SCHOOL OF ECONOMIC SCIENCES

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LIFE CYCLE ASSESSMENT FOR A MALL COMPLEX IN GREECE

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I, Nikolaos Chaidemenos, certify that the work conducted and presented in this submitted thesis is solely my own. Any information and material contained that have been sourced from other references have been duly cited in this thesis. Furthermore, I am aware that should it be discovered that the claims made herein are not accurate, the title granted to me can be revoked at any time.

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IPCC	Intergovernmental Panel for Climate Change
GDP	Gross Domestic Product
CFCs	Chlorofluorocarbons
GHG	Greenhouse Gas
COP	Conference of the Parties
UNFCCC	United Nations Framework Convention on Climate Change
NDCs	Nationally Determined Contributions
EGD	European Green Deal
EU	European Union
SCMs	supplementary cementitious materials
GGBFS	ground granulated blast furnace slag
AHP	Analytic Hierarchy Process
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ISO	International Organization for Standardization
EPDs	Environmental Product Declarations
PCRs	Product Category Rules
GFA	Gross Floor Area
FAR	Floor Area Ratio
ILCD	International Life Cycle Data Handbook
BoQ	Bill of Quantities
BIM	Building Information Model
RICS NRM	Royal Institution of Chartered Surveyors New Rules of Measurement
GCCA	Global Cement and Concrete Association
AP	Acidification Potential
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
EP	Eutrophication potential
ADP	Depletion of Abiotic Resources
POCP	Photo-oxidant creation potential
FF&E	Furniture, fixtures, and equipment
NOx	nitrogen oxides
CO	carbon monoxide
VOC	volatile organic compounds
EEW	Early and Enabling Works
CO_2e	Carbon dioxide equivalent
SO_2e	Sulfur dioxide equivalent
PO_4e	Phosphate ion equivalent
MJ	Mega Joules
R11e	CFC refrigerant
C_2H_4e	Ethylene equivalent
EE	Embodied Energy
BWC	Blue water consumption

SUMMARY

This dissertation presents the well-defined and standardized methodology of Life Cycle Assessment according to the ISO norms. Following this, the methodology is implemented in a case study.

In the beginning, through an in-depth literature review, the urgent need for the construction sector to adopt sustainable practices is highlighted, given its dual role as both a significant contributor to citizen well-being and a major source of environmental stress.

The core of the thesis is the application of LCA methodology to a specific case study – a Mall Complex in Greece. This analysis covers various construction phases, which include materials procurement and use, energy and water consumption, focusing on understanding the environmental impacts of the project. By examining the environmental implications of the above the research identifies critical areas for environmental improvement and sustainability integration in construction practices.

Throughout the Life Cycle Impact Assessment phase, emphasis was placed on a broad range of environmental impact indicators crucial for assessing the sustainability of construction projects such as Acidification Potential, Global Warming Potential, Ozone Depletion Potential, Eutrophication Potential, Depletion of Abiotic Resources, Photo-oxidant Creation Potential, Embodied Energy and Blue Water Consumption. The thesis proposes actionable strategies for mitigating these impacts, such as adopting low-carbon materials, enhancing recycling and waste management practices, and optimizing construction operations.

In conclusion, the dissertation underscores the important role of LCA in guiding the construction industry towards sustainability and it calls for an integrated strategy that includes policy support, technological progress, and creative construction methodologies. This detailed examination enriches the ongoing discussion on sustainable construction, providing significant observations and suggestions for the industry.

1. INTRODUCTION – LITERATURE REVIEW

1.1. Sustainable development and the construction industry

Today's world stands at the crossroads of major global challenges, ranging from poverty and inequality to climate change and environmental degradation. These urgent challenges emphasize the importance of embracing sustainable development as a foundational principle in sculpting a future characterized by prosperity, equity, and peace for all.[1]

Climate change refers to long-term shifts in temperatures and weather patterns. Such shifts can be natural, due to changes in the sun's activity or large volcanic eruptions. But since the 1800s, human activities have been the main driver of climate change, primarily due to the burning of fossil fuels like coal, oil and gas [2]. Climate change is presently impacting the global environment, leading to an increase in extreme weather events including droughts, heat waves, heavy rainfall, floods, and landslides. Additional effects of this swift climate shift encompass escalating sea levels, intensifying ocean acidification, and diminishing biodiversity. To confine global warming to 1.5 degrees Celsius – a limit proposed by the IPCC as secure – achieving carbon neutrality by the middle of the 21st century is crucial.[3]

Sustainable development was defined in the World Commission on Environment and Development's 1987 Brundtland report ´Our Common Future` as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. It seeks to reconcile economic development with the protection of social and environmental balance. [4]

Construction industry refers to the industrial branch of manufacturing and trade related to building, repairing, renovating, and maintaining structures. It is a determinant of the country's technological and technical advancement, often regulating the growth of the country's infrastructural development [5]. The industry stands as a major domain, wielding substantial influence on both the economy and the environment [6]. Specifically, regarding the EU, the sector plays a vital role in economic contributions, constituting approximately 9% of the European Union's GDP. Furthermore, it serves as a significant source of direct and indirect employment, generating around 18 million direct jobs within the EU, and meets the populace's demands for various structures and facilities [7][8]. Beyond its economic and environment impacts, the construction industry has also a major role in enhancing the quality of life and meeting societal needs [9][10]

1.2. Construction as a major contributor to environmental stress

Despite the highlighted importance of the construction industry and its contribution to society's progress and development, nowadays, it confronts a stark reality:

1.2.1. Overconsumption of raw materials and energy

The construction industry, along with its associated materials industry, emerges as a prominent consumer of both physical and biological natural resources [11] accounting for approximately 50% of the total raw material usage and 36% of the global energy consumption [12][13]. It notably consumes metals with dwindling reserves, such as lead, copper, and zinc, beyond its share of fossil fuels[14].

Specifically, regarding the buildings sector, a typical building’s energy consumption can be broken down into two primary areas [15]: energy used during the creation of buildings and other structures, and energy used once these structures are operational. The energy during construction comes from both the construction process itself and the production of building materials. On the other hand, the energy used post-construction is largely determined by the end-users. However, the initial design of a structure can heavily influence its long-term energy requirements. For instance, a structure specifically designed for air conditioning will likely need to maintain this feature throughout its existence. The energy used during the construction phase, known as "embodied energy”, accounts for approximately 10-20% of a building's total energy consumption over its lifespan [16] and it is wholly determined by the building’s construction process.

This embodied energy topic becomes even more pressing in developing countries undergoing swift urbanization. Transitioning from rural to urban living often means moving from low-energy, sustainable materials like earth, stone, and thatch to energy-intensive, permanent materials like bricks and concrete. As a result, there's a rapidly increasing number of factories producing these materials in developing nations, leading to a sharp rise in energy consumption, particularly of premium fuels, within the building materials sector. This trend is further amplified as production centralizes in larger facilities to leverage scale benefits, subsequently increasing the energy consumption related to transportation.

1.2.2. Atmospheric pollution

Air quality is another casualty of construction activities. The sector's operations leave indelible imprints on our natural habitats and heighten atmospheric contaminant levels, making a marked contribution to recognized environmental stress areas. At the local level, different construction activities contribute to environmental pollution, including but not limited to land clearing, emissions from equipment engines, demolition, burning, and the utilization of hazardous chemicals [17]. On a regional scale, building material production releases nitrogen and sulfur compounds. Globally, the sector exacerbates issues like ozone layer depletion through CFCs usage in structures and the emission of greenhouse gases like carbon dioxide. [18]

Like energy consumption, a typical building’s carbon emissions can be broadly categorized into two primary areas: embodied carbon and operating carbon emissions. Embodied carbon conventionally includes carbon emissions (both energy and materials related) incurred during the construction phase of a structure. Conversely, operating carbon encompasses emissions occurring during the operational lifespan of a building, encompassing carbon emissions associated with maintaining the indoor environment, including processes like heating, cooling, lighting, and appliance operation [19].

Given that the building and construction sector contributes 39% of GHG emissions and agents of acid rain, the persistence of such emissions at the current rate poses a concerning trajectory [12][20]. Notably, 18% of these emissions arise from the transportation and processing of construction materials. [21]

To further elaborate on the subject matter, GHG mainly include six gases with proven global warming effects, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6)

[22]Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) make considerably higher contributions to global warming than the other GHGs and account for about 97% of the total global warming potential [23]. For the sake of comparability and reporting, a composite measure referred to as carbon equivalent is commonly employed to quantify and communicate the overall global warming impact stemming from diverse greenhouse gases emitted during a process. The carbon equivalent is computed by converting the quantity of various GHGs into an equivalent quantity of carbon dioxide that elicits an equivalent global warming impact [24].

What is more alarming is the fact that without substantial enhancements in the energy efficiency of buildings, projections indicate that the ongoing trend of urbanization may result in a twofold increase in GHG emissions associated with the building and construction industry over the next two decades [25].

1.2.3. Impact on the physical environment

Construction activities impinge upon soil and farmlands in myriad ways. Frequently, agricultural territories are sidelined due to quarrying and mining endeavors targeting raw materials essential for construction. They're also repurposed for urban expansion, infrastructural developments like roads and dams, and might suffer degradation owing to pollution or waste from construction and its associated materials production.

Soil degradation primarily stems from five sources: overgrazing, deforestation and urbanization, agricultural practices, firewood overuse, and industrial pollution. A significant portion of this severely degraded land is in Africa and Asia, home to the bulk of the world's impoverished populace, with inadequate nutrition and the highest population growth. [26][27]

Forests and wilderness areas face erosion not only from direct repurposing but also from the unsustainable extraction of resources for construction. Tropical forests, crucial for the global carbon cycle and biodiversity, face alarming decline rates. Additionally, the World Resources Institute highlights the dire strain on global freshwater due to agriculture, forestry, industrial activities, and urbanization. [28]

The construction industry is implicated in these environmental pressures. Construction consumes materials that exacerbate land and water degradation. It plays a crucial role in agricultural land erosion due to urban expansion and the escalated need for raw materials from quarrying and mining. Moreover, construction is the primary consumer of tropical hardwoods, intensifying tropical forest loss.

Additionally, projections indicate a substantial growth in the middle-class population from 2 billion to over 4 billion people by 2030, necessitating the creation of urban capacity exceeding that built over the past 4000 years to sustain progress and contemporary well-being. [29]

On top of the above, the construction and demolition activities shoulder responsibility for nearly a third of the total waste generated in the EU while the global percentage varies between 45% and 65% [30]. A substantial portion of this waste finds its way to landfills, engendering severe environmental challenges throughout the entire life cycle of buildings, particularly during operation and end-of-life stages [31].

1.3. A shift towards sustainable standards

In light of these considerations, it becomes evident that there is an urgent imperative and mounting pressure on the construction industry to transition from its current paradigm to a more sustainable one. This shift necessitates a dedicated focus on adopting the circular economy approach, ensuring a more sustainable trajectory for the construction sector [32]. Recognizing the construction sector's important role in comprehensive initiatives addressing global climate change and cleaner production is imperative [33][34].

In essence in order to attain sustainable development within the construction industry, a holistic and integrated approach is imperative. This approach comprises, firstly, the establishment of a legislative measures at national, European, and global levels. This legislative framework serves the important role of promoting sustainability and environmental protection, thereby exerting pressure on the industry to embrace and adhere to evolving sustainable standards. Secondly, the achievement of requisite sustainability standards necessitates a concurrent focus on technical considerations and the adoption of enhanced construction practices. These considerations span a spectrum of factors including materials, methodologies, and technologies aimed at minimizing environmental impact and resource consumption. Furthermore, fostering a culture of innovation and research within the industry becomes paramount for the continuous evolution and implementation of sustainable practices. The confluence of legislative advocacy and technical advancements forms the foundational bedrock upon which sustainable development in the construction sector is predicated.

1.3.1. The legislative framework

1.3.1.1. Paris Agreement

In the annals of global climate diplomacy, the Paris Agreement, ratified during the 21st COP to the UNFCCC in 2015, stands as a watershed moment. The accord delineates an overarching ambition: to confine global temperature escalation to well below 2 degrees Celsius above pre-industrial levels, with a more stringent aspiration of limiting this increase to 1.5 degrees Celsius to minimize climatic risks and impacts. [35]

The Agreement is a legally binding international treaty. It entered into force on 4 November 2016. Today, 195 Parties (194 States plus the European Union) have joined the Paris Agreement. [36]

The Paris Agreement aims to enhance the global response to the threat of climate change on the basis of three pillars [37]:

- Limiting Global Warming: The Paris Agreement aims to keep the global temperature rise this century well below 2°C above pre-industrial levels, and to pursue efforts to limit the temperature increase even further to 1.5°C. This is consistent with what your excerpt mentions.
- Adaptation and Resilience: The Agreement also seeks to increase the ability of countries to deal with the impacts of climate change through increased resilience and better adaptation capabilities. Your excerpt aligns with this by discussing enhancing adaptability to the adverse effects of climate change, reinforcing resilience, and developing a low greenhouse gas emissions economy in a way that does not threaten food production.

- Financing: The Paris Agreement recognizes the importance of providing funds consistent with a pathway towards low greenhouse gas emissions and climate-resilient development. This is echoed in your excerpt which talks about the flow of funds that are consistent with the development of low greenhouse gas emissions and resilience to climate change.

Crucially, the Paris Agreement introduced the concept of NDCs, obligating both developing and developed nations to articulate and submit their respective climate action strategies. This decentralized approach ensures flexibility while promoting collective responsibility.

A salient feature of this accord is its 'ratchet mechanism.' It necessitates the periodic enhancement of NDCs and mandates quinquennial global stocktakes, ensuring a trajectory of continuous and incremental commitment augmentation. [38]

Ensuring accountability, a robust transparency framework was instituted, mandating consistent emissions reporting and NDC implementation tracking. Moreover, recognizing the differential capacities of nations, the Agreement underscores the imperative of financial, technological, and capacity-building support for developing countries. Affluent nations reaffirmed their commitment to mobilize an annual $100 billion by 2020 for climate actions in less-developed countries, with an escalated goal post-2025. [39]

Furthermore, the Paris Agreement acknowledges and addresses the 'loss and damage' associated with climate adversities, providing a structure for vulnerable nations' recuperation. A vast majority of global nations has ratified the Agreement, underscoring its crucial role in international climate governance.

1.3.1.2. EU Green Deal

While the Paris Agreement sets out the global consensus and framework for climate action, the EGD is the European Union's comprehensive plan to achieve those aims and even go beyond them. The Green Deal is the EU's operationalization of its commitments under the Paris Agreement, highlighting its leadership role in global climate action. Specifically, EGD is the most ambitious action plan of European Union that aims at increasing the EU’s greenhouse gas emission reductions target for 2030 to at least 50% compared with 1990 levels. [1]

The EGD represents one of the most audacious and comprehensive strategies put forth by the European Union (EU) to transition to a sustainable economic model. This transformative roadmap seeks to address climate change, environmental degradation, and economic challenges simultaneously, intending to secure a carbon-neutral continent by 2050. [40]

Central to the EGD's vision is the imperative to drastically reduce greenhouse gas emissions. The initiative has brought about a commitment to amplify the 2030 target for emissions reduction, propelling the EU toward a more ambitious trajectory. These new targets demonstrate the EU's intensified commitment to lead in global climate action.

Beyond the central focus on climate change mitigation, the EGD's multidimensional approach extends to several key sectors. In the energy sector, the EGD promotes a transition from fossil fuels to renewable energy sources, emphasizing energy efficiency. This transition aims not only to reduce the carbon footprint but also to ensure that Europe's energy supply remains secure, diversified, and competitive on the global stage. [41]

- The transport sector, recognized as a significant contributor to the EU's GHG emissions, is targeted for comprehensive modernization. The EGD advocates for boosting the railway transport of passengers and goods, increasing the use of public transport, and accelerating the shift to sustainable and smart mobility solutions, including electric vehicles.
- Agriculture, too, is at the forefront of the EGD's vision. The strategy recognizes the need to preserve Europe's land and marine resources. Consequently, the "Farm to Fork" strategy within the EGD aims at fostering a fair, healthy, and environmentally friendly food system. By addressing challenges from production and processing to distribution and consumption, it seeks to reduce the environmental and climate footprint of the EU's food system.
- Furthermore, the EGD acknowledges the crucial role of biodiversity in ensuring ecosystem health and resilience. Plans to restore degraded ecosystems, reduce pollution, and green the urban environment are central tenets of this commitment. Protecting Europe's natural capital is seen not only as an environmental necessity but also as a strategy to buffer against future pandemics and ensure long-term food security.
- Economic prosperity and the well-being of its citizens are foundational to the EGD's ethos. As such, a cornerstone of the initiative is the pledge to ensure a just transition. Recognizing that the shift to a green economy may pose challenges for regions dependent on carbon-intensive industries, the EGD emphasizes the importance of support mechanisms, including the Just Transition Fund, to aid these regions. [42]

In conclusion, the European Green Deal is not merely a climate strategy; it represents the EU's vision for a future where economic growth is decoupled from resource use. By placing climate action, ecological sustainability, and social equity at the heart of its growth strategy, the EGD aspires to shape a resilient and prosperous Europe for generations to come.

1.3.1.3. Fit for 55% [43][44]

The "Fit for 55%" package represents a monumental stride in Europe's climate agenda, fortifying the European Union's (EU) mission to curb the impacts of global warming. Nested within the broader framework of the European Green Deal, this initiative manifests the EU's dedication to ensure a substantive reduction in greenhouse gas emissions by 2030.

At the heart of the "Fit for 55%" framework is the ambitious yet strategic target: reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. This goal signifies a marked intensification from the initial aim of a 40% reduction, highlighting the EU's accelerated commitment to achieving climate neutrality by 2050.

To ensure the realization of this objective, the "Fit for 55%" initiative encompasses a suite of proposals designed to impact various sectors of the economy. It envisions a holistic transformation, ranging from sectors such as energy, land use, and transport to buildings and industrial activities. These comprehensive measures underscore the initiative's overarching goal: to create a synergistic impact that not only reduces emissions but also propels Europe towards a sustainable and resilient future.

1.3.1.4. Climate Law

The EU Climate Law [45]represents an important step in Europe's commitment to confront and mitigate the implications of climate change. Envisioned as the legal backbone of the European Green Deal, this regulation anchors the EU's ambition to transition to a climate-neutral continent by 2050.

Central to the EU Climate Law is its legally binding nature, ensuring member states collectively achieve climate neutrality by the mid-century mark. This implies that the net GHG (taking into account emissions and removals) within the EU should reach zero by 2050. The law underscores the EU's leadership position in global climate governance, setting a benchmark for other international actors.

To ensure consistent progress toward this overarching goal, the Climate Law delineates an interim target for 2030 [45]: a reduction of at least 55% in net GHG emissions compared to 1990 levels. This revised target exhibits the EU's intensified commitment, marking a significant increase from the previous objective of a 40% reduction.

A noteworthy aspect of the Climate Law is its emphasis on transparency and accountability [46]. It mandates a biennial assessment of European and national measures' effectiveness in light of the collective progress toward the 2050 objective. In instances where measures fall short, the European Commission is empowered to provide recommendations, ensuring member states adopt and implement appropriate corrective measures.

To help the adaptive capacity of various sectors, the Climate Law also calls for the development of a European Climate Adaptation Strategy [46]. Recognizing that the impacts of climate change are already tangible, this strategy seeks to strengthen Europe's resilience to climate-induced threats and amplify its preparedness for future challenges.

Economic sustainability [46] is woven into the fabric of the Climate Law. It envisions a transformation that not only ensures environmental sustainability but also considers socio-economic imperatives. The transition to a green economy, as outlined in the law, emphasizes the significance of innovation, technological advancements, and investment in green solutions. By fostering a symbiotic relationship between economic growth and sustainability, the Climate Law aspires to fortify the EU's global competitiveness.

In essence, the European Union Climate Law is a testament to Europe's unwavering dedication to a sustainable and resilient future. By integrating stringent targets with accountability mechanisms and emphasizing the intertwined nature of economic prosperity and environmental stewardship, the law charts a course for the EU to lead and inspire global climate action.

1.3.2. Environmentally sustainable construction practices

Extensive research has been carried out to explore different tactics for promoting environmentally sustainable construction practices. These approaches can generally be categorized into five groups:

1.3.2.1. Low-Carbon Materials Strategies

A. *Material Selection:*

Nowadays, designers choose materials for construction based solely on technical and economic criteria. However, it is now important for sustainability criteria to be included in the decision-making process. In other words, decisions should be made taking into account the impact of each material on the overall environmental burden caused by the new construction. [47][48] Research extensively investigates the influence of material types on the embodied carbon of buildings, emphasizing the potential for minimizing carbon footprints through low-carbon material selection. Special consideration has been devoted to structural materials like concrete and reinforcement steel which constitute a significant portion of total embodied energy in buildings.[49][50][51][52]

B. *Strategies for Reducing Embodied Carbon:*

Apart from material selection, two common strategies to reduce embodied carbon involve increasing recycled or waste material content and developing new low-carbon materials [53][54]. Efforts include reducing cement and concrete embodied carbon by partially substituting Portland cement with SCMs like fly ash and GGBFS, and amorphous silica (silica fume) [55][56] because cement and concrete contribute to global emissions up, to 7% [57][58]. In the other approach to diminish the embodied carbon of constructions, alternative low-carbon materials have been explored for substituting Portland cement. Within this context, hydraulic cement and geopolymer concrete are widely endorsed as viable alternatives to traditional Portland cement. [59][60]

C. *Utilization of Waste Materials*

The utilization of waste materials in construction presents a significant opportunity to reduce environmental impact and foster sustainability. The integration of waste materials, including mineral, agricultural, and demolition wastes, into construction processes can effectively alleviate the environmental strain associated with traditional practices such as quarrying, mining, and logging. This strategy not only addresses resource depletion concerns but also mitigates issues related to waste disposal.

However, it is essential to highlight that while the use of waste materials in construction holds promise for environmental sustainability, careful attention must be paid to material performance alongside environmental criteria [47][61]. Multi-attribute decision-making methods, such as TOPSIS and AHP, have been explored for the sustainable selection of building materials, ensuring a comprehensive evaluation of technical, environmental, and performance criteria [47][62][63][64][65]. This approach helps strike a balance between environmental benefits and structural integrity.

D. *Material Minimization Strategies*

Material Minimization Strategies play an important role in reducing the overall embodied carbon of structures by intricately linking the total embodied carbon to the quantity of materials used in construction [66]. The optimal selection and use of materials, influenced by factors such as material types, chosen structural systems, and the structure's height, are vital considerations in achieving substantial reductions in embodied carbon [61].

One fundamental aspect of material minimization involves embracing optimal design practices that avoid unnecessary overdesign, leading to significant reductions in material quantities and, consequently, embodied carbon. [67]

It is crucial to emphasize that while material minimization aims to reduce embodied carbon, careful consideration must be given to ensuring that the structure maintains its capability to meet all technical and performance requirements [67]. This holistic approach to material minimization aligns with the broader objective of sustainable construction practices, where minimizing resource consumption is coupled with maximizing structural efficiency and longevity.

E. Local Sourcing Strategies

Local sourcing of construction materials is an important strategy in mitigating the environmental impact of the construction industry, particularly in reducing transportation-related carbon emissions. The quantity and size of materials, transportation distance, and chosen mode of transport are critical factors influencing the embodied carbon of structures [68][69]. Given the pronounced influence of these factors, a thoughtful consideration of transport requirements during material selection is essential for sustainable construction practices. Nevertheless, it is essential to acknowledge that the final decision on material and supplier selection should weigh other crucial economic, social, and environmental factors [47][70].

1.3.2.2. End-of-Life Strategies: Recycling and Reuse

A. Environmental Considerations in Building Demolition:

The end-of-life phase of a building's lifecycle presents a critical juncture where environmental considerations play an important role [71][72]. The traditional "demolition and landfilling" strategy poses significant challenges to sustainability. Not only does it fail to preserve the embodied carbon invested in material integration, but it also triggers additional carbon emissions during building demolition and debris transportation to distant landfills [71]. This approach exacerbates the environmental impact by contributing to pollution and escalating waste management concerns.

B. Recycling as a Sustainable Approach:

In contrast, recycling emerges as a longstanding sustainable strategy for managing construction and demolition waste [73][74]. Concrete recycling, in particular, has been identified as an effective approach to mitigate carbon emissions and reduce costs related to debris transportation and disposal. This method lessens the demand for landfill space while providing an eco-friendly source of alternative aggregate [66][75].

However, the recycling process itself introduces complexities the most important of which is that the degree of emissions is contingent on the material type being recycled and the sophistication of the recycling process [71][76], introducing a discernible trade-off between achieved quality and the carbon footprint of recycled products.

C. Reuse as a Viable Alternative:

Parallel to recycling, reuse of materials and components stands out as a viable alternative end-of-life strategy. It aims to conserve materials, costs, energy, and embodied carbon invested in the structure. [77][78]. Properly designed elements within a building, at the end of its service life, could retain sufficient quality for reuse in similar or different applications [72][78].

Component reuse not only safeguards the initially invested energy, carbon, and capital in creating the components but also preserves the materials used. Despite the above, reuse, while contributing significantly to sustainability goals, also requires careful evaluation, technological innovations, and comprehensive frameworks to overcome inherent challenges and promote its broader adoption in the construction sector's pursuit of a more sustainable future.

1.3.2.3. Construction Optimization Strategies

The carbon emissions linked to construction operations, including the operation of construction equipment and the use of temporary construction materials, represent a contributor to the overall embodied carbon of a building [79][80]. Various strategies can be employed to minimize carbon emissions during the construction phase, ranging from optimizing construction operations to reduce equipment idle time, selecting optimal equipment, and optimizing the operation of equipment, to minimizing on-site transport, which includes both horizontal and vertical movements [81][82][83]. Notably, earthmoving, concreting, and lifting operations have been identified as primary contributors to carbon emissions during construction [24][80][84], accounting for a significant portion of overall construction phase emissions [84][85]. Attention has been primarily directed towards quantifying and mitigating the environmental impacts of earthmoving operations by optimizing operational parameters like fleet size. [86][87]

Consequently, the industry's profound commitment to holistic and environmentally conscious practices signifies a major change, marking a definitive transition towards a more sustainable trajectory. The industry's gradual adaptation to these changes highlights the pressing need for new technologies, investment strategies, and procedural transformations. Noteworthy in this context are methodological frameworks, such as the Life Cycle Assessment (LCA), which emerge as indispensable guiding tools for navigating this trajectory towards sustainability. Life Cycle Assessment is the established methodology for the quantification of environmental impacts, and therefore has been increasingly applied to assess the environmental performance of buildings. The incorporation and active embrace of such methodologies within industry practices are instrumental in fostering a comprehensive and enduring commitment to environmental stewardship and holistic sustainability.[88]

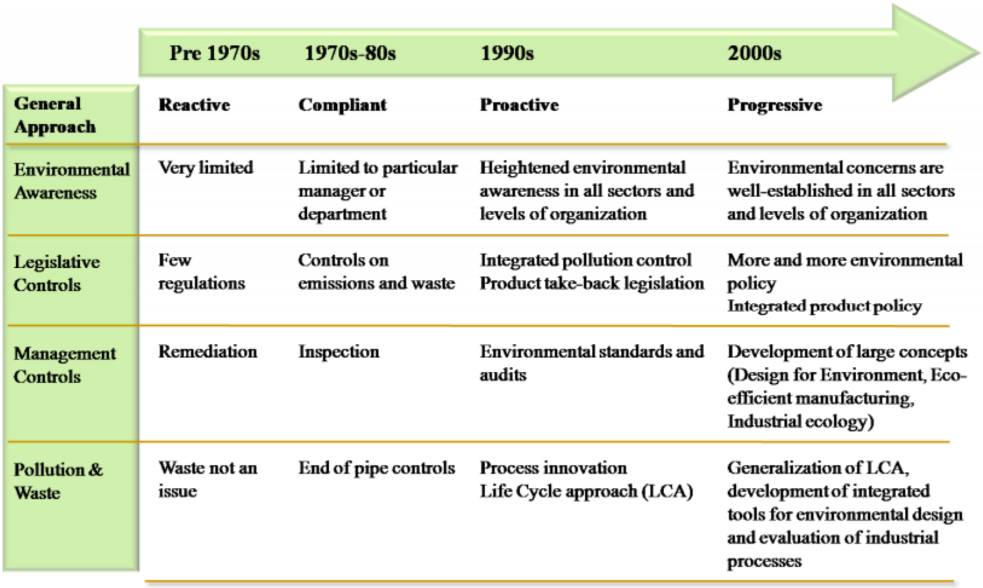
2. LIFE CYCLE ASSESMENT

2.1. Overview of Life Cycle Assessment

LCA stands as a prominent tool among various methods used to assess environmental performance. It is widely acknowledged for its comprehensive approach in contrasting the environmental footprints of different goods, technologies, or services throughout their entire life span or a specific life cycle phase. This approach allows for a detailed examination of the environmental implications of a product throughout its existence, enhancing resource efficiency and reducing potential environmental liabilities. [89]

LCA illuminates the life cycle phases that substantially influence the environment and identifies the major types of impacts. Utilizing the findings from an LCA can support the effectiveness of environmental preservation efforts by pinpointing and prioritizing the most impactful mitigation measures [90]. To further elaborate, the fundamental role of LCA lies in identifying areas within a value chain where efficiency improvements can be made. It provides a detailed understanding of the complex systems involved in producing goods and delivering services. LCA reveals critical "hot spots" in these systems, directing attention to areas with significant potential for environmental improvement [91]. Additionally, it serves as a safeguard against unintentionally worsening environmental challenges during system modifications, known as "burden shifting." A crucial aspect is stakeholder education, where LCA communicates the environmental repercussions of specific decisions, ensuring a comprehensive understanding of the implications of adopting particular technologies or methodologies [92]. LCA enables systematic comparisons between systems offering similar services or products, clarifying the environmental significance of differences. Importantly, LCA supports environmental claims by generating precise impact data, such as carbon footprints, enhancing transparency and credibility in environmental assertions. Overall, it is a versatile and essential analytical framework that substantially contributes to strategic decision-making, advocates for sustainability, and promotes environmental awareness across diverse operational contexts. [93]

This method is not just a modern framework for evaluating environmental impacts but also a reflection of the heightened environmental consciousness among industries, the public, and governmental bodies. Tracing its origin to global modeling and energy assessments, LCA has evolved in response to the escalating environmental concerns and demands for sustainable practices. The evolution of industrial response to these environmental challenges, depicted in Figure 1, underscores the progression from an initial reactive phase in the 1970s, transitioning through a compliance phase in the 1970s-80s, and ultimately arriving at a proactive stance in the 1990s. Today, the advancement of LCA is fueled by the industrial imperative for a unified analytical approach to evaluate the lifelong environmental repercussions of a product. [94]



	Pre 1970s	1970s-80s	1990s	2000s
General Approach	**Reactive**	**Compliant**	**Proactive**	**Progressive**
Environmental Awareness	Very limited	Limited to particular manager or department	Heightened environmental awareness in all sectors and levels of organization	Environmental concerns are well-established in all sectors and levels of organization
Legislative Controls	Few regulations	Controls on emissions and waste	Integrated pollution control Product take-back legislation	More and more environmental policy Integrated product policy
Management Controls	Remediation	Inspection	Environmental standards and audits	Development of large concepts (Design for Environment, Eco-efficient manufacturing, Industrial ecology)
Pollution & Waste	Waste not an issue	End of pipe controls	Process innovation Life Cycle approach (LCA)	Generalization of LCA, development of integrated tools for environmental design and evaluation of industrial processes

Figure 1 Industrial response to environmental issues [95]

- *Strengths and Limitations of the LCA method* [96][97]

LCA emerges as a methodologically robust approach rooted in data analysis, constituting a comprehensive foundation for environmental evaluation. A distinctive strength lies in its capacity for exhaustive lifecycle analysis, encompassing the entire lifespan of a product or process. This attribute grants LCA the ability to provide a holistic understanding of environmental impact, further augmented by its adept identification and elucidation of trade-offs inherent within diverse processes. The methodology's resilience is fortified by a diverse array of impact assessment tools, offering a nuanced spectrum of perspectives on environmental effects. LCA demonstrates adaptability through its accommodating framework, capable of integrating various assessment methodologies, thus ensuring flexibility and applicability across diverse contexts. Serving as an informative aid to decision-making, LCA furnishes stakeholders with crucial insights, empowering them to make judicious choices cognizant of environmental implications.

Conversely, limitations of LCA are discerned in its intensive data requirements, posing challenges due to the substantial resources necessitated for accurate analysis. The methodology adopts a static temporal perspective, constraining its adaptability to dynamic and evolving systems. While providing valuable insights, LCA does not offer definitive answers, acknowledging the inevitability of trade-offs in environmental decision-making. Challenges persist in the quantification of impacts for areas lacking numerical models, constraining the methodology's comprehensiveness in assessing certain environmental aspects. Notably, the absence of a standardized scoring system poses a significant challenge, with current aggregation methods lacking universality in producing a comprehensive score. In essence, the duality of LCA's strengths and limitations underscores the need for a nuanced and contextually sensitive application, acknowledging its significance within environmental assessments while addressing inherent constraints.

2.2. Life Cycle Assessment Framework

Life Cycle Assessment provides the methodological framework for assessing the environmental impacts associated with all stages of a product/service/technology's life, which should include upstream processes, downstream manufacturing, use stage, recycling and end-of-life processes.

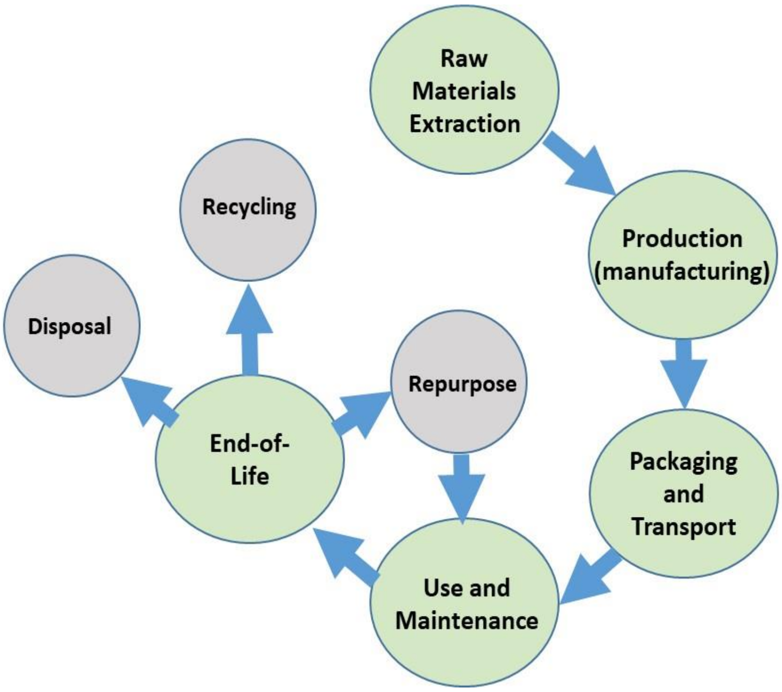


Figure 2 Depiction of "Cradle to Grave" LCA

It is noted that Life Cycle Assessment is a well-defined and standardised methodology, according to the ISO norms 14040:2006 and 14044:2006/A1:2018 (based on ISO 14044:2006/Amd 1:2017) and the International Life Cycle Data (ILCD) Handbook.

The ISO Technical Committee 207 SC 5 has published the ISO14040 series, in order to internationally standardise the LCA methodology and its main steps. The series have been recently reorganised as follows:

- ISO14040: 2006 - Environmental Management - Life Cycle Assessment - Principles and Framework
- ISO14044: 2006 - Environmental Management – Life Cycle Assessment — Requirements and Guidelines.

In addition, the European Commission's Joint Research Centre (JRC) has made a significant contribution via its Institute for Environmental and Sustainability (IES). They have introduced the ILCD Handbook, comprising a set of technical papers that elucidate best practices for LCA. This handbook offers a more in-depth interpretation of the ISO 14040 and 14044 environmental LCA standards. Broadly speaking, the ILCD framework includes a myriad of resources, publications, and tools, all designed to uphold the excellence in LCA and LCI dataset creation, dissemination, and collaboration. [98][99][100]

Based on ISO 14040:2006 [98], ISO 14044:2006 [99], and the ILCD Handbook [100], the LCA process encompasses four primary phases:

These phases as well as their interaction are presented in Figure 3.

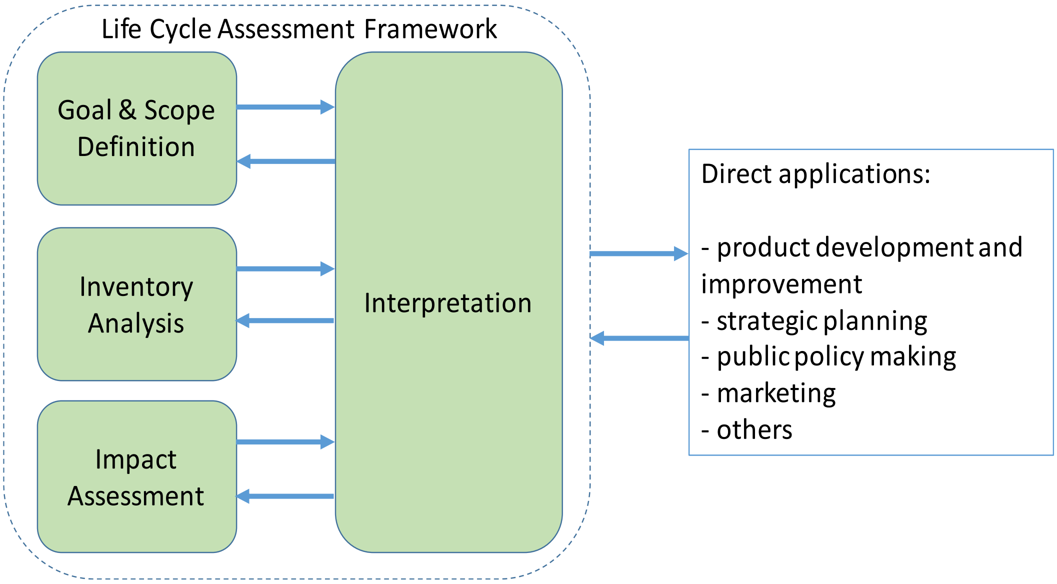


Figure 3 LCA framework according to ISO 14040 standard [98]

2.2.1. Goal and Scope Definition:

This step outlines the study's objective, the system under examination, the desired application of results, any restrictions on alternative uses, desired data quality, documentation needs, included impact categories, and the appropriate review methods. Additionally, it specifies geographical and temporal limits, system limits, required data, decision-making guidelines, and other foundational assumptions.

When initiating an LCA, it's essential to first establish the goal and scope of the investigation. As stated in ISO 14040, the goal of an LCA clarifies its intended use, the rationale for undertaking the study, and its target audience. Essentially, the goal communicates the study's objectives and highlights the potential beneficiaries of its findings.

A crucial element within the scoping phase is determining the “Functional Unit (FU)”, defined as a quantifiable measure of a product system's performance, serving as a benchmark. This facilitates the comparison of various product systems based on a shared service rendered.

Every environmental impact result from the LCA will be measured against this functional unit, necessitating the FU to be quantifiable. This ensures comparability with other LCAs using the same functional unit. Nonetheless, it's crucial to remember that system outlines might differ across studies. The scoping phase also involves choosing impact categories, determining the specific environmental impacts pertinent and essential to the topic at hand. The choices made during this phase significantly influence the study's results. Still, since LCA is an iterative process as per ISO, 2006a, adjustments can be made throughout the process to better align with the study's objectives.

Scopes commonly used in LCA to define the boundaries of the study include the following primary categories:

- Cradle to Gate: This assessment covers the life cycle stages from the extraction of raw materials (the "cradle") up to the point where the product leaves the production facility (the "gate"). It does not include transportation, use, and end-of-life phases.
- Gate to Gate: This is a partial LCA that focuses on a single or a few processes within the supply chain. It might be used to compare the environmental impacts of different production methods within a specific industry.
- Gate to Grave: This assessment starts from the point when the product leaves the production facility (the "gate") and covers transportation, use, and disposal or recycling (the "grave").
- Cradle to Cradle: This is a more holistic and sustainable approach to LCA, which looks at the entire life cycle but emphasizes that end-of-life materials should become inputs for new products, creating a closed-loop system. Instead of being "disposed of" in the traditional sense, products are ideally designed to be disassembled and recycled or upcycled.

It's worth noting that the chosen category or scope largely depends on the goals and objectives of the LCA. For example, a manufacturer might be more interested in "cradle to gate" if they want to understand the impacts of their production process, while a waste management company might focus on the "gate to grave" to analyse post-consumer disposal and recycling impacts.

2.2.2. Life Cycle Inventory:

This phase focuses on collecting and quantifying the system's inputs and outputs. During the life cycle inventory analysis, pertinent data related to inputs, outputs, and emissions essential for the LCA are gathered and assessed. This data compilation is known as the LCI for the product's system. The inventory serves as the foundational framework for the entire analysis, making it vital to acquire comprehensive information regarding mass and energy balances. The process of data collection is cyclical. As the process unfolds, one might identify new data needs, constraints, or other challenges. To ensure alignment with the LCA's objectives, these newfound insights might necessitate tweaks to the study's goal or scope.

The ease of data access varies which is why inventory analysis is frequently seen as the most challenging phase of an LCA. This often involves reaching out to companies or industries associated with distinct processing stages. However, issues of confidentiality can complicate data collection. Specific details on inputs, outputs, and emissions are sensitive and can provide businesses with a competitive edge, particularly if their technology is unique. As a result, companies are often reluctant to disclose this information unless mandated by law or if confidentiality assurances are provided.

2.2.3. Life Cycle Impact Assessment:

This stage delves into assessing the potential environmental impacts linked to the product system in question. During the life cycle impact assessment, the collected inventory aids in analysing the prospective environmental repercussions tied to the product system. This phase involves three essential procedures (impact category selection, classification, and characterization) and can be expanded by incorporating supplementary steps like normalization and weighting.

2.2.3.1. Impact Categories, Indicators, and Characterization Models Selection:

In this sub-phase, decisions are made regarding the environmental impacts to account for, denoted by impact categories, and the methods to measure them using suitable indicators and characterization approaches. These choices align with the LCA's objectives and scope. Typically, the selection of a characterization model determines the impact categories used since it frequently comes with pre-established categories.

2.2.3.2. Classification:

This involves categorizing the components of the LCI into specific impact categories, essentially sorting the inventory items based on their potential environmental influence. An individual LCI entry can be associated with multiple impact categories.

2.2.3.3. Characterization:

During characterization, category indicator outcomes are computed. In essence, the inventory outcomes are transformed into potential impacts within the varied impact categories. Different emissions contribute distinctively to the potential impact of an impact category. To ascertain the impact of a specific emission on an impact category, the emission's value is multiplied by a characterization factor. This factor showcases the emission's relative influence, compared to a standard substance. The subsequent impact values are then accumulated according to their corresponding impact category.

2.2.3.4. Normalization and Weighting:

Normalization involves adjusting the results from the characterization phase in relation to a benchmark scenario. This highlights the significance of impacts from the analysed system when compared against the benchmark. The normalization process segments the characterization results into varied categories, providing a more structured view of the environmental impact.

The weighting procedure involves making value judgements to allocate varied weights of significance to the different impact categories, and then consolidating them into a singular score representing the comprehensive environmental impacts of the product system. It's crucial to understand that this score isn't rooted in pure science. While this consolidated score might be more comprehensible to the public, it introduces uncertainties.

2.2.3.5. Life Cycle Interpretation:

In this concluding phase, results from both the inventory and impact assessment are integrated in accordance with the set goal and scope. This synthesis often results in final observations and suggestions for stakeholders, as outlined in the study's initial goal and scope. This entails understanding the contributions of various processes and emissions (known as stressors) to distinct impact categories. The analysis should pinpoint the key environmental concerns and potential solutions to mitigate the explored impacts. To gauge the robustness of the results against variations in data or assumptions, a sensitivity analysis might be performed. It's essential to address the data quality within the LCI and any study limitations. A conclusion is drawn, aligned with the study's established goal and scope.

2.3. Life Cycle Assessment applied in the construction industry.

Energy consumption and carbon emissions manifest across various stages in the life cycle of a construction, described as (1) Raw Materials Extraction; (2) Material Processing and Component Fabrication; (3) Construction and Assembly; (4) Operation and Service phase; and (5) End-of-Life phase [101]. The transitions between these phases typically involve noteworthy emissions related to transportation, an aspect integral to the comprehensive estimation of the carbon footprint. Therefore, based on the aforementioned information for the construction industry, Figure 2 is transformed as follows:

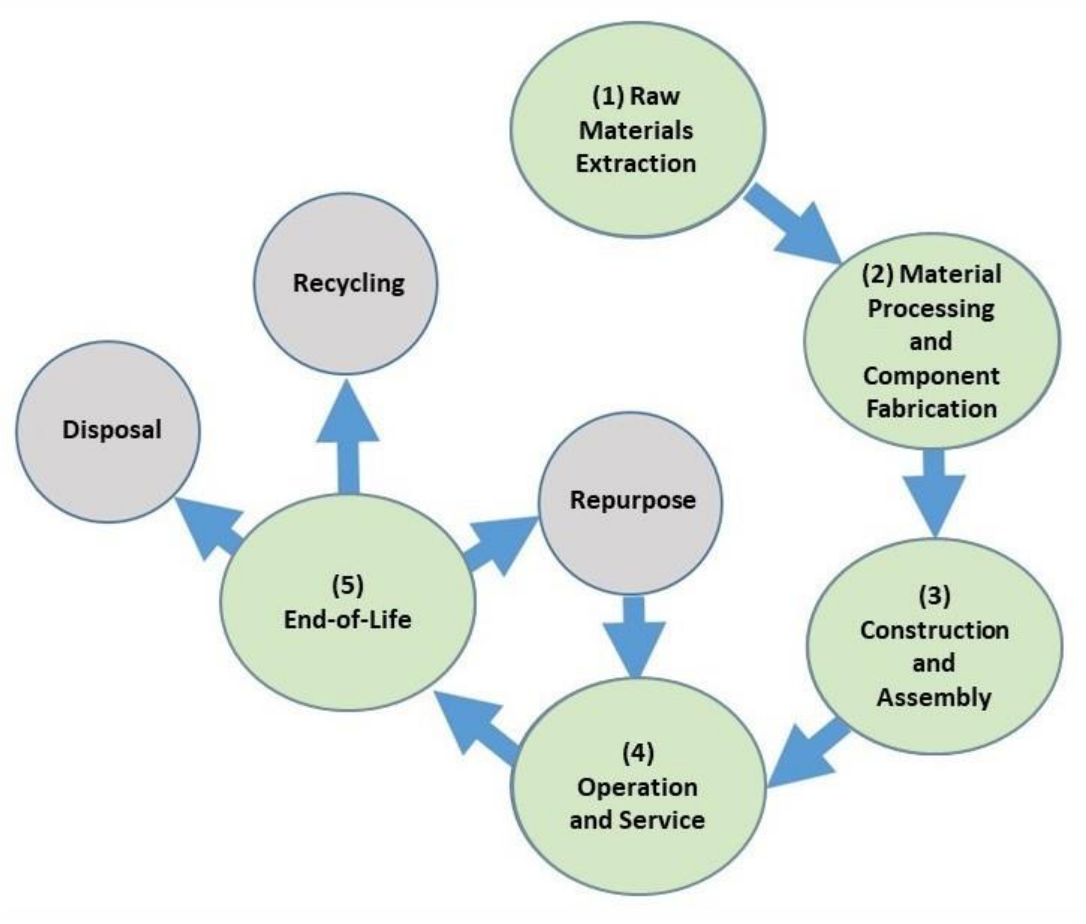


Figure 4 Depiction of "Cradle to Grave" LCA for the construction industry

Embodied carbon conventionally includes carbon emissions incurred during stages 1 to 3 of the construction's life cycle. To elucidate the considered life cycle phases, embodied carbon may be reported as:

- *"Cradle to gate" embodied carbon*: Initiation of Phase 1 until the completion of Phase 2
- *"Cradle to site" embodied carbon*: Initiation of Phase 1 until the initiation of Phase 3
- *"Cradle to service" embodied carbon*: Initiation of Phase 1 until the completion of Phase 4
- *"Cradle to grave" embodied carbon*: Initiation of Phase 1 until the completion of Phase 5

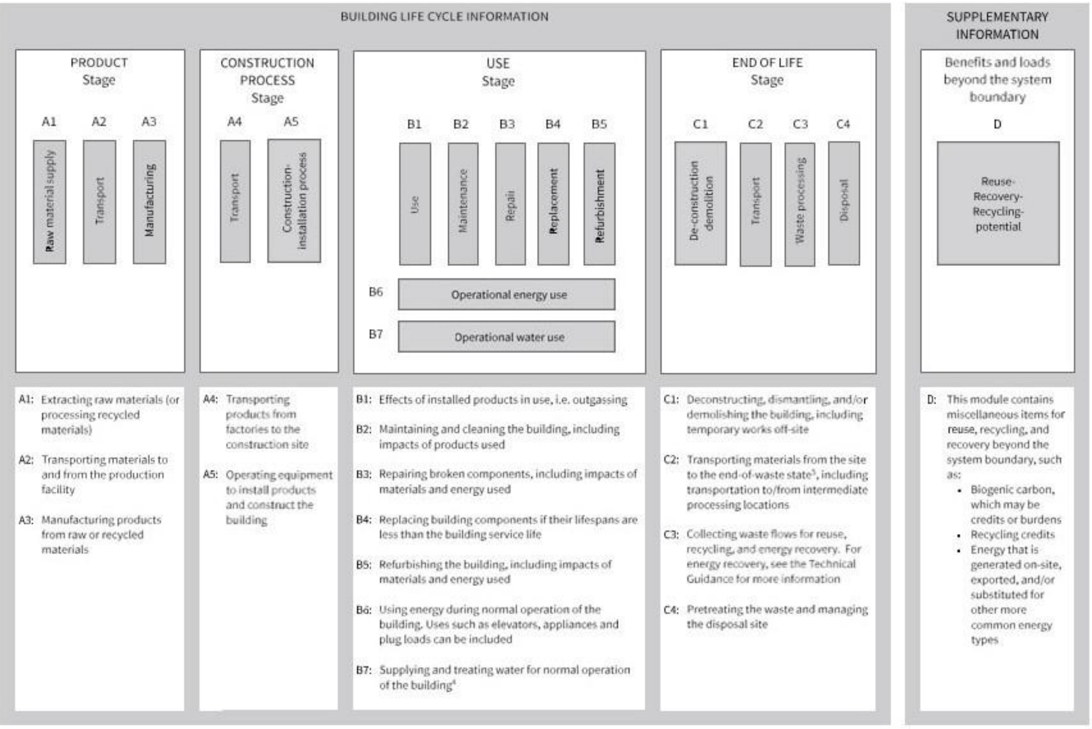
These terms encompass the respective emissions incurred inclusive of the associated transportation emissions. The same rule applies in the case of calculating the embodied energy of the construction instead of the embodied carbon.

Meanwhile, in recent years, there has been significant progress in establishing norms, standards, and guidelines for the LCA of Buildings. While the ISO [102] has integrated life cycle thinking into ISO 14001 and detailed LCA and the life cycle stages of buildings in ISO 14040 and ISO 14044, ISO 21930 focuses on EPDs for building construction.

An EPD, is a standardized document providing comprehensive information about a product's environmental impact throughout its life cycle. EPDs are based on a product’s LCA and offer a transparent, comparable, and credible way to communicate the environmental performance of a product.

In parallel, the European Committee for Standardization – CEN TC350, focusing on the Sustainability of Construction Works, has defined building assessment in EN15643, developed a method for calculating environmental performance of buildings [103] and civil engineering works [104] in EN 15978, and outlined the PCRs for EPDs of construction products in EN 15804. These standards are also adopted in the national standards of European member states, including the British Standards.

The TC350 standards utilize LCA to evaluate the ‘cradle to grave’ impact of buildings and civil engineering works, as depicted in *Figure 5* [105]. The product stage encompasses raw material supply (A1), transportation of materials from extraction to manufacturing site (A2), and the manufacturing process itself (A3). The construction process stage is bifurcated into transport from gate to site (A4) and the construction-installation process (A5). The use stage accounts for the impacts resulting from anticipated conditions of use of components (B1), along with maintenance (B2), repair (B3), replacement (B4), and refurbishment (B5). Notably, operational energy use (B6) and operational water use (B7) are not included in the embodied CO2e assessment but are considered in the whole life CO2e calculations. The end-of-life stage comprises deconstruction and demolition (C1), transportation to disposal or recycling facilities (C2), waste processing (C3), and disposal (C4). Additionally, potential benefits and burdens of reuse, recovery, or recycling (D) are also considered. As per EN 15978, the data used should be up-to-date and comply with the stipulations of EN 15804. It's also important that the data are geographically consistent with the production location. [106]



A1: Extracting raw materials (or processing recycled materials)

A2: Transporting materials to and from the production facility

A3: Manufacturing products from raw or recycled materials

A4: Transporting products from factories to the construction site

A5: Operating equipment to install products and construct the building

B1: Effects of installed products in use, i.e. outgassing

B2: Maintaining and cleaning the building, including impacts of products used

B3: Repairing broken components, including impacts of materials and energy used

B4: Replacing building components if their lifespans are less than the building service life

B5: Refurbishing the building, including impacts of materials and energy used

B6: Using energy during normal operation of the building. Uses such as elevators, appliances and plug loads can be included

B7: Supplying and treating water for normal operation of the building[4]

C1: Deconstructing, dismantling, and/or demolishing the building, including temporary works off-site

C2: Transporting materials from the site to the end-of-waste state[5], including transportation to/from intermediate processing locations

C3: Collecting waste flows for reuse, recycling, and energy recovery. For energy recovery, see the Technical Guidance for more information

C4: Pretreating the waste and managing the disposal site

D: This module contains miscellaneous items for reuse, recycling, and recovery beyond the system boundary, such as:
  - Biogenic carbon, which may be credits or burdens
  - Recycling credits
  - Energy that is generated on-site, exported, and/or substituted for other more common energy types

Figure 5 Standard life cycle stages and modules, adopted from EN 15978. [105]

One of the critical skills necessary for implementing sustainable strategies in practical applications is the capacity to assess the efficacy of such strategies within a project context. The quantification of potential embodied carbon reductions resulting from the adoption of diverse strategies offers valuable insights into the design of low-carbon construction. By estimating the achievable reduction in a construction's embodied carbon, added to the estimated operating carbon, the life cycle carbon of the construction can be calculated. These estimated life cycle carbon reductions then serve as the primary selection criteria for identifying the optimal strategy or combination of applicable strategies, considering their impact on the economic, environmental, and social aspects of the building. Life Cycle Assessment has been extensively employed to estimate the embodied carbon of various construction materials, components, machinery, and operations involved in construction and respective operation [19]. LCA adopts a holistic approach to quantify environmental impacts, including associated emissions and energy use.

3. CASE STUDY: A MALL COMPLEX IN GREECE – LCIA METHODOLOGY

3.1. Project Overview

3.1.1. The Mall Complex

The Mall Complex is envisioned as a premier commercial district with a GFA of 300.000 m^2. It includes a mix of open-air and enclosed shopping zones, restaurants, cafes, cinema and wellness centre. This project, sited on an "urban centre" plot, is governed by the Greek Building Regulation and the Urban Planning Regime. The building's height cannot exceed 20m, and the FAR is capped at 1.53. The average height between floors in the mall is set at 6m, while the basement and visitor parking areas are planned to have an average height ranging between 3.5m to 4m, inclusive of services. The Mall Complex construction is estimated to last 4 years.

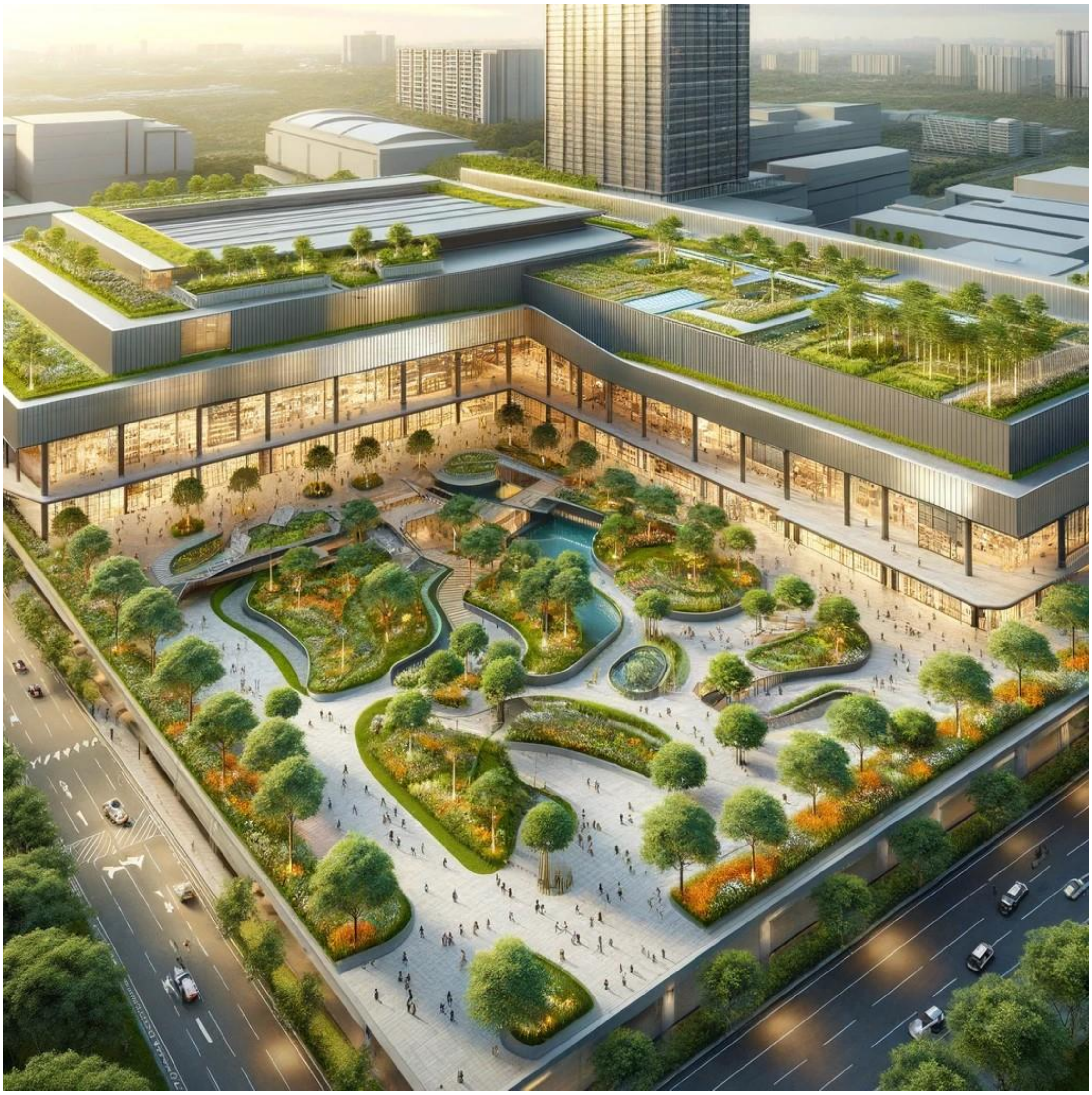


Figure 6 Mall Exterior Rendering

3.1.2. LCIA methodology summary

A summary of the methodological approach applied in this analysis is presented in Figure 7. The guiding principles of the LCA model are according to the ISO norms 14040:2006 and 14044:2006 and the ILCD, as mentioned in the previous chapter. In the framework of the project, the goal and scope are determined, followed by the collection of classified data regarding the overall design of the Mall Complex and statistical analysis of this data.

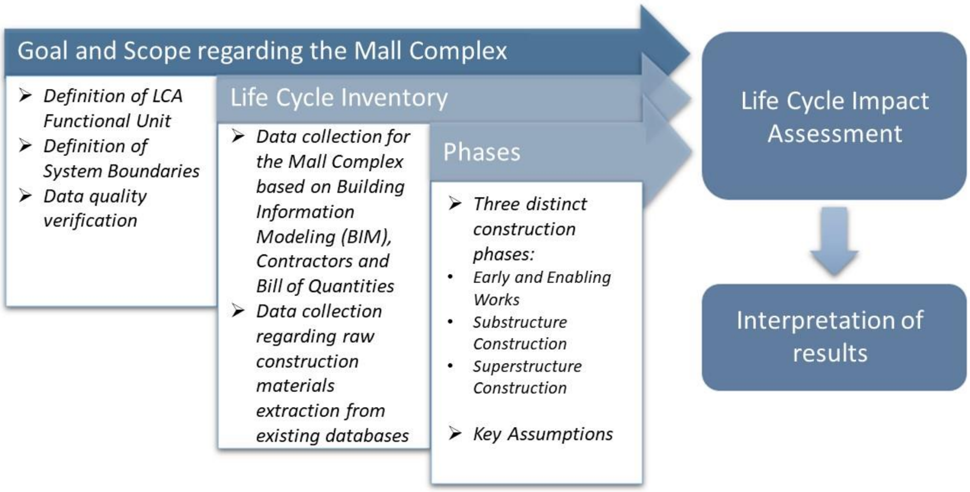


Figure 7. Overall presentation of the methodology for the LCA analysis

Operationally, the complete life cycle assessment is conducted using the commercial software package Sphera LCA FE (GaBi). It functions as a process model Life Cycle Assessment tool where each step in the product life cycle is identified as a distinct object. To enhance the reliability of LCA, both Sphera LCA FE (GaBi) and Ecoinvent databases are employed, concerning processes and flows, for the preparation of each LCA model.[107][108]

3.2. Goal

The primary objective of this LCA study is to conduct an in-depth evaluation of the potential environmental impacts associated with the construction of the Mall Complex in Greece, utilizing detailed, actual preconstruction data. By focusing on the precise quantification of materials and processes, the study aims to identify and assess critical environmental "hotspots" in the construction phases where substantial environmental impacts may occur. This thorough approach allows for the development of specific, actionable strategies to mitigate these impacts, enhancing environmental sustainability. The findings are intended to serve academic purposes, offering a detailed comparative analysis with conventional construction practices, and contributing to the advancement of sustainable construction methodologies.

3.3. Scope

3.3.1. Product system and Functional Unit

The scope of this LCA study is focused on the construction phase of a Mall Complex in Greece, which constitutes the product system. The studied system accounts for the entire construction process spanning from the initial vacant plot to the final completion of the Mall Complex including the sourcing of materials, transportation, energy consumption and waste management during construction (reference to Figure 5, stages A1 – A5)

A critical aspect of this study involves differentiating between the 'hot-shell' parts and 'cold-shell' parts of the mall's construction. In this context, the term 'hot-shell' refers to the public spaces of the Mall Complex while the term 'cold-shell' refers to the Mall Complex tenancies.

- **Hot-Shell Construction (or Turnkey):** Hot-shell spaces are fully finished and ready for immediate use. These spaces include all necessary interior finishes, fixtures, and amenities. The end user can essentially move in and start operating their business with minimal or no modifications required.
- **Cold-shell Construction:** The space includes the exterior walls and roof, the basic structure, and all essential services connections to the main MEP systems of the Mall Complex. However, it lacks interior finishes such as flooring, ceilings, internal HVAC systems, lighting, and interior walls. Tenants who lease a cold-shell space will need to complete the interior work before the space is usable.

Each construction stage will be recognized and analyzed as a separate sub-system. The system under study is presented in Figure 14. All relevant details and categorization is presented in the Life Cycle Inventory Analysis paragraph. The Functional Unit (FU) is thus defined as 300,000m^2 complete Mall Complex building after a four-year construction period.

3.3.2. System boundaries

As per ISO standard 14044, the system boundary serves as the criteria outlining which processes belong to a product's system, where a unit process refers to the most basic component assessed in the life cycle inventory analysis with measured input and output data. The chosen system boundaries must align with the study's objectives, ensuring a thorough representation of the product's life cycle. To gain a complete understanding of a product's environmental impact, it's essential to adopt a "cradle-to-grave" methodology, encompassing everything from initial resource acquisition to production, usage, recycling, and ultimate disposal.

Notably, the scope of this study does not extend to the operational use phase or the end-of-life scenarios of the Mall Complex, as the primary focus is on the environmental impacts during construction. Thus, a “cradle-to-gate” approach will be considered, from the extraction of all raw materials used (cradle) to their complete construction and assembly (gate), excluding the operation and maintenance and disposal face of the building.

Table 1. Summary of system boundaries examined in the current LCA study

Included	**Excluded**
• Extraction of all raw materials • Use of all raw and processed materials • Transportation of all raw and processed materials • Energy and fuel inputs • Construction equipment • Waste management during construction	• Resources used for the design of the building • Maintenance of construction equipment • Liquid waste discharges • Labor and corresponding wastes • Tenancies construction • Use stage • End of Life stage

3.3.3. Assumptions and limitations

Assumptions:

- *Construction Timeline:* The study assumes that the construction of the Mall Complex will be completed within a four-year timeframe, proceeding without significant errors or delays.
- *Data Sources:* Information regarding raw construction materials extraction has been sourced from existing databases. However, this data may not accurately reflect current conditions or the latest specifications and innovations in construction materials and methods.
- *Worst case scenario for materials:* The analysis assumes that all materials are newly produced and exclusively allocated to the project, disregarding the potential for using reused, recycled, or more sustainable materials. This approach aims to conservatively estimate the project's maximum potential environmental impact, thereby ensuring the proposed mitigation strategies address the most adverse outcomes.

Limitations:

- *Equipment Consumption Estimates:* Consumption data for construction equipment is based on technical specifications rather than direct measurements, which may result in some discrepancies.
- *Exclusion of Employee-Related Resources and Wastes:* The study does not account for the resources and wastes associated with the workforce involved in the construction, such as their living necessities or personal waste generation.
- *Liquid Waste Discharges:* Although stormwater runoff within the construction site is considered, other liquid waste discharges, including vehicle wash water, runoff from material storage areas, and leaks from construction equipment and transportation vehicles, are not quantified.
- *Monitoring Exclusions:* The LCA does not incorporate the monitoring aspects such as noise, dust, ground movement, vibration, and temperature and moisture management. Additionally, the study does not consider the impact of construction activities on adjacent structures. It's worth noting that monitoring aspects like noise, dust, and vibration are typically more relevant to immediate environmental health and safety concerns rather than the long-term environmental impacts that are the

focus of an LCA. While their inclusion could provide a more holistic environmental profile, their exclusion is a strategic decision to focus the LCA on quantifiable impacts directly related to resource consumption and emissions.

3.3.4. Cut-off Criteria:

- Exclude materials and processes which are not available in the database and contribute less than 1% to the total energy use or material quantity.
- Focus on environmental impact categories where significant impacts are expected, excluding negligible impact areas.
- Prioritize materials and processes relevant to the geographic and regulatory context of Greece.
- Limit the scope to the construction phase, excluding operational and end-of-life stages.
- Simplify the analysis by excluding processes that are too complex to model accurately without significantly affecting the study's accuracy.

3.4. Data quality

3.4.1. Confidentiality of Data

This Life cycle assessment study incorporates actual construction data derived from the building's BoQs, BIM model, and Contractors' data, all governed by strict confidentiality agreements. Due to the sensitive nature of this information, the data are not openly disclosed, shared, or reproduced. However, access to the specifics of the data may be granted for researchers and stakeholders upon a formal request to the author and subject to the approval of all relevant parties.

Though the analysis and conclusions of this case study are grounded in detailed data, specific individual or proprietary information is not revealed. This approach allows for the disclosure of key findings and insights while preserving the confidentiality of the data sources. In an effort to maintain both transparency and confidentiality, the study utilizes total quantities and aggregated data where appropriate. This ensures that crucial insights are shared without exposing sensitive information.

Adherence to confidentiality agreements is a standard practice in industry-related studies involving sensitive business information. This approach does not detract from the study's validity; rather, it respects the requirements of data providers while still offering a comprehensive environmental assessment of the Mall Complex construction.

3.4.2. Materials - RICS NRM

In this LCA study, a detailed examination of the materials and resources integral to the construction of the Mall Complex is undertaken. The data pertaining to these materials, forming the foundation of the LCI analysis, is calculated and documented in adherence to the RICS NRM standard.

The application of the RICS NRM2 standard ensures that the study's approach to material quantification is consistent, accurate, and reliable. By categorizing and structuring all materials in numerical order according to this internationally recognized standard, the LCI data aligns with industry best practices. This standardization is particularly important in the construction industry, where precision in material measurement is crucial. The use of RICS NRM not only enhances the study's credibility but also allows for better comparability with other studies and industry benchmarks, thereby contributing to a broader understanding and integration into wider construction and environmental assessments. [109]

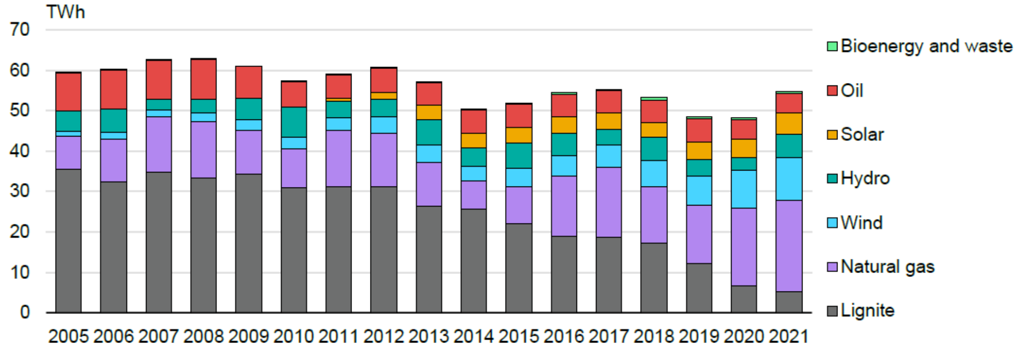
3.4.3. Specific datasets and processes

3.4.3.1. Energy

The consumption of energy related to construction activities primarily comprises electricity and diesel used for operating all construction machinery and equipment. This consumption is crucial to the LCA, as it directly correlates with GHG emissions and other environmental impacts.

A. Electricity [110]

Understanding the energy mix, including the proportions of renewable and non-renewable energy sources, is essential for a comprehensive environmental assessment of the construction process. In Greece, the energy mix for generating electricity has been evolving, with a significant shift towards renewable sources. As of 2022 data, the country's electricity generation relies on a combination of energy from fossil fuels and energy from renewable sources. The total electricity production amounts to 55 TWh, with the following distribution: gas-fired generation constitutes approximately 40% (22 TWh) of the total, mirroring the share of renewable energy generation, which also accounts for about 40% (22 TWh). Within the renewable energy category, wind power leads with approximately 18.2% (10 TWh), followed by solar PV generation at around 9.6% (5.3 TWh), and hydroelectric generation contributing about 10.7% (5.9 TWh). Lignite-fired generation represents about 9.6% (5.3 TWh) of the total electricity generation. Additionally, oil-fired generation accounts for 8.5% (4.7 TWh), while bioenergy and waste-to-energy sources contribute approximately 1.8% (1 TWh) to the total electricity mix. This diverse energy mix reflects the country's ongoing transition towards more sustainable energy sources and has significant implications for the environmental impact of construction activities, particularly in terms of associated greenhouse gas emissions and resource use. This diversification in the energy mix has implications for our LCA, as different sources of electricity have varying environmental footprints, particularly in terms of greenhouse gas emissions and resource depletion.



IEA.CC BY 4.0.

Source: IEA (2022b).

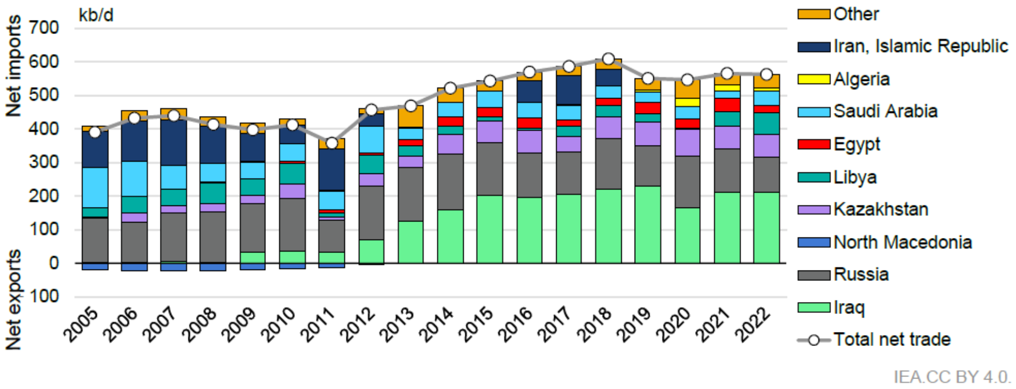
Figure 8 Greece's electricity energy mix [110]

B. *Diesel* [110]

For diesel, the environmental impact extends beyond its combustion. The diesel used in Greece is imported, involving transportation from different countries. This transportation process contributes additional environmental impacts, particularly in terms of emissions from transportation vehicles (such as tanker ships and trucks) and the energy used in the refining process. Understanding these aspects of diesel sourcing and transportation is vital for a holistic assessment of the environmental impacts associated with construction energy use in this study.

As of 2022 data, Greece's crude oil imports are presented below:

- Imports from **Iraq** accounted for approximately **37.2%** of Greece's total crude oil imports, with 210 kb/d.
- Imports from **Russia** contributed around **23.0%**, with 130 kb/d.
- Imports from **Kazakhstan** made up about **11.9%**, with 67 kb/d.
- Imports from **Libya** were around **7.6%**, with 43 kb/d.
- Imports from **Egypt** constituted approximately **7.1%**, with 40 kb/d.
- Imports from **Saudi Arabia** accounted for about **4.1%**, with 23 kb/d.
- Finally, imports from **Algeria** represented around **3.2%**, with 18 kb/d.



Source: IEA (2022a).

Figure 9 Greece's crude oil imports [110]

3.4.3.2. *Water* [111][112][113]

Water is one of the most important resources in construction. Construction sites use water for a variety of purposes of direct activities and indirect activities. LCA considers both direct and indirect water use to evaluate the total environmental footprint of construction activities. Direct water use primarily relates to the on-site activities essential to the construction process, such as mixing building materials, dust suppression, and curing. Indirect water use, on the other hand, encompasses water consumed during the production of construction materials, manufacturing of construction equipment, and other upstream and downstream processes associated with the lifecycle of the building project.

The most important uses of water in construction are presented below:

- *Mixing Materials:* Water is a key component in mixing construction materials such as concrete, mortar, and plaster. The right water to material ratio is crucial for achieving the desired strength and consistency.
- *Dust Control:* Construction sites generate a lot of dust, especially during demolition and dry earth moving processes. Water is sprayed to control the dust and minimize air pollution.
- *Compaction:* Water is used to moisten soil and other materials to aid in compaction. Proper compaction ensures a solid foundation and ground stability.
- *Cooling:* For construction equipment that generates heat, such as drills and mixers, water can be used to cool down these machines and prevent overheating.
- *Curing:* After concrete and other cement-based materials are laid, they require an adequate amount of moisture to cure properly. Water is often sprayed over these materials to help maintain the necessary moisture content for optimal curing.
- *Landscaping:* On construction sites where landscaping is part of the project, water is used for sodding, planting, and maintaining vegetation.
- *Hydrodemolition:* Water under high pressure can be used to remove or demolish existing concrete structures, known as hydrodemolition.
- *Drilling and Cutting:* Water is often used as a coolant and lubricant in drilling and cutting operations, particularly when working with concrete or masonry.
- *Concrete Sawing and Coring:* Water is used during sawing and coring activities to reduce friction and prevent dust, similar to its use in drilling and cutting operations.
- *Worker Hydration:* Adequate water supply is essential to ensure that workers remain hydrated, particularly in hot and arduous conditions. Construction work is physically demanding, and maintaining proper hydration is vital to the health and safety of the workforce.
- *Sanitation Facilities:* Water is required for sanitation facilities on construction sites, including portable toilets and handwashing stations, which are essential for maintaining hygiene.
- *Cleaning:* Water is used for cleaning the construction area, equipment, tools, and for washing away waste materials.
- *Fire Prevention and Suppression:* Construction sites must have water readily available for fire prevention and suppression in case of an emergency.
- *Pressure Testing:* Water is often used for pressure testing of plumbing lines to ensure there are no leaks and that the system can handle the operational pressures.

- *Environmental Protection Measures:* Water may be used as part of erosion and sediment control measures. For instance, it can be applied to prevent soil erosion on slopes or to aid in the settling of sediment in retention ponds.

When leaks, poor sanitary and hydraulic installations, and unsatisfactory project designs occur on a construction site, not only a lot of water is wasted but also its runoff may pollute the water-bearing horizon.

Minimizing water pollution on construction sites is crucial for protecting the environment and complying with legal and regulatory standards. Construction companies can reduce water pollution by adhering to environmental regulations and adopting green practices. Laws like the Clean Water Act in the U.S. and the EU's Water Framework Directive mandate standards for protecting water bodies. Proper waste management and disposal, securing materials, and cleaning nearby streets are key. Innovative water conservation techniques, such as recycling water on construction sites, are also being utilized. Companies are encouraged to use erosion control measures and train employees in environmentally responsible practices.

Furthermore, reducing water usage is crucial, construction companies must implement effective water management strategies and adhere to both regulatory standards and sustainable practices. Efficient use of water in processes like material mixing and dust suppression is crucial. Emphasizing the recycling and reuse of water on-site can significantly cut down consumption. For example, reusing water for multiple purposes, such as cleaning equipment or suppressing dust, can be an effective measure. Additionally, employing water-efficient technologies and equipment can lead to substantial savings. Construction firms are also encouraged to train their staff in water conservation methods, ensuring that water use on sites is optimized and waste is minimized. Adapting to practices that reduce water usage not only supports environmental sustainability but also enhances the overall efficiency of construction operations.

3.4.3.3. Construction materials

As discussed in Section 1.2 materials are the fundamental parts of structures development. There are various kinds of materials used for buildings in the construction industry. In different regions, local and national standards govern building materials in construction. [114]

The primary construction materials considered in this study include concrete, steel, aluminum. The selection of these materials is based on their prevalence in the construction of the studied Mall Complex, and their environmental impact profiles. For example, concrete and steel are two of the most resource-intensive materials, both in terms of raw material extraction and energy consumption during production. The study also accounts the environmental footprint due to transportation of these materials to the construction site. Furthermore, the study considers that all the materials are sourced locally in Greece, which impacts outcomes in terms of local environmental and economic implications. [115]

3.4.3.3.1 Cement – Concrete [115], [116], [117], [118]

Cement is an industrial material produced by heating a mixture of grinded limestone and clay in special kilns at temperatures of around 1,450°C. The product resulting in these conditions from the transformation of the raw materials is called clinker and is then grind into powder to become the cement.

Concrete or beton is a product of cement. Specifically, it is a composite material crafted from a mixture of fine and coarse aggregate bonded with cement and water. Following the mixing process, the substance undergoes a curing phase, typically requiring seven days to cure partially and approximately 28 days to achieve its full-strength potential. A primary benefit of concrete is its malleability when wet, allowing it to be cast into various shapes and subsequently solidify into a robust, stone-like substance.

Owing to its cost-effectiveness and adaptability, concrete is prevalently employed in multiple construction facets, including but not limited to: foundations, residential structures, commercial edifices, bridges, culverts and sewer systems.

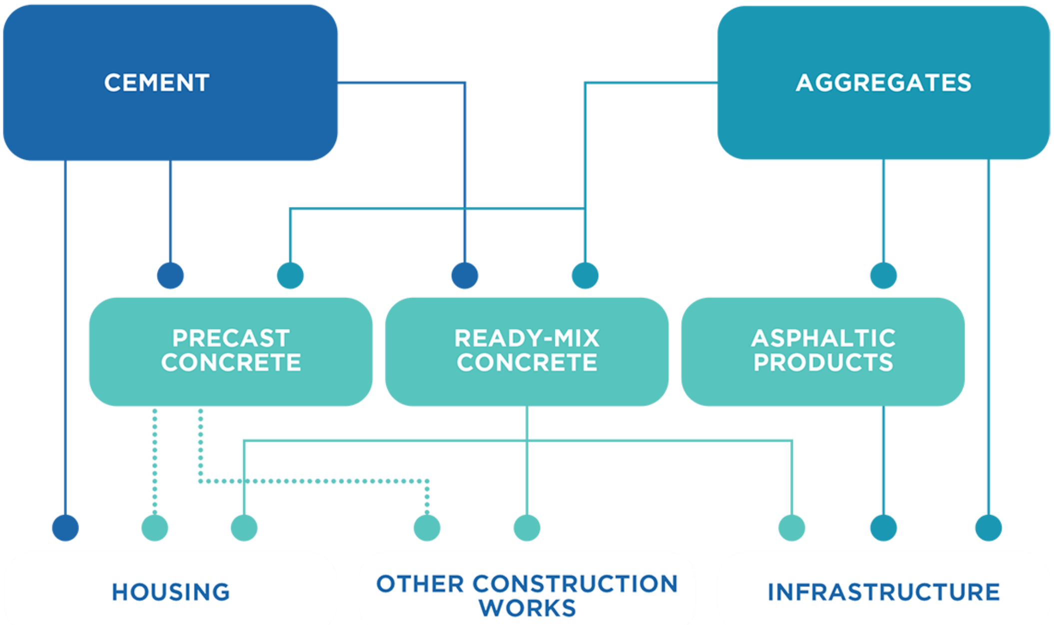


Figure 10 Cement and Concrete used in the construction industry [116]

Cement production is one of the most important industrial activities in Greece, contributing significantly to the national economy. Limestone, the main raw material for the production of cement and aggregates, is abundant in Greece, which is a strong advantage for the development of the domestic cement industry. At the same time, the intense seismic activity in the country and the requirement for durable construction of private and public projects, result in an increased demand for concrete, as a building material, due to its great durability and strength. Today, the cement industry in Greece has an annual production capacity of approximately 15 million tons.

The cement production process is illustrated in *Figure 11*:

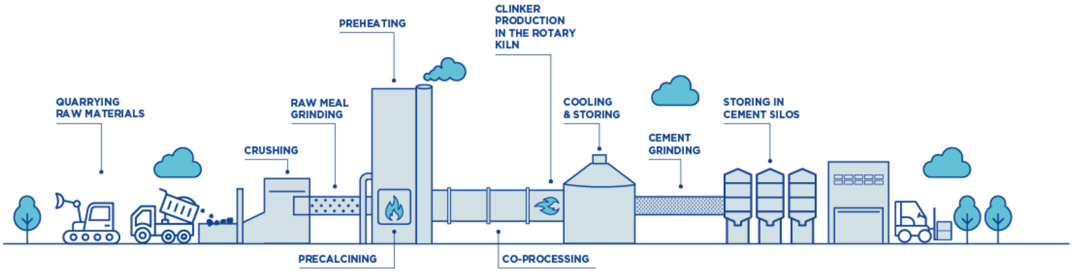


Figure 11 Production process of cement

Cement – Concrete is the second most used material after water in the construction industry. This fact highlights the need for a dynamic and coordinated effort to save energy and resources during its production and use, a major challenge in combating climate change. The cement industry's response to this challenge comes at an accelerating pace. The companies within the sector have already introduced significant innovations in the production process of their products. The Greek companies follow a plan which is based on a joint Action Program formulated by the proposals of the GCCA. It aims to reduce carbon dioxide emissions by investing significantly in innovative technologies and alternative fuels in particular, the cement industry's climate change strategy focuses, among others at: Reduction of CO2 emissions, Environmental Product Declarations, Energy efficiency.

3.4.3.3.2 Steel [115], [119], [120], [121]

Steel is a composite material made from alloys of iron and carbon. Steel has high strength and functionality. It is also lightweight, easy to work with, and cheaper to ship than other building materials. Steel does not easily deform unless we place a tremendous amount of weight on it, and it retains its structural properties even when it is bent. Due to its structural stability, we use steel to make tall modern buildings' structural frameworks.

Steel has distinguishing qualities such as high strength to weight ratio. It is less time-consuming to install than concrete, and we can install it in any environment. If not correctly installed, however, steel is susceptible to corrosion. One of the significant drawbacks of steel as a construction material is that it is likely to break down during high-temperature levels. Its level of fire resistance depends on the type of steel.

It is commonly used in construction for the following purposes:

- For structural sections: We use steel as reinforcing bars to increase the tensile strength of structures.
- Roofing: We use steel to make roofing products such as purlins, internal walls, ceilings, and cladding.
- Internal fixtures: We use it to make interior fittings such as rails and stairs.
- Utilities: We construct underground water, fuel, power, and gas lines using steel.

In 2021, crude steel production in Greece amounted to almost 1.5 million metric tons, representing a six percent increase compared to the previous year.

The steel production process is illustrated in Figure 12:

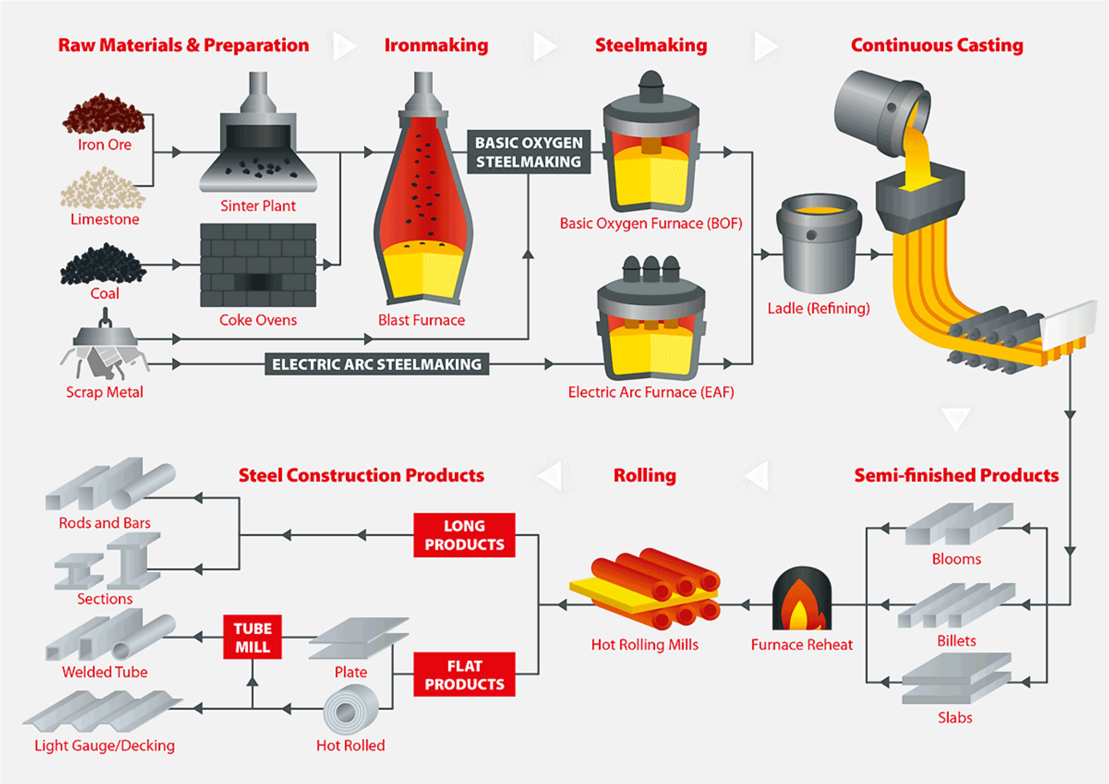


Figure 12 The steel production process [122]

Nowadays, the industry is focusing on reducing its carbon footprint and enhancing energy efficiency to meet global environmental standards and goals. Key strategies include adopting cleaner and renewable energy sources, such as solar and wind power, to power production facilities. Additionally, the sector is investing in innovative technologies to increase recycling rates of steel, as steel is a highly recyclable material, thereby reducing the need for raw material extraction and minimizing environmental impact.

Energy-efficient manufacturing processes are also being developed and implemented. These processes not only reduce energy consumption but also decrease greenhouse gas emissions. The industry is also committed to water conservation, implementing closed-loop water systems to reduce water usage and minimize wastewater discharge.

Furthermore, the steel sector is engaging in carbon capture and storage (CCS) initiatives, aiming to capture CO2 emissions from steel production and store them safely, thus mitigating their impact on the environment.

Through these commitments, the steel production and manufacturing industry is playing a significant role in addressing climate change and promoting sustainable industrial practices, aligning itself with broader environmental and energy sustainability goals.

3.4.3.3.3 Aluminum [123], [124], [125]

Aluminum, due to its unique combination of properties, is increasingly vital in various industries. It is the third most abundant element in the Earth's crust and is derived from bauxite ore. The metal is known for its light weight, high strength, and formability, making it ideal for producing lighter vehicles with lower energy consumption and reduced emissions. Its corrosion resistance, thermal and electrical conductivity, impermeability, non-toxic nature, and non-magnetic properties broaden its application scope. Additionally, aluminum's recyclability aligns with circular economy principles, contributing to waste reduction and energy conservation. The metal's applications range from everyday consumer products to specialized uses in construction, packaging, and transportation sectors, marking it as a material of the future.

Regarding building construction, the major uses of the aluminum are presented below:

- *Cladding and Facades:* Aluminum cladding is popular due to its aesthetic appeal and protective qualities. It can be used as panels or sheets to cover the exterior of a building, providing a sleek and modern look while also protecting against weather elements.
- *Windows and Doors:* Aluminum frames for windows and doors are common due to their durability and low maintenance requirements. They are resistant to warping, cracking, and are not prone to rust or corroding.
- *Roofing:* Aluminum roofing materials are lightweight, durable, and resistant to corrosion, making them ideal for various types of roofs. They also reflect heat and light, which can help in reducing energy costs.
- *Interior Applications:* Inside buildings, aluminum is used for fittings, railings, staircases, and various fixtures due to its malleability and aesthetic qualities.
- *Insulation:* Aluminum foil is often used as a layer in insulation materials due to its reflective properties, helping in heat retention and energy efficiency.
- *Curtain Walls:* In commercial buildings, aluminum is frequently used in curtain wall systems – non-structural cladding systems for the external walls of buildings.
- *Solar Panels and Renewable Energy Systems:* Aluminum frames are widely used to mount solar panels and other renewable energy systems due to their durability and resistance to environmental conditions.
- *Suspended Ceilings:* Aluminum is used in the grid system of suspended ceilings for its lightweight and aesthetic properties.
- *HVAC Components:* Due to its excellent thermal conductivity, aluminum is often used in the construction of HVAC systems, including ductwork and radiators.

Aluminum production involves several key stages, starting from mining bauxite ore, which is the primary raw material. This ore is then refined to produce alumina, a process known as the Bayer Process. The alumina undergoes electrolysis in a smelter to extract pure aluminum. This process, known as the Hall-Héroult process, requires significant electrical energy. Modern aluminum production focuses on efficiency and environmental sustainability, with recycling playing a crucial role. Recycled aluminum requires only a fraction of the energy compared to new aluminum, making it a more environmentally friendly option. The industry is continuously evolving with technological advancements to improve the efficiency of production processes and reduce environmental impact.

The aluminum production process is illustrated in Figure 13:

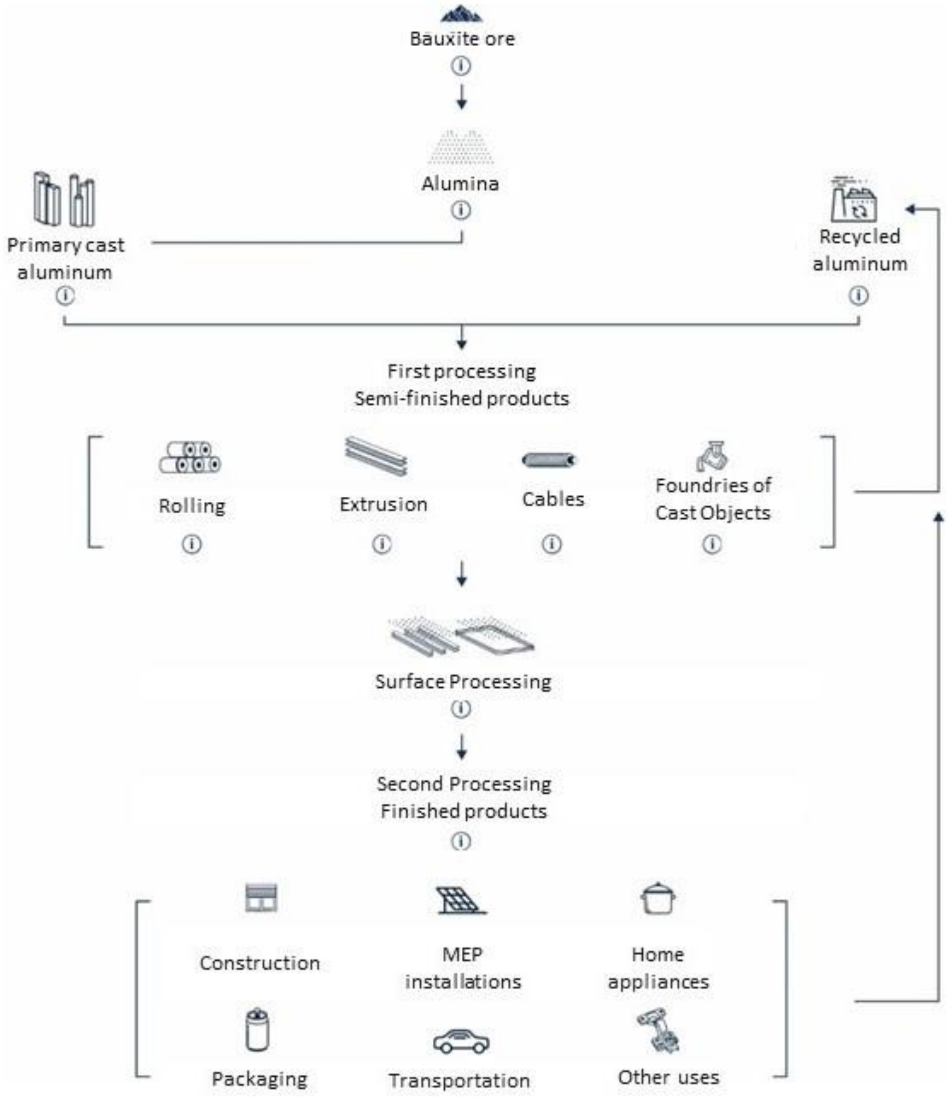


Figure 13 The aluminum production process[123]

Nowadays, the aluminum industry is advancing its environmental and energy commitments by adopting sustainable practices and renewable energy to reduce its carbon footprint. Emphasizing aluminum recycling, which is more energy-efficient than primary production, the industry is minimizing environmental impacts and conserving resources. Technological innovations are further enhancing production efficiency and waste management, ensuring the industry's operations align with stringent environmental standards and contribute to global sustainability efforts.

3.5. Impact categories

The impact categories that were taken into consideration are the following: Global Warming Potential; Ozone Depletion Potential (steady state); Acidification Potential; Eutrophication potential; Depletion of Abiotic Resources elements; Photo-oxidant creation potential; Embodied Energy and Blue Water Consumption.

The impact categories assessed in this study are presented in **Table 2**, while **Table 3** gives a short explanation and definition of these impact categories. [108], [126]

Table 2 Pre-defined list of environmental impact categories considered in this LCA study

Impact category	Unit	Methodology
Acidification Potential (AP)	Kg SO_2e	CML2001 – Aug. 2016
Global Warming Potential (GWP 100 years)	Kg CO_2e	CML2001 – Aug. 2016
Ozone Depletion Potential (ODP, steady state)	Kg R11e.	CML2001 – Aug. 2016
Eutrophication potential (EP)	Kg PO_4e	CML2001 – Aug. 2016
Depletion of Abiotic Resources (ADP) - fossil	MJ	CML2001 – Aug. 2016
Photo-oxidant creation potential (POCP)	Kg C_2H_4e	CML2001 – Aug. 2016
Embodied Energy	MJ	Energy – Sphera LCA FE
Blue Water Consumption	Kg H_2O	Water – Sphera LCA FE

Table 3 Brief description of the selected environmental impact categories [108], [126]

Impact category	Short description
Acidification Potential (AP)	This relates to the increase in quantity of acid substances in the low atmosphere, at the cause of “acid rain” and the decline of surface waters and forests. AP is caused by direct outlets of acids or by outlets of gases that form acid in contact with air humidity, which are then deposited to soil and water. Examples are: SO2, NOx, ammonia. The main sources for emissions of acidifying substances are agriculture and fossil fuel combustion used for electricity production, heating and transport. AP is described as the ability of certain substances to build and release H+ ions and is given in sulphur dioxide equivalents (SO2-Eq.).
Global Warming Potential (GWP 100 years) – Embodied Carbon	The “greenhouse effect” is the increase in the average temperature of the atmosphere caused by the increase in the average atmospheric concentration of various substances of anthropogenic origin (CO2, CH4, CFC...). Greenhouse gases are components of the atmosphere that contribute to the greenhouse effect by reducing outgoing long wave heat radiation resulting from their absorption by these gases like CO2, CH4 and PFC. The GWP

	is calculated in carbon dioxide equivalents (CO2-Eq.), meaning that the greenhouse potential of an emission is given in relation to CO2. Since the residence time of gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified. A usual period is 100 years. Embodied Carbon refers to the sum of all the GHG emissions (expressed as CO2 equivalents) associated with a product or project's lifecycle. This includes emissions from the extraction of raw materials, manufacturing, transportation, installation, maintenance, and disposal. Embodied Carbon is essentially a measure of the total environmental impact of a project in terms of GHG emissions
Ozone Depletion Potential (ODP, steady state)	Stratospheric ozone depletion (especially above poles) results mainly from a catalytic destruction of ozone by atomic chlorine and bromine. The main source of these halogen atoms in the stratosphere is photo dissociation of chlorofluorocarbon (CFC) compounds, commonly called freons, and of bromofluorocarbon compounds known as halons. These compounds are transported into the stratosphere after being emitted at the surface. In Gabi 7 methodology, the halon 1301 has been replaced by CFC 11 as elementary flow in the petrochemical chain, in line with the recent requirements in the Montreal protocol which regulated and phased out the use of ozone depleting substances. A scenario for a fixed quantity of emissions of a CFC reference (CFC 11) is calculated, resulting in an equilibrium state of total ozone reduction. The same scenario is considered for each substance under study where CFC 11 is replaced by the quantity of the substance. This leads to the ozone depletion potential for each respective substance, which is given in CFC 11-equivalents.
Eutrophication potential (EP)	Aqueous eutrophication is characterized by the introduction of nutrients in the form of phosphatised and nitrogenous compounds for example, which leads to the proliferation of algae and the associated adverse biological effects. This phenomenon can lead to a reduction in the content of dissolved oxygen in the water which may result to the death of flora and fauna. All emissions of N and P to air, water and soil and of organic matter to water are aggregated into a single measure, as this allows both terrestrial and aquatic eutrophication to be assessed. EP is calculated in phosphate eq. (PO4-Eq.).
Depletion of Abiotic Resources (ADP) - fossil	Resources are classified on the basis of their origin as biotic and abiotic. Biotic resources are derived from living organisms. Abiotic resources are derived from the non-living resources (e.g., land, water, and air) that are non-renewable. Non-renewable means a time frame of at least

	500 years. Mineral and power resources are also abiotic resources. The ADP is typically split into two sub-categories, elements and fossil (i.e. energy). ADP elements estimates the consumption of these abiotic resources using the so -called ultimate reserve methodology which refers to the quantity of resources that is ultimately available, estimated by multiplying the average natural concentration of the resources in the earth's crust by the mass of the crust. Similarly, the ADP-fossil measures the consumption of fossil fuels (crude oil, natural gas, coal resources). ADP-fossil is expressed in MJ.
Photo-oxidant Creation Potential (POCP)	The majority of tropospheric ozone formation occurs when nitrogen oxides (NOx), carbon monoxide (CO) and volatile organic compounds (VOCs), such as xylene, react in the atmosphere in the presence of sunlight. NOx and VOCs are called ozone precursors. There is a great deal of evidence to show that high concentrations (ppm) of ozone, created by high concentrations of pollution and daylight UV rays at the earth's surface, can harm lung function and irritate the respiratory system. POCP) is often referred to in ethylene equivalents (C2H4-Eq.).
Embodied Energy	Embodied Energy represents the total energy required to produce a product or service, from the extraction of raw materials to end-of-life disposal. This includes energy consumed during manufacturing, transportation, construction, operation, maintenance, and recycling or disposal phases. It highlights the energy efficiency and environmental impact of materials and processes used throughout the lifecycle of a project or product. Embodied Energy is quantified in megajoules (MJ), offering insights into the energy demand and potential areas for energy conservation and efficiency improvements.
Blue water consumption	Blue Water Consumption measures the volume of surface and groundwater used by a project or product throughout its life cycle, including water consumed in the production of materials, construction processes, and operational use. It addresses the impact on water resources, emphasizing sustainability concerns related to water scarcity, ecosystem health, and the need for efficient water use and management. Blue Water Consumption is expressed in kilograms or cubic meters, highlighting the importance of reducing water use and promoting water conservation and recycling efforts to mitigate environmental impacts.

4. LIFE CYCLE INVENTORY PHASE

In this stage, by employing a strategic segmentation methodology, the construction process is divided into three distinct phases named “Early and Enabling Works”, “Substructure Construction” and “Superstructure Construction”, allowing for the isolation and in-depth examination of each stage's complexities. This approach facilitates a detailed analysis that considers the individual environmental contributions of each phase.

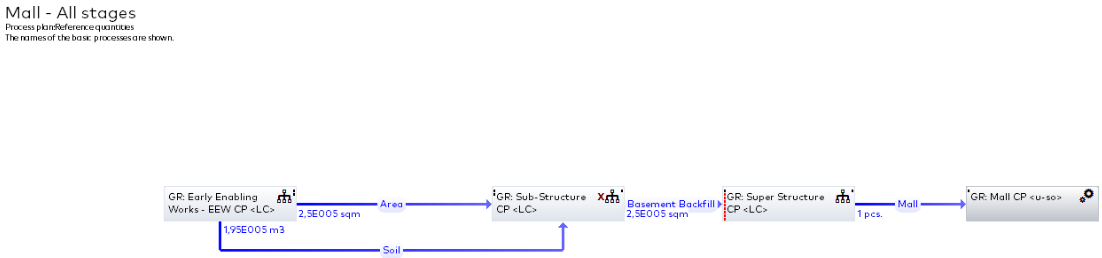


Figure 14 General model of the Mall Complex construction using Sphera LCA FE (GaBi)

4.1. Early and Enabling Works (1st year of construction)

Prior to primary construction activities, foundational operations are imperative in setting the stage for subsequent phases. This includes essential tasks such as site clearance, where environmental considerations are taken into account, especially in the removal and management of vegetation. Dewatering and pumping are crucial for preparing the site, ensuring it is free from water accumulation and suitable for construction. The establishment of construction staff facilities and fencing is also undertaken, with the fencing not only ensuring safety but also clearly marking the working boundary. A significant task in this phase is the extensive excavations for the building's basement, which may include the construction of retaining walls where necessary. These preliminary efforts are crucial in determining the direction and efficiency of the entire construction process.

4.1.1. Machinery – Energy – Water

The machinery used for excavations and related tasks contributes to carbon emissions, noise pollution, and potential ecological disruptions. Based on the above description and the data provided this particular phase includes the usage of the following machinery: Water pumping activities, including machinery such as the Well Drilling Rig, Water Pumps, Dump Trucks, and Excavators in order to manage and transport of water and soil effectively. Site clearance employed machinery like Excavators and Trucks, ensuring efficient demolition and transportation of materials. The construction of retaining walls for excavation slopes, involve the use of equipment like piling rig specifically the Liebherr LB 20.1 with drilling capabilities, and additional supporting machinery like JCBs. Earthworks activities encompassed the use of Excavators, Trucks, Hydraulic Hammers, Kelly Drilling Rig, and Bulldozer D6. The data also encapsulates the extensive hours of operation for each activity, reflecting the intensity of the construction processes undertaken.

The Life Cycle Inventory (LCI) data also include information on diesel and electricity consumption for the equipment and site operation and the overall site water usage.

The total equipment operating hours are estimated at about 96,000 hours for this phase.

For the electricity consumption, site clearance activities demand power for machinery and equipment used in vegetation removal and site preparation. The dewatering and pumping processes involve significant electricity usage to operate pumps that remove water from the site. Setting up and maintaining temporary offices, including lighting, heating or cooling, and powering electronic equipment in construction staff facilities, also requires electricity. Fencing activities use electricity to operate power tools and machinery during installation. Lastly, extensive electricity use is observed in operating heavy machinery for basement excavations and in powering tools and equipment for constructing retaining walls.

Concerning the water usage, during site clearance, water is essential for dust control and cleaning as vegetation and debris are removed. In the dewatering and pumping process, water is utilized to remove accumulated water from the site. The construction of staff facilities necessitates water for sanitation, drinking, and general use within these temporary setups. Fencing involves minimal water usage, primarily for cleaning and preparation purposes. Excavations for the basement require water for soil compaction, dust control, and occasionally for concrete mixing when constructing retaining walls.

4.1.2. Materials

- **Site Offices and Facilities:** A total area of 4000 m^2 was designated for portable office containers, serving as the operational hub for management and coordination. The establishment of these offices required the use of specific materials such as plasterboard for walls, tiles for flooring, and amenities including 16 toilets and 10 sinks, along with two site showers. The roof was predominantly constructed from plasterboard.
- **Fencing:** To demarcate and secure the construction zone, approximately 1,700 meters of fencing were installed around the site perimeter. This fencing not only ensures safety but also designates the working boundary for construction activities.
- **Site Clearance:** Clearance activities predominantly involved the removal of hard surfaces and vegetation spanning 250,000 m2. The site clearance process, particularly the handling of vegetation, is approached with careful environmental considerations. This involves the removal of trees, bushes, and scrubs in a manner that minimizes ecological disruption. Prior to clearance, a detailed ecological survey is conducted to identify and protect any endangered or native species. Strategies such as transplanting mature trees or salvaging usable plant materials for landscaping purposes are employed wherever feasible. The process also adheres to local environmental regulations regarding vegetation management, ensuring minimal impact on local biodiversity and adherence to ecological conservation standards.
- **Site Dewatering and Pumping**: Given the need to keep the site free from water accumulation, extensive dewatering activities were conducted.
- **Retaining Walls:** Critical to the stability of the site, the construction of retaining walls was conducted. This involved the use of RC piles with a combined length of 2,651.5 meters, reinforced with 108,000 kg of B500c reinforcement. Additionally, shotcrete application covered an area of 4,200 m^2, utilizing a wire mesh T131 weighing 9,200 kg.
- **Excavation:** The excavation, which is fundamental to the entire construction process, resulted in the excavation of approximately 1,200,000 m^3 of material, 70% of which consisted of soil and the remaining 30% being rock.

- **Temporary Services:** Ensuring the smooth operation of the construction site involved setting up temporary services. This included 2,000 meters of water distribution pipes and an electricity network containing 1520 meters of cables. Additionally, a temporary drainage system was set up using 584 meters of drainage pipes.

4.1.3. Waste Management Strategies

The waste generated from site clearance activities, including removed vegetation and hard surfaces, is managed through a comprehensive waste management plan. This plan prioritizes the reuse and recycling of materials to reduce environmental impact. Hard surface materials, such as concrete or asphalt, are processed for reuse in other construction projects or recycled into new building materials. Organic waste, like vegetation, is either composted or, if suitable, used in landscaping activities. Any non-recyclable waste is disposed of responsibly, following environmental guidelines to minimize landfill impact. The waste management strategy aims to achieve a high rate of material recovery and recycling, aligning with sustainable construction principles and reducing the overall environmental footprint of the clearance phase.

4.1.4. Schematic of the model

The model regarding the Early and Enabling Works construction phase, as it was developed by Sphera LCA FE (GaBi) software, is schematically shown in Figure 15.

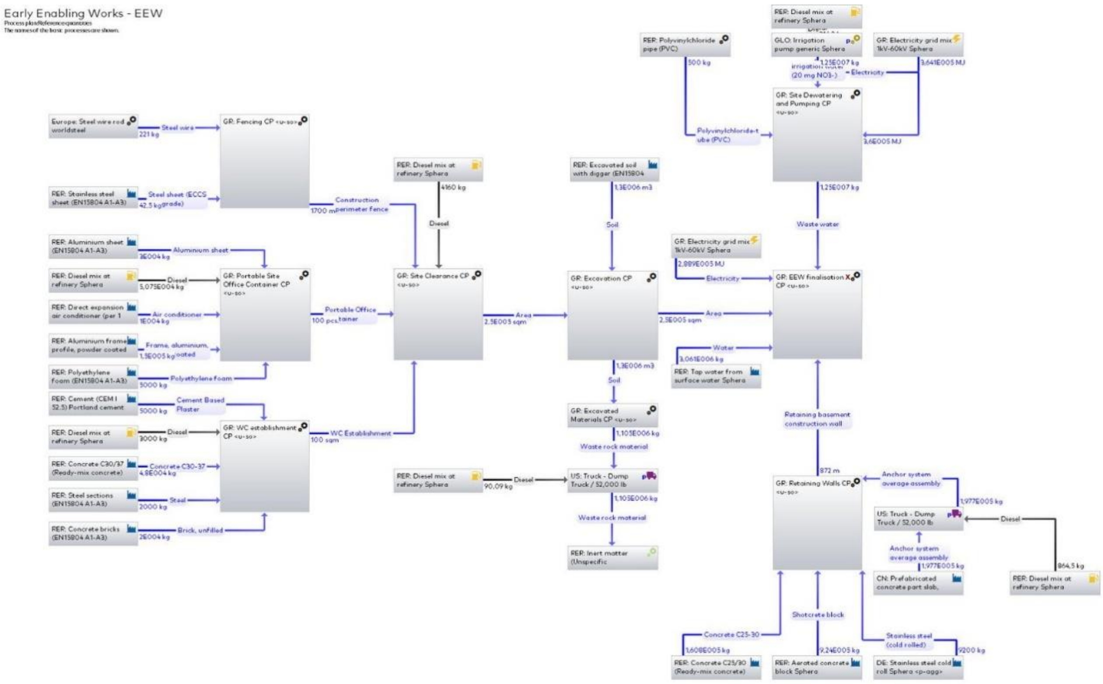


Figure 15 Model of the Early and Enabling Works construction phase using Sphera LCA FE (GaBi)

4.2. Substructure Construction (2nd year of construction)

The Substructure Construction phase lays the groundwork for the Mall Complex, establishing a robust foundation essential for the durability and safety of the entire structure. This phase involves piling, establishing footings, and constructing the building's basement, the external enclosing walls below ground level and some backfilling. The construction of the basement is a major undertaking in this phase. This below ground level serves multiple functions, such as providing parking, housing mechanical systems, and offering storage spaces. It necessitates meticulous coordination as it involves complex formwork, reinforcement, and concrete pours to create a watertight and pressure-resistant structure capable of withstanding the surrounding earth's load and any groundwater pressures. In tandem with the basement construction, the external enclosing walls below ground level are erected. The construction process for these walls is carried out with precision to ensure a seamless integration with the basement and footings, forming a continuous barrier against soil and water ingress.

4.2.1. Machinery – Energy – Water

As in the previous case, the machinery used for substructure construction contributes to carbon emissions, noise pollution, and potential ecological disruptions. This phase involves the use of specialized machinery as follows: Telescopic Mobile Concrete Pumps deliver concrete with precision, while JCBs manage material handling and site preparation. Dump Trucks and Concrete Mixer Trucks handle the transportation and mixing of concrete. Tower Cranes and Telescopic Mobile Cranes move heavy materials, and Telehandlers provide versatile on-site logistics. Tandem Rollers ensure the sub-base is compact and level. Bobcat E26 Mini Excavators perform precise excavation work for the assembly of underground walls and slabs. Concrete Pumps and Mixer Trucks are central to the concrete operations, with Tower Cranes facilitating vertical construction and Mini Dump Trucks removing site debris. For Tower Crane Base Works, Concrete Mixer Trucks supply concrete for the crane base, and Concrete Pumps ensure its precise placement. Bobcat Excavators and Mini Dump Trucks prepare the site, while Telescopic Mobile Cranes position heavy equipment and materials. During backfilling, Excavators are used for earthmoving, Water Tanks manage soil moisture control, and Trucks transport materials. Rollers compact the soil, and graders level the area.

The LCI data also include information on diesel and electricity consumption for the equipment and site operation and the overall site water usage.

The operations reflect the construction process's intensity, with total equipment operating hours estimated at approximately 150,000 hours for the phase.

Regarding electricity consumption, the piling process requires power for the machinery that drives the piles. The construction of footings uses electricity to operate mixers, concrete pumps, and related machinery. Basement construction demands extensive use of electricity for excavation, operating formwork machinery, and concrete pouring equipment, in addition to powering lighting and tools for below-groundwork. The formwork and reinforcement phase consumes electricity in operating tools for assembling formwork and cutting and placing reinforcement bars. For concrete pours, electricity powers concrete mixers, pumps, and vibrators. In the construction of external enclosing walls, electricity is used for machinery and tools involved in the construction process. Finally, the backfilling process requires electricity to power machinery such as compactors and excavators.

In terms of water usage, during the piling process, water is occasionally used to lubricate piles or manage dust. For footings, water plays a crucial role in mixing concrete, as well as in dust control and cleaning activities. In the critical task of basement construction, water is extensively used for concrete mixing, curing, and dust control, and is necessary for soil compaction and preparation. Formwork and reinforcement stages require minimal water, mostly for cleaning purposes. The concrete pouring process relies heavily on water for mixing concrete and may also require additional water for curing processes. In constructing external enclosing walls, water is used for mixing concrete and potentially for cleaning and preparing surfaces. Lastly, during backfilling, water is employed for moisture conditioning and compaction of fill material.

4.2.2. Materials

During the substructure phase of construction, a variety of materials were utilized, each chosen for their specific properties and environmental certifications.

- **Basement Construction:** The construction of the lowest floor incorporated reinforced concrete raft slabs of varying thicknesses, supported by up-to-date EPD to ensure compliance with ISO standards. Cast in-situ concrete with a grade of C30/37 formed the basis of the slabs, pads, and water tank constructions, with precise volumes calculated for each element. The reinforcement quantities were substantial, with weights of 78,000 kg for the 500mm slab, 6,400,000 kg for the 700mm slab, and 3,944,000 kg for the 1800mm slab. Additional elements included pad foundations for columns and blinding beds below the raft, with concrete volumes of 8,500 m^3 for the 1200mm thick pads and 10,500 m^3 for the blinding beds, each complemented by the necessary reinforcement. Environmental considerations extended to the water tank construction and the installation of under-slab waterproofing membranes and geotextiles. These measures not only provided structural integrity but also ensured the longevity and resilience of the construction against water ingress.
- **Backfilling:** For the backfilling process, 15% of the excavated volume was reutilized to shape the landscape and support the newly constructed substructure elements, completing the phase with attention to both structural and environmental detail.

4.2.3. Waste Management Strategies

A well-established waste management strategy for the Substructure Construction phase has been implemented. It prioritizes resource efficiency and the minimization of environmental impacts. It involves the systematic sorting and recycling of waste materials, such as concrete and steel, which are prevalent in this phase due to piling, footing establishment, and basement construction. A clear protocol for separating reusable and recyclable materials from waste is followed established on-site. Additionally, strategies which include the use of low-impact materials with valid EPDs, which ensure compliance with sustainability standards and provide transparency regarding their production and potential recyclability, are applied. Waste reduction is also achieved by accurate ordering and inventory control to prevent excess materials. Water used in the process is managed and recycled where possible, for instance in dust suppression or as part of the concrete curing process. Energy consumption is also optimized by employing machinery that meets the latest emissions standards and by scheduling operations to maximize efficiency.

4.2.4. Schematic of the model

The model regarding the substructure construction phase, as it was developed by Sphera LCA FE (GaBi) software, is schematically shown in Figure 16:

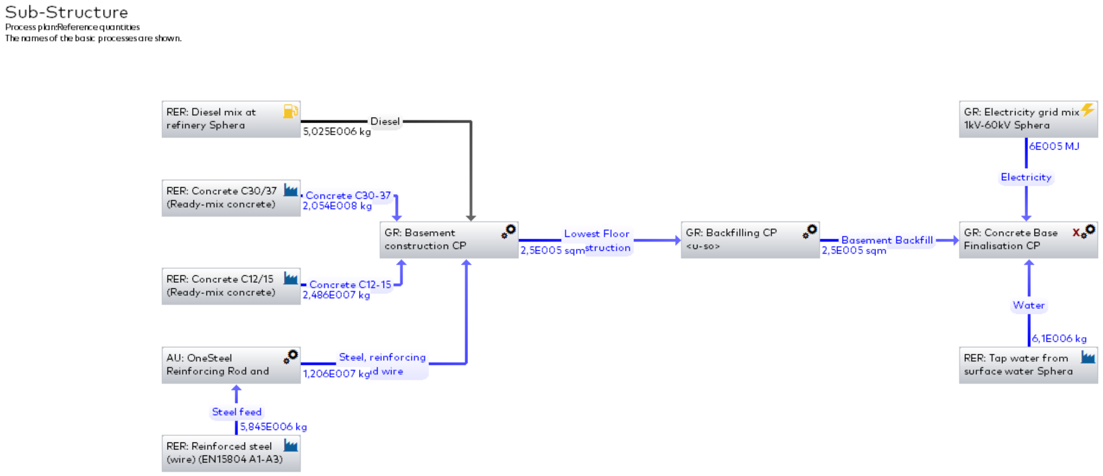


Figure 16 Model of the Substructure construction phase using Sphera LCA FE (GaBi)

4.3. Superstructure Construction (3rd and 4th years of construction)

The Superstructure which constitutes the above ground construction of the Mall Complex, shapes the building's visual profile and functional identity. This the most intricate phase of the project, so it is further divided into six distinct sub-phases/packages, each characterized by unique elements, allowing for an in-depth analysis of each component:

Table 4 Superstructure Construction breakdown

Superstructure Construction breakdown	
1	Structural Elements
2	Conveying Systems
3	Façade
4	MEP (Mechanical Electrical and Plumbing)
5	Finishes
6	External works

It needs to be highlighted that from a construction standpoint, the interdependency of the above-mentioned packages is critical because the completion of one often relies on the progress of another. For instance, the structural elements must be in place before the façade can be attached, and the MEP systems need to be installed before or concurrently with certain finishing works. On the other hand, from a LCA perspective, it is practical to evaluate these packages individually. This LCA treats all packages as separate entities. This approach allows for an in-depth analysis and facilitates the identification of specific environmental impacts and the implementation of mitigation strategies for each distinct package. It also enables a more detailed assessment of potential improvements in materials selection, construction techniques, and waste management practices. This detailed analysis is crucial for understanding the full scope of the project's environmental footprint and for informing decisions that lead to a sustainable building process. The findings contribute to a comprehensive LCA that encompasses all aspects of construction while maintaining accurate results.

4.3.1. Machinery – Energy – Water

The execution of the Superstructure Construction phase encompasses the utilization of specialized machinery across various packages as follows:

- Structural Elements require Tower Cranes for erecting components, while Mobile Concrete Pumps and Truck Mounted Concrete Pumps facilitate the distribution of concrete. Skid Steer Loaders, Mini Excavators, and Mini Dump Trucks are engaged in material handling and site preparation, critical for laying the foundation and erecting structural frameworks.
- For the Conveying Systems and MEP systems, Telehandlers provide the precise placement of materials, and Telescopic Mobile Cranes are essential for the installation of heavier elements.
- The Façade work utilizes Construction Manriders and Cherry Pickers for high-elevation access, while Telehandlers and Tandem Rollers assist in material preparation and placement.
- Finishes involve Electric Power Tools for detailed work, with Telehandlers moving materials as needed. Skid Steer Loaders' flexibility is crucial for space management during interior finishing tasks.
- External Works incorporate the use of Asphalt Spreaders and Pavers for laying road surfaces, with Dump Trucks handling bulk material transport. Tandem Rollers are vital for surface compaction, impacting the final look and utility of outdoor areas.
- Noteworthy, alongside the primary construction equipment, an array of smaller tools is essential Electric Power Tools execute precision tasks required for the majority of the packages. Scaffolding Systems and Scissor Lifts facilitate access for the construction of the façade and MEP installations. Hand Trolleys and Pallet Jacks move materials within the site. Portable Mixers provide concrete mixing capabilities on demand, particularly useful in the finishing stages and for External Works. Laser Levels ensure the precision of structural installations, while Air Compressors drive various pneumatic tools to boost productivity. Portable Lighting ensures visibility across the construction site, and Pressure Washers are employed to clean areas before finishing. Additionally, Portable Generators supply power where needed, and Vibratory Plate Compactors prepare the ground in External Works.

The LCI data also include information on diesel and electricity consumption for the equipment and site operation taking into consideration the smaller tools extensive usage and the overall site water usage.

The total operating hours for the primary construction equipment are estimated at approximately 260,000 hours for this phase.

Regarding electricity consumption, structural elements involve the use of electricity to power tools and the corresponding machinery for cutting, welding, and assembling steel structures, and for operating cranes and lifting equipment. Electricity is essential in the installation and testing of elevators and escalators in conveying systems, also powering assembly and alignment tools. The construction of the façade requires electricity for tools needed in cutting, fitting, and securing façade materials. A substantial amount of electricity is consumed during the MEP phase, where it's used for installing wiring, lighting, HVAC systems, and other electrical components. In the finishes phase, electricity is used for lighting, power tools, and machinery for painting, flooring, and ceiling and partition installation. Lastly, external works involve the use of electricity for outdoor lighting systems, power tools, and machinery in landscaping and installing external features.

For water usage, the mixing and curing of concrete for structural elements such as columns, beams, and slabs require significant amounts of water, alongside its use for dust control during cutting and assembly processes. In the construction of conveying systems, water usage is relatively minimal, primarily for cleaning and sanitation. The façade construction utilizes water for surface cleaning and preparation, as well as for mixing adhesives or mortars when necessary. In the Mechanical, Electrical, and Plumbing (MEP) phase, water is crucial for testing plumbing lines, leak detection, and the commissioning and testing of HVAC systems. The finishing phase extensively uses water for plastering, mortar mixing, and surface cleaning. Additionally, significant water usage is observed in landscaping activities during the external works, where it's used for planting, irrigation, and preparing external areas.

4.3.2. Materials

4.3.2.1. Structural Elements Package

The Structural Elements Package pertains to the structural items required for the above ground construction of the building. All structures related to the façade systems (e.g., entrance canopies, steel subframes), skylight systems (steel structures, space frames, etc.) are included in either the Façade or Finishes Packages. All structures required for landscaping/hardscaping and other ancillary structures that are not part of the main buildings (e.g., MEP enclosures, access ladders, etc.) are included in the External Works Package. The works included in the Structural Elements Package are the following and comprise the supply and furnishing of materials, and their installation:

- **Steel Frames**: Steel frames are structural supports made from steel components such as beams, columns, and connections, providing a high strength-to-weight ratio and flexibility in design. They are used to resist both vertical and horizontal forces in a building's structure.
- **Space Frames/Decks**: Space frames are three-dimensional truss systems that support loads through interlocking struts in a geometric pattern, offering great spans without internal columns. Decks are flat structural panels, like floors or roofs, typically made of metal or concrete, providing a surface and structural support.
- **Concrete Frames**: Concrete frames consist of a rigid skeleton made of reinforced concrete columns and beams. They are designed to carry the loads of the building and withstand external forces, offering durability and fire resistance.
- **Floors**: Floors are horizontal structures in buildings that divide levels and provide a flat surface for occupants and furniture. They are constructed from materials like concrete, timber, or composite elements and can include insulation, acoustic, and thermal properties.
- **Roof Structure**: The roof structure is the uppermost part of a building, designed to provide protection from the weather and to support roof coverings. It often includes sloped or flat structural elements such as rafters, trusses, or purlins.

- **Stairs and Ramps**: Stairs are a series of steps providing vertical circulation between different floors of a building, while ramps are sloped surfaces that allow easier access, particularly for wheelchairs or as an alternative to steps. Only the structural elements are included in this particular package.
- **External Enclosing Walls Above Ground Level**: These are the outer walls of a building that define its perimeter and provide security and protection from external elements. They can offer thermal insulation, support structural loads, and contribute to the building's aesthetic.

4.3.2.2. Conveying Systems Package

The Conveying Systems Package pertains to the items required for the vertical circulation of passengers and goods. The works included in the Conveying Package are the following and comprise the supply and furnishing of materials, and their installation:

- **Lifts and Enclosed Hoists:** Lifts (elevators) are vertical transportation systems that move people or goods between floors within a building, using a cabin that travels in a shaft. Enclosed hoists are similar but are typically used in industrial settings for lifting heavy goods, often with open or mesh enclosures.
- **Escalators and Travelators**: Escalators are moving staircases that facilitate the transportation of people between floors of a building, operating on a continuous loop. Travelators, or moving walkways, are horizontal or inclined conveyors that transport people across flat or slightly angled distances within areas like airports or malls.
- **Ramps and Related Mechanisms**: Ramps are inclined planes installed in addition to or instead of stairs, designed to enable easy access for wheelchairs, carts, and people with mobility issues. Related mechanisms can include wheelchair lifts and inclined platform lifts, which are devices specifically designed to move wheelchairs.

4.3.2.3. Façade Package

The Façade Package pertains to the items required for the build-up of the above ground external wall systems, parapets, skylights, as well as facade windows and doors. Structural steel elements of skylights, main entrance facades and canopies/pergolas, façade ventilation enclosures, Pavilion façade and entrance. The works included in the Façade Package are the following and comprise the supply and furnishing of materials, and their installation:

- **Rooflights, Skylights, and Openings**: Rooflights and skylights are glazed openings in a roof designed to allow natural light to enter the building. They can provide ventilation and can also be an aesthetic feature. Openings in the roof are designed to provide light, air, or access and can be covered with transparent or translucent materials.
- **External Enclosing Walls Above Ground**: These are the exterior walls of a building from the ground level up, providing structural support, thermal insulation, and protection from the weather. They also contribute to the building's appearance and can include features like windows and doors.
- **External Soffits**: Soffits are the undersides of architectural structures such as arches, balconies, or overhanging eaves. External soffits are often used to conceal roof overhangs and the underside of decks, providing a finished look and protecting against the elements.
- **Subsidiary Walls, Balustrades, and Proprietary Balconies**: Subsidiary walls are secondary walls that divide spaces within a structure. Balustrades are protective

barriers that can be found on staircases, balconies, and decks. Proprietary balconies are pre-engineered and manufactured balcony systems that can be attached to a building structure as a feature.

- **Ancillary Buildings and Structures**: Ancillary buildings and structures are additional constructions that support the function of the main building. These can include sheds, garages, storage buildings, and other small structures.

4.3.2.4. MEP Package

The MEP Package pertains to the below and above ground services, excluding conveying systems (e.g., lifts, escalators, travelators, etc.) which are part of the Conveying Systems Package, and passive firefighting systems (fire curtains, fire shutters, etc.), which have been included in the Finishes Package. The works included in the MEP Package are the following and comprise the supply and furnishing of materials, and their installation:

- **Sanitary Appliances**: Fixtures such as toilets, urinals, sinks, and bidets that are installed for personal hygiene and are connected to the building's plumbing system.
- **Sanitary Ancillaries**: Additional fittings and accessories that support the use of sanitary appliances, including taps, soap dispensers, towel racks, and toilet paper holders.
- **Foul Drainage**: A system designed to carry away wastewater from sanitary appliances and kitchen facilities to a sewer or treatment facility.
- **Irrigation**: An infrastructure system that supplies water to plants for agriculture, landscaping, and maintaining green spaces.
- **Mains Water Supply**: The primary pipeline and infrastructure that brings potable water from a municipal supply or other sources into a building.
- **Cold Water Distribution**: The system within a building that distributes cold water from the mains supply to various outlets and appliances.
- **Hot Water Distribution**: The network of pipes and fixtures that convey hot water from the heating source to taps and appliances throughout a building.
- **Heat Source Equipment**: Devices and systems such as boilers, heat pumps, or solar thermal panels that generate heat for a building.
- **Central Air Conditioning Systems**: A single system that provides conditioned air to multiple spaces within a building from a central location.
- **Local Air Conditioning System**: Individual air conditioning units installed in specific areas or rooms, providing localized temperature control.
- **Central Ventilation Systems**: Ventilation systems that supply fresh air and exhaust stale air throughout a building from a central point.
- **Local Ventilation Systems**: Individual ventilation units installed in particular areas, typically where localized airflow is needed.
- **Smoke Extraction and Control Systems**: Systems designed to remove smoke from a building in the event of a fire and to control the movement of smoke.
- **Electrical Mains and Submains Distribution**: The infrastructure that distributes electricity from the main supply point to subsidiary circuits or locations within a building.
- **Power Installations**: The components and systems installed in a building to distribute and control electrical power for various uses.
- **Lighting Installation**: All fixtures, wiring, and controls installed to provide artificial illumination in a building.

- **Local Electricity Generation Systems**: Systems such as solar panels or wind turbines that generate electricity on-site for use within the building.
- **Earthing and Bonding**: Safety systems designed to protect against electrical shock by providing a path to the ground for electrical currents.
- **Natural Gas Distribution System**: The infrastructure that conveys natural gas from a main supply to appliances and systems within a building.
- **Dock Levellers and Scissor Lifts**: Mechanical devices used to bridge the gap between a dock and a vehicle or to lift goods to different heights within a facility.
- **Firefighting Systems**: Equipment and systems, including hydrants, hose reels, and fire extinguishers, installed for combating fires.
- **Fire Suppression Systems**: Automated systems such as sprinklers and gas suppression systems that detect and extinguish fires.
- **Lightning Protection**: Systems designed to protect a structure from damage due to lightning strikes, typically by safely conducting the electrical charge to the ground.
- **Communication Systems**: Infrastructure for telecommunications, including telephone, internet, and data communication networks.
- **Security Systems**: Systems installed to ensure the safety of a building's occupants and to protect property, including alarms, cameras, and access control systems.
- **Central Control Building Management System**: An integrated system that monitors and controls various building systems for efficiency and comfort.
- **Specialist Refrigeration Systems**: Custom-designed refrigeration systems for specific applications, such as medical storage or industrial cooling.
- **Specialist Electrical/Electronic Installations**: Highly specialized electrical or electronic systems designed for specific functions within a building, such as medical equipment, data centres, or laboratory apparatus.
- **Water Features**: Installations such as fountains, ponds, and waterfalls designed for aesthetic purposes and to enhance the landscape or interior spaces.
- **Builder's Works in Connection with Services**: Structural modifications or accommodations made in a building to facilitate the installation of services like plumbing, HVAC, or electrical systems.
- **Irrigation Systems**: A network of pipes and outlets designed to deliver water efficiently to landscapes, crops, or green spaces for growth and maintenance.
- **Surface Water and Foul Water Drainage**: Systems that manage rainwater runoff (surface water) and wastewater (foul water) from buildings and their surrounding areas.
- **Ancillary Drainage Systems**: Supplementary systems that support primary drainage by managing overflow, providing access for maintenance, and separating different types of wastewaters.
- **External Chemical, Toxic, and Industrial Liquid Waste Drainage**: Specialized drainage systems designed to safely transport potentially hazardous or contaminated liquids away from a site.
- **Land Drainage**: Infrastructure that removes excess water from the soil to prevent waterlogging, typically used in agricultural and landscaping applications.
- **Water Mains Supply**: The primary pipeline that delivers potable water from municipal or regional sources to buildings and facilities.
- **Electricity Mains Supply**: The main electrical distribution system that provides power from the grid or power stations to buildings and other structures.

- **External Transformation Devices**: Equipment such as transformers that alter the voltage of electrical power for safe and efficient distribution and use in external applications.
- **Electricity Distribution to External Plant and Equipment**: The network that provides electrical power to outdoor machinery, lighting, and other equipment.
- **Gas Mains Supply**: The supply system that delivers natural gas from utility providers to consumers for heating, cooking, and other uses.
- **Telecommunication and Other Communication System Connections**: Infrastructure for connecting a building to external telecommunication networks, including internet, phone, and data services.
- **External Fuel Storage and Piped Distribution Systems**: Facilities for storing fuels like oil or gas and the associated piping systems that deliver the fuel where needed.
- **External Security Systems**: Outdoor security installations including surveillance cameras, motion detectors, and perimeter security systems.
- **External Street Lighting Systems**: Public or private lighting installations that illuminate streets, pathways, and outdoor areas for visibility and safety.
- **Builder's Work in Connection with External Services**: Construction activities and adaptations made to the external parts of a building to accommodate services such as water, gas, and electricity infrastructures.

4.3.2.5. Finishes Package

The Finishes Package pertains to the architectural items required for the build-up of the interior of the buildings, e.g., internal partitions, doors, floors, walls, ceilings, etc., as well as all FF&E. The works included in the Finishes Package are the following and comprise the supply and furnishing of materials, and their installation:

- **Stair/Ramp Finishes**: The surface materials applied to stairs or ramps, which can include tiles, wood, carpet, or any durable surface that contributes to the aesthetic and safety through non-slip properties.
- **Stair/Ramp Balustrades and Handrails**: Protective barriers along the side of stairs or ramps, which include vertical posts (balustrades) and a horizontal top piece (handrail) to aid in stability and safety for users.
- **External Soffits**: The finished underside of external architectural elements, such as the roof overhang or arches, which can provide a decorative touch and protect the structure from weather elements.
- **External Walls Above Ground (Taxi Drop-off)**: The outside walls of a building that face the taxi drop-off area, typically designed to be durable and may include doors, windows, or protective barriers.
- **Walls and Partitions**: Vertical structures that divide spaces within a building, which can be permanent (walls) or movable (partitions).
- **Balustrades and Handrails**: Safety features installed alongside stairs, balconies, or elevated areas, consisting of a row of balusters topped by a handrail, to prevent falls.
- **Cubicles**: Small, enclosed areas often used in office spaces or public toilets, separated by partitions.
- **Internal Doors**: Doors within a building that provide access to rooms, contribute to the interior design, and offer privacy, security, and acoustic isolation.
- **Wall Finishes**: The final layer or coating applied to a wall that provides a decorative surface and may also protect the wall from damage.

- **Finishes to Floors**: The top layer of flooring material that is visible, such as carpet, hardwood, tile, or laminate, providing a certain look and durability.
- **Raised Access Floors**: A type of floor that creates a void for the passage of mechanical and electrical services. It is often used in commercial buildings to facilitate underfloor air distribution and cable management.
- **Finishes to Ceilings**: The final treatment of the ceiling surface, which can include paint, plaster, or decorative elements that contribute to both aesthetics and functional aspects like acoustics.
- **False Ceilings**: A secondary ceiling hung below the main structural ceiling, which can conceal infrastructure like wiring and ductwork, and can contribute to thermal insulation and acoustics.
- **Demountable Suspended Ceilings**: Suspended ceilings that are easily removable, allowing access to the void above for maintenance of services or alterations.
- **General Fittings, Furnishings, and Equipment**: The movable items that outfit a building's interior, such as furniture, fixtures, and general equipment that are not permanently attached to the building's structure.
- **Domestic Kitchen Fittings and Equipment**: The cabinetry, appliances, and accessories specific to the function and operation of a domestic kitchen.
- **Special-Purpose Fittings, Furnishings, and Equipment**: Items that are designed for specific functions within a building, such as laboratory benches, hospital beds, or theater lighting systems.
- **Signs/Notices**: The posted information within a building used to direct occupants, provide information, safety warnings, or regulatory postings.
- **Works of Art**: Decorative elements that are intended to be aesthetically pleasing and contribute to the cultural ambiance of a building, such as paintings, sculptures, or installations.
- **Internal Planting**: Indoor landscaping that includes the use of plants and greenery to enhance the indoor environment, air quality, and aesthetics.
- **Passive firefighting systems:** Built-in structural features that slow fire spread without manual activation or electricity, such as fire-resistant walls, doors, fire curtains and fire shutters. These systems aim to contain fires, protect the building's structural integrity, and provide more time for evacuation. They complement active systems to enhance overall building safety against fires.

4.3.2.6. External Works Package

The External Works Package pertains to the items required for the build-up of the landscaping (hardscape and softscape), in addition to ancillary structures/finishes that do not form part of the main buildings (e.g., external staircases, MEP enclosures, chimney enclosures, planter walls, etc.). The works included in the External Works Package are the following and comprise the supply and furnishing of materials, and their installation:

- **Stair/Ramp Finishes**: The surface treatments applied to stairs and ramps, enhancing aesthetics and safety with materials like stone, tile, rubber, or wood, often with non-slip textures.
- **Roads, Paths, and Pavings**: The constructed surfaces for vehicular and pedestrian use, including highways, walkways, and patios, using materials such as asphalt, concrete, pavers, or gravel.

- **Seeding and Turfing**: The process of establishing new grass areas by either sowing seeds or laying pre-grown turf to create lawns or grassed spaces.
- **External Planting**: The strategic placement and cultivation of plants and trees in outdoor areas for aesthetic, environmental, or functional purposes.
- **Irrigation Systems**: Engineered networks of pipes and sprinklers designed to distribute water to landscapes for maintenance and growth of vegetation.
- **Walls and Screens**: Vertical structures that define spaces, provide privacy, and protect against elements, with screens often serving a more decorative and permeable partitioning function.
- **Barriers and Guardrails**: Safety installations along edges of roads, paths, or elevated areas to prevent accidental falls or to control the flow of traffic or people.
- **Site/Street Furniture and Equipment**: Functional and decorative objects placed in public spaces, such as benches, trash bins, lighting, bollards, and bike racks.
- **Ornamental Features**: Decorative elements within a landscape, like statues, fountains, or arches, that contribute to the visual appeal and character of an area.
- **Ancillary Buildings and Structures**: Supplementary constructions on a site that support the main building's functions, such as sheds, garages, or utility buildings.

4.3.3. Waste Management Strategies

Waste management in the Superstructure Construction phase is a multifaceted approach that is incorporated into each sub-phase in order to reduce environmental impact and promote sustainability.

- For Structural Elements, waste management includes recycling scrap metal and concrete. Excess steel from frames and decks is sent to metal recycling facilities, while concrete waste is crushed and reused in new mixes or as aggregate.
- Conveying Systems and MEP require careful dismantling of obsolete systems for component recycling. Metals, plastics, and electronics are sorted and recycled according to local regulations.
- The Façade involves managing waste from cut-to-size materials, with offcuts being recycled or repurposed where possible. Glass and metal recycling is prioritized to minimize the impact of façade construction.
- Finishes generate a significant amount of waste too, including offcuts from materials like drywall, wood, and carpeting. These are reduced by precise measurement and cutting, with any waste being separated for recycling or donation for reuse.
- External Works produce waste from excess materials like paving stones, asphalt, and soil. With proper planning these wastes are minimized and materials are often reused on-site.

4.3.4. Schematic of the model

The model regarding the superstructure construction phase, as it was developed by Sphera LCA FE (GaBi) software, is schematically shown in Figure 17:

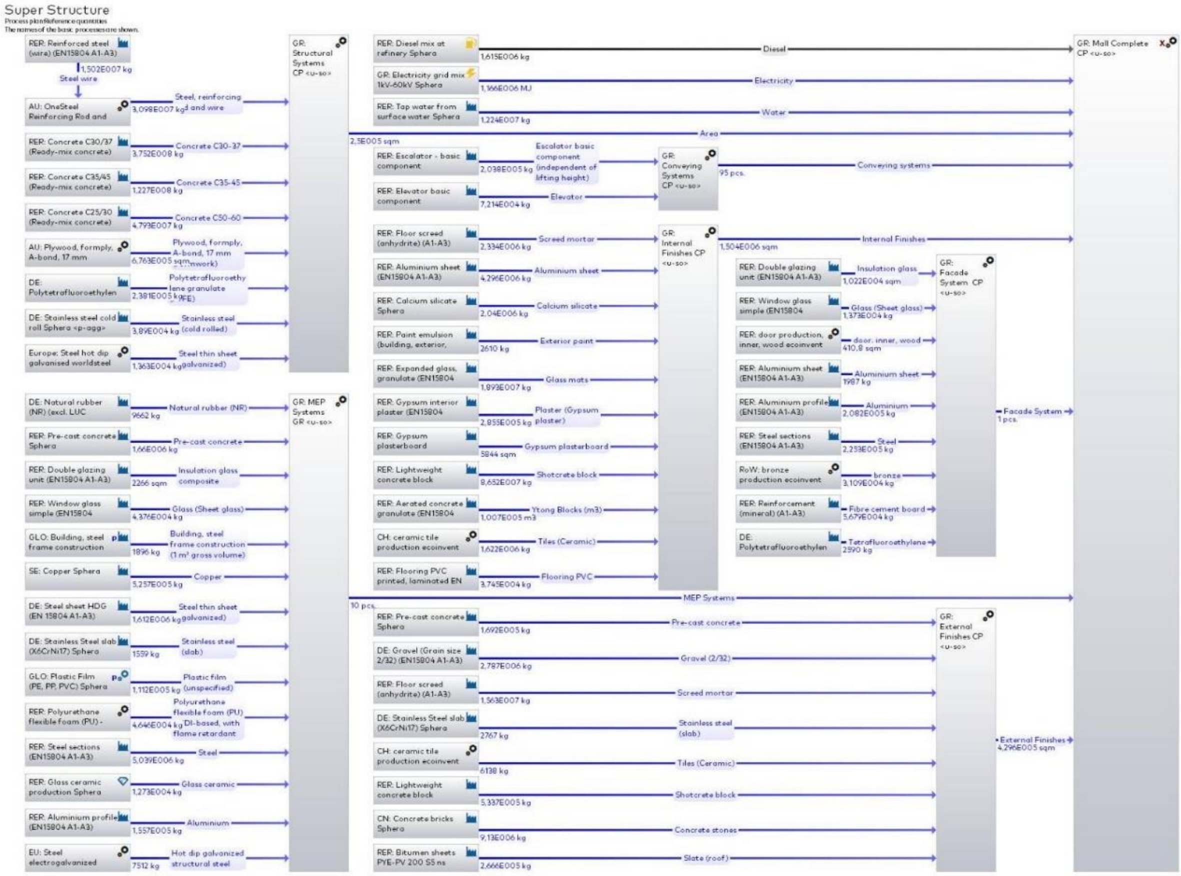


Figure 17 Model of the Superstructure *construction phase using Sphera LCA FE (GaBi)*

5. LIFE CYCLE IMPACT ASSESSMENT RESULTS

5.1. Impact categories analysis

A LCA measures the environmental impacts of a product or service, considering the emissions attributed from materials extraction and products use and disposal and acquired from computational models or actual measurements. These emissions are processed and interpreted into environmental impacts by applying characterization factors. LCA covers various environmental impact categories, which represent broad measures of environmental change caused by different types of emissions.

ISO 14044 [99] established the selection of impact categories to be align with the study's goals and the intended applications of the results. It also emphasizes comprehensiveness, covering all significant environmental issues related to the system under study. The adopted impact categories in this study conform to the standards set by CEN TC 350 (EN 15804 [127]) for assessing the sustainability of construction works, ensuring a comprehensive and goal-aligned selection. These indicators address each primary environmental issue from a life cycle perspective. [128]

The impact categories that were taken into consideration in this study and the associated environmental indicators for these categories are presented in **Table 2** and **Table 3**.

The standard categories selected for the LCIA include Abiotic Depletion Potential for fossil resources, Acidification Potential, Eutrophication Potential, Global Warming Potential over 100 years (which can be treated as Embodied Carbon for the scope of this study), Ozone Depletion Potential in a steady state, and Photo-oxidant Creation Potential. These categories are fundamental to LCA studies and provide a framework for assessing the broad environmental impacts of projects/process/products.

The selected LCIA method for the above-mentioned impact categories is CML due to its established framework for environmental impact analysis. Developed by the Institute of Environmental Sciences at Leiden University, the CML method provides a detailed set of impact categories and characterization factors. This method enables precise quantification of all the relevant environmental impacts. Its use in the study ensured that the environmental assessment was up to date, incorporating the latest updates in impact categories. [126]

In order to address specific environmental concerns related to the construction of buildings this study also considers, in addition to the standard categories, Embodied Energy and Water Consumption as extra impact categories and they are calculated by other libraries of Sphera LCA FE (GaBi). Embodied Energy quantifies the total energy consumption associated with the building's materials and construction processes, identifying opportunities for energy savings. Water Consumption evaluates the project's use of water resources, highlighting the importance of efficient water management.

Finally, by defining and explaining the significance of each impact category, this study aims to offer a clear understanding of how each category contributes to the overall environmental footprint of the project:

5.1.1. Global Warming Potential [129]

The “greenhouse effect” is the increase in the average temperature of the atmosphere caused by the increase in the average atmospheric concentration of various substances of anthropogenic origin (CO_2, methane, etc.). The GWP is a measure of the emission GHG, such as CO_2, perfluorocarbon (PFC) and methane (CH_4), and is expressed as kilograms of CO_2-equivalents. GHG emissions are found to cause an increase in the absorption of radiation emitted by the sun and reflected by the earth, magnifying the natural “greenhouse effect”. Since the residence time of gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified. The common period is 100 years. [126]

For the scope of my LCA study, which focuses on stages A1-A5 of a construction project (covering material extraction through to installation), Embodied Carbon is effectively equated with the Global Warming Potential (GWP) over 100 years. Embodied Carbon measures the total greenhouse gas (GHG) emissions in CO2 equivalents (CO2e) from all lifecycle stages of construction materials and processes. This assessment is crucial for identifying and mitigating the climate impacts of construction activities by pinpointing significant emission sources and implementing reduction strategies. These strategies may include selecting materials with lower carbon footprints, optimizing processes, and incorporating recycling and carbon capture technologies.

Embodied Carbon is vital in the urgent global effort to reduce GHG emissions and combat climate change. It offers a detailed perspective on emissions related to construction materials and processes, complementing the broader GWP category. This specificity enables targeted actions to decrease emissions throughout the design, construction, and operational phases of projects.

Incorporating Embodied Carbon into the Life Cycle Impact Assessment (LCIA) process is aligned with ISO 14044 and CEN TC 350 (EN 15804) standards, ensuring a comprehensive evaluation of a project's impact on climate change. This approach highlights the importance of addressing carbon emissions in sustainability efforts, guiding the construction industry towards practices that minimize environmental impacts and contribute to global sustainability goals.

5.1.2. Acidification Potential [129]

Acidification potential describes the acidifying effect of substances in water and soil, highlighting the environmental impact of increased acidity due to substances like carbon dioxide dissolving in water. This effect, primarily noted on a local scale within LCA context, includes the reduction of pH levels, leading to acid rain and the consequent degradation of surface waters and forests. Beyond local implications, acidification extends to global concerns, particularly ocean acidification, which threatens marine biodiversity and, by extension, human food sources by jeopardizing the survival of certain species. [130]

Acidification is attributed to the emission of acid substances and their precursors, such as sulfur dioxide (SO_2), nitrogen oxides (NOx), and ammonia, into the lower atmosphere. These emissions originate from various sources, including agriculture and the combustion of fossil fuels for electricity production, heating, and transport. Upon reacting with atmospheric moisture, these gases form acidic compounds that subsequently deposit onto soil and water bodies, further contributing to environmental acidification.

AP serves as a metric to quantify these emissions' acidifying effects, expressed in terms of kilograms of SO_2-equivalents. This quantification not only facilitates the assessment of the environmental impact but also enables the development of strategies aimed at mitigating the adverse effects of acidification on ecosystems and human health.

5.1.3. Ozone Depletion Potential [129]

Ozone Depletion Potential is a measure used to describe the adverse effects of certain substances on the ozone layer in the stratosphere, particularly their role in diminishing the layer's capacity to block excessive ultraviolet radiation from reaching the Earth's surface. The significance of this issue has been globally recognized, leading to concerted efforts under the Montreal Protocol to mitigate the impact through international cooperation. Although the impact of building materials on ozone depletion is generally minimal, the use of refrigerants in mechanical systems presents a notable concern due to their potential for contributing to ozone layer damage.

The primary mechanism of stratospheric ozone depletion involves the catalytic destruction of ozone molecules by atomic chlorine and bromine. This process is predominantly initiated by the photodissociation of man-made compounds, namely chlorofluorocarbons (CFCs), also known as freons. Once released at ground level, these substances ascend to the stratosphere, where they undergo decomposition under UV radiation, releasing chlorine and bromine atoms that catalyze ozone breakdown. The Montreal Protocol, an international treaty established to phase out the production and consumption of ozone-depleting substances, has led to significant adjustments in industrial practices, including the substitution of halon 1301 with CFC 11 in the petrochemical industry, as per the Sphera LCA FE (GaBi) methodology. Consequently, ODP is quantified in terms of kilograms of R11-equivalents, reflecting the global commitment to reducing the emission of ozone-depleting chemicals and safeguarding the ozone layer.

5.1.4. Eutrophication potential [129]

Eutrophication Potential (EP) refers to the environmental impact arising from the enrichment of soil and water bodies with nutrients, leading to imbalances in ecosystems. This process is primarily triggered by the addition of nitrogenous and phosphatised compounds, often through agricultural fertilizers, which foster the unchecked growth of certain species, notably algae. The resultant algal blooms deplete oxygen levels in aquatic environments, endangering the survival of aquatic flora and fauna by significantly reducing the dissolved oxygen content necessary for their existence.

The phenomenon of aqueous eutrophication is marked by a series of adverse biological effects, including the potential collapse of aquatic ecosystems due to oxygen depletion. This condition not only threatens biodiversity but also disrupts water quality and the broader ecological balance. To quantify the impact of nutrient enrichment, EP is measured in terms of kilograms of phosphate-equivalents, providing a standardized metric for assessing the extent of eutrophication across different environments.

The assessment of EP includes all emissions of nitrogen (N) and phosphorus (P) to the air, water, and soil, in addition to the dispersal of organic matter into aquatic settings. This comprehensive approach facilitates a holistic evaluation of both terrestrial and aquatic eutrophication impacts. For the purposes of characterization and quantification, the use of phosphate (PO4) equivalents is preferred, although nitrogen oxide (NO3) and oxygen (O2) equivalents can serve as interchangeable metrics. This methodological framework enables the concise assessment of eutrophication potential, offering insights into the environmental consequences of nutrient overload and guiding mitigation strategies.

5.1.5. Depletion of Abiotic Resources – fossils [129]

Resources are categorized based on their origin into two main types: biotic and abiotic. Biotic resources originate from living organisms, including all biological materials. In contrast, abiotic resources are derived from the inanimate environment, including elements such as land, water, and air, along with mineral and power resources. These abiotic resources, particularly minerals and energy sources, are predominantly non-renewable, implying they cannot be replenished within a human lifespan or, more specifically, within a timeframe of at least 500 years.

The concept of ADP is integral to understanding the impact of resource consumption, particularly in terms of non-renewable resources. ADP is divided into two sub-categories: elements, which cover mineral resources, and fossil, relating to energy resources. The ADP for fossil resources, or ADP-fossil, is a critical measure that estimates the consumption of fossil fuels. This estimation is based on the ultimate reserve methodology, which calculates the total available resources by considering the average concentration of these resources in the Earth's crust and the mass of the crust itself. Expressed in megajoules (MJ), ADP-fossil provides a quantifiable measure of the energy consumption impact on non-renewable abiotic resources, highlighting the importance of sustainable resource management and the need for alternative energy solutions to mitigate depletion.

5.1.6. Photo-oxidant creation potential [129]

The majority of tropospheric ozone formation occurs when NOx, CO and VOCs, such as xylene, react in the atmosphere in the presence of sunlight. NOx and VOCs are called ozone precursors. There is a great deal of evidence to show that high concentrations (ppm) of ozone, created by high concentrations of pollution and daylight UV rays at the earth's surface, can harm lung function and irritate the respiratory system. POCP is expressed as kg C2H4-equivalent.

5.1.7. Embodied Energy [131]

Embodied Energy is a critical indicator within the LCIA, representing the total amount of energy required to produce any goods or services, from the extraction of raw materials to the end of their life cycle. This includes energy consumed during manufacturing, transportation, construction, maintenance, and disposal processes. By evaluating Embodied Energy, we can understand the energy efficiency of products and services and their overall impact on resource depletion and environmental degradation. This metric is crucial for identifying opportunities to reduce energy consumption through more efficient processes, the use of renewable energy sources, and the selection of materials with lower embodied energy. Embodied Energy is typically measured in MJ and provides a comprehensive view of the energy demands associated with the life cycle of construction works, aiding in the pursuit of sustainability goals and the reduction of carbon emissions.

5.1.8. Blue Water Consumption [132][133]

Freshwater scarcity is increasingly recognized as a critical environmental challenge, with its significance expected to grow in the future. This has led to a rising interest within the Life Cycle Assessment community in evaluating water use through an LCA lens. The approach to water assessment in Sphera LCA FE (GaBi) is guided by methodologies and definitions established by the UNEP/SETAC working group on water, along with the newly introduced ISO standard (ISO 14046)

The Sphera LCA FE (GaBi) software contains inventory quantities for water use and water consumption, as well as the impact assessment quantities, WSI, AWaRe, WAVE+ and others.

Water Consumption: This is defined as water that is withdrawn from and not returned to the same drainage basin. Reasons for water consumption include evaporation, transpiration, incorporation into products, or discharge into a different drainage basin or the sea. Evaporation from reservoirs also qualifies as water consumption.

Blue Water Consumption: This category includes various sources of freshwater usage, such as Freshwater, Groundwater, Lake water (including water used in turbines), and River water (including water used in turbines), minus the water returned to lakes, rivers, and groundwater through cooling processes or after being treated. Essentially, it's the net amount of freshwater, groundwater, and surface water utilized, accounting for any reductions due to water being returned or reused in lakes, rivers, or as groundwater. [134]

5.2. Data analysis

The LCIA “raw” results derived from Sphera LCA FE (GaBi) are presented in Annex 1.

The environmental impact of the construction of the Mall Complex can be understood by examining the different construction phases and their respective contributions to various environmental depletion categories. Thus, by further examining and clustering the “raw” results the following tables emerge:

The LCIA results for each construction phase for the selected impact categories are summarized in Table 5.

Table 5 LCIA results for each Construction phase of a Mall Complex in Greece

Impact Category	**Unit**	**Early Enabling Works**	**Substructure Construction**	**Superstructure Construction**	**Total**
GWP, 100 years	kg CO_2 equiv.	3.97E+06	5.75E+07	2.22E+08	2.83E+08
	%	1.4%	20.3%	78.3%	100.0%
AP	kg SO_2 equiv.	1.43E+04	1.31E+05	7.12E+05	8.58E+05
	%	1.7%	15.3%	83.0%	100.0%
ODP, steady state	kg R11 equiv.	7.77E-06	2.05E-04	3.09E-02	3.11E-02
	%	0.0%	0.7%	99.3%	100.0%
EP	kg PO_4 equiv.	1.91E+03	1.75E+04	7.95E+04	9.89E+04
	%	1.9%	17.7%	80.4%	100.0%
ADP, fossils	MJ	4.93E+07	6.83E+08	2.25E+09	2.98E+09
	%	1.7%	22.9%	75.4%	100.0%
POCP	kg C_2H_4 equiv./t	1.05E+03	2.30E+04	8.98E+04	1.14E+05
	%	0.9%	20.2%	78.9%	100.0%
EE	MJ	6.78E+07	7.82E+08	2.99E+09	3.84E+09
	%	1.8%	20.4%	77.9%	100.0%
BWC	kg	4.44E+07	2.13E+08	1.31E+09	1.57E+09
	%	2.8%	13.6%	83.5%	100.0%

Each Construction phase overall impact can be further analyzed into the impact of all input flows (materials, machinery, energy, water) used for the corresponding phase. This gives us Table 6, Table 7 and Table 8.

Finally, by summing up the impact of each input flow per construction phase the Table 9 can be produced which presents the LCIA results for each component contribution for the selected impact categories across the whole construction of the Project.

Table 6 LCIA results per each input flow of the Early and Enabling Works Construction phase

Impact category	Steel	Concrete	Aluminium	Dewatering Pumps	Digger Excavation	Plastics	Trucks	Electricity	Other	Total
ADP- fossil (%)	0.75	5.92	53.88	0.00	30.05	0.74	3.84	4.42	0.40	100.00
AP (%)	1.06	3.15	54.05	28.14	3.34	0.24	2.51	0.49	7.02	100.00
EP (%)	0.77	6.04	44.29	0.00	38.47	0.87	3.46	5.66	0.44	100.00
GWP, 100 years (%)	1.44	2.69	54.82	0.05	34.78	0.19	4.61	0.74	0.68	100.00
ODP, steady state (%)	0.48	3.03	28.31	0.10	63.55	0.20	2.61	1.14	0.58	100.00
POCP (%)	0.81	11.77	47.22	0.02	35.16	0.35	3.79	0.47	0.41	100.00
EE (%)	0.75	5.91	53.88	0.00	30.05	0.75	3.84	4.42	0.40	100.00
BWC (%)	1.06	3.15	54.05	28.14	3.34	0.24	2.51	0.49	7.02	100.00

Table 7 LCIA results per each input flow of the Substructure Construction phase

Impact category	Steel	Electricity	Concrete	Diesel	Other	Total
ADP- fossil (%)	52.72	0.18	12.35	34.74	0.00	100.00
AP (%)	66.48	0.30	26.74	6.48	0.00	100.00
EP (%)	58.25	0.13	31.80	9.81	0.00	100.00
GWP, 100 years (%)	55.84	0.19	41.64	2.33	0.00	100.00
ODP, steady state (%)	83.01	0.84	15.27	0.88	0.00	100.00
POCP (%)	78.57	0.10	14.36	6.94	0.02	100.00
EE (%)	52.14	0.25	15.00	32.61	0.00	100.00
BWC (%)	66.30	0.39	21.76	8.68	2.87	100.00

Table 8 LCIA results per each input flow of the Superstructure Construction phase

Impact category	**Steel**	**Rubber**	**Concrete**	**Aluminium**	**Glass**	**Plaster**	**Bronze**	**Copper**	**Electricity**	**Plastics**	**Ceramics**	**Gravel**	**Diesel**	**Other**	**Total**
ADP- fossil (%)	44.86	2.29	19.30	19.95	3.63	0.03	0.13	0.33	0.11	4.81	0.38	0.00	3.39	0.80	100.00
AP (%)	33.93	1.29	30.78	23.29	1.38	0.01	2.18	1.39	0.11	3.94	0.94	0.00	0.38	0.37	100.00
EP (%)	35.37	0.91	27.77	13.46	4.18	0.01	5.98	0.61	0.06	9.08	1.49	0.01	0.69	0.38	100.00
GWP, 100 years (%)	40.54	1.77	36.06	18.00	2.05	0.02	0.10	0.37	0.10	0.00	0.31	0.00	0.19	0.49	100.00
ODP, steady state (%)	1.56	22.86	0.41	0.16	0.05	0.00	7.31	0.01	0.01	0.08	66.66	0.00	0.00	0.89	100.00
POCP (%)	54.81	0.72	11.46	10.39	0.46	0.01	0.76	0.58	0.05	19.38	0.50	0.00	0.57	0.32	100.00
EE (%)	38.79	2.18	18.42	25.93	3.65	0.03	0.13	0.55	0.13	6.30	0.43	0.00	2.74	0.70	100.00
BWC (%)	29.13	3.29	12.67	43.97	1.98	0.01	0.43	1.94	0.12	4.67	1.06	0.00	0.45	0.26	100.00

Table 9 LCIA results for each input flow contribution for the selected impact categories across the whole construction of the Project

Impact category	**Steel**	**Rubber**	**Concrete**	**Aluminium**	**Glass**	**Plaster**	**Bronze**	**Copper**	**Electricity**	**Plastics**	**Ceramics**	**Gravel**	**Diesel**	**Other**	**Total**
ADP- fossil (%)	45.93	1.73	17.49	15.78	2.74	0.02	0.10	0.25	0.18	3.64	0.28	0.00	11.25	0.61	100.00
AP (%)	38.37	1.07	29.70	20.25	1.14	0.01	1.81	1.15	0.21	3.27	0.78	0.00	1.90	0.32	100.00
EP (%)	38.75	0.73	28.00	11.36	3.36	0.01	4.81	0.49	0.12	7.30	1.20	0.00	3.55	0.32	100.00
GWP, 100 years (%)	43.07	1.39	36.85	14.78	1.61	0.01	0.08	0.29	0.17	0.00	0.24	0.00	1.11	0.40	100.00
ODP, steady state (%)	2.10	22.70	0.51	0.17	0.05	0.00	7.26	0.01	0.02	0.08	66.21	0.00	0.01	0.89	100.00
POCP (%)	59.12	0.57	11.98	8.58	0.36	0.00	0.60	0.46	0.09	15.29	0.39	0.00	2.31	0.26	100.00
EE (%)	40.84	1.70	17.51	21.14	2.85	0.02	0.10	0.43	0.22	4.92	0.33	0.00	9.38	0.56	100.00
BWC (%)	33.40	2.75	13.64	38.27	1.66	0.01	0.36	1.62	0.23	3.91	0.89	0.00	1.67	1.60	100.00

5.3. Interpretation of results

5.3.1. Overall project

Based on the data presented on Table 5, Figure 18 is produced which depicts the LCIA results for each construction phase for the selected impact categories.

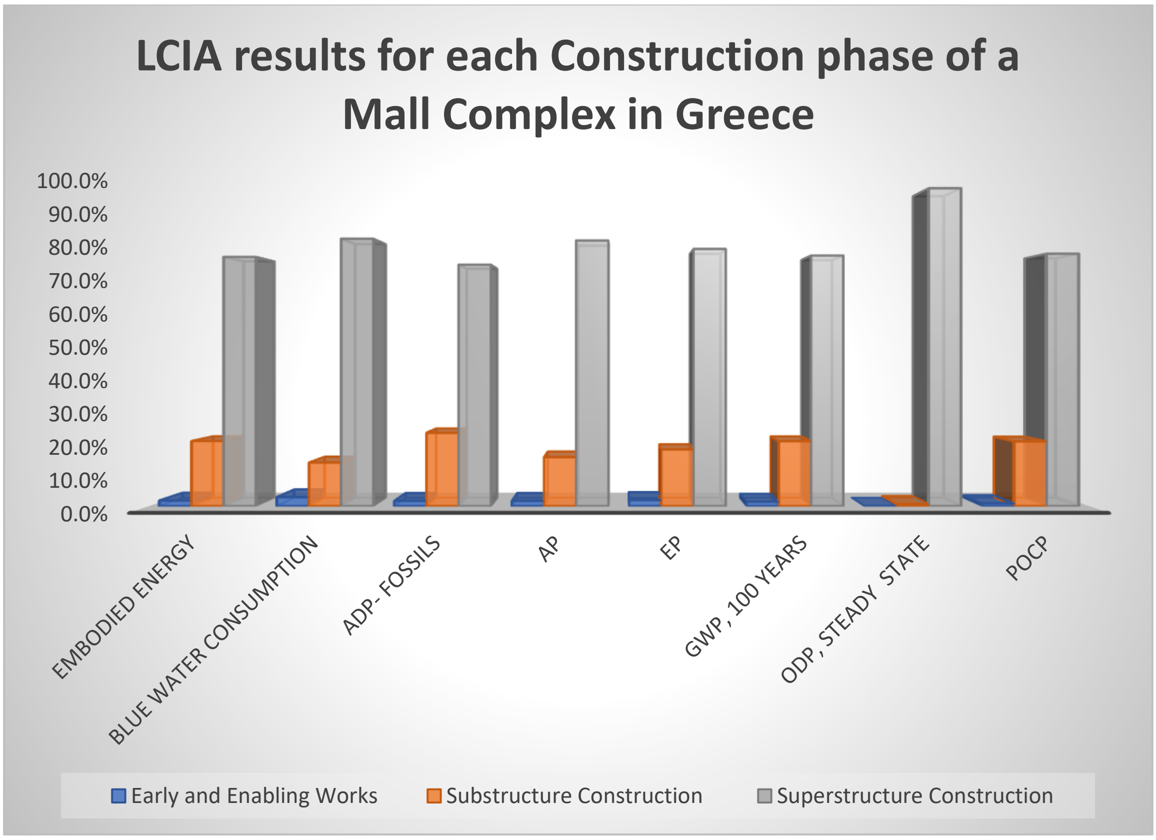


Figure 18 LCIA results for each Construction phase of a Mall Complex in Greece

1. **Global Warming Potential**
   - The construction of the Mall Complex is estimated to emit approximately 283 million kg of CO2 equivalents. A striking 78.3% (about 222 million kg) of this total is emitted during the Superstructure Construction phase, signifying that this phase is the most carbon intensive.
   - The Substructure Construction phase, while less impactful than the Superstructure phase, still contributes a significant 20.3% (approximately 57.5 million kg) of the total GWP, highlighting the environmental impact of foundational works.
   - Early and Enabling Works have the least GWP impact, with just 1.4% of emissions. Despite being the smallest proportion, this still represents nearly 4 million kg of CO2 equivalents, which is not negligible.
2. **Acidification Potential**
   - The total emissions responsible for acidification are around 858,000 kg of SO_2 equivalents. The vast majority of these emissions (83%, or approximately

712,000 kg) come from the Superstructure Construction phase, from the use of sulfur-containing materials and the extensive machinery used.

- Substructure Construction accounts for 15.3% of AP (about 131,000 kg), while Early and Enabling Works contribute a relatively small 1.7% (around 14,300 kg). These figures indicate that while AP is less during early stages, efforts to reduce sulfur emissions could still be beneficial.

3. **Ozone Depletion Potential**

- The ODP is predominantly impacted by the Superstructure Construction phase, contributing 99.3% of the total. This percentage equates to only 0.031 kg of R11 equivalents, which suggests the use of substances with generally low ODP.

- Substructure Construction contributes only 0.7%, and Early and Enabling Works have no significant impact. These low values suggest that the ODP is not primarily a concern in general and especially during the earlier stages of construction.

4. **Eutrophication Potential**

- The total EP for the project is about 99,800 kg of PO4 equivalents. The Superstructure phase is responsible for 80.4% of this impact (around 79,500 kg), which can be attributed to the runoff of nutrients from construction materials and site activities.

- The Substructure phase contributes 17.7% (approximately 17,500 kg), while the Early and Enabling Works contribute 1.9% (around 1,900 kg). These numbers highlight the Superstructure phase as the primary focus for eutrophication mitigation strategies.

5. **Abiotic Depletion Potential (fossils)**

- The total ADP-fossils are calculated at nearly 3 billion MJ. The Superstructure Construction phase accounts for a substantial 75.4% (over 2.25 billion MJ), reflecting the significant use of fossil fuels for energy and material production. This aligns with expectations, as this phase is typically the most intensive in terms of energy requirements and material usage.

- The Substructure phase has a notable impact of 22.9% (about 683 million MJ), and Early and Enabling Works contribute the least at 1.7% (nearly 49.3 million MJ). This suggests that energy efficiency and alternative energy sources could have a considerable impact on reducing fossil depletion even in the early stages of the Project.

6. **Photochemical Ozone Creation Potential**

- The total POCP is approximately 114,000 kg of C_2H_4 equivalents. The Superstructure phase is the largest contributor with 78.9% of the impact (around 89,800 kg), due to major VOC emissions from construction processes.

- The Substructure phase accounts for 20.2% of the POCP (about 23,000 kg), and the Early and Enabling Works are responsible for 0.9% (1,050 kg). This indicates that controlling VOC emissions during the Superstructure phase could significantly reduce the POCP.

7. **Embodied Energy:**
    - The total embodied energy for the construction of the Mall Complex is around 3.84 billion MJ. The Superstructure Construction phase accounts for 77.9% of the energy used, which amounts to nearly 2.99 billion MJ. This underscores the energy-intensive nature of this phase.
    - The Substructure Construction phase also has a significant impact, contributing 20.4%, or approximately 782 million MJ. This result highlights the energy demands of foundational construction activities.
    - Early and Enabling Works have the least impact on embodied energy, constituting 1.8% of the total, or about 68 million MJ, suggesting that the initial stages of construction are comparatively less energy intensive, but it still corresponds to a significant amount of energy that should not be discounted.
8. **Blue Water Consumption:**
    - The project's total blue water consumption is estimated at 1.57 billion kg. The Superstructure Construction phase is again the largest consumer, responsible for 83.5% of the total water used, equating to about 1.31 billion kg. This reflects the extensive water demand during this construction stage.
    - The Substructure Construction phase accounts for 13.6% of the water consumption, which is roughly 213 million kg, indicating the significance of water usage during the laying of foundations.
    - The proportion of water used during Early and Enabling Works is relatively small at 2.8%, corresponding to approximately 44 million kg, yet even this smaller percentage represents a substantial volume, reinforcing the importance of water management across all phases of construction.

5.3.2. Early and Enabling Construction phase

Utilizing the information provided in Table 6, Figure 19 is generated to illustrate the findings for the Early and Enabling Construction phase across the designated impact categories.

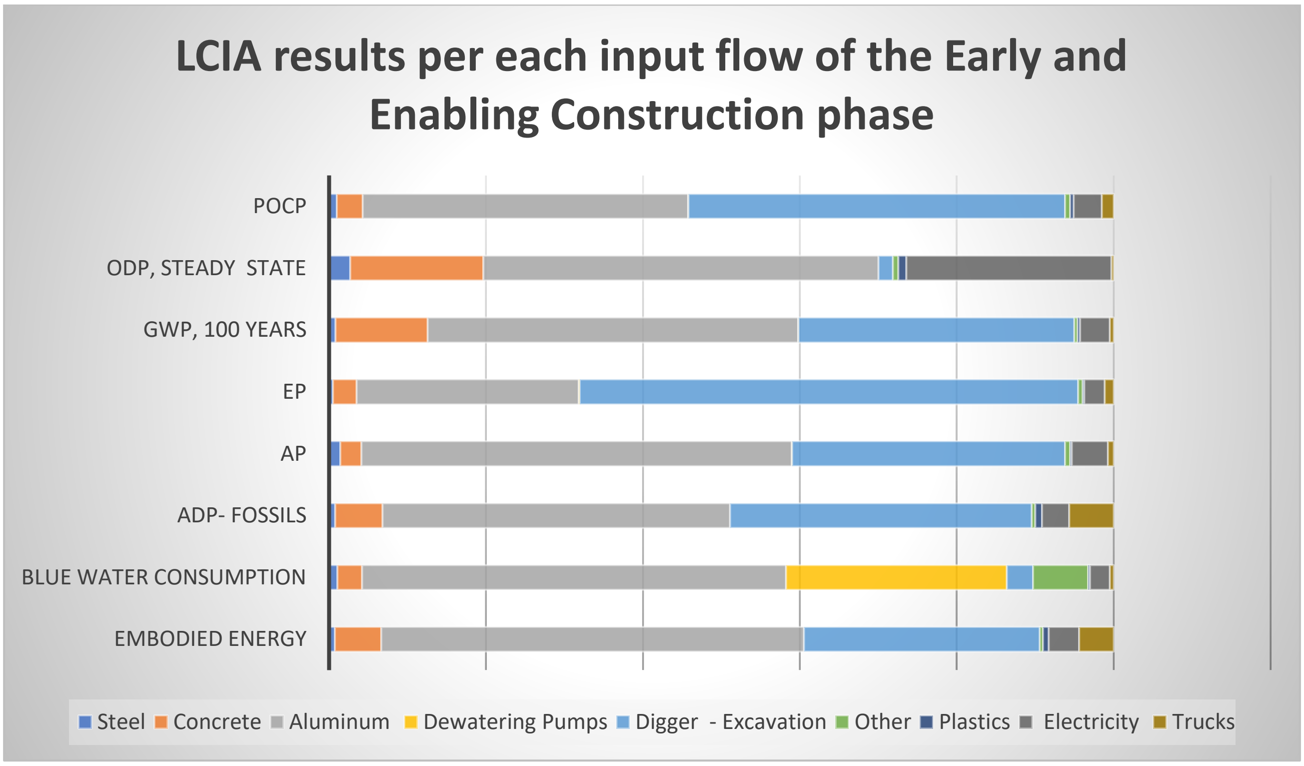


Figure 19 LCIA results per each input flow of the Early and Enabling Construction phase.

Analyzing the EEW phase of construction, the environmental impact is distributed among in the various input flows, referred in Table 6 and the diagram presented in Figure 19

1. **Abiotic Depletion Potential - Fossils (fossils)**

   - Aluminum is the primary contributor with 44.29% of the impact in this category, highlighting the resource-intensive nature of its production and its extensive use, particularly for the construction of the ISO box – Site Offices [ref kef 3].
   - Excavation is also substantial, accounting for 38.47%, due to heavy machinery's reliance on fossil fuels. And this value is solely due to the operation of the excavators. By combining the environmental footprint from the trucks that transport soil, a total contribution of 44.13% arises from the general excavation process. [ref kef 3]
   - Steel, Concrete, Electricity, Plastics, dewatering pumps and “other” input flows have no significant impact with ratios under 6.1%. Compared to the first two contributors their use is limited in the phase.

2. **Acidification Potential**

   - Aluminum stands out significantly with 54.82%of the impact, due to sulfur dioxide and other emissions during its production. [ref kef 3]

- Excavation activities contribute 35.52% (Excavators and Trucks), which can be attributed to machinery emissions. [ref kef 3]
- All other input flows have a combined relative impact of less than 10%.

3. **Eutrophication Potential**

   - Excavation activities lead with a considerable almost 65% of the impact in this category, due to soil disruption and nutrient-rich runoff.
   - Aluminum (28.31%) and concrete (3.03%) also contribute to this impact, suggesting nutrient management in additives and runoff will be necessary.
   - All other input flows have a combined relative impact of less than 4%.

4. **Global Warming Potential, 100 years:**

   - Aluminum use is associated with 47.22% of the GWP, indicating high carbon emissions from its manufacturing process. [ref kef 3]
   - The excavation activities contribute 35.63% of the phase GWP, due to the corresponding emissions of the machinery.
   - Concrete's impact is also notable at 11.77%, stemming from CO2 emissions during cement production. [ref kef 3]
   - All other input flows have a combined relative impact of less than 5.5%.

5. **Ozone Depletion Potential, steady state:**

   - Electricity usage is by far the largest contributor at 26.14%, suggesting the source of electricity or its usage should be optimized for environmental protection.
   - Despite not having a direct contribution in this category, concrete (16.96%) and aluminum (50.49%) have significant indirect impacts, related to their production processes.
   - All other input flows have a combined relative impact of approx. 6.5%.

6. **Photochemical Ozone Creation Potential:**

   - Overall excavation activities are the primary contributor at 49.49%, due to VOC emissions from the machinery.
   - Aluminum production follows with a considerable 41.46% of the impact, which is attributed to the use of solvents and other VOC-emitting processes during its production. [ref kef 3]
   - All other input flows have a combined relative impact of approx. 9%.

7. **Embodied Energy:**

   - Aluminum has the highest percentage of embodied energy in the EEW phase at 53.88%, which aligns with its known energy-intensive production process, underscoring the importance of considering the life cycle energy use in material selection. [Refer to 3.4.3.3.3]

- Excavation activities account for 34.47% of the embodied energy, due to the energy demands of operating the heavy excavation machinery and the dump trucks.

- The contributions of concrete and electricity usage are relatively lower, at 5.91% and 3.84% respectively. All other input flows have a combined relative impact of approx. 2%.

8. **Blue Water Consumption:**

   - Aluminum is again the most impactful on blue water consumption, accounting for 54.05% of the total. This suggests that the production of aluminum demands a significant amount of water, which may need to be addressed through water conservation strategies or change of material.

   - Dewatering Pumps also contribute a substantial share to water consumption, at 28.14%. This figure reflects not only the direct water use but also the impact on the water balance in the construction site environment.

   - Concrete, with a 3.15% contribution, and “other” input flows collectively account for 10.87%.

5.3.3. Substructure Construction phase

Based on the data in Table 7, Figure 20 can be generated.

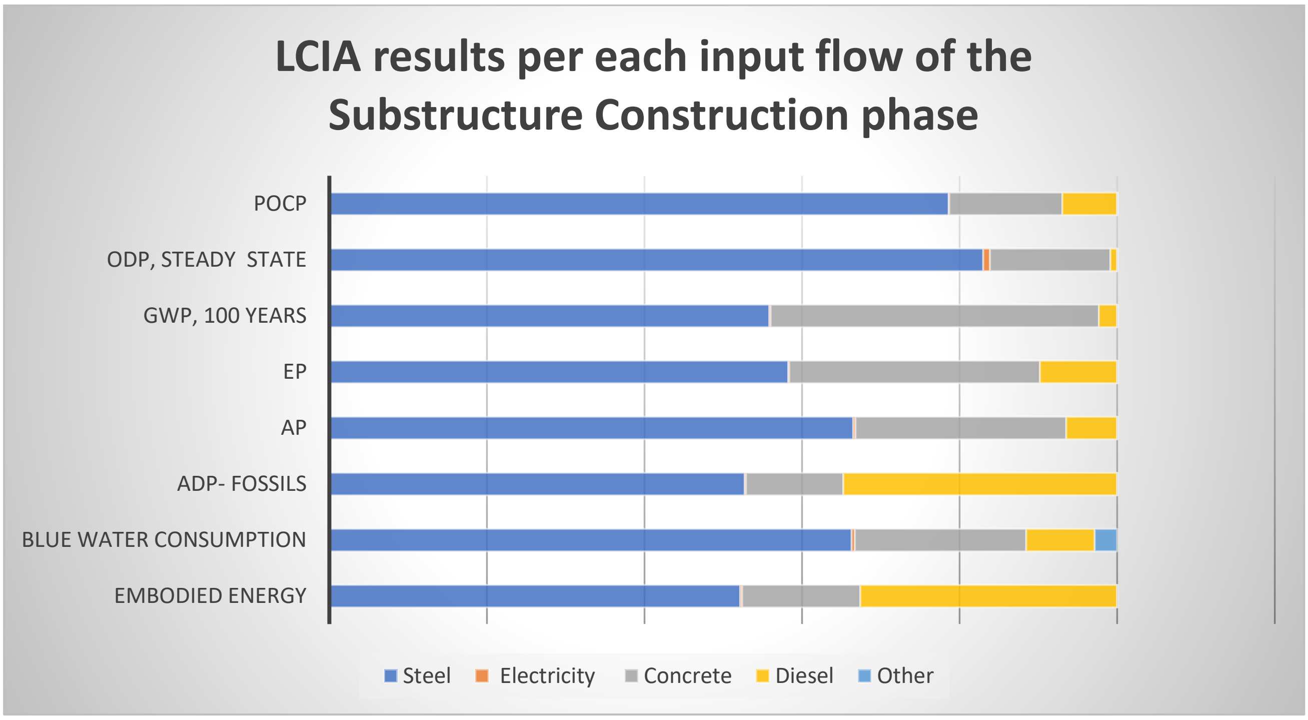


Figure 20 LCIA results per each input flow of the Substructure Construction phase.

1. **Abiotic Depletion Potential (fossils)**
   - Steel has the highest impact at 52.72%, indicating the resource-intensive nature of its production, which involves the extraction and processing of iron ore, a non-renewable resource. [Refer to 3.4.3.3.2]
   - Diesel fuel comes in second at 34.74%, which is expected given its use in heavy machinery and transportation vehicles that are active during substructure work. [Refer to 3.4.3.1.]
   - Concrete is the third most important input flow with 12.35% and all other categories present percentages near 0% but as the Project size is vast and this phase is a major contributor to the overall impact, even these percentages can represent big quantities.
2. **Acidification Potential**
   - Again, steel is the dominant factor at 66.48%, not only due to the extensive quantity used during this phase but also due to the release of sulfur dioxide and other acidic emissions during its production. [Refer to 3.4.3.3.2]
   - Concrete contributes 26.74%, again due to the high quantity used and also the chemical processes involved in cement production that release acidifying gases. [Refer to 3.4.3.3.1]
   - All other input flows have a combined relative impact of 7% approx.
3. **Eutrophication Potential**

- Steel leads with 58.25%, which is related to the runoff from metal processing plants and the subsequent nutrient load on water bodies. [Refer to 3.4.3.3.2]
- Concrete's contribution of 31.80% can be attributed to the use of additives and admixtures that contain nutrients like nitrogen and phosphorus. [Refer to 3.4.3.3.1]
- Diesel contributes 9.81% through the emission of nitrogen oxides during combustion, which can deposit into water systems and stimulate excessive plant growth.

4. **Global Warming Potential, 100 years:**
    - Steel production is responsible for 55.84% of the GWP, reflecting its carbon-intensive manufacturing process. [Refer to 3.4.3.3.2]
    - Concrete follows at 41.64%, due to CO2 emissions from the calcination of limestone and the burning of fossil fuels in cement kilns. [Refer to 3.4.3.3.1]
    - All other input flows have a combined relative impact of less than 3%.
5. **Ozone Depletion Potential, steady state:**
    - Steel has the most significant impact on ODP at 83.01%. However, it's important to note that the project's impact on ozone depletion is quite small for its overall size. In other words, the materials used, steel included, don't really harm the ozone layer much. Steel's significant percentage is more about its extensive use and its relative more harmful potential compared to other materials rather than its harmful effects on the ozone.
    - Electricity and concrete have much smaller contributions, at 0.84% and 15.26%, respectively. The same logic applies here, too.
6. **Photochemical Ozone Creation Potential (POCP):**
    - Steel is the largest contributor at 78.59%, which can be attributed to the VOC emissions during its production or coating processes. [Refer to 3.4.3.3.2]
    - Concrete's contribution to Photochemical Ozone Creation Potential is 14.36% and it is tied to cement production, which emits VOCs during the energy-intensive manufacturing process, leading to ozone formation. [Refer to 3.4.3.3.1]
    - Diesel has a moderate impact at 6.94%, again due to the VOCs released during combustion.
7. **Embodied Energy:**
    - Steel is the predominant contributor, accounting for 52.14% of the embodied energy, reflecting its significant use and the energy-intensive processes involved in its production. [Refer to 3.4.3.3.2]
    - Diesel, used for excavation machinery and dump trucks, also has a major impact, contributing to 32.61% of the embodied energy. [Refer to 3.4.3.1.]

- Concrete's share of embodied energy is 15%, due to the energy requirements in the production of cement, an essential component of concrete. [Refer to 3.4.3.3.1]

8. **Blue Water Consumption:**

   - Steel again has the largest share, representing 66.30% of blue water consumption, which may be associated with water used in cooling processes during steel production or other related activities. [Refer to 3.4.3.3.2]
   - Concrete comes next with 21.76%, hinting a considerable water use during its mixing, processing, and curing stages. [Refer to 3.4.3.3.1]
   - Diesel has a smaller, yet significant impact on water consumption at 8.68%, which is related to the water used in the extraction, refining, and production processes of diesel fuel.

5.3.4. Superstructure Construction phase

Based on Table 8, Figure 21 can be produced.

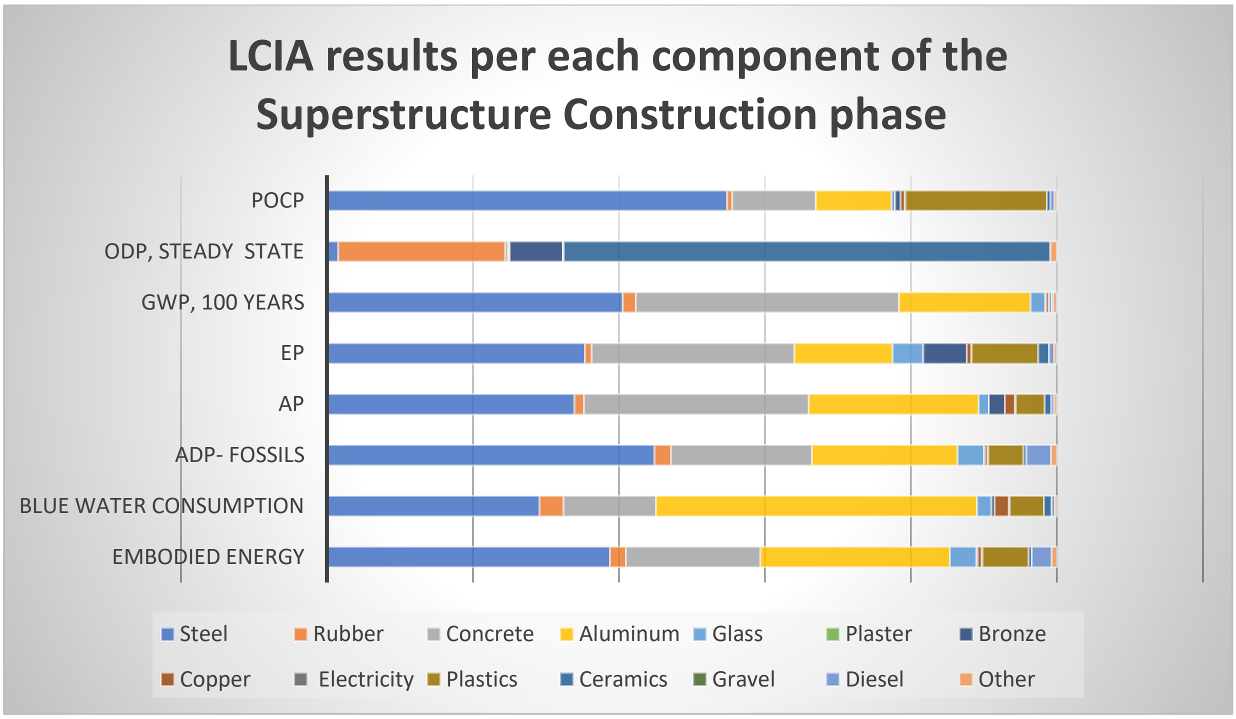


Figure 21 LCIA results per each input flow of the Superstructure Construction phase.

1. **Abiotic Depletion Potential - Fossils (fossils)**

    - Steel is the most significant contributor with 44.86% to the depletion of fossil resources, which reflects the energy-intensive production process that involves mining, smelting, and processing and extensive use. [Refer to 3.4.3.3.2]
    - Concrete and aluminum also have notable impacts, at 19.30% and 19.95% respectively, indicating the substantial resource use for these materials. [Refer to 3.4.3.3.1]
    - Rubber, Glass, Plastics and Diesel have contributions between 2.00% - 5.00%, which is less than the major contributors but still enough to add to the overall impact of the Project as this phase is the most resource intensive.
    - All other input flows have relative impacts of less than 2.00%, but still mitigation measure need to be examined due to the impact of the Superstructure phase to the Project.

2. **Acidification Potential**

    - Steel again has a large impact at 33.93%, due to relevant emissions during its production. [Refer to 3.4.3.3.2]

- Concrete contributes 30.78% and aluminium 23.29%, both of which are substantial and point towards their production processes as significant sources of acidifying emissions. [Refer to 3.4.3.3.1 and 3.4.3.3.3]
- Rubber, Glass, Bronze, Copper and Plastics have contributions between 1.00% - 4.00% which points that some mitigation measures need to be applied.
- All other input flows have relative impacts less than 1.00%, but still mitigation measure need to be examined due to the extensive impact of the Superstructure phase.

3. **Eutrophication Potential**

- Steel again is the leading contributor at 35.37%, followed by concrete and aluminum as expected with relative impacts 27,77% and 13,46% respectively. The same factors apply as already discussed above.
- Plastics have a relatively high impact at 9.08%, suggesting that the materials or processes used in their production may contribute to nutrient load in water bodies.
- Glass, Bronze, and Ceramics have impacts between 1.00% - 6.00%, thus some mitigations could be applied.
- All other input flows contribute less than 1.00% to the overall phase.

4. **Global Warming Potential, 100 years**

- Steel and concrete are the main contributors with 40.54% and 36.06% respectively, reflecting their high carbon emissions during production. [Refer to 3.4.3.3.1 and 3.4.3.3.2]
- Aluminum comes as the third major contributor with a relative impact of 18.00%. The total impact of the 3 major input flows adds up to almost 95.00% of the total GWP generated during the phase. This means that they should be the primary focus of the mitigation measures taken to decrease the impact of the phase. [Refer to 3.4.3.3.3]

5. **Ozone Depletion Potential, steady state**

- Ceramics appear to have the highest impact at 66.66%, in this category, followed by rubber at 22.86% and bronze at 7.31%. Their impact is linked to their manufacturing process or the raw materials used. [135][108]
- It's noteworthy that the project's contribution to ozone depletion is relatively minor considering its scale. That is to say, the input flows employed have a limited adverse effect on the ozone layer. The notable percentages attributed to these materials are indicative of their higher potential for harm in comparison to all other input flows, rather than a measure of significant actual damage to the ozone.

6. **Photochemical Ozone Creation Potential:**

- Steel has the highest contribution to POCP, potentially due to VOCs emitted during the manufacturing and coating processes.
- Plastics are also significant contributors, which could be related to the VOCs released from the production and processing of plastic materials, followed by concrete and aluminum as expected due to their extensive quantities in the phase.
- The total impact of the 4 major input flows adds up to 96.00% of the total POCP generated during the phase. This means that they should be the primary focus of the mitigation measures taken to decrease the impact of the phase.

7. **Embodied Energy:**
   - Steel stands out with the highest embodied energy at 38.79%. This suggests that steel manufacturing is highly energy intensive. [Refer to 3.4.3.3.2]
   - Aluminium and Concrete follow at 25.93% and 18.42%, indicating significant energy use in their production processes. [Refer to 3.4.3.3.3]
   - Plastics, Glass, Diesel, Rubber contribute 6.30%, 3.65%, 2.74% and 2.18 respectively to the embodied energy, a moderate impact compared to the major contributors.
   - All other input flows present very low relative embodied energy, with percentages under 1.00%.
8. **Blue Water Consumption:**
   - Aluminum has the highest blue water consumption at 43.97%, suggesting that the production of aluminum is particularly water intensive.
   - Steel and Concrete also have considerable blue water consumption at 29.13% and 12.67%.
   - Plastics and Rubber are responsible for 4.67% and 3.29% of the blue water consumption, indicating a moderate water footprint.
   - On the lower end, the rest of the input flows consume less than 2.00% of blue water.

5.3.5. Sensitivity analysis [136], [137]

Sensitivity analysis (SA) is a significant tool for evaluating the stability of outcomes and their responsiveness to uncertainties in LCA. It identifies the key model parameters, shedding light on the necessity for data quality enhancement and facilitating a better understanding of the results.

Based on the data presented on the cumulative Table 9, Figure 22 Sensitivity analysis for the Mall Complex construction. is produced which shows the LCIA results per each input flow of the Mall Complex construction for the selected impact categories and thus enables a sensitivity analysis for the whole Project.

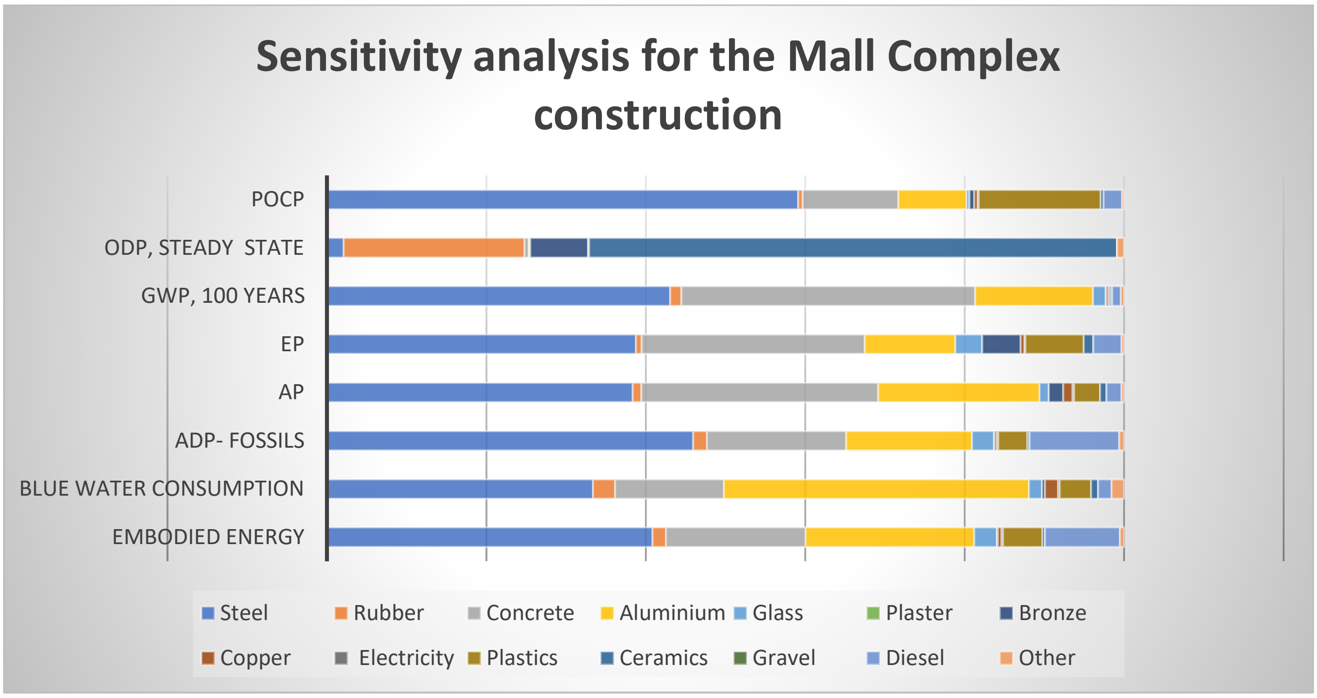


Figure 22 Sensitivity analysis for the Mall Complex construction.

The landscape does not change dramatically from the previous case when analyzing the overall picture of the project.

1. **Abiotic Depletion Potential (fossils):**
    - Steel has the highest overall impact at 45.93%, indicating the energy-intensive nature of its production, involving mining and processing. [Refer to 3.4.3.3.2]
    - Concrete and aluminum follow with 17.49% and 15.78% respectively, indicating their production processes also consume significant fossil resources. [Refer to 3.4.3.3.1]
    - Diesel has a notable 11.25% impact, due to its use in construction machinery and transportation vehicles throughout the construction phases.
    - All other input flows have a relative impact less than 4.00%, but as already discussed in previous paragraphs, mitigation measures should also be examined where applicable as the Project has a significant overall impact.
2. **Acidification Potential:**

- Steel is the predominant contributor at 38.37%, due to the emissions of sulfur and nitrogen oxides during its production that contribute to acid rain. [Refer to 3.4.3.3.2]
- Concrete comes next at 29.70%, and its impact is due to similar emissions from the cement manufacturing process. [Refer to 3.4.3.3.1]
- Aluminum's contribution is also notable at 20.25%, which may include emissions from the production and refining processes. [Refer to 3.4.3.3.3]
- Plastics present a relative impact of 3.27%, which is much smaller than the previous percentages but still represents a big AP.
- All other input flows have relative impacts below 2.00%, but as already discussed mitigation measures should be examined for all input flows where applicable.

3. **Eutrophication Potential:**

- Again, steel is at the forefront with a 38.75% contribution, suggesting runoff or emissions from its production that contribute to nutrient loading in water systems. [Refer to 3.4.3.3.2]
- Concrete and aluminum follow with 28.00% and 11.36% respectively, indicating their roles in nutrient runoff. [Refer to 3.4.3.3.1]
- Plastics 7.30%, Bronze 4.81%, Diesel 3.55% and Glass 3.36% are also notable contributors within the EP category. Even though their impact is not that much of the major contributors they still represent a big impact of the EP. This means that mitigations should also be focused on these input flows.
- All other input flows present a relative impact less than 1.20%, which seems not significant as a percentage, but it still is a lot of EP as an amount, thus mitigations should be applied, too.

4. **Global Warming Potential, 100 years:**

- Steel and concrete are significant contributors at 43.07% and 36.85%, underscoring the carbon-intensive nature of their production processes as well as their extensive use in the Project. [Refer to 3.4.3.3.1 and 3.4.3.3.2]
- Aluminum at 14.78% also shows a substantial impact, reflecting the greenhouse gas emissions associated with its energy-intensive production. [Refer to 3.4.3.3.3]
- The total impact of the 3 major input flows adds up to almost 95.00% of the total GWP generated during the phase. This means that they should be the primary focus of the mitigation measures taken to decrease the impact of the phase.
- Still mitigation measures should also be examined and applied where applicable to all other input flows which present a relative impact below 1.61% but still account for a big amount of GWP, considering the vast impact of the Project overall.

5. **Ozone Depletion Potential, steady state:**
   - As already mentioned in the context of this category, the project's impact on ozone depletion is quite small for its overall size. In other words, the materials used do not really harm the ozone layer much. This means that certain materials that present more ODP than others will have significant percentages in their relative impact but not that much actual ODP.
   - Ceramics appear to have the highest overall impact at 66.21%. This suggests specific production processes or materials used in ceramics might have ozone-depleting potentials.[135] [108]
   - Rubber at 22.70% and bronze at 7.26% have also significant relative contributions, suggesting the presence of ozone-depleting chemicals in their production or treatment processes, too. [108]
6. **Photochemical Ozone Creation Potential:**
   - Steel has the highest impact at 59.12%, likely due to VOC emissions during its production or from coatings applied to the metal.
   - Plastics (15.29%), Concrete (11.98%) and aluminum (8.58%) also contribute to this category, again from VOCs released during their manufacturing processes.
   - The combined effect of the four input flows discussed earlier accounts for nearly 95.00% of the Project's overall POCP. Consequently, these should be prioritized in any mitigation strategies implemented. However, it's also important to address the remaining input flows; even though they have a smaller relative impact, reducing their environmental influence is still advantageous.
7. **Embodied Energy:**
   - Steel has the highest embodied energy, accounting for 40.84% of the total. This is a significant proportion, indicating that the production and processing of steel are highly energy intensive. [Refer to 3.4.3.3.2]
   - Aluminum follows with 21.14%, also highlighting its high energy consumption in production. [Refer to 3.4.3.3.3]
   - Concrete and Diesel are other notable contributors with 17.51% and 9.38% respectively, showing their significant roles in the overall embodied energy and their extensive quantities.
   - All other input flows contribution is less than 4%, which indicates that the primary concern is the above-mentioned contributors. Nevertheless, mitigation measures should be examined for all input flows in a Project of this magnitude.
8. **Blue Water Consumption:**
   - Aluminum leads in blue water consumption, taking up 38.27% of the total. This suggests that aluminum production is not only energy-intensive but also demands significant water resources. [Refer to 3.4.3.3.3]

- Steel and Concrete also have substantial shares at 33.40% and 13.64%, respectively, indicating their high-water footprint. [Refer to 3.4.3.3.1 and 3.4.3.3.2]
- Rubber and Plastics show moderate consumption at 2,75% and 3,91% respectively, while all other input flows have relative impacts less than 1.70%.

5.4. Comparison of overall results with the Literature

Comparing LCA studies for buildings presents numerous challenges, primarily due to the variability in methodologies, data sources, and the scope of assessments. It needs to be noted that while the construction sector globally is advancing in tools, databases, and practices for measuring the embodied CO2 equivalent in buildings, there is no consensus on the execution of these assessments. Innovations and regulations have improved the management of operational impacts, yet discrepancies in methodologies, data quality, and regulatory frameworks continue to hamper efforts towards reducing embodied impacts.

The LCA of buildings is intricate, influenced by the selection of life cycle stages, material types, and the inclusion of various building components. Additionally, the geographical context and the time frame during which studies were conducted add layers of complexity to direct comparisons. This diversity in practice stems from a lack of standardized methods and the challenges in collating reliable data across different regions and materials. Consequently, efforts to benchmark or derive meaningful comparisons across studies are fraught with uncertainty, underscoring the need for improved data quality and harmonized methodologies to facilitate a more straightforward comparison and foster a broader understanding of buildings' environmental impacts. [138]

Among the available sources, efforts are directed towards comparing case studies within publications that focus on Life Cycle Assessment (LCA) in different kinds of buildings (commercial buildings and residential buildings). The LCA analysis in these studies concentrates specifically on stages A1-A5, which encompass the construction phase, excluding considerations related to the operational phase or the end-of-life phase. [Refer to 3.3.2]

5.4.1. Comparing the case study with the Embodied Carbon Benchmark Study [139]

The Embodied Carbon Benchmark Study analyzed over a thousand LCA studies, it's noted that the standard embodied carbon for a building's core structural elements – specifically, the structure, foundation, and enclosure – is commonly less than 1000 kg CO2e/m².

In comparing the results from the Life Cycle Assessment (LCA) of the Mall Complex in Greece with the Embodied Carbon Benchmark Study, several critical observations emerge. The LCA shows an overall embodied carbon of 944.56 kgCO2e/m², which closely approaches but does not exceed the upper limit established by the Benchmark Study, suggesting a comparatively high but not unusual environmental impact for a building of its scale and complexity. This is particularly relevant considering that the Benchmark Study's scope is limited to the structure, foundation, and enclosure of buildings, excluding site work, mechanical/electrical systems, and furnishings, which are included in the LCA.

It's essential to recognize that the mall complex's LCA includes a broader range of construction aspects, likely contributing to the overall higher embodied carbon value. If these additional components were excluded, aligning the scope more closely with that of the Benchmark Study, it's plausible that the mall complex would exhibit a reduced embodied carbon footprint, more in line with industry benchmarks.

For example, focusing specifically on the concrete and steel components of the Substructure and Superstructure phases, which are commonly accounted for in the Benchmark Study, the LCA reveals an embodied carbon impact of approximately 760 kgCO2e/m². This places the project well within the typical range of the Benchmark Study, indicating that the structural aspects of the building are designed with environmental considerations in mind.

When making direct comparisons, the distinction in scope between the two studies must be carefully considered to ensure an accurate assessment. The comprehensive nature of the mall complex's LCA provides a more detailed picture of its environmental impact, showcasing a commitment to thorough and responsible environmental analysis in the construction sector.

5.4.2. Comparing the case study with other commercial buildings – Malls [140]

Jiao, Y. , Lloyd, C. R. and Wakes, S. J. in their study examine the relationship between the total embodied energy and cost of commercial buildings. The research explores detailed embodied energy and cost data for commercial buildings in China and New Zealand, finding correlations between the embodied energy of individual building components and the total cost. It considers both the embodied energy incurred by labor and its associated costs, emphasizing their significance in overall analysis. The study suggests that while concrete is the predominant material by weight in buildings, steel, though less by weight, significantly contributes to embodied energy due to its manufacturing processes. It concludes that a general relationship between embodied energy and construction cost can simplify estimates and aid in reducing energy consumption and carbon emissions in the building sector.

In assessing this dissertation findings alongside the referenced study, both investigations acknowledge concrete and steel as the primary materials in construction by mass. Notably, steel's contribution to the total embodied energy is disproportionately large relative to its use, which can be attributed to its energy-intensive production process. [Refer to 3.4.3.3.2]

Comparative data extracted from figure 7 of the publication provides preliminary figures for the embodied energy of the buildings examined. This data, coupled with their respective gross floor areas, facilitates a calculation of embodied energy per square meter (EE/sqm). Consequently, a comparative table is formulated:

Table 10 Comparison of the Mall Complex in terms of Embodied Energy per m^2 with other commercial buildings – Malls

	Embodied Energy	**m^2**	**EE /m^2**
Building A	1.20E+08	10330	1.16E+04
Building B	5.80E+08	82882	7.00E+03
Building D	2.00E+07	4644	4.31E+03
Mall Complex	3.84E+09	300000	1.28E+04

At an initial review, the mall complex's embodied energy per square meter appears to surpass those reported in the study. Nonetheless, the comprehensive nature of the current analysis encompasses a broader array of the building's attributes. For a fair assessment, it's important to closely examine the embodied energy contributions from concrete and steel—the materials central to both inquiries.

Further scrutiny of figure five from the publication reveals the relative share of these materials in the total embodied energy of each building. These findings can then be methodically compared to the respective proportions in the current analysis.

Thus, an additional comparative framework is established to contextualize and interpret the embodied energy attributed to these fundamental materials across the two studies.

Table 11 Comparison of the Mall Complex (concrete and steel only) in terms of Embodied Energy per m^2 with other commercial buildings – Malls

Concrete and Steel only	EE/m^2
Building A	9.87E+03
Building B	6.51E+03
Building D	3.36E+03
Mall Complex	7.77E+02

The latest analysis indicating that the Mall Complex has the lowest Embodied Energy (EE) per square meter (m^2) value for the materials concrete and steel suggests that the Mall Complex is constructed in a more energy-efficient manner than the other buildings in the study. In other words, for the concrete and steel used, the mall has managed to achieve a lower energy input per unit area.

The implication that the Mall Complex has the smallest embodied energy per square meter for concrete and steel could point to a variety of contributing factors. It may indicate that the mall is utilizing these materials more efficiently, perhaps through superior design or construction techniques that maximize structural efficiency with less material. The types of concrete and steel used could also be inherently lower in embodied energy, potentially sourced from production processes that are less energy-intensive or incorporate a higher percentage of recycled content. Moreover, the scale of the project might confer logistical and material usage efficiencies that are not as easily achieved in smaller projects like those of the publication, thus leading to a reduced energy signature. Finally, the construction methods for the Mall Complex might be more advanced, incorporating strategies or technologies aimed at minimizing energy use, suggesting a high level of planning and sophistication in the project's execution. [Refer to 1.3.2]

Additionally, it is also important to contextualize the comparison within the broader landscape of environmental policies and practices. Buildings A and B, located in China, are in Chiba, a region historically characterized by environmental policies that may not prioritize sustainability to the same extent as other areas. This distinction is crucial when comparing the embodied energy values of different projects. Given this context, it would be more appropriate to compare the Mall Complex in Greece with Building D, a mall in New Zealand, which reports the lowest embodied energy per square meter among the case studies. New Zealand's approach to environmental sustainability and its regulatory framework offers a more comparable backdrop to the Mall Complex's efforts in minimizing embodied energy. This comparison would provide a more balanced understanding of the Mall Complex's achievements in reducing embodied energy, acknowledging the influence of both regional environmental policies and the specific efforts undertaken in the project's design and construction phases. Moreover, it's crucial to acknowledge that the buildings referenced in the study were constructed in the timeframe of 2005 to 2010, placing them in a specific context in terms of the technological and methodological advancements available at that time.

5.4.3. Comparing the case study with commercial office buildings [141]

The study investigates the embodied energy in office buildings of various heights in Melbourne, focusing on structures ranging from 3 to 52 stories. It finds that high-rise buildings have about 60% more embodied energy per gross floor area compared to low-rise ones due to increased structural demands. The analysis, which spans substructure to finishes, employs a hybrid method combining input-output and process analysis to determine energy coefficients for materials. Key insights reveal the structural elements significantly contribute to the total embodied energy as building height increases, highlighting the need for sustainable construction practices in managing the environmental impact of high-rise buildings.

Comparing the Mall Complex of 300.000 m^2 to office buildings analyzed in the study, which range from low-rise to high-rise constructions and GFAs from 6.480 to 129.950, it's essential to explore the similarities and differences in embodied energy between these structures.

The comparison between commercial malls and office buildings, rather than residential buildings, is grounded in their construction and functional similarities. Both types of buildings are designed to support large open spaces suited for various tenants, along with complex utility, HVAC systems, and infrastructure to manage significant pedestrian and vehicle traffic. They also share requirements for security, parking, and easy access, which are less commonly needed in residential constructions.

Shared aspects include the use of common construction materials like concrete, steel, and glass, contributing to the embodied energy through their production and transportation. The design complexity, seen in the architectural details such as atriums, facades, and external wall systems, affects the material needs and thus the embodied energy. Furthermore, the critical structural components such as the foundation and superstructure are integral in determining the embodied energy in both malls and office buildings, with a tendency towards steel frameworks and minimal use of concrete to avoid additional weight.

However, the comparison also uncovers differences, notably in the relationship between building height and structural demands. Office buildings, especially high-rises, show a higher embodied energy primarily due to their structural needs. In contrast, a relatively low-rise Mall might not face the same demands, potentially resulting in lower embodied energy per unit of Gross Floor Area (GFA). Additionally, while office buildings and malls might cater to different functional requirements, the design and operational needs significantly influence their overall embodied energy.

As anticipated, the Mall Complex, with an embodied energy value of 12.81 GJ/m^2, aligns with the lower end of embodied energy figures reported for office buildings, though it is not among the very lowest.

This outcome is influenced by two main factors. Firstly, as already mentioned, the scenario considered for the case study does not incorporate any environmental optimization strategies, which is not reflective of real-world practices where such strategies are likely implemented.

The second reason is the distinct configuration of the Mall Complex. While the Mall Complex's design optimizes horizontal space for commercial use, this approach naturally leads to an increase in embodied energy due to the extensive use of construction materials, increased perimeter for external walls and roofing, and the logistical challenges associated with large-scale horizontal construction. This understanding reconciles the observed higher embodied energy value, which might initially seem unusual when compared to more vertically-oriented office buildings.

5.4.4. *Comparing the case study with a residential construction project of the same size* [142]

The study presents the development of the Environmental Model of Construction (EMoC) to assess the environmental impacts of building construction projects in Hong Kong, emphasizing the construction phase rather than the operational phase or the entire lifecycle. EMoC offers a comprehensive analysis of 18 environmental impact categories at both midpoint and endpoint levels, enabling detailed evaluations of over two hundred construction processes. A case study on a public rental housing project demonstrates the model's application, revealing materials as the major contributors to environmental impacts during construction, with carbon emissions reaching 637 kg CO2e per square meter.

Comparing a commercial building to a residential project might not always be direct due to the distinct purposes and design requirements of each. Commercial malls are designed to host a variety of retail stores, entertainment options, and food services, necessitating large open spaces, high ceilings, and strong infrastructure to support substantial foot traffic. Residential projects are tailored for living, emphasizing privacy, comfort, and residential amenities over wide-open spaces. Malls often incorporate complex designs with unique architectural features to attract visitors, such as elaborate entrances and atriums, while residential projects focus on practical and comfortable living spaces. The structural demands of malls include extensive support systems for wide spans to accommodate various tenants and public areas. In contrast, residential buildings, especially low-rise ones, usually have simpler structural needs focused on dividing space into individual units. Material usage in malls encompasses a wide range of finishes to create visually appealing environments, including high-quality flooring and extensive glass facades. Residential construction prioritizes durability and cost-effectiveness, with aesthetic considerations tailored to living standards. Building services and infrastructure in malls are extensive, with advanced HVAC system for large open spaces, sophisticated fire safety, PAVA, data and security systems. Residential projects include similar services but adapted to the scale and complexity of living environments, focusing on individual comfort and safety. Despite these differences, in this particular case, a comparison is beneficial due to the similar big size of both projects at approximately 300.000 m^2 each.

Upon analyzing specific indicators, GWP and ODP are identified as common metrics in both studies. For ODP, the mall exhibits a lower impact, registering 1.04E-07 kg CFC/m^2 compared to 4.2E-05 kg CFC/m^2, indicating a smaller contribution to ozone depletion, as expected due to its design guidelines and legislative framework. So, this metric will not be the focus of further analysis, despite some variances in LCA methodologies. Conversely, the residential project initially appears more environmentally friendly in terms of GWP. However, this initial impression needs further examination.

Reviewing the overall embodied carbon, the Mall Complex reports 944.56 kg CO2e/m², while the public rental housing project shows 637 kg CO2e/m². The mall's LCA is notably more thorough, encompassing a wide array of material categories beyond just concrete and steel, unlike the residential project. After considering the above, the Mall Complex's adjusted overall embodied carbon is 760.52 kg CO2e/m² (including only the common materials in both studies of concrete and steel) , placing it within a comparable range to the residential project but still higher.

Upon examining the overall embodied carbon, the Mall Complex presents an embodied carbon of 944.56 kg CO2e/m², in contrast to the public rental housing project, which has an embodied carbon of 637 kg CO2e/m². This difference can be explained by the fact that the LCA conducted for the mall is extensive, covering a broader spectrum of materials besides concrete and steel, which is not the case with the residential project. When focusing solely on the common materials analyzed in both studies the Mall Complex's recalculated embodied carbon stands at 760.52 kg CO2e/m². This recalibration places it in a similar spectrum as the residential project, albeit at a slightly higher level.

It's important to note that the data for the mall originates from design plans, bills of quantities (BOQ), and contractor pricing, as mentioned in a specific chapter. This contrasts with the residential project's data, derived from the actual execution of construction. Consequently, the analysis adopts a 'worst-case scenario' approach in evaluating material sourcing, presuming the full environmental impact of materials as if they were newly procured. The possibility of using recycled materials will be considered in a later sensitivity analysis. The use of recycled materials in significant quantities could offer considerable environmental advantages, potentially allowing the mall to achieve markedly improved sustainability metrics.

5.4.5. *Comparing the anticipated water usage in construction materials and processes of the case study with available construction data* [113]

The paper presented at the 38th International Conference of Architectural Science Association ANZAScA explores the direct and indirect water requirements of construction, introducing the concept of embodied water, which encompasses both the water used directly in construction and indirectly in the production and delivery of materials and products. Highlighting Australia's high-water consumption despite its status as the driest populated continent, the study aims to fill the research gap on water usage in construction materials and processes. Through an analysis combining input-output data with industry data for a typical commercial building, the research finds that indirect water usage for material manufacturing significantly outweighs direct usage in construction activities. A case study demonstrates that less than one-fifth of the total water requirements are covered by available process water data, underscoring the need for more detailed data collection and industry collaboration to improve embodied water assessments and promote sustainable water management in construction.

In the concluding section of the paper, it is highlighted that “the direct water intensity accounts for merely 1.34% of the overall water intensity as determined by the comprehensive input-output model. This finding underscores the significance of indirect water requirements in construction processes”.

An examination of the “raw” data provided in Appendix 1, yields the table below:

Table 12 Comparison of the Mall Complex in terms of Embodied Energy per m^2 with other commercial buildings – Malls

Phase	**Direct Water Consumption**	**Total Water Consumption**
Early and Enabling Works	3.06E+06	4.44E+07
Substructure	6.10E+06	2.13E+08
Superstructure	1.22E+07	1.31E+09
Total	***2.14E+07***	***1.57E+09***

By calculating the ratio of the total direct water consumption to the total water consumption for the entire project, the direct water intensity is found to be 1.37% of the total. This figure reveals that the ratio for the project closely corresponds with the findings from the study presented at the 38th International Conference of the Architectural Science Association (ANZAScA). This similarity in results emphasizes the precision and reliability of the methodologies employed in both studies, contributing valuable insights into the discourse on sustainable construction practices. Particularly, it highlights the significance of indirect water requirements in the construction industry's water footprint.

6. CONCLUSIONS – SUGGESTIONS

6.1.1. Overall project

This LCA case study verifies the theoretical framework mentioned in Section 1.2 that a construction is a major contributor to environmental stress (given the fact that the environmental depletion is notable)

In this worst-case scenario, the overconsumption of raw materials and energy is visible + Atmospheric pollution and Impact on the physical environment.

Upon examining the various factors that contribute to the environmental impact of the project, the following key observations have been made:

- Steel is a major environmental impactor across most categories, highlighting the need for optimizing its use within construction process and recycling wherever possible.
- Concrete and aluminum also have significant impacts, particularly on GWP and AP, emphasizing the need for sustainable production practices.
- Diesel's contribution to ADP-fossils underlines the reliance on fossil fuels and the potential benefits of alternative, cleaner energy sources.
- Plastics contribute significantly to EP and POCP, indicating that their production and disposal need careful management to minimize environmental harm.
- Across all materials, there is a clear opportunity to reduce the environmental footprint by optimizing material selection, improving production efficiency, and employing more sustainable practices.

Considering these inputs constitute the primary environmental concerns for the project, it is imperative to explore dedicated mitigation actions tailored to each one:

In order to reduce the environmental impact associated with steel in construction, efforts can be directed toward enhancing the material efficiency of structures, allowing for less steel to be used while maintaining the required safety and integrity. Additionally, the incorporation of recycled steel can decrease the demand for newly produced steel. The industry should also consider the use of alternative materials such as advanced composites or engineered timber in appropriate situations.

For concrete, adopting mixes that include supplementary cementitious materials such as fly ash or slag can cut down the cement requirement, thus reducing its environmental footprint. Employing precast concrete can contribute to better waste management and quality control. Moreover, concrete recycling involves crushing and reusing concrete waste from demolition, presenting a significant opportunity to reuse materials in new construction projects.

When it comes to aluminum, giving preference to recycled aluminum can significantly lower the environmental impacts since it demands less energy than producing new aluminum. Optimizing alloys to reduce the need for primary aluminum without compromising material properties can be a forward-thinking approach. Conducting thorough life cycle assessments helps identify and diminish the environmental impacts associated with aluminum throughout its production and use.

Addressing the environmental impacts of diesel involves transitioning to vehicles and machinery that run on low-emission alternative fuels such as biodiesel, electricity, or hydrogen. Investing in the latest energy-efficient construction equipment with improved emissions control can also be instrumental. Moreover, enhancing the operational efficiency of machinery to reduce idle times can contribute to energy savings and lower emissions.

Mitigation efforts for plastics should focus on substituting single-use plastics with biodegradable or reusable alternatives wherever viable. Stringent waste management practices, including waste sorting and recycling on construction sites, can mitigate the environmental harm caused by plastics. Furthermore, the utilization of eco-friendly plastics, which are either made from recycled materials or produced via less harmful processes, can reduce the environmental impact of plastic use in construction.

Additionally, a series of overarching mitigation measures are crucial to the project's sustainability and can be implemented at various stages to enhance overall environmental performance. Creating a sustainable construction environment starts with a strategic procurement policy that chooses materials recognized for their environmental benefits. This approach extends to the design phase, where energy efficiency becomes a cornerstone, complemented by leveraging renewable energy for the construction processes. Waste management is another critical area, focusing on reducing, tracking, and handling waste, with an emphasis on recycling. Close monitoring of the carbon footprint helps pinpoint areas for emission reduction. Water conservation techniques are implemented to curb excessive use of this vital resource. Educating employees about sustainability ensures that eco-friendly practices are understood and adopted at all levels. Investment in innovative construction methods promises less environmental harm, while aiming for green building certifications establishes and upholds high sustainability standards. Preservation of local ecosystems is integral during construction to maintain biodiversity. Lastly, community engagement ensures that sustainable initiatives have the backing and support of local stakeholders, aligning the industry's efforts with the interests of the community.

Delving deeper into the different stages of the project reveals the following findings:

6.1.2. Early and Enabling Works Phase

This phase has the least environmental impact across all categories, with contributions between 1.50% to 3.00% depending on the impact category. Despite its relatively small impact, it still contributes to a non-negligible environmental footprint indicating that even the earliest stages of construction mitigation actions should be implemented. Indicatively, nearly 4 million kg of CO_2e, 14300 kg SO_2e, 1910 kg PO_4e are released during this phase, while almost 70 million MJ and 44 million kg of water mass are used directly and indirectly during this phase.

Key contributors to environmental impact during this phase include the aluminum used for the construction of site offices and facilities, as well as excavation activities involving fuel-intensive equipment such as excavators and dump trucks, pointing to these as key areas for improvement. For instance, employing environmentally friendly designs that use less material, utilizing more sustainable methods for excavation, improving logistical efficiency, and controlling vehicle emissions could be beneficial.

Specifically, the establishment of the site offers opportunities for impact reduction. Strategies such as using low-carbon and recycled materials and integrating previously used ISO box offices from other projects, could be effective. Moreover, minimizing material use and reusing waste materials are practical approaches for the site setup phase.

Optimizing construction strategies and logistics may lessen impacts associated with excavation. Adopting sustainable excavation methods and alternative fuels, like electricity or hybrids for vehicles, can cut down energy use and emissions, particularly from equipment running on diesel.

The impact of concrete and electricity usage—especially concerning ozone depletion—highlights the potential gains from using alternative materials or improving concrete mix designs. Implementing energy efficiency measures and switching to renewable energy sources are also important.

While the effects of soil waste, plastics, and water use are relatively small, optimizing waste reduction strategies is still crucial. By focusing on high-impact areas such as aluminum use, excavation activities, and managing the environmental footprint of concrete and energy use, the EEW phase can see significant reductions in its overall environmental impact, contributing to a more sustainable construction process.

6.1.3. Substructure Construction Phase

Compared to the earlier phase, this stage has a more pronounced effect, contributing 20.3% to the total GWP, 15.3% to AP, a minimal 0.7% to ODP, 17.7% to EP, a substantial 22.9% to ADP-fossils, and 20.2% to POCP. Approximately 57.5 million of CO_2e, 131000 kg SO_2e, 17500 kg PO_4e are released during this phase, while 782 million MJ and 213 million kg of water mass are used directly and indirectly during this phase.

By targeting the high-impact areas of steel, concrete and diesel use, the substructure phase could see a significant reduction in overall environmental impacts.

Focusing on mitigation strategies for steel and concrete, the two dominant input flows in this phase, is critical. For steel, revisiting the design to minimize material use, sourcing recycled steel, and reducing transportation are key strategies. Similar approaches for concrete include optimizing mix designs, using environmentally friendly alternatives, and substituting a portion of Portland cement with supplementary cementitious materials (SCMs) like fly ash, GGBFS, and silica fume.

Regarding energy usage, specifically diesel, the adoption of vehicles that utilize alternative fuels such as electric or hybrid options, or the use of newer vehicles with better performance, should be explored when feasible. Electricity usage has a relatively low impact, which implies that while it may not be a priority, utilizing green energy sources remains beneficial. The minimal impact of the "Other" category compared to the major contributors suggests that resources are being used effectively in these components, and their environmental impact is considerably lower.

Construction Optimization Strategies should also be applied throughout the foundational work to enhance efficiency and reduce environmental impact. This comprehensive approach can lead to significant reductions in the overall environmental impacts of the Substructure Construction phase.

6.1.4. Superstructure Construction Phase

The Superstructure phase is the most environmentally impactful, dominating across all categories with 78.3% of GWP, 83% of AP, 99.3% of ODP, 80.4% of EP, 75.4% of ADP-fossils, and 78.9% of POCP. This phase is characterized by extensive material use and energy consumption, leading to the majority of emissions and resource depletion. Notably, this phase alone is estimated to emit about 222 million kg of CO_2e, 712000 kg SO_2e, 79500 kg PO_4e are released during this phase, while 2.99 billion MJ and 1.31 billion kg of water mass are used directly and indirectly during this phase, highlighting the critical need for carbon footprint reduction measures during this stage.

Strategies to lessen the environmental impact during the Superstructure phase should include the optimization of the usage and manufacturing processes of key materials like steel, concrete, and aluminum. Employing greener materials, enhancing production efficiency, and increasing the incorporation of recycled materials are ways to minimize the environmental footprint.

The significant environmental impacts linked to steel and concrete production necessitate their careful management. This involves optimizing for lighter construction that retains structural integrity and integrating more recycled materials. Aluminum impact can be addressed by sourcing from recycled materials, which has a considerably lower energy requirement than the production of primary aluminum.

To tackle the contributions to POCP, reducing volatile organic compound (VOC) emissions is essential. This may require changes in material selection or the advancement of production technologies.

Overall, there is a broad scope to decrease environmental impacts in this phase through various approaches like material substitution, process efficiency improvements, increased recycling efforts, and a shift towards the use of renewable energy sources. These collective efforts can significantly reduce the environmental footprint of the Superstructure Construction Phase.

6.1.5. Suggestions for dissertation expansion

To build upon the foundation laid by this work, it is suggested that future research should broaden its scope and delve deeper into the following aspects:

This may include expanding the range of impact categories. For example, it would be beneficial to compare the energy derived from non-renewable resources, against energy from renewable resources or to gather wastes environmental footprint.

An important element would also be to involve incorporating actual construction data gathered from contractors' previous projects, offering a more grounded and empirical basis for analysis.

Moreover, the scope of the study could be broadened to encompass additional dimensions such as the resources expended in the design phase of the building or the the environmental footprint associated with the maintenance of construction equipment, as well as the implications of liquid waste discharges. The examination should also extend to consider the labor involved, the wastes corresponding to this labor and the construction of tenancies. Additionally, for future work, a focused analysis on each sub-package of the superstructure phase could be undertaken to identify which package exerts the most significant environmental impact. Understanding this can guide targeted mitigation actions more effectively. Finally, the scope could also be broadened to encompass the significant phases of use and end of life of the building.

This approach would not only contribute valuable insights into the immediate environmental impacts but also inform strategies for reducing long-term ecological footprints, ensuring that future construction projects are more sustainable.

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ANNEX 1

LCIA raw results derived from Sphera LCA FE (GaBi)

FU: 300,000.00 m^2 1 Mall 4 years A1-A5

Environmental quantities

	All					
	TOTAL	EEW TOTA	GR: Early E	GR: Early E	GR: Early E	GR: Early E
	GR: Mall - All stages CP <LC>	*GR: Early Enabling Works - EEW CP <LC>*	*CN: Prefabricated concrete part slab, 20cm Sphera*	*DE: Stainless steel cold roll Sphera <p-agg>*	*Europe: Steel wire rod worldsteel*	*GLO: Irrigation pump generic Sphera <u-so>*
Embodied energy (net cal. value) [MJ]	3.84E+09	6.78E+07	3.59E+05	4.78E+05	5.07E+03	0.00E+00
Blue water consumption [kg]	1.57E+09	4.44E+07	5.56E+04	1.54E+05	3.11E+05	1.25E+07
CML2001 - Aug. 2016, Abiotic Depletion (ADP fossil) [MJ]	2.98E+09	4.93E+07	3.07E+05	3.57E+05	4.23E+03	0.00E+00
CML2001 - Aug. 2016, Acidification Potential (AP) [kg SO2 eq.]	8.58E+05	1.43E+04	9.73E+01	2.01E+02	1.06E+00	7.65E+00
CML2001 - Aug. 2016, Eutrophication Potential (EP) [kg Phosphate eq.]	9.89E+04	1.91E+03	1.24E+01	8.63E+00	6.66E-02	2.00E+00
CML2001 - Aug. 2016, Global Warming Potential (GWP 100 years) [kg CO2 eq.]	2.83E+08	3.97E+06	4.07E+04	2.99E+04	3.77E+02	6.89E+02
CML2001 - Aug. 2016, Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	3.11E-02	7.77E-06	9.22E-08	1.94E-07	8.15E-10	0.00E+00
CML2001 - Aug. 2016, Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	1.14E+05	1.05E+03	7.09E+00	9.37E+00	1.39E-01	6.02E-01

														EEW						
GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E
GR: EEW finalisation CP <u-so>	*GR: Electricity grid mix 1kV-60kV Sphera*	*GR: Electricity grid mix 1kV-60kV Sphera*	*GR: Excavated Materials CP <u-so>*	*GR: Excavation CP <u-so>*	*GR: Fencing CP <u-so>*	*GR: Portable Site Office Container CP <u-so>*	*GR: Retaining Walls CP <u-so>*	*GR: Site Clearance CP <u-so>*	*GR: Site Dewatering and Pumping CP <u-so>*	*GR: WC establishment CP <u-so>*	*RER: Aerated concrete block Sphera*	*RER: Aluminium frame profile, powder coated (EN15804 A1-A3) Sphera*	*RER: Aluminium sheet (EN15804 A1-A3) Sphera*	*RER: Cement (CEM I 52.5) Portland cement (economically allocated binders) Sphera*	*RER: Concrete bricks (EN15804 A1-A3) Sphera*	*RER: Concrete C25/30 (Ready-mix concrete) (EN15804 A1-A3) Sphera*	*RER: Concrete C30/37 (Ready-mix concrete) (EN15804 A1-A3) Sphera*	*RER: Diesel mix at refinery Sphera*	*RER: Diesel mix at refinery Sphera*	*RER: Diesel mix at refinery Sphera*
0.00E+00	1.19E+06	9.40E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.51E+06	3.16E+07	4.98E+06	1.83E+04	1.52E+04	8.18E+04	2.48E+04	4.57E+03	2.11E+05	2.58E+06
0.00E+00	5.09E+05	4.04E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.29E+06	2.03E+07	3.70E+06	3.61E+03	5.01E+03	3.20E+04	9.83E+03	3.32E+02	1.53E+04	1.87E+05
0.00E+00	7.52E+05	5.96E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.57E+06	1.90E+07	2.89E+06	1.26E+04	1.08E+04	6.17E+04	1.78E+04	4.25E+03	1.96E+05	2.40E+06
0.00E+00	2.42E+02	1.92E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.48E+02	6.77E+03	1.07E+03	6.01E+00	3.07E+00	2.28E+01	7.47E+00	1.53E-01	7.05E+00	8.60E+01
0.00E+00	1.37E+01	1.09E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.94E+01	4.73E+02	6.89E+01	9.25E-01	5.41E-01	3.59E+00	1.18E+00	3.08E-02	1.42E+00	1.74E+01
0.00E+00	6.72E+04	5.33E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.00E+05	1.62E+06	2.60E+05	4.22E+03	2.02E+03	1.54E+04	5.10E+03	2.40E+01	1.11E+03	1.35E+04
0.00E+00	1.05E-06	8.31E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.19E-06	3.62E-06	3.03E-07	5.60E-09	4.06E-09	1.91E-08	6.68E-09	3.23E-11	1.49E-09	1.82E-08
0.00E+00	1.40E+01	1.11E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.42E+01	3.74E+02	6.01E+01	6.07E-01	2.06E-01	2.10E+00	7.05E-01	2.87E-02	1.32E+00	1.61E+01

													Sub-Structure							
GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	GR: Early E	Sub TOTAL	GR: Sub-St	GR: Sub-St	GR: Sub-St	GR: Sub-St	GR: Sub-St	GR: Sub-St	GR: Sub-St
RER: Diesel mix at refinery Sphera	*RER: Diesel mix at refinery Sphera*	*RER: Diesel mix at refinery Sphera*	*RER: Direct expansion air conditioner (per 1 kW) (EN15804 A1-A3) Sphera <p-agg>*	*RER: Excavated soil with digger (EN15804 A5) Sphera*	*RER: Inert matter (Unspecific construction waste) on landfill Sphera*	*RER: Polyethylene foam (EN15804 A1-A3) Sphera*	*RER: Polyvinylchloride pipe (PVC) PlasticsEurope*	*RER: Stainless steel sheet (EN15804 A1-A3) Sphera <p-agg>*	*RER: Steel sections (EN15804 A1-A3) Sphera <p-agg>*	*RER: Tap water from surface water Sphera*	*US: Truck - Dump Truck / 52,000 lb payload - 8b Sphera <u-so>*	*US: Truck - Dump Truck / 52,000 lb payload - 8b Sphera <u-so>*	*GR: Sub-Structure CP <LC>*	*AU: OneSteel Reinforcing Rod and Wire (EN15804 A1-A3) OneSteel <p-agg>*	*GR: Backfilling CP <u-so>*	*GR: Basement construction CP <u-so>*	*GR: Concrete Base Finalisation CP <u-so>*	*GR: Electricity grid mix 1kV-60kV Sphera*	*RER: Concrete C12/15 (Ready-mix concrete) (EN15804 A1-A3) Sphera*	*RER: Concrete C30/37 (Ready-mix concrete) (EN15804 A1-A3) Sphera*
1.52E+05	4.39E+04	1.09E+04	4.83E+05	2.04E+07	2.57E+05	4.73E+05	3.13E+04	2.40E+03	2.63E+04	8.75E+03	0.00E+00	0.00E+00	7.82E+08	3.48E+08	0.00E+00	0.00E+00	0.00E+00	1.95E+06	1.13E+07	1.06E+08
1.11E+04	3.19E+03	7.90E+02	2.04E+05	1.48E+06	5.58E+04	7.08E+04	3.72E+04	1.06E+03	4.59E+03	3.06E+06	0.00E+00	0.00E+00	2.13E+08	1.20E+08	0.00E+00	0.00E+00	0.00E+00	8.39E+05	4.37E+06	4.21E+07
1.42E+05	4.08E+04	1.01E+04	3.57E+05	1.90E+07	2.14E+05	4.01E+05	2.73E+04	1.77E+03	1.69E+04	6.45E+03	0.00E+00	0.00E+00	6.83E+08	3.29E+08	0.00E+00	0.00E+00	0.00E+00	1.24E+06	8.36E+06	7.60E+07
5.08E+00	1.46E+00	3.63E-01	2.24E+02	4.97E+03	9.45E+01	2.00E+01	7.40E+00	9.46E-01	3.07E+00	8.76E-01	5.71E-01	5.48E+00	1.31E+05	8.16E+04	0.00E+00	0.00E+00	0.00E+00	3.99E+02	3.17E+03	3.20E+04
1.03E+00	2.96E-01	7.33E-02	2.53E+01	1.22E+03	1.08E+01	3.16E+00	5.97E-01	3.96E-02	3.75E-01	3.57E-01	1.49E-01	1.43E+00	1.75E+04	9.52E+03	0.00E+00	0.00E+00	0.00E+00	2.27E+01	5.01E+02	5.07E+03
7.99E+02	2.30E+02	5.71E+01	3.00E+04	1.40E+06	1.58E+04	1.24E+04	1.66E+03	1.44E+02	1.64E+03	4.29E+02	2.89E+02	2.78E+03	5.75E+07	2.96E+07	0.00E+00	0.00E+00	0.00E+00	1.11E+05	2.12E+06	2.18E+07
1.08E-09	3.10E-10	7.68E-11	1.50E-07	1.44E-07	4.97E-08	8.02E-08	0.00E+00	6.02E-10	1.50E-08	2.91E-09	0.00E+00	0.00E+00	2.05E-04	1.41E-04	0.00E+00	0.00E+00	0.00E+00	1.73E-06	2.74E-06	2.86E-05
9.54E-01	2.75E-01	6.82E-02	1.23E+01	5.02E+02	7.05E+00	4.03E+00	5.92E-01	4.60E-02	6.14E-01	6.94E-02	-2.70E-01	-2.59E+00	2.30E+04	1.69E+04	0.00E+00	0.00E+00	0.00E+00	2.31E+01	2.92E+02	3.02E+03

GR: Sub-St	GR: Sub-St	GR: Sub-St	Super TOT.	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super
RER: Diesel mix at refinery Sphera	*RER: Reinforced steel (wire) (EN15804 A1-A3) Sphera <p-agg>*	*RER: Tap water from surface water Sphera*	*GR: Super Structure CP <LC>*	*AU: OneSteel Reinforcing Rod and Wire (EN15804 A1-A3) OneSteel <p-agg>*	*AU: Plywood, formply, A-bond, 17 mm (formwork) (EN 15804 A1-A3) FWPA*	*CH: ceramic tile production ecoinvent 3.9.1*	*CH: ceramic tile production ecoinvent 3.9.1*	*CN: Concrete bricks Sphera*	*DE: Gravel (Grain size 2/32) (EN15804 A1-A3) Sphera*	*DE: Natural rubber (NR) (excl. LUC emissions) Sphera*	*DE: Polytetrafluoroethylene granulate (PTFE) Mix Sphera*	*DE: Polytetrafluoroethylene granulate (PTFE) Mix Sphera*	*DE: Stainless steel cold roll Sphera <p-agg>*	*DE: Stainless Steel slab (X6CrNi17) Sphera <p-agg>*	*DE: Stainless Steel slab (X6CrNi17) Sphera <p-agg>*	*DE: Steel sheet HDG (EN 15804 A1-A3) Sphera <p-agg>*	*EU: Steel electrogalvanized (2020) worldsteel*	*Europe: Steel hot dip galvanised worldsteel*	*GLO: Building, steel frame construction (1 m³ gross volume = 125 kg) Sphera <u-so>*	*GLO: Plastic Film (PE, PP, PVC) Sphera <u-so>*
2.55E+08	6.02E+07	1.74E+04	2.99E+09	8.93E+08	1.89E+08	1.28E+07	4.84E+04	6.31E+06	1.22E+05	2.29E+05	5.85E+07	6.36E+05	2.02E+06	7.21E+04	1.28E+05	4.09E+07	2.13E+05	4.03E+05	0.00E+00	0.00E+00
1.85E+07	2.19E+07	6.10E+06	1.31E+09	3.07E+08	6.11E+07	1.39E+07	5.25E+04	2.40E+06	1.50E+04	5.84E+06	2.24E+07	2.44E+05	6.52E+05	3.05E+04	5.41E+04	4.59E+06	3.03E+05	-6.31E+04	0.00E+00	0.00E+00
2.37E+08	3.08E+07	1.29E+04	2.25E+09	8.46E+08	1.08E+08	8.44E+06	3.19E+04	5.63E+06	8.29E+04	9.79E+04	4.56E+07	4.97E+05	1.51E+06	5.68E+04	1.01E+05	3.69E+07	2.02E+05	3.85E+05	0.00E+00	0.00E+00
8.51E+03	5.82E+03	1.75E+00	7.12E+05	2.10E+05	2.80E+04	6.65E+03	2.52E+01	2.12E+03	1.98E+01	8.83E+01	8.27E+03	9.00E+01	8.50E+02	3.84E+01	6.81E+01	7.86E+03	3.96E+01	7.31E+01	0.00E+00	0.00E+00
1.72E+03	6.81E+02	7.11E-01	7.95E+04	2.45E+04	7.22E+03	1.18E+03	4.48E+00	3.31E+02	4.11E+00	8.00E+01	5.50E+02	5.98E+00	3.65E+01	1.55E+00	2.76E+00	8.65E+02	3.75E+00	6.49E+00	0.00E+00	0.00E+00
1.34E+06	2.46E+06	8.54E+02	2.22E+08	7.61E+07	-2.78E+06	6.77E+05	2.56E+03	8.53E+05	6.51E+03	-1.01E+04	3.67E+06	3.99E+04	1.26E+05	5.15E+03	9.15E+03	4.01E+06	1.87E+04	3.29E+04	0.00E+00	0.00E+00
1.80E-06	2.90E-05	5.81E-09	3.09E-02	3.63E-04	2.59E-05	2.05E-02	7.76E-05	1.00E-06	6.58E-08	2.46E-08	2.33E-05	2.54E-07	8.19E-07	2.07E-08	3.67E-08	3.51E-06	1.64E-10	5.24E-09	0.00E+00	0.00E+00
1.60E+03	1.23E+03	1.38E-01	8.98E+04	4.33E+04	1.74E+04	4.47E+02	1.69E+00	-9.63E+01	-3.29E+00	3.75E+00	5.43E+02	5.91E+00	3.96E+01	1.82E+00	3.24E+00	1.06E+03	5.82E+00	1.27E+01	0.00E+00	0.00E+00

Super-Structure																				
GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super
GR: Conveying Systems CP <u-so>	*GR: Electricity grid mix 1kV-60kV Sphera*	*GR: External Finishes CP <u-so>*	*GR: Facade System CP <u-so>*	*GR: Internal Finishes CP <u-so>*	*GR: Mall Complete CP <u-so>*	*GR: MEP Systems GR <u-so>*	*GR: Structural Systems CP <u-so>*	*RER: Aerated concrete granulate (EN15804 A1-A3) Sphera*	*RER: Aluminium profile (EN15804 A1-A3) Sphera*	*RER: Aluminium profile (EN15804 A1-A3) Sphera*	*RER: Aluminium sheet (EN15804 A1-A3) Sphera*	*RER: Aluminium sheet (EN15804 A1-A3) Sphera*	*RER: Bitumen sheets PYE-PV 200 S5 ns (slated) (EN15804 A1-A3) Sphera*	*RER: Calcium silicate Sphera*	*RER: Concrete C25/30 (Ready-mix concrete) (EN15804 A1-A3) Sphera*	*RER: Concrete C30/37 (Ready-mix concrete) (EN15804 A1-A3) Sphera*	*RER: Concrete C35/45 (Ready-mix concrete) (EN15804 A1-A3) Sphera*	*RER: Diesel mix at refinery Sphera*	*RER: door production, inner, wood ecoinvent 3.9.1*	*RER: Double glazing unit (EN15804 A1-A3) Sphera*
0.00E+00	3.80E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.51E+06	3.55E+07	2.66E+07	7.14E+08	3.30E+05	9.41E+06	2.37E+06	2.44E+07	1.94E+08	6.67E+07	8.19E+07	7.02E+05	4.24E+06
0.00E+00	1.63E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.26E+06	2.59E+07	1.94E+07	5.30E+08	2.45E+05	4.81E+05	3.67E+03	9.53E+06	7.69E+07	2.54E+07	5.95E+06	2.33E+05	7.23E+05
0.00E+00	2.41E+06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.34E+06	2.03E+07	1.52E+07	4.13E+08	1.91E+05	8.92E+06	2.14E+06	1.84E+07	1.39E+08	4.90E+07	7.63E+07	2.54E+05	3.74E+06
0.00E+00	7.75E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.01E+02	7.44E+03	5.56E+03	1.53E+05	7.07E+01	3.18E+02	1.06E+02	6.81E+03	5.84E+04	1.95E+04	2.74E+03	1.14E+02	1.23E+03
0.00E+00	4.40E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.02E+02	4.78E+02	3.57E+02	9.86E+03	4.56E+00	4.48E+01	2.76E+01	1.07E+03	9.26E+03	3.08E+03	5.52E+02	5.63E+01	2.40E+02
0.00E+00	2.15E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.79E+05	1.83E+06	1.37E+06	3.72E+07	1.72E+04	1.76E+05	2.83E+05	4.58E+06	3.98E+07	1.32E+07	4.30E+05	-9.77E+03	3.05E+05
0.00E+00	3.35E-06	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.79E-06	2.86E-06	2.14E-06	4.34E-05	2.01E-08	5.70E-07	2.25E-07	5.70E-06	5.22E-05	1.68E-05	5.79E-07	2.73E-04	5.27E-07
0.00E+00	4.48E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.66E+00	4.15E+02	3.10E+02	8.61E+03	3.98E+00	6.27E+01	8.08E+00	6.25E+02	5.51E+03	1.82E+03	5.14E+02	1.35E+01	7.22E+01

GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super	GR: Super
RER: Double glazing unit (EN15804 A1-A3) Sphera	*RER: Elevator basic component (Independent of floor) (EN15804 A1-A3) Sphera <p-agg>*	*RER: Escalator - basic component (independent of lifting height) (EN15804 A1-A3) Sphera <p-agg>*	*RER: Expanded glass, granulate (EN15804 A1-A3) Sphera*	*RER: Floor screed (anhydrite) (A1-A3) Sphera*	*RER: Floor screed (anhydrite) (A1-A3) Sphera*	*RER: Flooring PVC printed, laminated EN 649 ERFMI*	*RER: Glass ceramic production Sphera*	*RER: Gypsum interior plaster (EN15804 A1-A3) Sphera*	*RER: Gypsum plasterboard ELCD/EUROGYPSUM <p-agg>*	*RER: Lightweight concrete block (expanded clay, hollow block, density class 1,6) (EN15804 A1-A3) Sphera*	*RER: Lightweight concrete block (expanded clay, hollow block, density class 1,6) (EN15804 A1-A3) Sphera*	*RER: Paint emulsion (building, exterior, white) (EN15804 A1-A3) Sphera*	*RER: Polyurethane flexible foam (PU) - TDI-based, with flame retardant EUROPUR*	*RER: Pre-cast concrete Sphera*	*RER: Pre-cast concrete Sphera*	*RER: Reinforced steel (wire) (EN15804 A1-A3) Sphera <p-agg>*	*RER: Reinforcement (mineral) (A1-A3) Sphera*	*RER: Steel sections (EN15804 A1-A3) Sphera <p-agg>*	*RER: Steel sections (EN15804 A1-A3) Sphera <p-agg>*	*RER: Tap water from surface water Sphera*
9.40E+05	2.42E+06	6.06E+06	1.03E+08	3.67E+06	2.46E+07	1.91E+06	6.55E+05	6.10E+05	2.25E+05	2.21E+08	1.36E+06	1.03E+05	4.04E+06	1.27E+06	1.29E+05	1.55E+08	2.01E+05	2.97E+06	6.63E+07	3.50E+04
1.60E+05	7.28E+05	1.87E+06	2.47E+07	1.97E+06	1.32E+07	1.16E+06	2.82E+05	8.86E+04	4.22E+04	3.46E+07	2.13E+05	3.03E+04	1.18E+06	3.61E+05	3.68E+04	5.63E+07	6.70E+04	5.17E+05	1.16E+07	1.22E+07
8.29E+05	1.81E+06	4.75E+06	7.58E+07	3.15E+06	2.11E+07	1.62E+06	4.84E+05	4.66E+05	1.76E+05	1.89E+08	1.17E+06	8.80E+04	3.62E+06	1.02E+06	1.04E+05	7.90E+07	1.50E+05	1.90E+06	4.26E+07	2.58E+04
2.72E+02	6.50E+02	1.46E+03	7.64E+03	5.83E+02	3.91E+03	4.17E+02	1.77E+02	3.30E+01	1.68E+01	1.26E+05	7.79E+02	2.05E+01	3.44E+02	2.08E+02	2.12E+01	1.50E+04	3.56E+01	3.46E+02	7.73E+03	3.50E+00
5.33E+01	4.48E+01	1.28E+02	2.93E+03	9.99E+01	6.69E+02	3.29E+01	4.45E+01	5.40E+00	4.30E+00	7.39E+03	4.56E+01	1.53E+00	5.37E+01	2.75E+01	2.80E+00	1.75E+03	7.56E+00	4.23E+01	9.45E+02	1.43E+00
6.77E+04	1.69E+05	4.81E+05	4.12E+06	2.23E+05	1.50E+06	9.95E+04	3.44E+04	3.07E+04	1.19E+04	2.00E+07	1.23E+05	4.63E+03	1.66E+05	1.85E+05	1.89E+04	6.32E+06	2.12E+04	1.85E+05	4.14E+06	1.71E+03
1.17E-07	7.49E-07	1.37E-06	1.45E-05	4.44E-07	2.97E-06	5.40E-03	1.84E-07	1.38E-07	-1.17E-07	4.39E-05	2.71E-07	1.98E-08	1.64E-03	4.16E-07	4.24E-08	7.46E-05	4.00E-08	1.69E-06	3.77E-05	1.17E-08
1.60E+01	5.11E+01	1.51E+02	3.75E+02	-3.23E+01	-2.17E+02	5.12E+01	9.72E+00	3.60E+00	1.30E+00	2.64E+03	1.63E+01	1.92E+00	4.00E+01	2.78E+01	2.84E+00	3.15E+03	2.39E+00	6.92E+01	1.55E+03	2.77E-01

GR: Super	GR: Super	GR: Super	GR: Super Structure CP <LC>
RER: Window glass simple (EN15804 A1-A3) Sphera	*RER: Window glass simple (EN15804 A1-A3) Sphera*	*RoW: bronze production ecoinvent 3.9.1*	*SE: Copper Sphera*
2.12E+05	6.75E+05	4.01E+06	1.66E+07
2.54E+04	8.10E+04	5.61E+06	2.54E+07
1.84E+05	5.88E+05	2.88E+06	7.43E+06
1.19E+02	3.81E+02	1.55E+04	9.90E+03
1.24E+01	3.95E+01	4.75E+03	4.86E+02
1.51E+04	4.80E+04	2.21E+05	8.39E+05
2.74E-08	8.72E-08	2.26E-03	1.76E-06
-1.47E+01	-4.69E+01	6.79E+02	5.20E+02