021	Journal Article
11	Herrmann, F.F.; Barbosa-Povoa, A.P.; Butturi, M.A.; Marinelli, S.; Sellitto, M.A.	Green Supply Chain Management: Conceptual Framework and Models for Analysis	green supply chain management; green practices; green strategy; green innovation; green operations	2021	Journal Article
12	Butturi, M.A.; Barbi, S.; Marinelli, S.; Montorsi, M.; Gamberini, R.	Circular design options for wearables integrated sportswear to be employed in adverse outdoor conditions	wearable technologies; circular design; review; design-for-disassembly; fashion industry; safety	2021	Conference Proceedings
13	Marinelli, S.; Gamberini, R.; Rimini, B.; Nesi, F.	Implementing the nearly zero-energy buildings notion in industrial facilities	sustainable buildings; nearly zero-energy; industrial buildings; precast constructions; indoor environmental quality	2021	Conference Proceedings

14	Barbi, S.; Barbieri, F.; Marinelli, S.; Rimini, B.; Merchiori, S.; Bottarelli, M.; Montorsi, M.	Phase change materials evolution in thermal energy storage systems for the building sector, with a focus on ground coupled heat pumps	phase change materials; latent thermal energy storage; sustainable buildings; ground-coupled heat pumps; energy reduction; materials design, eco-friendly materials; sustainable materials; green economy	2022	Journal Article
15	Signorini, C.; Marinelli, S.; Volpini, V.; Nobili, A.; Radi, E.; Rimini, B.	Performance of concrete reinforced with synthetic fibres obtained from recycling end-of-life sport pitches	Fiber Reinforced Concrete; recycled polyolefins; life cycle assessment; flexural behavior	2022	Journal Article
16	Marinelli, S.; Butturi, M. A.; Rimini, B.; Gamberini, R.	Circularity Performances of the Production of a Cement Mortar Reinforced with Recycled Synthetic Fibers	fiber-reinforced concrete; sustainable construction material; supply chain; industrial symbiosis; circular economy	2022	Journal Article *Accepted for publication in "Engineered Materials for Sustainable Structures"*
17	Lolli, F.; Balugani, E.; Butturi, M. A.; Coruzzolo, A. M.; Ishizaka, A.; Marinelli, S.; Romano, V.	A decision support system for the selection of insulating material in energy retrofit of industrial buildings: a new robust ordinal regression approach	energy retrofit; PROMETHEE; Bézier curves; indirect elicitation	2022	Journal Article *Accepted for publication in "Transactions on Engineering Management"*
18	Marinelli, S.; Butturi, M. A.; Lolli, F.	A framework to assess the sustainability of additive manufacturing for spare parts	additive manufacturing; spare parts, sustainability; life cycle perspective; methodological framework	2022	Conference Paper *Submitted to the "10th IFAC Conference on Manufacturing Modelling, Management and Control"*

Participation to regional projects

- “HEGOS, nuove pompe di calore per l’Harvesting EnerGeticO in Smart buildings” – Progetto Regione Emilia Romagna POR-FESR 2014-2020
- “CLIWAX, Materiali a cambio di fase per l’harvesting energetico in climatizzazione” - Progetto Regione Emilia Romagna POR-FESR 2014/202
- “Progetto IMPReSA, Impiego di Materiali Plastici da Riciclo per malte e calcestruzzi Strutturali Alleggeriti” - Progetto Regione Emilia Romagna POR-FESR 2014/2020

Participation to working groups

- GBCItalia (Green Building Council Italia), GdL LCA - Life Cycle Assessment in edilizia
- SUN (Symbiosis Users Network), Network Italiano di Simbiosi Industriale, GdL 4 - Certificazione e standard per la simbiosi industriale
- WGBC (World Green Building Council), GdL #BuildingLife - Strumenti per la decarbonizzazione