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Life Cycle Analysis of Materials for Radiant Floor Heating Systems

Case study in a new building development

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Life Cycle Analysis of Materials for Radiant Floor Heating Systems

by

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Master of Science Thesis TRITA-ITM-EX 2024:502
KTH Industrial Engineering and Management
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Livscykelanalys av material för golvvärmesystem

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Abstract

The environmental impact of the construction sector with new buildings and renovations is among the highest of sectors. Therefore, the introduction of new measures and the promotion of improvements to address emissions reduction can be seen in advances for energy consumption systems in housing, the search for new, more sustainable materials, as well as the study of how this affects the supply chain.

The research conducted in the thesis investigates the actual challenges within the construction sector in order to elaborate the Life Cycle Analysis (LCAs), and increase the knowledge of emissions for the comparison of Environmental Product Declarations (EPDs). With this information and the extensive recent literature review, it has been obtained how certifications drive information transparency to make decision-making better. Allowing companies with the LCA study to access a wider market with environmental requirements. This makes it more attractive to the buyer, thus providing a competitive advantage in the industry. Thanks to the LCA study and the elaboration of EPDs for each of its products, the company has been able to highlight its products with greater transparency in terms of the impacts they have during their supply chain. In addition, it also makes it possible to know which of the stages have the greatest impact.

This allows the implementation of a transition to reduce emissions in the sector, both for its supply chain and its useful life. The thesis seeks answers on how changes affecting the choice of a more sustainable material for the production of a product can affects the overall emissions. The study of the LCA of a product provides the necessary information for the elaboration of EPD, as well as the knowledge of the impacts in each of the stages of the supply chain. An introductory study of the LCA is made, with previous information in the literature review for its better understanding. Elaborated with the data of a company that supplies the products to install the radiant floor. Resulting in a comparison that shows how a more sustainable raw material improves the emissions of a product by reducing them.

Key-words Supply Chain Design, Product Designs, Life Cycle Analysis, Network Configuration, Sustainability, Construction, Supply Chain Management

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Sammanfattning

Miljöpåverkan från byggsektorn med nya byggnader och renoveringar är bland de högsta inom alla sektorer. Införandet av nya åtgärder och främjandet av förbättringar för att minska utsläppen kan därför ses i framsteg för energiförbrukningssystem i bostäder, sökandet efter nya, mer hållbara material samt studier av hur detta påverkar leveranskedjan.

Den forskning som bedrivs i avhandlingen undersöker de faktiska utmaningarna inom byggsektorn för att utarbeta livscykelanalyser (LCA) och öka kunskapen om utsläpp för jämförelse av miljövarudeklarationer (EPD). Med denna information och den omfattande litteraturgenomgången har man kommit fram till hur certifieringar driver på informationstransparensen för att förbättra beslutsfattandet. Företag med en LCA-studie får tillgång till en bredare marknad med miljökrav. Detta gör dem mer attraktiva för köparen och ger dem därmed en konkurrensfördel i branschen. Tack vare LCA-studien och utarbetandet av EPD:er för var och en av sina produkter har företaget kunnat lyfta fram sina produkter med större transparens när det gäller den påverkan de har under leveranskedjan. Dessutom gör det också möjligt att veta vilka av stegen som har störst påverkan.

Detta gör det möjligt att genomföra en omställning för att minska utsläppen i sektorn, både för dess leverantörskedja och dess livslängd. Avhandlingen söker svar på hur förändringar som påverkar valet av ett mer hållbart material för tillverkningen av en produkt kan påverka de totala utsläppen. En LCA-studie av en produkt ger den information som behövs för att utarbeta en EPD, samt kunskap om påverkan i varje steg i leverantörskedjan. En inledande studie av LCA görs, med tidigare information i litteraturgenomgången för bättre förståelse. Den fördjupas med data från ett företag som levererar produkter för installation av golvvärme. Detta resulterar i en jämförelse som visar hur ett mer hållbart råmaterial förbättrar en produkts utsläpp genom att minska dem.

Nyckelord Design av försörjningskedjor, produktdesign, livscykelanalys, nätverkskonfiguration, hållbarhet, konstruktion, hantering av försörjningskedjor

Contents

List of Figures

List of tables

Foreword

First of all, I would like to express my sincere thanks to my supervisor Luca Urciuoli at KTH. Without his support and guidance throughout these months the completion of this thesis would not have been possible.

I am also deeply grateful to the sustainability manager from Uponor for giving me the opportunity to carry out this study, thanks to the information and help with my doubts during the study. And lastly, I am also very grateful to all the participants who were kind enough to answer the questionnaire, since without their contribution the study could not have been carried out.

Finally, I would like to express my deepest gratitude to my family and friends for their continuous support and patience during these last years of university.

Acronyms

Abbreviation	Explanation
CE	Circular Economy
EIA	Environmental Impact Assessment
EoL	End-of-Life
EPD	Environmental Product Declaration
EU	European Union
Gt	Gigatons
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
PCR	Product Category Rules
RQ	Research Question
SCM	Supply Chain Management
SDGs	Sustainable Development Goals
UN	United Nations

1. Introduction

In order to demonstrate the importance of the research questions of this thesis, the following introduction aims to clarify the current background and to present the problem on which this thesis has based its research.

A brief description of the structure of the thesis will be introduced in order to know the process used in the development of the study.

1.1 Background

The energy crisis that emerged in the 1970s has driven the growth of technologies for ventilation, heating, and insulation of dwellings. This has introduced new aspects for the building industry to consider in the creation of new homes, improving the quality of life so that heating and ventilation are adapted to the latest developments (González-Torres *et al.*, 2022).

In order for companies to optimize their processes and thus increase their competitiveness in the market, a complete analysis of their supply chain is necessary (Thunberg, no date). This analysis should be carried out from the procurement of raw materials to the final delivery for the customer. After the analysis, it is easier to identify areas for improvement and bottlenecks in order to anticipate possible risks. These risks can be interruptions in the supply of raw materials or changes in market supply and demand over time.

As always, the construction sector is essential for the renovation and creation of new housing. This is why it is a sector that has an impact on emissions on a daily basis, whether it is the procurement of materials or the use of energy for its implementation. Currently, thanks to the Paris Agreement signed in 2015, which agreed to limit the average global temperature increase to below 1.5ºC, many measures have been put in place to meet the proposed objectives. This agreement proposed a reduction of the emission values between 1990 and 2030 by 55% (Paris Agreement on climate change - Consilium, no date).

However, although these efforts have been successful in reducing emissions through various measures, they have not been sufficient to meet the proposed targets. The construction sector plays an important role, particularly in achieving the United Nations (UN) Sustainable

Development Goals (SDGs): number 11 regarding sustainable cities and communities, and also number 13 on climate action (*THE 17 GOALS | Sustainable Development*, no date).

This has led to the Net Zero Emissions transition plan by 2050, where a roadmap has been designed with the necessary changes for the global energy sector. In the case of the European Union, this is the 2023 revision of the Energy Performance of Buildings Directive (EPBD). This is due to the fact that CO_2 emissions in the building sector represented in 2018 39% of the global total, driving the transformation of the industry (*Buildings - Energy System - IEA*, no date). For residential energy consumption specifically, several measures have been proposed to achieve this, such as retrofitting, where existing buildings adopt more efficient technologies and the use of cleaner appliances to help reduce energy consumption (Energy Agency, 2021).

Recent research, such as Chen, Hammad and Alyami (2024) , has investigated how to make improvements in the resilience of supply chains in the construction sector. This addresses the uncertainties caused by supplier capacity and demand for materials. These changes also aim to reduce impacts on emissions as well as costs and time.

Apart from these improvements, a better analysis of the life of the materials has also been made once they are disposed of. This aspect has been quite challenging to quantify in the study of the lifetime of materials, as there are different solutions, and all of them produce emissions. By taking this into account, there must be a decision to be made as to which option to choose when the life of a material has come to an end (Kirchherr *et al.*, 2023).

This is why Life Cycle Assessment (LCA) has emerged as a tool to quantify the emissions associated with the materials used. In this way, the complete life cycle of these materials is analyzed, from their collection to their end-of-life disposal. With the information that the LCA provides, it is possible to make a better choice of materials to use, taking into account the impacts of different factors during their life cycle. In addition, to support the effective use of this tool, European standards and guidelines have been established. This serves as a guide to facilitate such studies, with the aim of fostering greater sustainability in organizations (Barbhuiya and Das, 2023).

1.2 Problem Statement

Within the changes for a better understanding of emissions, the supply chain is analyzed from beginning to end. In this case, the study focuses on the changes in one of the initial phases and also on the problems that currently exists in preparing the necessary documents for the publication of a product's emissions at each of its stages.

Inside the construction sector, the necessary transition to a circular economy implies an integrated approach from the beginning of the design concept to the end-of-life (EoL) of buildings. Therefore, the decisions made at the product design stage will have consequences throughout the supply chain. This means that studying the relationship between the product design and its supply chain allows to have the knowledge of the environmental impacts that will occur. Although in recent years the impact on emissions has been increasingly analyzed with the development of LCA, studies such as the one by Dsilva, Zarmukhambetova and Locke (2023) qualify as necessary the use of LCA as a tool for the knowledge and subsequent improvement of each of the phases in the development of a product.

As the construction sector is one of the sectors with the highest emissions and environmental impacts, it is of vital importance to promote the use of LCA for the study of how a product's design impacts the footprint. This allows for greater transparency of the system, so that better comparisons and improvements can be made. In addition, a better knowledge of the information related to the products allows to improve the knowledge of the information. Since the recollection of data is another of the challenges that exists in the development of LCA (Barbhuiya and Das, 2023).

This is something that is being achieved thanks to the drive for change through regulations and certifications. However, it is also true that companies often have to do this on their own initiative. As it is a study of many steps inside the supply chain, it may happen that there is a lack of information either by suppliers or in the chain itself. In particular, according to Cardoso et al. (2024), there is a problematic correlation between the LCA and the way it is done. Since this is something new, there is great uncertainty. Mainly due to complicated harmonization between the Product Category Rules (PCR) for the elaboration of LCA (Moins *et al.*, 2024). In addition, the comparison of Environmental Product Declarations (EPDs) also represents a challenge within the industry. Although there are more and more studies, most of them relate PCRs to LCAs or study EPDs. But there is a big gap regarding the relationship between the input information for the LCAs, the LCAs exact methodology for the elaboration and lastly, the different types of EPD that are available. And since they are all interrelated, this presents a problem to be studied in order to improve their future understanding and use.

The research gap marks a need to understand better the changes that need to be made in order to meet environmental objectives. Moreover, addressing and communicating the uncertainty, as seen in Marsh, Allen and Hattam (2023), specifically in construction LCAs, is a barrier that can be seen. That is the reason why this specific gap should be studied in order to increase transparency by reporting the made assumptions.

1.3 Purpose and Research Questions

The main purpose of this thesis is to analyze the supply chain in the construction industry, particularly by comparing materials used for heating. This makes it possible to analyze two types of materials and the effects they can have on the supply chain. The use of these pipes will be targeted to new construction projects in this particular case. These systems are becoming increasingly important for improving energy efficiency, and also have better surface utilization as they are located within walls, ceilings, and floors.

However, apart from the known savings it is also important to study the real emissions and costs that also need to be compared in order to see in reality how long it takes for these new systems to be more advantageous. This is why the existing data will be analyzed in order to gain a better understanding of how the supply chain is like for these types of products.

The principal research questions will be centered on the Life Cycle Assessment of a product used in radiant floor heating systems. LCA will allow a comparison of how the difference in choice of material influences the impact a product has on the environment. To this end, the role that circularity can play in the dismantling of projects is introduced at the end of this analysis (Demuytere et al., 2024).

The questions that this thesis will be focused on are how the environmental impact differs in two different cases within the context of a building's life cycle.

> ***RQ 1:*** *How does a company in the construction sector align Life Cycle Assessments (LCAs) with existing data and regulatory compliance?*
>
> ***RQ 2:*** *How does material substitution in the design of a product impact the environment?*

Since the LCA must be prepared for certifications and this is something that is increasingly being done. It is important to check how the current situation is in the construction sector with regard to its elaboration, with the elaboration of a questionnaire. Moreover, the study of the literature review added to the results of the questionnaire will show the reality of nowadays compared to what has been studied so far. Barriers to information (Marsh, Allen and Hattam, 2023), as well as harmonization among the PCRs dictating the requirements for each type of material (Moins et al., 2024). As this is a sector with suppliers abroad and a vast supply chain, it is important to have transparency in the process in order to be able to have the knowledge of the improvements that could be made.

A greater knowledge of the current tools that allow the collection and analysis of data on materials is sought (Barbhuiya and Das, 2023). Identifying the different existing regulations and quality standards. This is enabled through greater collaboration between countries in order to optimize the management in the supply chain that materials have depending on the destination.

In this context, it is also interesting to consider how exactly the regulations and certifications that are put in place work. In particular, since they need the elaboration of LCAs and their harmonization with the selected requirements (Moins *et al.*, 2024).

For a correct EPD it is of vital importance to reduce the uncertainty that can be had in the elaboration of the LCAs (Marsh, Allen and Hattam, 2023). In this way, it is possible to draw a conclusion on which aspects are usually taken into account to designate a material or a project as more sustainable.

For this purpose, the thesis will focus more on the key factors that have contributed to the differentiation of emissions between the two different materials studied in the first research question. This will help to gain a better understanding of the steps that a company like Uponor needs to take in order to establish a product that is more sustainable in the market and how the certification works.

1.4 Thesis Outline

In the first chapter of this thesis, a brief background will be introduced in order to understand the current situation on which the thesis will be based. Secondly, we will arrive at the problem statement, which will expose the current problem that it is going to study how to improve. Then, the purpose and research questions of this thesis will be discussed. Finally, a brief description of the company that provides the data for the analysis of the materials to be studied.

After this first introduction, in the second chapter, an analysis of the relevant literature is conducted to have a better understanding of the theory on which these comparisons of materials for the LCA supply chain will be based and also the difference they provide in comparison to other existing products in the market.

The third chapter will present the methodology used for the elaboration of the thesis, where the questionnaire guidelines will be shown, targeted to the participants inside the construction sector. Moreover, the case study provided by Uponor will be presented for the elaboration of the LCA, with the aim to compare two different materials for the same product.

Afterward, the results and an analysis of the results will be presented. For this purpose, the knowledge presented in the literature review will be used. In this last chapter, the thesis will be concluded with an evaluation of the questionnaire and the study results and its limitations for the future.

1.5 Company Description

Uponor is a company specializing in pipe systems for air conditioning, water, and sanitation. Their products can be used in new constructions or in renovations of old buildings. Priority is given to the easy installation of the pipes and the energy efficiency they provide. One of its main objectives as a company is to reduce CO_2 emissions, and to this end, the LCA study, with the development of Environmental Product Declarations, makes it possible to achieve it.

2. Literature Review

In the following chapter, the theoretical aspects necessary for the understanding of the theoretical framework in which the thesis is developed will be described. Emphasis will be placed on the relationship between the development of LCAs and their application in supply chains.

2.1 Supply Chain Management (SCM)

As is commonly known, the management of the supply chain aims to maximize the value of a company by using its resources as efficiently as possible. The supply chain encompasses all manufacturers, suppliers, warehouses with stock materials, transporters, retailers, and customers of the products. Moreover, to implement an effective supply chain management is of great importance to stay competitive in the field and deliver the best product with the highest quality and at an attractive price for customers. Therefore, investing in new techniques and equipment is key to the effectiveness of supply chain management (Sukati *et al.*, 2012).

Supply chain management is key in getting a business to a competitive level. Companies are pushed into adopting the perfect model of strategy for supply chain management (Osei *et al.*, 2023). However, the implementation of this comes with its challenges, as it needs a perfect rapport between all departments as well as with all companies taking part in the supply chain. Therefore, it opens a door for improvement in techniques as well as development in shared learning to move forward at a good pace.

Today, companies compete in terms of how effectively they use the supply chain. Therefore, improving the supply chain is a strategy that many companies know is key to enhancing against their competitors (Forbes and Ahmed, 2010). This requires good design and efficient management in order to offer higher quality products with shorter lead times compared to their competitors. In addition, good management also allows companies to differentiate themselves in an already saturated market, as it can attract more customers by standing out.

In terms of business differentiation, optimal supply chain management will allow companies to have a more significant competitive advantage (Li *et al.*, 2006). As an example, when there are two companies offering quite similar products, the greatest differentiation will be due to the supply chain. As supply can be faster and more flexible, reducing costs and maintaining quality, it will be quicker to respond to market demand over time. In conclusion, this not only improves the internal functioning of the company with good supply chain management, but also has a direct impact on the company's competitive position in the market.

Right now, another challenge faced by companies in the actual landscape is the need for improvement in their efficiency towards sustainability, so that all regulations that have been put in place to tackle climate change can be passed.

This is why there is increasing pressure to improve their practices at every stage of production. Including everything from the procurement of raw materials to the management of waste at the end of the project. These regulations include those related to the energy efficiency of buildings, the substitution of traditional raw materials to more sustainable ones, and the reduction of carbon emissions when constructing and operating buildings.

In response to these emerging challenges for change, companies are increasingly turning to more sustainable supply chain practices. This implies a re-evaluation of the choice of suppliers and subcontractors, as well as optimizing the various processes that take place from the choice of raw materials, their transport, management, and end of life.

Some of the problems faced by every project are the search for raw materials, which makes the planning of a project extremely critical. Every relationship with material suppliers is different and some of those relationships cannot be changed because of availability. Within the supply chain, this search can become very complex because relationships with certain suppliers are difficult to change or replace.

On the other hand, there are also other aspects of supply chain improvement apart from cost reduction and carbon footprint improvement. The aim of shortening times has led to the prefabrication of certain tasks being done externally, meaning that when they are transported to the project, the time is reduced. This has allowed certain tasks to be done remotely, causing the lead time to change and, with it, the planning. In addition, this means more control over the demand and the planification of the workforce (Forbes and Ahmed, 2010).

2.1.1 Information Systems for Supply Chain Management

To improve the efficiency of supply chain management, it is important that there is good communication and relationships between suppliers and subcontractors. In addition, management with advanced technological programs can optimize inventory management and create contingency plans for potential risks during the project.

Thanks to the software used for supply chain management, many aspects can be analyzed and monitored to see where the efficiency of the system can be improved. Aspects to be considered are material availability and lead times, quality control, cost management, and seasonal demand. In addition, measures that promote sustainability throughout the project cycle can help to reduce emissions (European Commission, no date).

Some of the most commonly used programs for the management and optimization of processes in the supply chain are the following:

- SCM (Supply Chain Management): integration of key processes in the supply chain. To improve efficiency and visibility, this includes planning for future demand, procurement, production, and distribution.
- ERP (Enterprise Resource Planning): this platform can be designed specifically for a particular sector. It allows the management of various aspects of a business, such as project and resource management.
- PMP (Project Management Programs): help in planning with the management of resources, execution and control of the project to follow its progress.
- CRP (Capacity Requirements Planning): useful for good scheduling and allocation of available resources. During the execution of the project, it is possible to control the workforce, machinery, and materials required.
- QMS (Quality Management Systems): necessary to maintain the quality standards required to ensure compliance with regulations, standards, and customer satisfaction.

Similarly, for each type of project and its needs, a different choice will be made for the program to be used during supply chain management (Hussein *et al.*, 2021).

2.1.2 Supply Chain Design

The process of designing the supply chain is critical to the efficient and effective management of the flow of products and services. It plays a fundamental role in meeting market demand, as a well-designed network can reduce costs and delivery time. In addition, it will also allow for greater flexibility in being able to respond as well as possible to changes in demand.

For its design, a number of aspects must be taken into account that add to the complexity of the network. There is a great deal of complexity in managing logistics, as the nature of the building materials can be very different and in large volumes. This requires the management of multiple suppliers and subcontractors, which can affect cost and time constraints. As timescales are tight and there is an order of execution within projects, it is important to have planning and coordination to avoid delays or increased costs.

Some key factors to consider are the proximity of suppliers, warehouses, or distribution centers. This can reduce transport costs and delivery times. In addition, knowing the available storage capacity or existing inventory helps to ensure the availability of needed materials before changes in demand or shortages of materials. By incorporating a particular strategy into supply chain design, companies can find a balance between the efficiency and flexibility they desire in order to meet the demand. Each of these strategies allows allocated resources to be optimized, thereby reducing day-to-day and future risks. When centralized distribution centers are used, resources and decisions are concentrated at a single point. Warehousing, order processing, and subsequent distribution activities are carried out at the same point, resulting in a leaner distribution. This allows for a more efficient management, as logistics management is simplified. Thus offering a greater focus on economy of scale. However, one of the negative aspects of this type of distribution network is that transportation costs and delivery times can be higher as it has to supply a wide location (Shamsuzzoha, Ndzibah and Kettunen, 2020).

On the other hand, when resources are distributed in different nodes, it is a decentralization of distribution centers in multiple locations strategically chosen in the geography. This strategy increases the capacity to respond to demand by being closer to customers, thus avoiding possible interruptions in consumption by having a greater response time. A negative aspect of this type of network is that it increases logistical complexity, making management more careful with better coordination between all available locations (Riese *et al.*, 2024).

In addition, a consideration that is becoming more and more relevant today is that the design of the supply chain should have a sustainable approach. Thus, apart from improving the operational efficiency of logistics, the aim is also to minimize the environmental impact of transportation and management of different distribution centers. In this aspect, the aim is to improve transportation routes and the balance of the demand response service from this perspective. Another advantage is that adopting these practices improves brand reputation by ensuring that throughout the value chain, there is a good balance between the different aspects that allow a smooth, profitable, and sustainable operation (Basheer *et al.*, 2024).

With respect to the supply chain network, when there are different suppliers, manufacturers and distributors located in different regions, it is a global supply chain. However, it presents additional challenges in terms of risk management, coordination, and regulations between countries. It is a network used when raw materials or components for a product must be sourced from different parts of the world and there is no closer alternative that exists and is more beneficial.

The other type of chain is the local supply chain, which focuses more on production and distribution closer to the customer. This approach is used when seeking to reduce dependence on a global chain, thus improving the risk of supply disruptions and also to promote sustainability by seeking products closer to the customer. However, as highlighted in the global chain, when seeking a closer option, production costs may be higher and the variety of products to choose from may decrease.

Finally, good communication between the participants in the supply chain is key to good coordination at every stage of the project. Sharing information not only involves the communication of information relevant to the operation of the organization, but also includes the understanding of the objectives, requirements, and challenges to be met. Increasingly, the business environment is becoming more dynamic, requiring fluid communication that promotes efficient collaboration by improving decision-making with greater knowledge.

2.2 Outsourcing

Outsourcing refers to the externalization of certain functions of services to an external company. It can be of certain departments or operations within the productive process. The aim is to delegate these functions to a specialized company so that you can direct all your resources to your core business (Liu *et al.*, 2024).

Within the logistics of a company, this function is used when it is more advantageous to contract specialized companies and thus gain efficiency, increasing the competitive advantage. The optimization of processes and the improvement of business management require good control over logistics. This is why outsourcing is necessary for certain tasks, allowing the company to concentrate all its efforts on its core business activities.

Outsourcing has advantages and disadvantages, and within each sector it is more or less common. The main advantages are the reduction of economic risks, reasons for the technical capacity of the company, increased workload flexibility, business strategy and improved efficiency of operations. However, this practice also entails a loss of control over processes, a lack of control over customers or trust, and resistance to change.

There are two types of outsourcing, depending on the importance. Tactical outsourcing deals with simple external activities, and strategic outsourcing is more focused on activities where the relationship with the supplier is of greater importance (Chen *et al.*, 2022). In conclusion, the main difference between these two forms of outsourcing lies in the cooperative relationship between the participants and the level of interdependence between the company and the function being outsourced.

Depending on the location there are three types, offshore where the supplier is located in another country and the objective is to reduce the cost of labor and taxes. The second is nearshore, where the supplier is located closer to the company, and finally, onshore, where the company and the supplier are located in the same country.

In addition, in the construction sector the company usually executes a specific part of the project. This is because most of the work can be subcontracted or carried out by other specialized companies, accounting for about 75% of the total work (Ranasinghe, Perera and Dilakshan, 2022).

Several of the advantages of outsourcing are greater cost efficiency, greater worker flexibility and risk mitigation. This is because subcontracting is a very positive relationship for the project as it allows each party to have a greater degree of specialization in their particular task. However, one of the consequences of this is that for the scheduling of tasks a small delay can translate into many delays in different subsequent tasks that are dependent. Typically, only half of the tasks assigned to a particular week during the project are actually completed in the allotted time (Forbes and Ahmed, 2010). In most cases this schedule failure is due to a lack of communication between the different trades.

In the construction sector, three different types of suppliers are used depending on the specific labor or material requirements. In making the selection, factors such as the availability of the materials required, the quality required for the work and the efficiency of delivery times are considered. Outsourcing can be done with each type of supplier: machinery and equipment, skilled labor, and materials.

Each of these suppliers is responsible for a fundamental role in the correct functioning of the process for the success of the project. Here a correct use of outsourcing allows optimizing resources in order to reduce costs and guarantee the efficiency of the project execution (Akhtar, 2023).

2.3 Supply Chain for Construction

Since 1990, interest in improving supply chain management in the construction sector has been increasing. This is due to the fact that projects in this sector require a large investment and time to be completed, which can lead to uncertainties. It is therefore crucial to have an optimized supply chain that does not affect the duration and budget of the project.

Nowadays, the construction sector is under constant change because every project can be in different areas and the specifications may vary. By being such a local market the volatility is very high (Segerstedt and Olofsson, 2010). This is the reason why it is critical to manage change successfully in order to improve the actions to tackle the change of plans. In this case, action is more important than planning, as there are a lot of unexpected changes, and it is how these are dealt with that will affect efficiency and performance. This aspect is what differentiates the construction sector from any other industry, as in other sectors the management of the supply chain and relationships with producers is more continuous. Control over the supply chain can be more difficult, as in this type of industry it is more focused on specific projects. This is why demand is highly influenced by the particularities and more focused on the acquisition of the needed materials. However, this can also prevent problems by having good coordination and planification aimed to the specific need of the particularities that differentiate every project.

Currently, as it can be seen in Figure 1 supply chain trends focus on labor availability, reliance on contractors, delays and cost increases with raw materials needed for the project, and pre-planning of material procurement (Segerstedt and Olofsson, 2010).

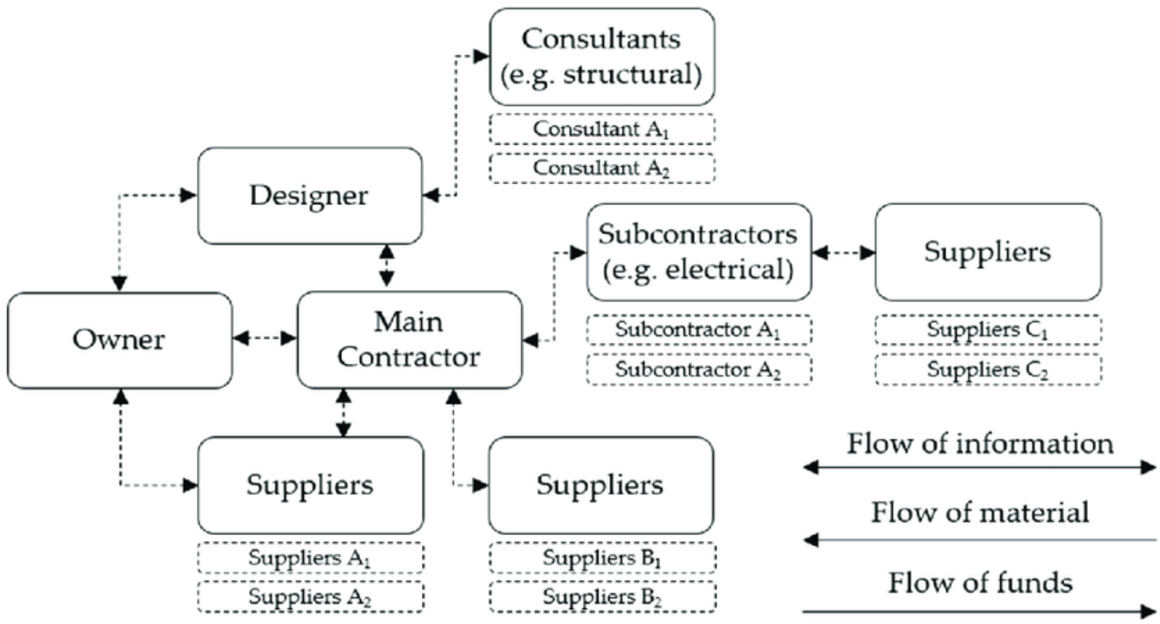

Figure 1. Typical Construction Supply Chain.

The arrival of the consumer's desired product specification is key to the material ordering and planning process. However, the preparation is different when the order arrives and also before starting the construction project (Segerstedt and Olofsson, 2010). Depending on the manufacturing process there are several steps to follow that depend on the control and specification. In Figure 2 these can be seen and are engineer-to-order, modify-to-order, configure-to-order and select variant. This can be compared to the typical process view in push-pull manufacturing, where there is a barrier that depends on the state of the desired product at the moment the consumer order arrives.

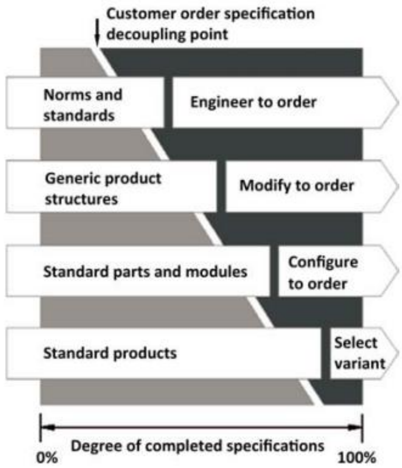

Figure 2. Product specification process for different variants of a building system. Source: Akhtar. M, 2023.

2.3.1 Energy-Exergy

In the context of the supply chain in the construction sector, the concept of energy and exergy takes on significant importance as it allows measuring the efficiency and also the sustainability of the processes that are part of the supply chain of materials and services required for the execution of a project.

Energy encompasses the total amount of energy resources that are used during all the stages that make up the procurement process. Starting with the extraction of the raw materials up to the final delivery of the materials to the project on site. It is an important indicator that allows measuring the energy consumption and demand necessary to carry out this activity.

On the other hand, to measure in a finer way the quantity and quality of energy that the system uses in a useful way. This therefore allows to differentiate between the energy that allows to work in an efficient way and the one that is of a lower quality, with a low useful work. This presents limitations at the time of performing the work since the level of utilization will be different (Rocco, Di Lucchio and Colombo, 2017).

Thus concluding that by making an analysis from the energy perspective during the process steps it is possible to identify in a more precise way the areas to be improved. As a consequence of the knowledge about the degree of efficiency and quality of the energy resources consumed. This allows the implementation of strategies to optimize the use and management of energy in the supply chain within this sector.

2.4 Value Chain and Life Cycle Analysis

The value chain of a building is directly related to Life Cycle Analysis. It encompasses from the conception of the project idea to the end of the building's life. As can be seen in Figure 3, there are a number of stages that describe the milestones within the life of a project: production, construction, operation, and end-of-life.

This framework based on the rules EN15804 and its revision EN15978 is the basis for defining which data are necessary to calculate when the LCA for the whole building has to be elaborated. These four main cycles, in turn, have several sub-modules.

The first steps identify the needs, develop, and correct the project by studying the feasibility and requirements of the clients. Then there are the stages of planning the necessary materials, contractors, and services in order to carry out the project. In these stages most of the decisions and negotiations have to be made. In addition, close project management is also followed to ensure that the required quality and deadlines are met.

The product stage (A1-A3) is cradle-to-gate, as it considers all stages from the creation of a product until it leaves the factory. Its main points of study for LCA are the emissions impacts associated with the raw material supply, the transport, and the manufacturing up to the point of sale.

Next, in the cradle-to-practical-completion are points A4-5 belonging to the construction process stage. Here the analysis collects more information on the product until its installation is completed for its intended purpose.

Finally, once the project has been completed it enters the cradle to grave. The maintenance phase (B1-7) involves the building care management and improvements to meet the needs of the inhabitants. At the end of the building's useful life (C1-4), the decision to renovate or demolish the building is presented, for which there are a number of key factors that will condition the final choice.

Additionally, the cradle-to-cradle module D analyses the potential for avoiding emissions if materials are reused, recycled or energy recovery when wasting materials. In both cases of leaving the system and re-entering. This is outside the system boundaries and aims to close the life cycle of products by focusing on sustainability and waste reduction for future use.

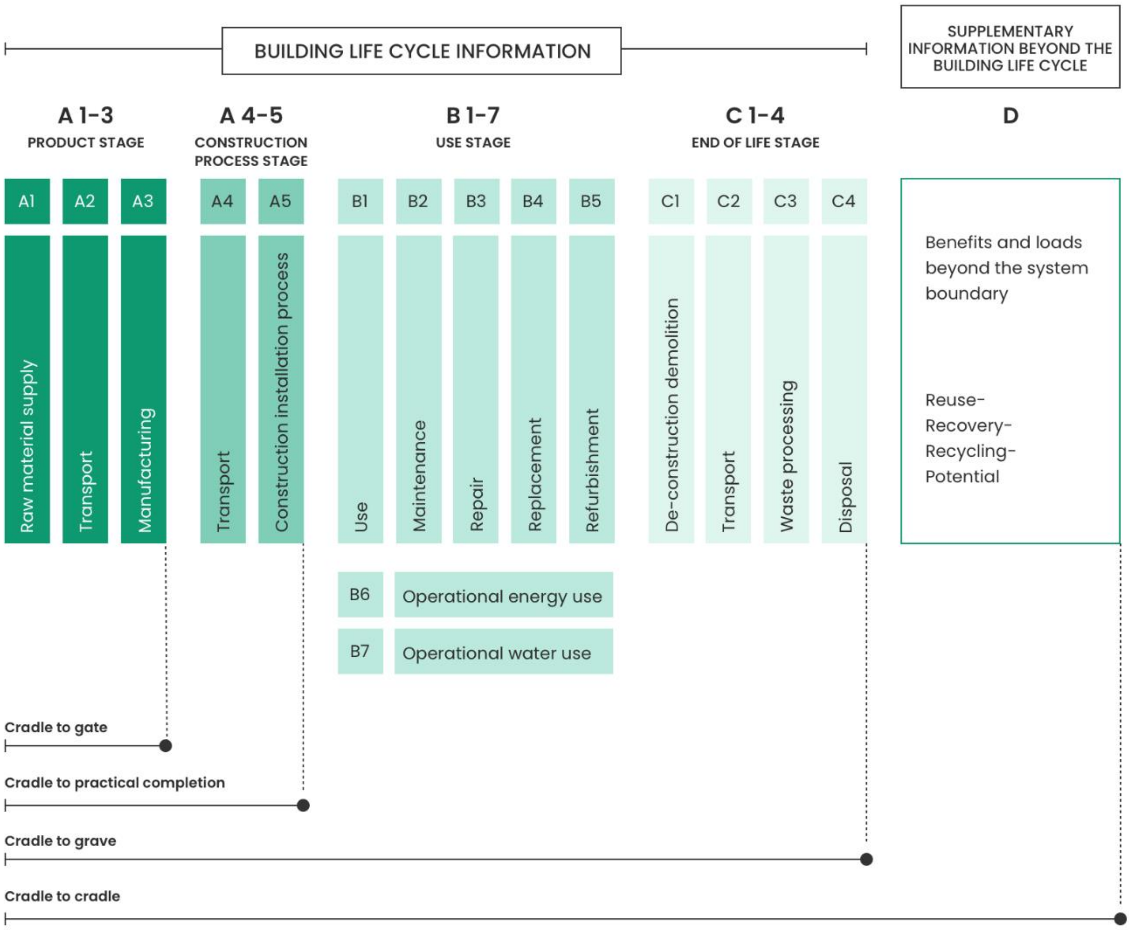

Figure 3. Life Cycle Stages according to EN 15978 standards

Life Cycle Analysis is a system used to measure the emissions of a product or process, from its creation to its disposal. This is why the End of Life (EoL) is also analyzed, which originates when a building reaches the end of its life and can only be renovated or demolished.

The main objective of the LCA analysis is to provide the necessary environmental information for decision making. Allowing to know the emissions that a product has at each stage of its life. These improvements in decision making are quite important as it allows the creators of a building to have better designs in terms of sustainability by considering the impacts on emissions that these choices can have as a consequence.

This method is standardized according to ISO 14040/44. As can be seen in Figure 4, within this framework there are 4 main steps: the definition of goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and the interpretation of each of the steps.

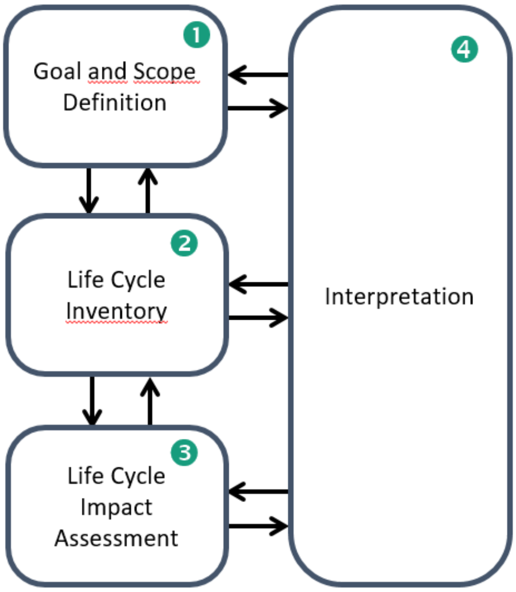

Figure 4. LCA phases according to the ISO standard

2.5 Product Design

Within the supply chain, product design plays a crucial role in increasing efficiency and sustainability. Since this stage encompasses everything from the selection of materials to the optimization of manufacturing processes. Each design decision has a direct and distinct impact on the supply chain, and thus on the final delivery of the project.

One of the main considerations in supply chain management is to procure the right raw materials, without compromising product quality. In this step, renewable, recyclable, or low environmental impact materials can be chosen, while also considering their subsequent recycling at the end of their life. The relationship between product design and the supply chain impacts the responsiveness and resilience of the chain. Knowing the benefits of this approach can improve a company's competitiveness. Focusing on the organization's design process allows identifying possible changes that would benefit the company economically. The result of this could shorten around 80% of the costs in the supply chain (Khan, Christopher and Creazza, 2023).

An important consideration in product design within the construction industry is modularization and standardization. This allows for reduced risk within the supply chain, as it allows for better adaptation to change due to reduced complexity. With modular product design, on-site assembly will be easier, thus reducing potential material waste by maximizing product utilization. In addition, it has a direct relationship with inventory management and manufacturing costs, since it allows to know in a more concrete way the necessary quantity of material to be used. This reduces the amount of material used and improves resource management.

The objective at this stage is to optimize the user's experience with the product. This is to ensure that the brand produces sustainable products that can be used for a long period of time. This is why, even if a product has a good design, new ways of improving it continue to be studied, either by changing its design or looking for alternatives in the composition of the materials used.

For materials used in construction, the durability and resistance of the product is crucial. Ensuring longevity of service, weight loads, temperature changes and adverse conditions that do not compromise the integrity of the product or its functionality. In addition, a well-optimized design allows for increased thermal efficiency of the system, improving heat transfer as well as insulation. This is due to a decrease in energy losses and thus the use of energy can be more optimal.

The following Figure 5 shows in detail the processes that are part of the design stage. It is important to highlight the continuous review between the processes, so that it can result in improvements.

Figure 5. Product Design Process. Source: Nebulem

In short, product design plays a critical role in any supply chain. Recent years have seen significant transformational changes in a number of industries. The drive for changes that positively impact the environment and cost reductions has been highlighted. The integration of product design into the supply chain has allowed for a broader view by focusing on aspects other than the aesthetic and functional aspects of the product. This has led to consider this stage as a strategic component in business, considering from the preliminary stages of the design process the constraints and requirements until the product reaches the hands of the consumer (Marsillac and Roh, 2013).

Specifically in the construction sector, improving materials for products has translated into greater energy efficiency for the consumer on a daily basis. Since the improvement in the level of insulation to maintain the temperature in the home allows to reduce the energy demand. In addition, in some cases it has also had an impact on reducing dependence on unsustainable materials, promoting the use of other materials that can be given a second life through innovation. In the context of the whole building, the use of LCA as a tool to analyze the materials to be used can achieve about 26% reduction in emissions (Dsilva, Zarmukhambetova and Locke, 2023).

2.5.1 Circular Economy

Traditionally, the linear model has been based on extract, produce, consume, and dispose of. On the other hand, the circular economy model seeks to minimize waste to maximize resource use efficiency, thereby reducing environmental impact. It has several fundamental principles that include durable design and recyclability of the product, as they will last longer and will be easy to maintain and repair. This not only “buys time” but also reduces the need for virgin materials (Macarthur, no date). In addition, their reuse, redistribution, recycling, and the regeneration of natural systems are also considered. This encourages the repeated use of products, giving them a second life.

Concerning the construction sector, a large amount of resources are used, and it also generates quite a lot of waste due to construction work. However, implementing the circular economy in this type of projects is changing this reality. This is due to the impulse of new regulations to manage the change and reduce the impact of this sector. With the development of these new regulations and standards for waste management and the improvement of energy efficiency, it has been possible to promote a change towards more sustainable practices within the sector.

From the first initiatives with the recycling of materials such as concrete, steel and glass. Various certifications have been developed to encourage sustainable construction practices. This has helped establish green building standards that promote energy efficiency and waste reduction. This introduced principles that allow for the disassembly and reuse of components, facilitating the transition to the circular model. One of the features that also contributed to the reduction of impact was using more sustainable materials, either because they are recycled or renewable.

For revolutionizing the construction sector, innovation and technology have been instrumental in order to advance circularity. Digitalization and programs like BIM have transformed resource management and life cycle monitoring, making them more efficient than ever before. This technological advancement has not only improved construction processes but also paved the way for new business models based on circular services. This exciting development in the sector demonstrates the potential of innovation in promoting circular economy practices (Mahmoumgonbadi, Genovese and Sgalambro, 2021).

In the last stage of a building, dealing with demolition, new selective projects have been implemented in order to recover valuable materials. In addition, the establishment of supply chains with circularity principles has been integrated from reuse and recycling to design in construction and the end of life of the building. This involves the modularity of materials and the use of innovative alternatives.

With the effect of supply chain disruptions, (Piila and Sarja, 2024) studied how new practices that emerged to meet demand affected circularity. Surprisingly, a lack of institutional support made it difficult to adopt greater circularity. This is because certain regulations and customer priorities outweighed the adoption of more sustainable measures, although this is exactly what is slowly being attempted to change going forward. The following Figure 6 shows the practices that promote circularity in each of the phases within the construction sector with respect to the reduction, reuse and recycling of a building's LCA.

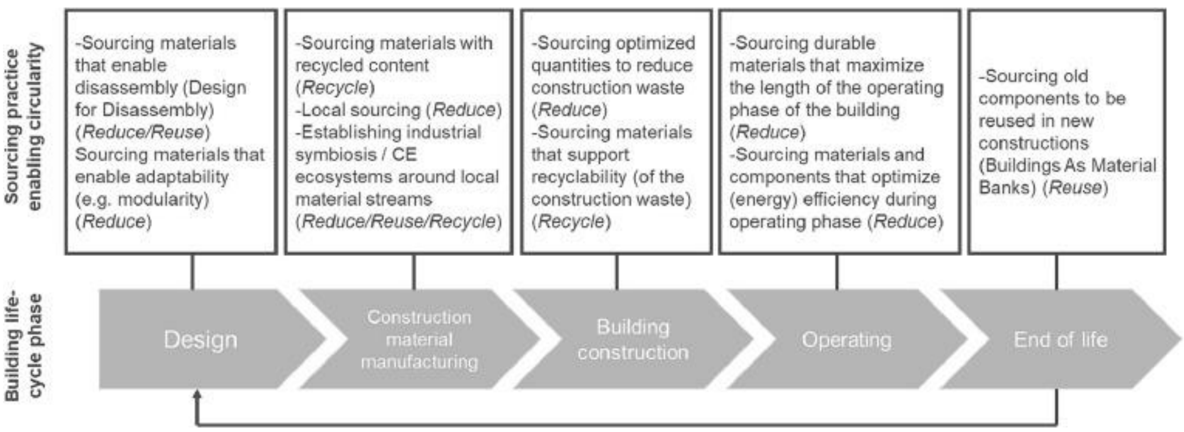

Figure 6. CE adoption in the sourcing of the supply chain. Source:(Piila and Sarja, 2024)

Thus, it concludes that the birth of the circular economy in the construction sector is not just about transforming the way in which a new building is designed, built, and managed. It's also about reaping the attractive economic benefits that come with optimizing the use of resources and minimizing waste. Through the adoption of these new measures and practices, with the help of the advancement of new technologies, it is possible to face a more sustainable future. This evolution is not just about less environmental impact, but also about a more prosperous and economically viable construction sector.

2.6 Energy Consumption in Construction

The sectors contributing the highest CO_2 emissions are electricity and heat generation, industry, transport, buildings, and other sectors.

One of the sectors with the highest CO_2 emissions was the construction sector, with a 39% share in 2019. This increase represents 321 Mt, reaching the record of more than 36.8 Gt. Within these emissions, 28% represents energy use in buildings and 10% in the manufacture of building materials.

However, due to COVID-19 in 2022 emissions were 5% lower compared to the previous year. Although emissions from industrial processes increased by 102 Mt, the higher use of clean technologies accounted for 550 Mt less emissions. Similarly, although emissions were reduced in 2022, in order to comply with the Paris Agreement, more action would be needed to decarbonize the sector (Energy Agency, 2021).

2.6.1 Trends in the Residential Sector

As can be seen in Figure 7, the total consumption by end use in Spain since 2005 has been progressively decreasing. Looking at the data for the last few years, for residential space heating in 2020 it was about 238.6 PJ and in 2021 it was 240.6 PJ. In other words, consumption did not decrease, but rather increased.

There are also residential appliances, which, on the contrary, have been increasing since 2000, peaking in 2010 and continuing a constant trend in the following years. And finally there is residential space cooling which, as can be seen, has a much lower total consumption compared to the other two household consumptions.

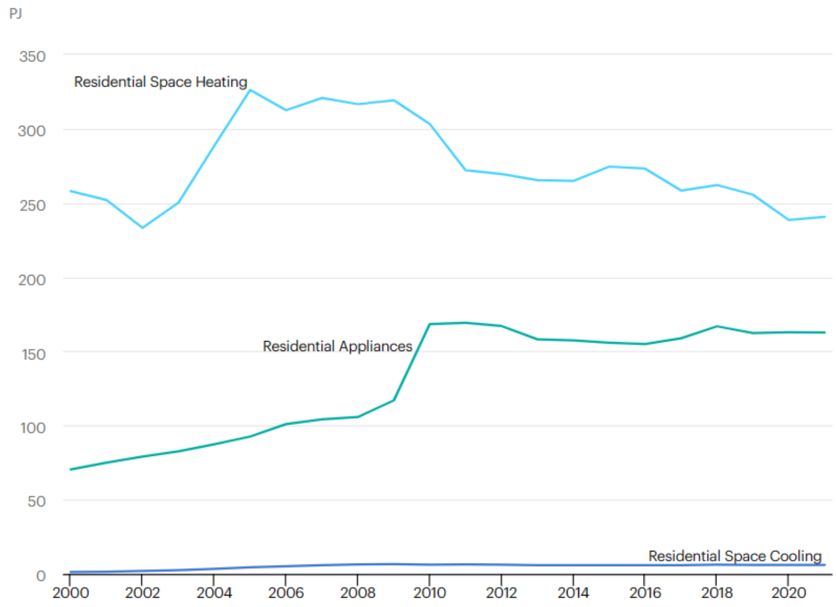

Figure 7. Total consumption by end use - Residential, Spain, 2000-2021. Source: IEA.

The impact that Heating Ventilation and Air Conditioning (HVAC) systems have on building consumption is quite significant. According to a report by the International Energy Agency (IEA), primary energy consumption can be reduced by 40% and CO_2 emissions by 50% when buildings use heat recovery ventilation systems and low-temperature heating and cooling systems such as underfloor heating compared to buildings with conventional HVAC systems (Energy Technology Perspectives 2020 – Analysis - IEA, 2020).

In addition, these radiant systems improve indoor air quality and thermal comfort for customers. The improvements of the quality of the air come from the fact that there is not generation of air currents, which do not remove dust and allergens. As they are heated in a uniform way from the ground, they avoid the circulation of particles in the environment. With underfloor heating the heat rises from the floor creating greater comfort and when it is turned off the hot water continues to emit heat until it cools down, making it an easy to control system. One of the advantages is that these systems provide additional thermal insulation and acoustics. In addition, they do not take up visual space like radiators.

The operation of this system consists of tubes that form a circuit and through which water circulates uniformly. This water will be cold or hot depending on the time of year, providing the chosen comfort. The water consumption of these systems varies depending on the design, the heating temperature, and the efficiency of heat exchange with the surfaces. The estimated water consumption for underfloor heating operation ranges from 0.1~0.3 liters per square meter per hour of operation. However, although water consumption is necessary for operation, this system allows the water used to be recirculated, reducing waste. In addition, compared to traditional systems, water consumption will be lower.

With this data it can be seen how this industry has a great potential to reduce emissions worldwide. By analyzing the LCA of the materials for these new systems, it will be possible to do an analysis of the emissions that these new materials have. In order to compare them with HVAC systems and to see how soon these new systems will become better.

2.6.2 Energy-Exergy

Within the building sector, and specifically in the energy consumed in buildings, the energy exergy system focuses on understanding and optimizing the use of energy used from two different perspectives.

On the one hand there is the energy consumed in the dwelling by the existing systems inside of it. This is represented in units such as kilowatt-hours (kWh) and mega joules (MJ).

Exergy measures the capacity of a form of energy to produce useful work. In the case of buildings, it is the proportion of energy consumed that can be considered as useful work, taking losses into account. In the case of heating, part of the energy consumed is used to maintain the temperature of the dwelling. The other may be due to the temperature difference between the two spaces separated by walls.

Proposed by Cornelissen in 1997, Energy Life Cycle Analysis (ELCA) extends energy analysis such as LCA to the entire life cycle of products. However, the objective is to maximize the useful work of energy in order to reduce the environmental impact (Sala Lizarraga and Picallo-Perez, 2020). For this analysis, the energy flows consumed at each stage of a product's life cycle can be analyzed. In this way, irreversibilities in the processes can be discovered in order to improve them.

In conclusion, this energy-exergy system involves an assessment of energy consumption and utilization, thus offering a holistic approach. This will be achieved by analyzing in which areas energy is lost, in order to improve energy efficiency by reducing consumption and at the same time maximizing useful work.

2.7 Regulations

In order to obtain the Environmental Product Declaration (EPD) it is necessary to have defined the steps to follow for its implementation. As well as to emphasize the role of the

Life Cycle Analysis (LCA) for its elaboration. The influence of local, national regulations and international standards promotes its creation and use to encourage sustainable practices in the industry through more informed decision making by builders and consumers.

2.7.1 Environmental Product Declaration (EPD)

An Environmental Product Declaration (EPD) is an environmental profile that describes the impact on emissions that a product or material will have during its lifetime. The aim of this declaration is to provide the information necessary to make the most sustainable choice when making decisions about materials. From the manufacturers' point of view, following this methodology leads to making a statement to the environment, as it is a way to make the information on the life of a product more transparent. This certification allows companies to demonstrate their commitment to having a positive impact and to differentiate their product or service as more sustainable.

EPDs are based on the LCA analysis within the framework of ISO 14040/44 (*ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework*, no date)and in European countries there is the EN 15804 standard.

The duration of the process to achieve the EPD is usually between 2 to 12 months and has 5 main steps that can be seen in Figure 8.

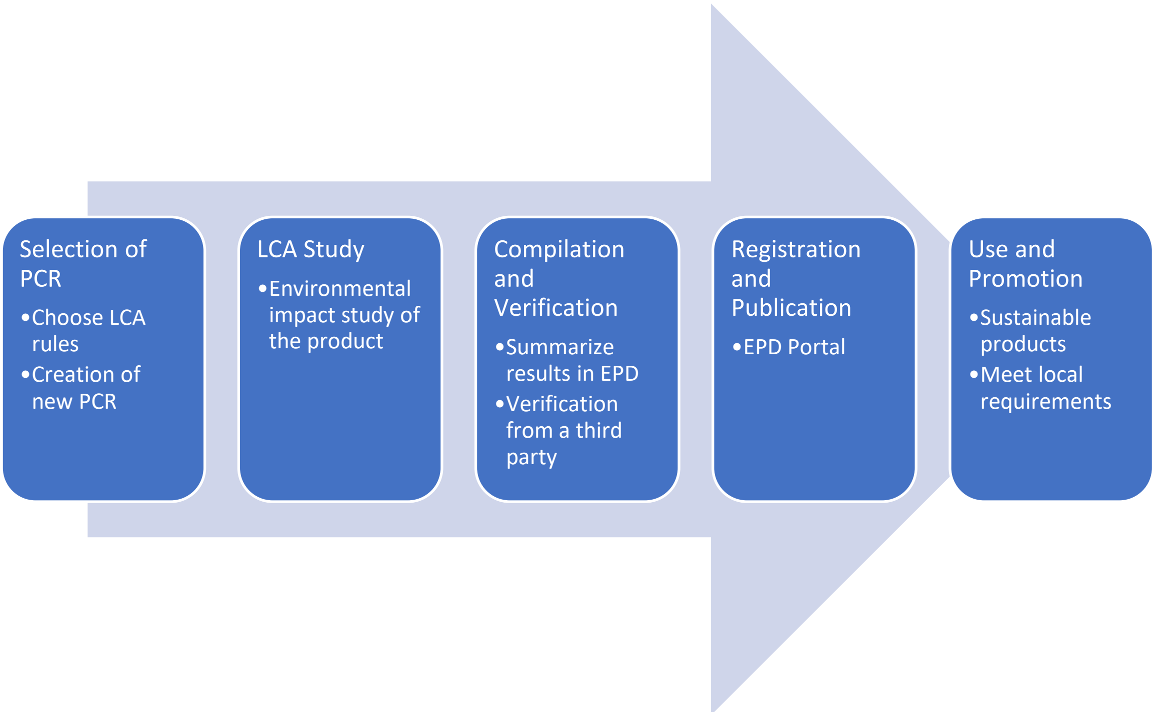

Figure 8. Steps in the process of obtaining an EPD.

The first one is the selection of the Product Category Rules (PCR) where a set of rules that the process for the calculation of the LCA has to comply with is set out, as each product affects the environment in a different way. There is a library of different PCRs depending on the product category. In case a product does not have a PCR defined, then a new one would be created.

In the following the conduction of the study of a Life Cycle Assessment (LCA) is done. Through this study, information is presented that describes the impact on emissions of a product or service during its entire life cycle. This is from the time it is a raw material until it is recycled or wasted.

The third step is to compile the information, all the results from the LCA study are summarized in an Environmental Product Declaration (EPD) that follows the specific guidelines. Then a third-party verification is carried out in which all these documents are analyzed and approved.

Finally, once drafted and approved, they are registered and published on the EPD portal.

Ecolabels are an official voluntary label for environmental excellence recognized throughout Europe (*About the EU Ecolabel*, no date). EPDs are Type III eco-labels, the main difference between them and Types I and II is that the rules imposed by the PCR have been taken into account for the LCA results. In addition, it is a rule that is more standardized and makes the information it contains more comprehensible. Type I serves to make a comparison of environmental quality between products with respect to a scale. Type II, on the other hand, only examines one characteristic of the product. In the EPD labels, the results of different environmental impacts are obtained, giving a more global view of the emission profile of the product (<i>ECO LABEL TM | Certificación de producto ecológico</i>, no date).

Within the EPDs the information that can be obtained depends on how extensive the LCA study has been done. In image X (the LCA in another of the previous sections), the minimum information needed for the publication of an EPD is the cradle-to-gate product stage (A1-A3) with the extraction of raw materials, transport, and manufacturing. The next is the cradle to grave, where the construction process stage (A4-5), the use stage (B1-7), and the EoL (C1-4) are included.

There is general information on the origin of the product as well as on the LCA indicators. However, it should be noted that the operational energy and water use is analyzed as well. Therefore, there may be a product that has a low impact on the energy it consumes and, at the same time, a high impact on the water it needs. For the choice of the product, it should be considered which of the product characteristics are most important for the end goal of the project (Sala Lizarraga and Picallo-Perez, 2020).

With regard to standardization, it should be taken into account whether the EPD has been prepared for a specific supplier or product. Or if, on the contrary, a group EPD has been made in which a range of products from the same supplier are compared. There is also a market EPD, where companies aim to be more transparent with their data by creating a joint EPD for a product type.

2.7.2 Implementation Requirements

Nowadays, depending on the country, there is a greater or lower requirement to obtain EPDs. This is due to changing local regulations, standards imposed on the industry, and market preferences. Specifically, in European countries, the standard regulating EPDs is EN 15804.

In the case of Spain, the requirement for this certification falls on the city council, and having it can give more points for public projects. The difference is that sometimes the LCA is required, but the EPD is needed to know which indicators to calculate.

On the other hand, in Nordic countries, EPDs are more often required to meet certain criteria. This is why there is a tendency to require more EPDs or to promote their use for various reasons. In the case of Sweden, the Swedish Environmental Management Council (SEMCo) is responsible for promoting and facilitating the use of EPDs in the country's different industries.

The role of the LCA study of materials provides the objective basis for the elaboration of EPDs and subsequent comparison of existing alternatives. It is fundamental to ensure the integrity and credibility of the EPDs, since it provides the evaluation of the aspects to be considered in terms of environmental impact in the life cycle.

In the future it will be a mandatory requirement as it helps to make the data more transparent and to improve the knowledge for the choice of products to be used. Right now it is within companies' goals to start using them to promote the use of more sustainable materials and to highlight their product in the market. This allows consumers and stakeholders to make better informed decisions regarding the choices of the available products.

2.7.3 Uncertainty of data standards, LCA and EPDs

One of the first challenges in the elaboration of the LCA is about the uncertainty that may exist. Therefore, reinforcement by analyzing the sources of uncertainty is an option to address this issue (Warrier, Palaniappan and Habert, 2024a). Another critical component of the LCA that represents a gap for the correct production of the results is the knowledge of the correct information. A study by Barbhuiya and Das (2023) highlights the importance of the aspects that the LCA should improve, and for this, it is necessary to understand the requirements for its elaboration.

This is something that is being achieved thanks to the drive for change through regulations and certifications. However, it is also true that companies often have to do this on their own initiative. As it is a study of many factors, it may happen that there is a lack of information either by suppliers or in the chain itself. In particular, according to Cardoso et al. (2024) there is a problematic correlation between the analysis and the way it is done. This is due to the fact that the application of data templates is sometimes challenging to use, existing here a gap in how the process is tackled.

To this end, several challenges are faced within the study of LCA, EoL and supply chains since a correct choice of PCR rules must be made for the elaboration of the LCA. However, it has been seen how the harmonization between the PCR and the LCA is sometimes not entirely clear, challenging the production of the EPD (Moins *et al.*, 2024). While more companies recognize the importance of integrating circular economy principles into their operations, greater collaboration and transparency are required to gain the benefits that can be achieved through these changes in the sector.

This new way of material management has undergone significant changes in recent years due to the need to comply with the SDGs. These changes in environmental objectives have affected the operations and practices previously used because of the need to adapt to the new regulations. Therefore, understanding how these changes affect the LCA, and hence supply chains, is essential to be able to recommend better practices and assist in future decision-making (Bisinella *et al.*, 2024).

The results obtained in the LCA are the product of the knowledge of emission data that products have during their whole life, and that is why its elaboration can be complex at certain times, with some challenges to take into account. In addition, for the choice of more sustainable materials, it is essential to know the legal restrictions and environmental regulations that exist in different countries.

Subsequently, once the EPDs for the products have been elaborated, the comparison can be made. However, studies such as Ivan, Juarez and Finnegan (2021) have noted the challenges that exist at the time of comparison. This is due to the need for further international progress in the standardization of emissions reporting.

Table 1. Challenges and key considerations in Life Cycle Assessment (LCA) Implementation.

Main Challenges in LCA Elaboration	**Uncertainty in Data**	Source Analysis (Warrier, Palaniappan, and Habert, 2024a)
	Knowledge of Correct Information	Importance of Correct Information (Barbhuiya and Das, 2023)
		Requirement Understanding
	Regulations and Certifications	Company Initiative
		Information Gaps (Suppliers/Chain)
Correlation Issues	**Analysis Methods and Data Templates**	Challenges in Application (Cardoso et al., 2024)
		Process Gaps
PCR Rules and Harmonization	**Choice of PCR Rules for LCA**	Harmonization Challenges (Moins et al., 2024)
	Integration of Circular Economy Principles	Need for Collaboration and Transparency
Impact of SDGs on Material Management	**Changes Due to SDG Compliance**	Effect on Operations and Practices (Bisinella et al., 2024)
		Adaptation to New Regulations
Results and Emission Data Knowledge	**Complexity in LCA Elaboration**	Emission Data Throughout Product Life
	Legal Restrictions and Environmental Regulations	Importance for Sustainable Material Choice
Comparison of EPDs	**Challenges in Comparison**	Need for Standardization in Emissions Reporting (Ivan, Juarez, and Finnegan, 2021)

2.8 Chapter Summary

The chapters within the literature review explore the aspects of supply chain management (SCM) and especially its application in the construction sector. The fundamentals of SCM, as well as the information systems used for its management, allow its design to be optimized in the best possible way to become better economically and environmentally.

In addition, within the construction industry, the focus has shifted in recent years to energy considerations within each step of the supply chain. Thus, adapting a holistic approach to assessing environmental impacts with the LCA study. In addition, studying variations in the design of a product emerged as a crucial factor in order to reduce the environmental footprint from the product's inception. This is due to the impact that the choice of the raw material to be used for the production of a product has, since it considerably reduces emissions because of the origin and also represents an alternative study in the EOL of the product.

Moreover, considering the trends in energy consumption in the residential sector is crucial to have a current knowledge of how the sector is working nowadays. In addition, energy information, new measures, and requirements to be implemented for projects in this sector are proposed. Thus concluding in a connected vision of several factors within this sector that influence the improvements towards a more sustainable future. This is due to the increasing development of new energy sources and technologies to improve the use of resources. In addition, this also allows to improve the knowledge of emissions leading to new promotions focused on more sustainable alternatives.

In relation to the study of LCA for the fulfillment of certifications and regulations, the latest papers published in recent years are reviewed. Since this is a current topic that is becoming more and more advanced. Therefore, knowing the relationship between LCA and EPD is of vital importance to be able to use it in the best possible way to achieve greater transparency in the sector. In this way, it is possible to obtain a current knowledge of the situation, in order to be able to focus on the aspects that represent a challenge in the sector for the present and the future.

All in all, the relationship between all these aspects is shown in order to create the theoretical framework on which the research questions are based and subsequently obtain results to discuss.

3. Methodology

In the following chapter the methods used for the realization of the thesis will be presented. As well as the organization behind the thesis and how the data for the study was collected.

3.1 Research Design

The elaboration of the thesis has been done with a qualitative and quantitative study. In order to arrive at the answer to the research questions it is essential to understand all the factors that can influence the results. First of all, an explanation will be necessary in order to have a theoretical basis for understanding the current situation and the progress made to date.

Then, with the data provided by the company on the materials, a comparative analysis can be made, leading to a discussion of the results. For this, the calculations that have been made on the needs of the building will be taken into account, since it is certain specific areas of each of the dwellings that need the product. Subsequently, in order to obtain the results, the main materials that make up each of the products, and the differences that their manufacture will have on the results, will also be needed.

For *RQ1: How does a company in the construction sector align Life Cycle Assessments (LCAs) with existing data and regulatory compliance?* A study of existing certifications in the construction sector and required data elements has been carried out by means of a literature review. In order to comply with these certifications it is necessary to study the results of an LCA and the improvements that can be made in the supply chain. As a consequence of adopting climate declarations for buildings as a new policy instrument in countries, it helps the promotion to reduce the emission impacts (Von Malmborg, Rohdin and Wihlborg, 2023).

Since the case study is located in Spain, this has been the choice for study in the questionnaire. However, the study in the literature review was more general, as the origin of the materials was from both Sweden and Spain. Both countries have a fairly diverse range of industries, which allows emphasis to be placed on the construction sector. In addition, the size of the economy in Spain is larger and more diverse, while in Sweden, the focus is on sustainable leadership towards greener technologies. This comparative perspective in allows the analysis of how the LCA would impact two countries that have different economic and cultural contexts (Chandrasekaran and Dvarionienė, 2022).

Geographically, both regions are located in Europe, but with different natural resources, consumption patterns and climatology. Which affects on how the supply chain distribution system is designed. Being European countries, both have a commitment to environmental sustainability in order to meet the targets of the reduction of 55% of GHG by 2030 imposed by the EU as part of the European Green Deal (*The European Green Deal - European Commission*, no date). This implies the implementation of new and more ambitious policies or a more circular economic approach in order to reduce greenhouse gas emissions.

To answer *RQ 2: "How does material substitution in the design of a product impact the environment?",* a scenario must first be created in which the literature provides the necessary information on the aspects to be sought in order to perform the LCA analysis and to have a theoretical framework that helps to understand the key considerations for the selection and comparison of materials.

The use of this case study allows an in-depth analysis and better comprehension of how changes in the beginning of the supply chain can affect on the long term in both environmental and economic aspects. Then, the selection of two types of materials is made in order to perform the comparative study. This analysis can be done with the data provided by the company to evaluate the environmental impact they have. This improves the knowledge of the LCA as a tool to study emissions (Dsilva, Zarmukhambetova and Locke, 2023).

For this reason, the order of the study for this question began with a literary and theoretical background to understand what LCAs are all about and the impact it can have on supply chains. This is followed by an analysis to identify and examine the key factors that influence the configuration, which may be different depending on the origin of the chain. It is of great importance to understand the information that will be used for the analysis (Barbhuiya and Das, 2023). These differences make it possible to see the impact that the LCA can have. For example, policies, practices, or culture may make the approach to LCA-based decision making different.

The organization from which the materials are being compared is Uponor, a large company with a competitive role in the construction sector, as they provide the necessary materials for large-scale projects with systems that provide greater energy efficiency.

This case is quite interesting, since Uponor believes that betting on more sustainable and efficient materials is key for the future in the sector to which they belong, thus improving on transparency in the knowledge about the environmental impact that their products have during their total life cycle.

At the beginning of the project, a Teams interview lasting approximately one hour was conducted to present the basis of the thesis. Subsequently, the necessary information and questions that arose during the work were collected by e-mail correspondence.

In section *4. Case Studies,* a better explanation of the system in which these materials are used will be provided. For this purpose, the Eco Audit tool will be used within the Ansys Granta program. This tool will allow the evaluation of the different aspects to be taken into consideration in order to make an interpretation. It is resulting in various differences on the environmental impact that will be identified and discussed.

The following Figure 9 shows the general summary of the steps to be followed in order to answer each one of the questions on which the thesis has based its study. For this purpose, the literature review, the Uponor case study and a deep analysis have been carried out in order to have a better understanding of the LCA in a sector as broad as the construction industry. Being a sector that requires a high level of organization for the execution of its projects.

The initial research question RQ1 was addressed through a comprehensive literature review in order to understand the current situation and what the papers related to the main concepts on which the study focused. This has allowed to identify the relevant key factors for the formulation of the questions for the questionnaire that has been carried out in companies related to the construction sector in Spain. Once the theoretical basis for the elaboration of the questions was established, the results were compiled for analysis. Finally, for the analysis of the results, as well as the conclusion, the initial theoretical framework was compared with the responses obtained.

For RQ2 the first step has been the creation of the building scenario. That is, with the plans of the houses, information about the materials that are part of the products and the theoretical basis to be able to explain the parts of the supply chain. Subsequently, it proceeded on to the collection of the actual data of the case by analyzing the initial information provided by the company, as well as an interview to be able to better understand how their supply chain works and other doubts that may have arisen throughout the work. Once all the theoretical framework, as well as the information has been summarized, the analysis has been carried out with the Eco Audit tool of the Ansys Granta EduPack program. Finally, with the results generated, the results were interpreted and discussed.

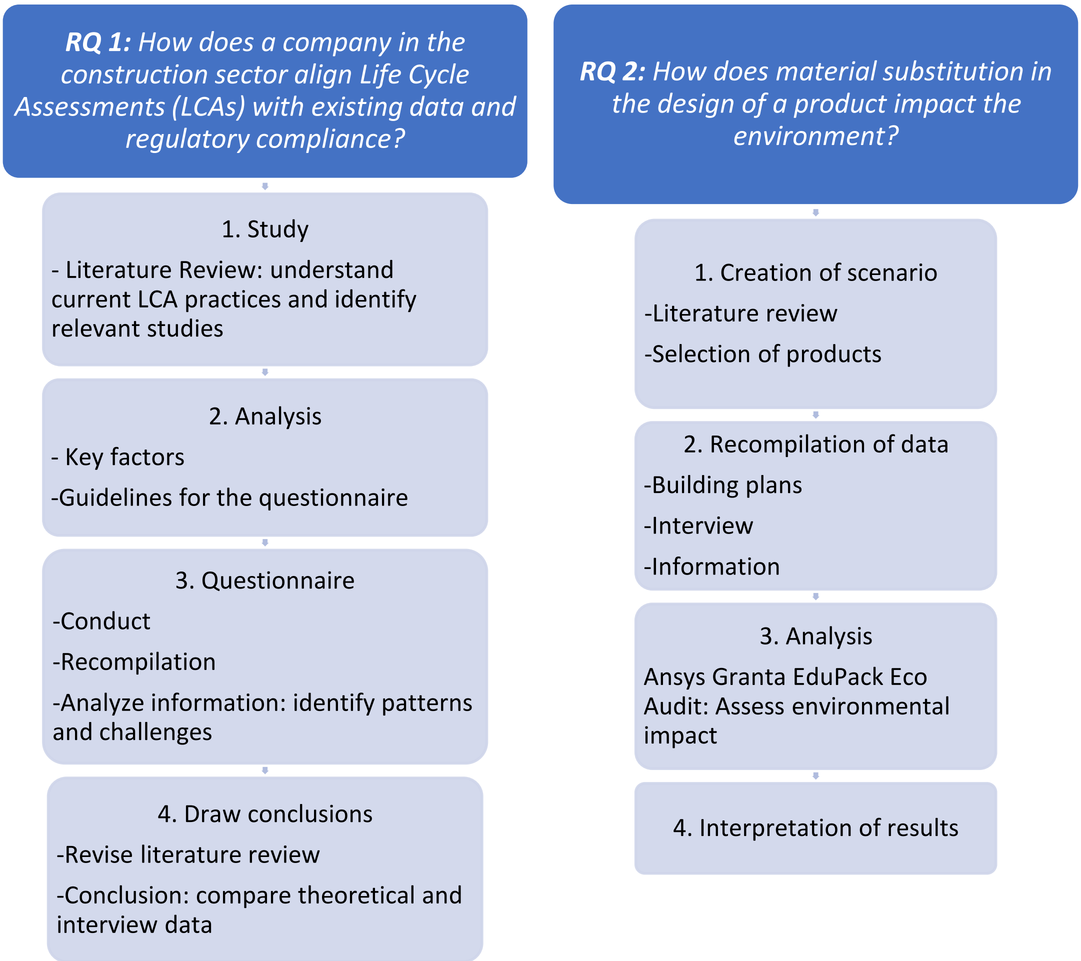

Figure 9. Diagram for the research process of each one of the questions.

3.2 Literature Review

In this section a review of current literature on relevant information for the elaboration of this thesis is presented. First, the evolution of the supply chain within the construction sector will be analyzed. Next, a brief explanation of what LCA is and how it influences the supply chain will be given. Finally, the consequences that these changes have had on the end-of-life management of materials will also be reviewed.

For the literature review, it will be first searched for general aspects relevant to the thesis. Then, a filter of the relevant documents will be done, to go more in depth with more specific topics that are related to the material analysis that is going to be done in this thesis.

Therefore, the order will go from more general to more specific as to how much influence the building consumption has when using Uponor materials.

The order of the literature review has been as follows:

1. Choice of the parameters to be studied for the review that are relevant for the elaboration of the thesis. Focusing on the study of the influence of materials and their consumption on the LCA of supply chains in the construction sector.
2. To carry out the research of the documents.
3. Analyze and select the most important documents.
4. Arrange the topics to be addressed in order of specification and write the literature review.

For the search of these documents it was used the Web of Science within the primo database of the KTH. All documents were then stored in the Mendeley Web Importer to facilitate access to the selected documents and production of the references.

Regarding RQ1, during the search the keywords (“construction”&“LCA”&“EPD”&“procur*”) were used, obtaining about 185 results.

In addition, all documents that were not in English were excluded from the search. In addition, documents that were not published before 2018 were not taken into account in order to have more recent references on how this sector has been evolving, as most of the publications were published during the searched years. This means that these are relatively new topics, with current studies that are making more and more progress.

Apart from this, other official websites, “grey literature”, with relevant information have been accessed such as the International Energy Agency and the European Commission. These types of sources provide up-to-date data, as well as news on relevant new policies related to energy efficiency.

In addition, information on sector-specific regulations is also provided, with an emphasis on energy. By consulting these official sources, a broader knowledge on the subject can be obtained.

However, the search with the key words for the RQ2 (“product design” & “supply chain design”) was highlighted in a range close to the present day (2018-2024). This resulted in about 300 documents, to which the addition of (“construction”) in keyword reduced to 115, less than half. Then the selection of the ones that really made the most relevant sense for the work, reducing even further the number of documents reviewed.

This served to learn more about the current context of the studies that relate product design to the supply chain, related to one of the RQs. Subsequently, the key word "LCA" was added to observe in which papers the elaboration of the LCA in the construction related to the product design and its chain. With the production of only 24 results. On the other hand, with the same search in Scopus, a lower number of results were obtained, thus concluding the existence of a research gap on this topic that is being addressed in the thesis.

Table 2. Literature Review Summary.

1. Overview	Analysis of supply chain evolution in the construction sector
	Explanation of Life Cycle Assessment (LCA) and its impact on the supply chain
	Review of changes in end-of-life management of materials
2. Methodology	General to specific literature search
	Use of Web of Science
	Documents stored in Mendeley Web Importer
3. Search Process	**Keywords:** "supply chain," "construction," "LCA," "outsourcing," "management"
	RQ1 Keywords: "construction," "LCA," "EPD," "procur*" (2018-2024)
	RQ2 Keywords: "product design" & "supply chain design" (2018-2024)
4. Exclusions	Non-English documents
	Non-recent publications, before 2018
5. Additional Sources	Official websites: IEA, European Commission
	Emphasis on energy efficiency and sector-specific regulations

For the implementation of the RQ1 questionnaire, after having elaborated the questions thanks to the literature review, the responses were collected using the Google Forms program. With this program it was possible to collect each of the questions anonymously by the participants, allowing to analyze individually and generally the answers obtained. This has allowed the analysis to observe which are the trends in the construction sector and its challenges.

With the RQ2 interview, contact was made with the sustainability manager from Uponor through a video call via Teams and later with email correspondence.

3.3 Method for the Questionnaire

The method for the development of the questionnaire has been focused as mentioned above on the construction sector. Therefore, the questions have a focus related to the procedures and challenges that in the literature review have been observed to exist. Focusing on the elaboration of the LCA to comply with regulations and certifications.

For this purpose, Uponor, with reputable individuals within the industry and the lobby Green Building Council España (GBCe) were contacted. The GBCe is a reference in Spain towards the transformation of a more sustainable model within the building sector. The questionnaire was sent to approximately 35 people, 20 of whom were contacted by GBCe. As a result, the participation of 23 of those contacted was obtained. Thus concluding with a response rate of 65.7%.

The Google Docs program was used to conduct the questionnaire, sending the participants a link to access the questions and collect their answers. To this end, the questionnaire was divided into three sections to improve data processing and ensure transparency. The first section was responsible for collecting the personal data of the participants.

The second section was designed to obtain the key data on which the work was based in order to answer the *RQ1: How does a company in the construction sector align Life Cycle Assessments (LCAs) with existing data and regulatory compliance?* The first step to operationalize the questions started with the literature review in order to acknowledge the current issues to be addressed and have a better understanding of the process. In addition, since the focus is on the current problems in processing data to comply with new regulations, the questions have been focused on the problems they have and how they deal with this data in order to comply with the regulations. This results in the presentation of the results on a percentage scale of the answers with the highest percentage of response. Since in this way it is possible to observe the level of consensus in the sector. With this, an analysis is made between the answers obtained and the information researched at the beginning of the work with the literature review, being able to verify the current situation with what has been studied previously.

And finally, the third section with a privacy question to the participants ensured that the data management was not violated.

In addition, the procedure for the conduction of the questionnaire is as follows:

1. Conducting the questionnaire by sending a link to Uponor and other individuals who are employed in or related to the industry.

2. Section 1 of the questionnaire: Collect information from the participants in the first questions: Name, position in the company, and company name. Questions 1 to 3 (seen in the APPENDIX).
3. Identify the different categories to which the participants of the questionnaire belong according to their job position (seen in Figure 14).
4. Section 2 of the questionnaire: the list of questions that are related to the key objectives are questions 4 to 12 (seen in the APPENDIX).
5. Analyze the general responses in order to identify the patterns represented in the presentation of the results on a percentage scale of the answers with the highest percentage of response (seen in Table 6).
6. Go back to the literature review to check the similarities and differences of what has been obtained in order to conduct the discussion.
7. Section 3 of the questionnaire: Check that the anonymity of the participants is respected. Question 13 (seen in the APPENDIX).

3.4 Method for the LCA

To analyze the LCA of a product process, it was required to use specific methodologies and adequate tools to introduce and analyze the relevant data. Therefore, the method used to obtain the LCA has been with the Ansys Granta EduPack program in order to process the data of the products that are part of the radiant floor in a new building.

3.4.1 Ansys Granta: Eco Audit tool

The tool used in this study is part of the Ansys Granta EduPack software and allows an analysis with a comparison of the materials to be used in a product from an environmental and sustainable perspective (Ashby *et al.*, 2021). This software includes several databases on different materials, depending on the user's level of use. Within each database are the sets of materials divided into families, which facilitates the search and selection of the desired material.

The tool makes an evaluation focused mainly on the analysis of the use of materials for the design project of a product and its development. The complete environmental impact of a product can be evaluated throughout its life. That is, the cradle to the grave, in which all parts of the life cycle are studied, from the choice of raw materials, manufacturing and transport, use, disposal and lastly the end-of-life potential that it has when it re-enters the supply chain with circularity principles. The analysis is done on the environmental metrics of energy use measured in MJ and carbon dioxide impact in kilograms.

The tool is used for panel and pipe analysis. In the case of the panel, the transportation is done from a different country than that of the pipe. On the other hand, there are two cases with differences in the composition of the material used to manufacture the pipe. The product breakdown is used to know the different components used, to enter them in the Eco Audit tool later and thus obtain the LCA. After entering all the data into the tool, you get a complete report encompassing all phases and with each phase analyzed individually. In addition, you can also create products once they have been created individually, which facilitates the comparison of two different scenarios for the same product.

With this tool you can understand the principles of sustainability that must be taken into account in materials engineering and product design. In the industrial field, it helps in decision making with relevant information to select different materials and minimize the environmental impact in a world that increasingly puts more weight on the knowledge and transparency of information that has an impact on emissions. This leads to the development of more sustainable products, meeting socially imposed environmental standards.

In conclusion, the Eco Audit Tool within the Ansys Granta EduPack program allows to analyze and improve sustainability in the manufacturing process of a product. Promoting greater awareness of relevant information to improve environmental responsibility in product design. Emphasizing the relationship between the design of a product and the sourcing for its manufacture.

Table 3. Inputs for the Eco Audit Tool.

Material (see Table 4)	Selection of database: Built Environment		
	Quantity of material for the case		
	Component name		
	Recycled content (%)		
	Generic mass of the component (kg)		
Building	Product components and materials	4700 kg for total surface	
	Drawings of the building 140 apartments	Surfaces covered 43763 m2	Kitchen Living room Bedroom Bathroom
Manufacture	Primary process	Extrusion	
Transport	Type	Truck	40 tonne (6 axle)
	Distance	Alicante-Madrid 420km	
		Virsbo-Madrid 3000km	
Disposal (see Table 4)	Landfill		
	Combustion		
	Downcycle		
	Recycle		
	Re-manufacture		
	Reuse		
	None		

For the specific data input that is different for each one of the materials, in the case of both types of pipes, once collected from the demolition of the project, 63% are recycled, 36% incinerated and 1% sent to a landfill. Because its main composition is polyethylene (PE), a material with great potential for recycling or incineration, since both options are valid to make the most of this material when it is no longer going to be used for what it was manufactured for.

In the following Table 4, it can be seen the characteristic inputs of each of the products. For the panel, as well as for each of the types of pipes, the materials are the main change in the structure of their design.

Table 4. Data input for the Eco Audit Tool.

	Input			
Product	**Material**	**Recycled content**	**EoL**	**Transport**
Klett Panel 25 Wls032	Polystyrene (PS)	10%	Combustion	420 km (Alicante-Madrid)
	Polyethylene (PE)			
Uponor Klett Pipe	Polyethylene (PE) crosslinked with additive and stabilizers	0%	63% Recycle	3000 km (Virsbo-Madrid)
			36% Combustion	
			1% Landfill	
Klett Comfort Pipe PLUS Blue	Polyethylene (PE) crosslinked with additive and stabilizers	97%	63% Recycle	
			36% Combustion	
			1% Landfill	

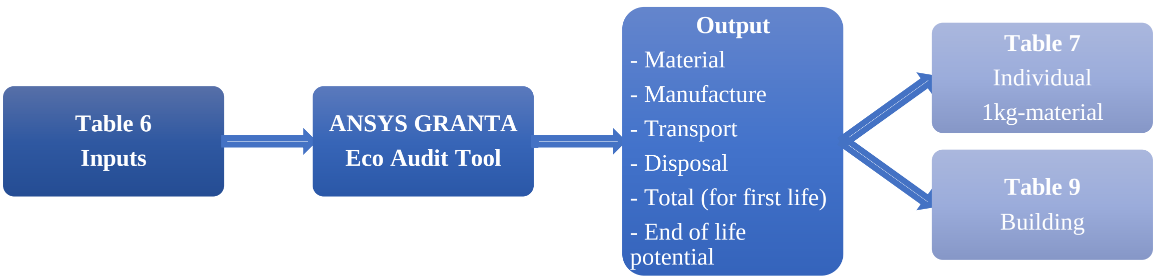

Figure 10. Outputs from the Eco Audit Tool.

3.4.2 Data collection, preparation, and analysis

For the study of the supply chain of the materials the program used will be ANSYS Granta Edu Pack Eco Audit. This tool will analyze the LCAs of two different materials used by Uponor for the same product. With this method, there are four steps to be taken into account: definition of the scope and objective, impact analysis, and interpretation of the results. When performing the analysis, there is a procedure that goes back and forth with the different steps to be performed since it is an iterative process of analysis. To justify the objective, a clear scope must be defined, depending on the characteristics of the product to be analyzed.

Within an LCA analysis, the level of detail may depend on the level of accessible information. Therefore, as there are different types of EPD, the scope of the study will depend on which of them is desired for the chosen product.

As it can be seen in both Table 3 and Table 4, the data processing includes a detailed breakdown of the product according to its origin, covering certain key aspects. For the calculation of emissions, information is included on the type of material used to manufacture the product, its recycled content percentage, total mass, and end-of-life destination. In addition, information is also collected on the type of transportation used from the time it leaves the factory to the time of delivery, along with the mileage done.

To evaluate the entire life cycle, the estimated life of the product in years is also included. Finally, the energy consumption of the product is analyzed, including several factors relevant to its analysis, with the origin of the energy being a key aspect to consider. The power rating needed for meeting the demand of the building, frequency of use per day and daily operating hours allow to provide further insight into the type of energy impact over time. Subsequently, these aspects allow to evaluate the environmental performance of the product and its level of sustainability compared to others. All this ends in an analysis of the results that help decision-making within the scope of the study.

The building from which the data was obtained is located in Madrid, Spain, and has around 140 apartments that represent about 43.763m2 that the solution is expected to cover. The work on which the data is going to be treated is about a project of radiant floor heating only. Each of the portals has a centralized installation with two pipes that can supply the radiant floor and the fan coils for recirculation. In order to obtain the information, a representative of Uponor has been in contact from the company with relevant information for the preparation of the work. With documents that collect information about the materials and the energy demand that needs the building.

With respect to the proportions, for the panel it is 0.33 kg/m2 used, and with the pipes it is 0.091 kg/m and 6.6mL/m2 (source: Sustainability Responsible) . In addition to the plans of the apartments to be able to observe how is the distribution in the floor and which areas are going to use this product.

For the analysis, the first individual calculations seen in Table 7 were made of the impact on the carbon footprint of each of the materials individually. Subsequently, the overall calculation of the building was made to find out how much material would be needed in total.

And finally, the values in Table 9 that are expected to be obtained in the chapter of the results for analysis encompass the whole building.

The tool is designed to help to know the environmental impacts caused by variations in the supply chain. Regarding the impacts of product design, the analysis of the material used encompasses quantity, recycled content, primary process and EoL. Regarding the products, the panels and the blue pipe do contain recycled raw materials, especially the blue pipe with a value of 97% of recycled material.

In contrast to this, the normal pipe has no percentage of recycled material, using instead virgin cross-linked polyethylene (PE). In addition, it should be noted that during installation it has also been taken into account that approximately 0.16% of the pipes are lost in installation waste.

As the aspect of interest lies mainly in the design of the product, a comparison will be made on how the change of material influences the same product. Since this change has already proven how important it is for the design of the supply chain (Christopher and Creazza, 2017).

The following Figure 11 shows the design of the supply chain depending on the location of the project. In the case study, being Spain, it can be seen how it would change with respect to the rest of Europe. This will be taken into account when calculating transport distances, as these are different for the panels and the pipes.

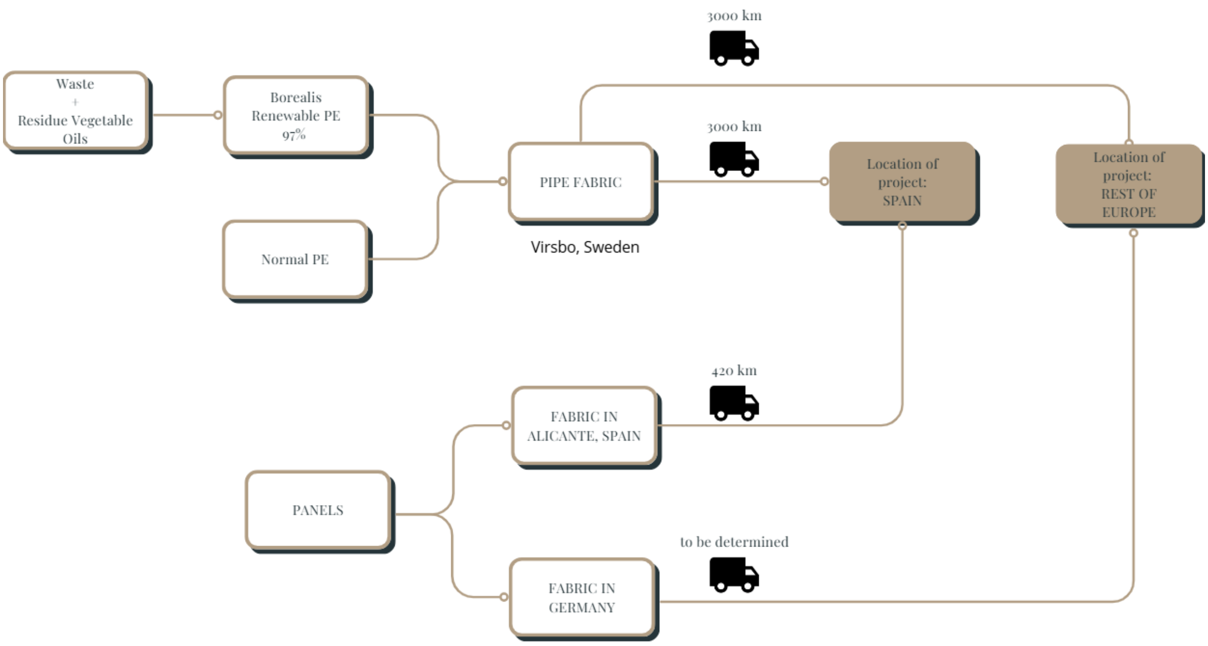

Figure 11. Network design based on the project location.

3.5 Validity and Reliability

The construction of the validity and reliability of the questionnaire is crucial in order to be able to trust that the results are true. Firstly, the validity must be guaranteed by a correct formulation of the questions in order to obtain in the answers the specific reality of the sector, and for that the literature review helped to formulate the questions by highlighting some of the current problems (View of Designing a Questionnaire for a Research Paper: A Comprehensive Guide to Design and Develop an Effective Questionnaire, 2008).

To strengthen the internal validity the framework for the research it needs to be consistent, so the results can be compared to the expected outcomes that were looked in the beginning of the literature review. To ensure that the results obtained are consistent, the response of companies in the same sector has been carried out. This allows to identify patterns or trends with greater confidence, as this results in opinions of a certain similarity with respect to the same topic (Gibbert, Ruigrok and Wicki, 2008).

For the generalization of the results, as well as the conclusions obtained, it is necessary to verify that the external validity is fulfilled. With the elaboration of several study cases related to the same problem, or to the same sector, a greater validation can be obtained. In the study carried out in this thesis, a study case has been carried out in the construction sector with emphasis on a specific issue under development (Quintão, Andrade and Almeida, 2020).

In order to be able to draw up the LCA of the materials used, it is important to have all the details of the design steps. One of the main challenges for the development of the LCA lies in the collection of accurate data to be able to associate the actual emissions to the related manufacturing processes in the production of a product. This means that detailed and up-to-date information on the raw materials, suppliers and production processes involved in a product are needed. In this way it is possible to make a better comparison with the use of new materials for the same product.

The elaboration of the LCA is also time-consuming and expensive. This is due to the need for training in order to understand how to process the data. In addition to the use of advanced and up to date software, as the reliability of the results must be guaranteed in order to be able to make a correct comparison. Moreover, in order to be able to make a correct LCA it is important to have access to environmental data that is relevant for the calculations, considering the uncertainty that exists with the estimates made in the analysis and their sensitivity (Warrier, Palaniappan and Habert, 2024b).

3.6 Ethical and Sustainable Considerations

For the selection of materials and the treatment of data, a series of considerations must be taken into account to promote a responsible and sustainable use within the work carried out during the thesis.

Ethical procurement of raw materials is the basis for ensuring that the standards imposed are met in order to meet environmental objectives. This requires a good choice of suppliers and good logistics within the supply chain in order to have increasingly sustainable alternatives.

In the supply chain, it is important to minimize the environmental impact of the product's journey to its sale or use. This can be achieved through various measures, such as the implementation of policies and practices that promote energy efficiency, while conserving scarce resources. In addition, it is also beneficial for the design of different warehouses to take this aspect into account, as it can also reduce costs if fewer facilities are needed.

3.6.1 Transparency and Accountability

One of the main objectives of requiring EPDs is to promote transparency of information related to the environmental impacts of products. This leads to greater responsibility for the sustainability of construction projects, as it is one of the sectors with the greatest impacts. In addition, apart from construction, the role of the systems during the total life of a building comes into play, as they require daily energy consumption for their operation.

This transparency with information regarding the practices to be implemented ensures that there is traceability of the products within the entire chain. This implies assuming new factors for decision making and benefits for the products with greater transparency in their procurement and use.

4. Case Studies

Currently, one of the most efficient and comfortable ways to heat a house is underfloor heating. Since it distributes heat evenly throughout the floor, creating a warmer environment in each room. It is a system that provides heating by radiation, without generating air currents.

4.1 Uponor

Uponor is a multinational company that is part of one of the divisions within the Georg Fischer Group (GF). The other divisions are piping systems, casting and machining solutions. GF is dedicated to products and solutions that enable water and gas to be transported safely within the home. They are also dedicated to lightweight cast components and high-precision manufacturing technologies (*Our Solutions - Georg Fischer Ltd*, no date)

In particular, Uponor's division is dedicated to the manufacture and marketing of piping systems and solutions for air conditioning, potable water and sanitation. These solutions are aimed at the movement of water in cities, buildings, and houses. Moreover, they can be used for both the scenario of a new construction or a renovation work.

One positive aspect is the ease of assembly of its solutions due to pre-assembly. This brings speed to construction projects, increasing efficiency.

In addition to all this, one of their most important objectives is to reduce CO_2 emissions by increasing energy efficiency. This is the reason why they are market leaders in energy-efficient radiant heating and cooling water systems. These solutions transport water through pipes that are not visible to the customer and are located in floors, walls, and ceilings.

Uponor uses the LCA tool to analyze its various products in order to assess the environmental impact that products and processes have. To do this, it is essential to explore the relationship of the LCA with the supply chain in order to understand better how production and distribution processes affect the environmental impact of the final product. There are two types of pipe materials, Uponor PEX Pipe Blue and the standard. The PEX Blue reduces the carbon footprint due to its bio-based origin compared to the standard. However, it is worth exploring how these environmental differences impact the supply chain and also the choice of materials when studying the whole life cycle of the product.

4.2 Information about Radiant Floor Heating Systems

To install the radiant floor, the ground must first be prepared to level it and the surface must be clean. The objective is to have a surface as smooth as possible so that later the panel installation is easy and does not break. Furthermore, in some cases, such as first floors, an insulating film is additionally included to prevent dampness. The distribution equipment is then installed, hidden from view in built-in cabinets.

The first product to be installed is the panel. Made of expanded polystyrene (EPS) and with added graphite for better adhesion of the pipes. It is responsible for increasing thermal and acoustic insulation, in addition to the fixation of the pipes in the indicated design.

The second is the pipe to be adhered to the panel. Its material is cross-linked polyethylene (PE-Xa), with a high resistance to corrosion to ensure a long service life. In addition, it has a layer of ethyl vinyl alcohol (EVOH) for adhesion to the panel. The main difference between the two types of tubes is that the Blue contains 97% of recycled material from the Borealis company. This highly recycled content contributes to the reduction of waste and the utilization of existing resources from other existing sources.

The combination of the panel with the pipe makes the installation of the underfloor heating system quick and easy. The pipes have a self-fixing tape that is wound in a spiral along the pipe, allowing secure fixing. Moreover, the panel has a coating that allows the adhesion of the pipes for the formation of the heating circuit.

In addition to its easy installation, the panels have a grid that serves as a guide to facilitate the installation of the pipes by guiding their direction. Likewise, these materials allow for corrections to be made to the installation without additional damage. As can be seen in Figure 12, this allows for easy and fast installation by a single person.

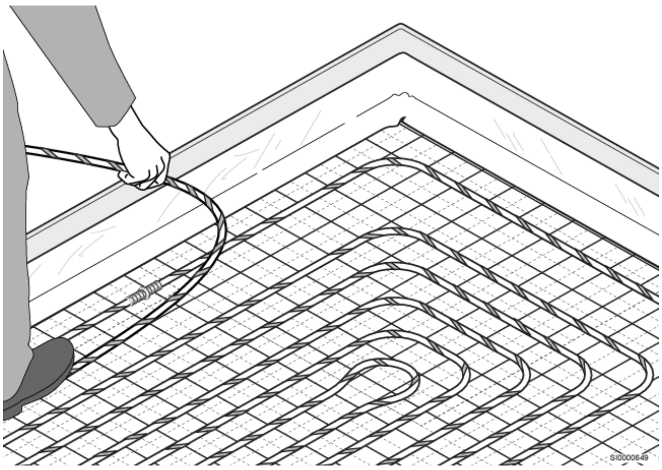

Figure 12. Example of installation with panel and pipes. Source: Uponor

When the installation has been completed, a pressure test at 6 bar should be carried out for 24 hours. To do this, the installation should be filled slowly, thus avoiding the entry of air as much as possible. Subsequently, when the test has been successfully completed, the mortar and screed are poured.

Finally, the hydraulic balancing of the installation will maintain a constant water temperature at each of the points of consumption. To know this, the correct balancing will be obtained when the return temperature is the same in all the circuits, with a thermal jump of less than 10ºC.

4.3 Sourcing Process of The Company

The supply chain for the materials required for the radiant floor heating project come mainly from Sweden, Spain, or Germany. For each of these countries the particular logistic and quality aspects must be considered. In the case of the supply of the panels, if the country to be supplied is Spain, then the supply chain will take place in the same country, concretely from Alicante. In the case of the rest of Europe this changes, with the origin of the supply being a factory in Germany. Delivery schedules and distribution costs may be impacted by this shift in the source of the supply for the pipes.

In addition, it is important to take into account the transport model to be used for the distribution of the materials. Since it is done entirely by road, it will involve the right coordination in logistics to ensure that the materials are transported on time and in optimal conditions for use in the projects due to the execution times. Since projects in the construction sector have a fairly tight schedule, it is important that delivery times are correct in order to minimize delays and thus possible additional costs.

With respect to the pipes used for water heating, the supply is exclusively sourced from Virsbo, in Sweden. Since the origin of this component is unique, this may influence transportation and logistics planning because it is a key component. Disruptions or delays in the supply chain for this product would seriously affect the execution of a project.

Effective supply chain management of these two materials is important to the success of an underfloor heating project. To this end, availability at the project location and at the right time are essential.

5. Results and Analysis

The following chapter will present the results obtained in order to answer the questions posed at the beginning of the thesis. To this end, it is worth analyzing the results in each of the sections, taking into account the current situation with respect to the construction sector. It is interesting to relate the results with the challenges and opportunities that this industry is currently facing, and which over time are improving to meet the sustainable objectives.

In the first chapter, to answer the following question: *RQ1: How does a company in the construction sector align Life Cycle Assessments (LCAs) with existing data and regulatory compliance?*

It should be taken into account that in a globalized environment, companies have to deal with changes in rules or regulations that affect the design of the supply chain. Currently, there is an increasing demand for greater responsibility with regard to the emissions that are produced with the aim of reducing them. This is why certifications promise consumers certain standards that differentiate the types of products available to them today.

5.1 Regulations and Environmental Impact Assessments

The most recent changes in the European Union regarding regulations in the building sector have occurred in the revision of the Energy Performance of Buildings Directive (EPBD). For this revision, a long-term plan has been requested for strategies in the renovation of buildings in each of the countries (Certificates and inspections, n.d).

The objective to be achieved is that all new buildings should have zero-emissions from 2030, and in particular establishing an earlier date for public buildings with a target year of 2027. In addition, it was proposed that photovoltaic solar energy technologies should be used for equipping these new buildings if possible (Carriages preview | Legislative Train Schedule, 2024). To this end, it has been stipulated that all new buildings must have an environmental declaration as of January 2022. In this declaration, the climate impact will be declared at all stages of construction.

There are a number of obstacles that prevent Environmental Impact Assessments (EIAs) from being as effective as they could be in identifying, predicting, and evaluating potential environmental impacts resulting from a product's supply chain. One of the primary ones is the intricacy and interdependence of systems, which makes it challenging to forecast future effects with precision. In addition, depending on the location, the necessary information can be challenging to obtain. To this can be added the lack of coordination and collaboration between different governments to improve their environmental requirements when starting a construction project.

The relationship between EIAs and PCRs is of significant importance since PCRs set the guidelines and criteria for conducting the environmental assessment of a product within a specific category. Both need a great deal of coordination to ensure that the products being assessed comply with the relevant legal and environmental requirements, without generating inconsistencies in the process that could make comparison difficult. Therefore, the integration of both tools improves the accuracy and elaboration of environmental assessments.

Regarding PCRs in Europe, the use of PCRs is becoming mandatory for product manufacturers. This means that there will be an alignment with the standards that EPDs require, thus creating a greater promotion of their use. As a consequence, standardization towards this clearer and more common system promotes their use among member states, eliminating possible bureaucratic barriers and promoting a more competitive market.

In the case of the Nordic countries, a mutual agreement has been reached for the recognition of EPDs, thus including each of the PCRs assigned to the various categories. The objective that this agreement represents for a larger market is that it improves the transparency and accessibility of the documents. Both suppliers and customers will be able to have easier access to information, leading to a more positive impact on new products in the construction sector.

Within the Spanish construction sector, EPD declarations are not a mandatory requirement at the national level according to the law. However, for specific projects that do seek sustainable certifications such as Breem, it will be necessary. In the case of LCAs, for certain eco-labels and public procurement projects it is a requirement.

5.1.1 Advantages of the EPD Certification

In order to obtain an EPD it is necessary to invest time and money in the beginning. However, this certification is becoming in time a prerequisite for construction projects as it allows the knowledge of the carbon emissions that a product has in each step of its supply chain. As a consequence, this can give a competitive edge by being favored in getting new projects. Moreover, it can also create a competitive difference for the buyer. Since these certifications ensure a commitment to the environment, reducing emissions and establishing more energy efficient systems that can have economic consequences for the use of the house in the long term.

Consequently, this opens the door for a bigger market. As for obtaining the green building certifications it is necessary to comply with various material and product EPD requirements. And to obtain this, the study of the LCA under the PCR requirements for the chosen product type will be needed.

By making the environmental impact of a product more transparent, it allows to be acknowledged where in all of the stages there can be improvement. This has implications for the future of the supply chain design.

In the case of Spain, EPD certifications are obtained when customers seek one of the certificates shown in Table 5. In addition, there are also several public tenders that ask for more criteria with respect to sustainability and in those cases EPD certification may also be required.

Table 5. Sustainable Building Certifications.

Country	**Certification**	**Description**
Spain	Breeam ES	Adaptation of the Breeam certification for Spain. This certification evaluates the sustainability of buildings. It considers various aspects such as energy efficiency, water management, the materials that have been used, the health and well-being of the occupants, as well as the impact on the environment.
	Leed ES	Adaptation of an international certification to Spanish regulations and practices in order to evaluate various aspects related to energy efficiency and sustainable design.
	Passivhaus	This standard guarantees the energy efficiency and thermal comfort of buildings. However, although it is not an official certification, many projects also seek to comply

		with these standards to ensure a good level of energy service and comfort for housing.
	Verde	This certification is associated with sustainable construction practices and standards. It promotes the use of environmentally friendly materials, energy efficiency, proper management of water use and the reduction of environmental impact in the process and operation of projects to construct a building.
Sweden	Breeam SE	Adaptation of the Breeam certification for Sweden, evaluating the sustainability of buildings. It considers several aspects but adapted to the specific country.
	GreenBuilding	It is a national program that certifies a positive assessment of the sustainability of the building taking into account the entire life cycle of the building.
	Svanen	Official Swedish ecolabel for the certification of sustainable products and services. In the case of buildings, it evaluates different environmental aspects, such as the life cycle of materials, energy efficiency and waste management.
	Miljöbyggnad	Specific certification for the evaluation of the sustainability of buildings. Reporting on energy efficiency, use of sustainable materials and water, indoor air quality and impact on the environment.
	Klimatdeklaration	This is a mandatory climate declaration in Sweden for both newly constructed and renovated buildings. The declaration provides information on the climate impact of the building's operation. It includes both greenhouse gas emissions, (GHG) and energy consumption.
	NollCO2	Certification that recognizes zero net carbon dioxide emissions. It requires high levels of energy efficiency and the use of renewable energy sources to supply and offset emissions.

Both	Level(s)	An initiative promoted by the European Commission that provides tools and guidance to assess and improve the environmental performance of buildings throughout their life cycle. It focuses on aspects of energy efficiency, indoor air quality, water management and adaptability to climate change.

5.1.2 Organizations

The following organizations exist for the control of standards in the construction sector in order to ensure cohesion and quality in the elaboration of EPDs and LCAs:

- International Organization for Standardization (ISO): international standards are developed that establish the norms for the correct selection of the aspects to be studied in the elaboration of an LCA. They are recognized worldwide, thus guaranteeing correct industrial practices.

- European Environmental Bureau (EEB): influences environmental policies in Europe. This promotes transparency in the life cycle assessment of products by promoting the required standards.

- European Committee for Standardizations: is responsible for the development of technical standards throughout Europe. Within the construction sector, with reference to European regulations, it establishes specific standards for the design and execution of projects.

- Swedish Environmental Management Council (SEMCo): coordinates the development of Sweden's environmental standards, thus elaborating norms and standards for EPDs according to Swedish law.

- Swedish Standards Institute (SIS): to adapt the LCA to Swedish conditions and regulations, this institute promotes the development of standards that will dictate the LCA. This ensures compliance with international and national standards related to information sharing.

5.2 Questionnaire Results

The questionnaire elicited responses to the challenges and key considerations Uponor and others in the construction sector face in preparing the LCA and consequently the EPDs with reference to Table 1.

Since each of the responses corresponded to a different position within the construction sector, Figure 13 first categorized them into four general categories to improve the understanding of the data obtained. Figure 14 below shows the distribution of the position in the company that each of the participants occupies.

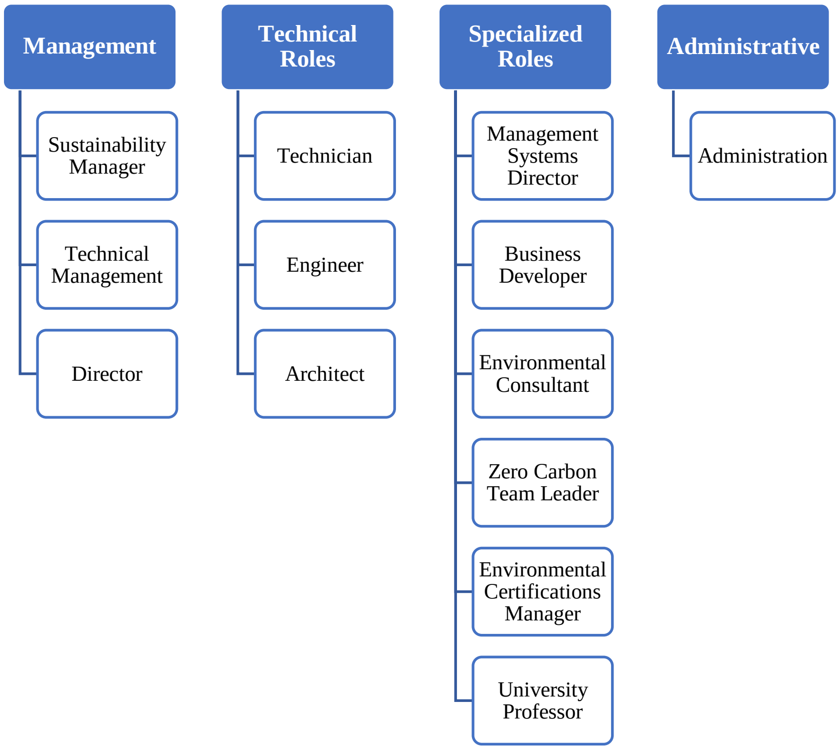

Figure 13. Categorized list of job descriptions.

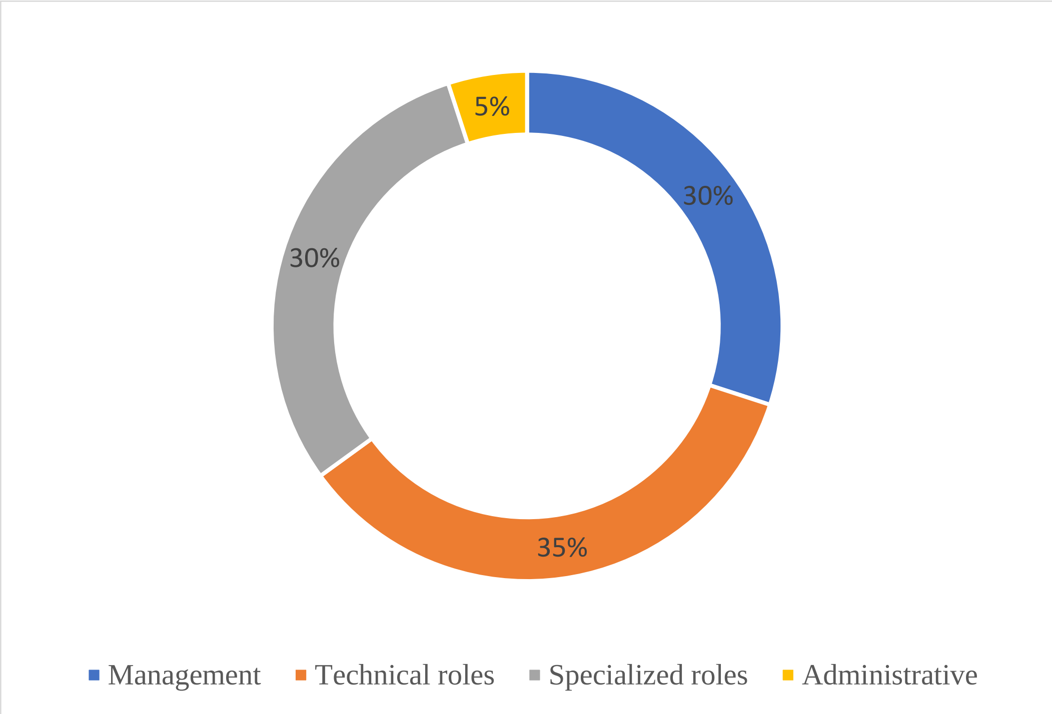

Figure 14. Distribution of Job Positions in the questionnaire.

Table 6. Questionnaire responses (n=23).

Question	Percentage of responses	Response
1. Main challenges in conducting Life Cycle Assessments (LCA)	39.1%	Lack of reliable data
	34.8%	Complexity in data analysis
	13%	High costs
	4.3%	Involvement of the entire supply/value chain
	4.3%	High costs - sampling is required
	4.3%	Difficulty in changing solutions for improve
2. Importance of accuracy of information and how to ensure the accuracy	56.5%	Very important: Internal audits and data verification
	39.1%	Important: Use of recognized databases

	4.3%	Moderately important: Cross-validation with other sources
3. How to address the regulations and certifications in the context of LCA	30.4%	Strict compliance with local and international regulations
	26.1%	Implementation of certified management systems (ISO 14001, etc.)
	26.1%	Collaboration with external certifying bodies
	8.7%	Continuous monitoring and updating of internal procedures
	4.3%	As it is possible due to insufficient resources
	4.3%	All options
4. Challenges encountered with analysis methods and data formats in LCA	52.2%	Difficulties in standardizing methods
	17.4%	Lack of industry consensus
	17.4%	Complexity in integrating different data formats
	8.7%	Limitations of available software tools
	4.3%	All options
5. Choosing Product Category Rules (PCR) for LCA and challenges in harmonizing these rules	43.5%	Based on current regulations and international standards
	26.1%	Consulting with subject matter experts
	21.7%	Considering applicability and relevance to specific products
	4.3%	Difficulty in interpreting and uniformly applying the rules
	4.3%	It is the designer who defines the solutions

6. Impact of compliance with Sustainable Development Goals (SDGs) on operations and practices, and adapting to new regulations	43.5%	Training and awareness-raising among staff
	26.1%	Increased transparency and sustainability reporting
	21.7%	Implementation of new sustainable processes
	4.3%	Investment in green technologies
	4.3%	The achievement of the SDGs has a limited impact
7. How to ensure the accuracy of data obtained from Environmental Product Declarations (EPDs) used in LCAs	34.8%	Third-party verification
	26.1%	Periodic review and updating of EPDs
	21.7%	Implementation of rigorous quality controls
	13%	Use of standardized data collection methodologies
	4.3%	Cannot say for sure
8. Influence of legal restrictions and environmental regulations on the choice of sustainable materials	65.2%	Selection of certified and approved materials
	21.7%	Prioritization of materials with lower environmental impact
	8.7%	Adapting products to specific market regulations
	4.3%	There are still no restrictions or regulations strict enough to influence the choice.
9. Challenges faced when comparing Environmental Product Declarations (EPDs)	39.1%	Variability in data quality and accuracy
	30.4%	Differences in methodologies and calculation approaches
	21.7%	Lack of harmonization in EPD formats

	4.3%	Complexity in interpreting comparative results
	4.3%	All options

Above in Table 6, the answers can be seen represented with their percentage of response. In addition, it can be highlighted how the responses with the highest consensus have a range between the percentages 30.4% and 65.2%. Concluding in the existence of a pattern within the construction sector, since the majority of the consensus is high.

The complexity in collecting and analyzing data from the entire supply/value chain is one of the main challenges, and for this the internal authoring for data verification takes an important place in the process for the success of this analysis.

Apart from that, the compliance of the regulations needs to be addressed in the proper way. Moreover, the implementation of certified management systems such as ISO is necessary to comply with regulations and so the collaboration with external bodies to reinforce that the correct steps have been taken. However, a current difficulty exists in regards of the standardizing methods used, as well with the lack of consensus in the industry for the adaptation of their products to market-specific regulations.

This lack of harmonization of formats complicates the preparation of the analysis. However, experts are consulted to resolve these discrepancies. Therefore, one of the main challenges to overcome in order to choose the right PCR for the preparation of the LCA will be the use of current regulations and international standards. Therefore, continuous checking with changes and developments is necessary to improve harmonization.

As a result of the adaptation of the SDGs, training and raising the awareness among stuff is crucial to understand the importance of the goals. Moreover, the aim is to increase transparency and sustainability reporting and the implementation of new processes that make the system more sustainable. To this end, the accuracy of the EPDs is mainly achieved through third-party verification, periodic reviews for updates and the rigorous quality controls that are periodically carried on.

With respect to legal restrictions and environmental regulations, the selection of certified materials is key as they must be approved. There are also cases where these regulations influence the prioritization of the choice of more sustainable materials for projects. Moreover, on the choice of materials, although there are no strict restrictions, companies are anticipating future demand by creating more and more sustainable products that meet future standards. Thus creating advances to prepare for the future changes in the market.

Lastly, when comparing different EPDs, there is variability in the data quality and accuracy, as well as the differences in the methodologies and the approach. This underlines the importance of increasing consensus and standardization within the industry in order to increase the harmonization of the EPDs for their future comparison. This has a major impact on product selection decisions.

Secondly, the interaction between the selection of materials and their environmental impact in construction projects will be analyzed in order to answer the question: *RQ2: How does material substitution in the design of a product impact the environment?* Through this analysis we seek to provide a practical example of how a change in the material selection can influence the impact on environmental sustainability.

5.3 LCA of Selected Products

Using the Eco Audit Tool of the Ansys Granta software, a breakdown of each of the aspects that influence the environmental impacts of a product prior to its use has been made. This analysis covers various aspects such as the materials used for the product, the type of manufacturing process, transport, and the final disposal of the product at the demolition site.

For the preliminary analysis performed, calculations of energy use after installation have been excluded. This is because it is the stage with the greatest impact on the life cycle of the product, estimated at 50 years. It will be addressed in more detail in a later section of the preliminary analysis.

As can be seen in Table 7, the carbon footprint analysis shows that the phase with the greatest impact is the choice of materials. This is due to the fact that the manufacturing process is done on a large scale. In addition, transportation can be optimized with the size of the load, and also with geographical logistics. Grouping several pieces of product together ensures that this step in the supply chain is carried out as efficiently as possible in order to reduce costs as well as environmental impact.

Within the choice of materials, it is worth mentioning their composition, since if they come from materials that have been recycled to give them a second life and take advantage of waste, the impact is reduced. For example, this is the case of the panel, which contains 10% recycled materials. Whereas the Blue pipe contains 97%, thanks to the supplier Borealis that specializes in advanced and sustainable solutions that focus on recycling.

These variations in the composition of materials highlight the importance of considering other suppliers to reduce the carbon footprint in the production of products. Thus promoting improvements in innovations to improve circularity within the life of a material.

In the transportation study, there is a notable difference in the distances required for panels and pipes. Considering that the origin of the panels is Alicante, the distance to Madrid where the project is located is much shorter than for the pipes. In the case of the pipes, the transportation is more distant, having a truck route from Virsbo, Sweden to Madrid. It should be noted that if the project were located in another European country, the panels would be delivered from Germany to the project. This is an improvement in the impact of transportation, since having two factories can reduce the distances to the project depending on its geographical location.

In terms of end-of-life potential, it can be seen that both the panel and the blue pipe have the greatest potential in this area. This potential represents the amount of impact that can be saved by using recycled or reused materials. However, depending on how the materials are disposed of at the end of their life also affects this indicator. In the case of the panels, the material can be easily recovered due to their modular design. Subsequently, all material is collected on site for subsequent incineration. This results in an option that is efficient and sustainable in producing energy and heat.

The following Table 7 shows in detail the individual emissions per kilogram of product in each of its phases within the supply chain and its potential EoL. This versatility in the options available at the end-of-life stage demonstrates the commitment to sustainability, thus being able to reduce the environmental impact in its last stage.

Table 7. Estimated footprint made by each kg of the components that can compose the system.

CO_2 footprint (kg) per material			
Phase	Klett Panel 25 Wls032	Uponor Klett Pipe	Klett Comfort Pipe PLUS Blue
Material	2,61	1,91	1,03
Manufacture	0,454	0,465	0,465
Transport	0,0284	0,181	0,181
Disposal	0,035	0,0439	0,0439
Total (for first life)	3,13	2,6	1,71
End of life potential	2,63	0,27	0,829

In the Table 8 the legend of the materials used for each of the options evaluated in the study that are arranged to compare can be seen. Using in both compositions of the radiant floor system the panel and subsequently the placement of the pipes.

In the following Table 9, an estimation of the carbon footprint and energy impact is made once the pipe type (normal or Blue) has been chosen for the whole building. Including also the information related to the panels. It can be concluded that, in the design process at the moment of choosing the type of product, there will be a different result in the impact depending on the materials used.

The knowledge of this information allows the supplier to improve the results of its products and transfer a greater knowledge to the consumers. Depending on the objectives of the project, these impacts will play an important role in the decision-making process.

Table 8. Legend for Klett Panel and Uponor Pipe Configurations.

	Composition of the system	
Type of product	**Normal**	**Blue**
Pipe	Uponor Klett Pipe	Klett Comfort Pipe PLUS Blue
Panel	Klett Panel 25 Wls032	Klett Panel 25 Wls032

Table 9. Estimated footprint and energy impact for the building compound when comparing the use of the normal pipe to the more sustainable option with greater recycled raw materials.

	Panel + type of pipe			
	Normal		**Blue**	
Phase	CO_2 footprint (ton)	Energy used (GJ)	CO_2 footprint (ton)	Energy used (GJ)
Material	13,6	518	9,47	276
Manufacture	3	40	3	40
Transport	0,9	12,5	0,9	12,5
Disposal	0,268	3,84	0,268	3,79
Total (for first life)	17,8	574	13,6	332
End of life potential	5,96	-19,6	8,58	-42,3

In Figure 15, a chart from the Eco Audit tool shows the comparison between both types of pipes regarding their CO2 footprint. Therefore, the main difference is seen on the percentile in grey, on the lower right part of the figure. Which accounts for 52% of the change, is the chosen material.

“EoL Potential” represents the EoL savings or 'credits' that can be realized in future life cycles by using the recovered material or components (Ashby *et al.*, 2021). Where the aim is to increase the EoL potential with the following actions:

- Selection of material with a higher recycling percentage.
- Reduction of the number of different materials in the product.
- Avoid the combination of materials that can be difficult to separate for future recycling.
- Avoid a material that may not minimize the use of energy when looking for substitutions.
- Design for an easy disassembly of the product.

Concluding that the first life energy, without the EoL potential, is increased by 52% when changing the raw materials of the pipes. This implies a lower impact on the carbon footprint, which is important to consider when selecting the type of material to use in the project.

Summing up, that the choice of Klett Pipe Blue with recycled materials is better from an environmental perspective by studying each of its stages of the supply chain with the LCA. Since the choice of sustainable materials increases the EoL potential, the choice of a product with a higher percentage of recycled material will be higher than that of a commodity product.

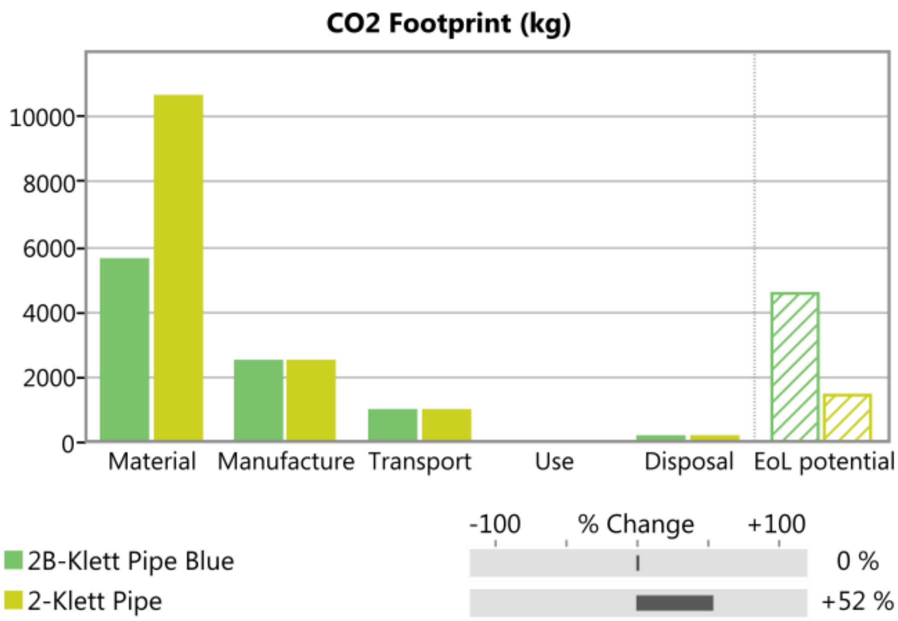

Figure 15. Summary chart for both pipes.

6. Discussion

The relationship between LCA, product design and design for supply chain management are an essential and important part of the quest for sustainability and improving the efficiency of industrial operations for products.

In this chapter, the importance of considering the analysis of the complete LCA of products for a correct design of the product and its supply chain will be highlighted. It is resulting in improvements for the future of the existing system and information knowledge.

6.1 Questionnaire Findings

With the response to the several questions in the questionnaire from Uponor and additional participants form within the sector it has been possible to highlight the common challenges faced in the elaboration of EPDs. This has been in particular with the issues raised in the literature review on data complexity, regulatory compliance and standardization. These are issues that need to be addressed going forward due to the drive to improve emissions transparency for products currently on the market.

After analyzing the results of the questionnaire, it has been possible to arrive at a discussion on *RQ1: How does a company in the construction sector align Life Cycle Assessments (LCAs) with existing data and regulatory compliance?* Companies align the use of LCAs with the data required for EPDs by making use of the existing standardization. However, due to the continuous development and lack of knowledge on the part of a company's employees, standardization methods are one of the challenges encountered to guide the development of LCAs. For this, international regulations and standards are key to reach a consensus to improve the understanding of the information when comparing products from the same or different countries, also the training of employees allows that the data used for its preparation can be better evaluated.

Since it is a sector in which raw materials in projects must be ordered in advance and since in Europe there is a large trade between countries, the products can be exported or imported. Therefore, the selection of materials can be very wide due to the supply, and environmental requirements allow a shift towards promoting the selection of more sustainable products. The impact that the substitution of raw materials has on the product design process is key to improving sustainability, since this stage is at the beginning of the supply chain.

The impact that the substitution of raw materials has on the product design process is key to improving sustainability, since this stage is at the beginning. Apart from this, the correct analysis of the different stages is essential to be able to know where improvements can be made to reduce the emissions of a product throughout the beginning of its life. In addition, this also means that the EOL potential is higher when changing the material to a more sustainable one.

In conclusion, although companies face several challenges in the elaboration of EPDs from LCAs, starting with good information management and consensus on what should be addressed is key to improving their use. The implementation of third parties also ensures the accuracy of the analysis, increasing its relevance in the regulatory environment and anticipating future changes in the market.

6.2 LCA Findings

The main objective with the Eco Audit tool has been to identify the environmental impacts that the stages in the creation of a product have. It has been particularly useful to be able to make a comparative analysis of each of the stages, highlighting how one of the first steps is so important. Agreeing with the importance of how product design in one of the first stages has on the environmental impact (Barbhuiya and Das, 2023). In addition to how the knowledge of the information helps to use the tool for the elaboration of the LCA (Dsilva, Zarmukhambetova and Locke, 2023).

In the product design stage, the choice of material has great consequences on the environmental impact. With the tool chosen, you can learn how to use it in a simple way as it has a large database of materials. The results are presented in a general way and also by stages in order to improve the understanding of each of the impacts generated. It is very useful for the analysis of the stages, helping to take advantage of the time of its use and accessibility at the time of analyzing several designs of the same product. Specifically, in the case study of this work it has been seen how the change to a more sustainable material improves the End of Life potential. This is due to energy savings and carbon footprint reduction as a consequence of recycling existing materials to give them a second life.

However, it also has weaknesses or difficulties such as the ability to access accurate and updated information, and the accuracy of the analysis due to the lack of other categories that may affect the impacts. Certain categories that also affect the impact of a product, such as water needed for its manufacture, land occupation, or others, may not be considered. This acknowledges the problem stated in Dsilva, Zarmukhambetova and Locke (2023), and agreeing with the need for further elaboration of LCA to have greater transparency.

To generate a comparative situation quickly and with concrete data allows to have a rough overview of what the impacts of the whole product's life would be like. As the development of the LCA depends to a large extent on the information collected, it is important to know the assumptions made and whether the data are actually correct for the estimates.

In addition, this also directly affects the supply chain. Since product design is the first step, it will have consequences for the design of the chain. The choice of the location of the factories from which to supply is also a key factor that will affect the logistics for supply. This has been seen in the difference in supply location when the country is Spain or another EU country, as the supply of panels will change.

6.2.1 Identification Of Areas for Improvement

With the LCA study, the phases of the supply chain that have the greatest environmental impacts are acknowledged. This identifies areas for improvement and how variations could improve results. Improved data collection and management at each of these stages is key to facilitating accurate and comprehensive analysis related to environmental impacts. This includes the development of tracking systems for more precise monitoring. In addition, the implementation of new information technologies and the study of new methods for measuring allows the personnel in charge of collection and analysis to work more easily to obtain results that are closer to the real case, thus reducing uncertainty.

Another area for improvement in the development of the LCA is the broadening of the scope of the analysis. This would involve considering long-term or indirect aspects of the supply chain that can have an influence of the current views. By incorporating this more holistic approach, additional areas of improvement can be identified to improve decision making.

With respect to the fundamental role of product design, changes at this stage will be key to the configuration and operation of the supply chain. Its implications deal with the choice of materials used, the manufacturing process, ease of disassembly and future with its EoL. Here the introduction of the circular product design surfaces, in which from the beginning it is studied how to make a design that can re-enter the chain in the best possible way (Burke, Zhang and Wang, 2023).

The difference in the network configuration of the supply chain when changing countries has consequences for the process, as regulations change. In recent years, bringing materials closer to the customer has meant a higher economic cost in cases where reshoring was possible. This means that, in the opposite case, environmental cost is sacrificed. However, although reshoring is not possible in all cases, it does greatly affect the LCA study (Günay, Okudan Kremer and Park, 2019).

To improve the efficiency and sustainability of the whole process, optimizing the distribution network and logistics is necessary. This can be achieved through a better selection of transport routes, better knowledge of the demand for its correct supply and optimization of vehicle loading. All this taking into account the capacities and times required for a correct supply on time in the projects.

With better product design for improved compactness, storage space is reduced, and warehouse space efficiency is improved. In addition, the standardization of the products allows to know rapidly the needs that each particular project would have.

Another final part of the network configuration deals with the EoL, at this stage the management of waste and disposal when it has reached the end of its useful life. Easy disassembly allows for better recovery of materials for later recycling. The study of how to improve the EoL of products promotes the circular economy, which is increasingly analyzed during the process of how it should be done (Favi *et al.*, 2017).

6.2.2 Energy consumption in radiant floor systems

Since the underfloor heating system is a departure from traditional heating systems, it will have an impact over the long life of the building. It is important to discuss this aspect, since the choice to implement this type of system has consequences during the lifetime of the building and on the daily energy consumption demanded.

In this case, the radiant floor system exists with the incorporation of fan coils and solar panels for the generation of demanded energy. Representing greater efficiency in terms of energy consumption in homes.

Mainly, energy consumption depends on how the heat is generated from the water circulating through the tubes that have been placed under the floor. Depending on whether the system used is a gas boiler, a heat pump, or electricity to heat the water will make the energy consumption higher or lower over the years, and thus also the household costs. However, as discussed above, underfloor heating is one of the most efficient heating systems due to its uniform heat distribution and lower operating temperature compared to other traditional radiator systems.

In the case of fan coils, these are devices that use fans to move the air for proper heating or cooling. For the fans, coils are used, the heat source used to heat them will be the one that affects consumption. If they are powered by heat sources such as gas or solar thermal energy, consumption will be lower than if they use electricity.

On the other hand, for the conversion of sunlight into electricity, the solar panels will be integrated into the system through the electrical grid. In this way it will be possible to feed the fan coils and any other component that requires electricity consumption. The amount of solar energy converted into electricity depends on several factors such as the inclination and orientation of the solar panels, as well as the geographical location and weather conditions of each day.

Thus, it can be concluded that a radiant floor system that incorporates the use of fan coils and electricity produced by solar panels has particularly good energy efficiency. The optimal energy consumption will depend on how efficient the components are and how well they are integrated with the system as a whole.

6.2.3 Residential sector: Trends in CO_2 emissions and energy generation. From an energy efficiency approach.

In the following Figure 16, the evolution of CO_2 emissions in the residential sector have been decreasing in recent years. As can be seen, it decreased from 20Mt in 2010 to 16 Mt in 2021. Representing 7.5% of emissions by sector in Spain, with the transport sector having the greatest influence of 40.9% share of the total.

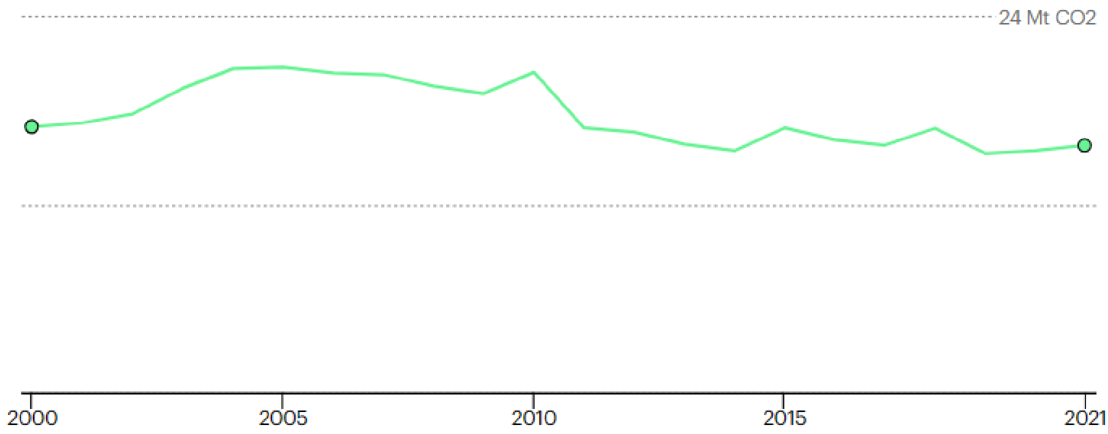

Figure 16. Evolution of CO_2 emissions by the residential sector in Spain since 2000. Source: IEA

Since the main consumption in households is electricity, this will also be the one that produces the highest emissions depending on its origin, with a value of 43.4% as of 2021. This is followed by natural gas consumption, which is fairly constant, and secondly oil products, which have been decreasing over the last few years.

With respect to the total electrical energy consumed, the residential sector represents 32%, which is practically the same as the one consumed by the industry.

As can be seen in the following Figure 17, the evolution of the energy generated by photovoltaic and thermal solar in Spain has been growing since 2005. Especially photovoltaic, as it has experienced a more accentuated growth since 2018, from 7800 to 30222 GWh in 2022. This is due to the increasing investment and promotion of panel installations due to the wide schedule in sunshine hours available in the country. In addition, as it is a renewable energy, the initial investment that must be spent is returned in most cases within a few years of its use. This is due to the fact that in the Spanish electricity system, the energy that is not used for self-supply is fed into the grid and deduced in the electrical bill to the owner who has invested in the solar panels of its residence.

It should be noted that photovoltaic solar energy is not the main source of renewable energy, since it would have to double the generation of electricity in order to reach the production originated by wind turbines. This growth in this type of energy, together with biofuels and the reduction of total waste in final consumption, has led to a positive evolution. Having a positive impact on the dependence of more sustainable energy sources in one of the sectors with the highest energy daily demand.

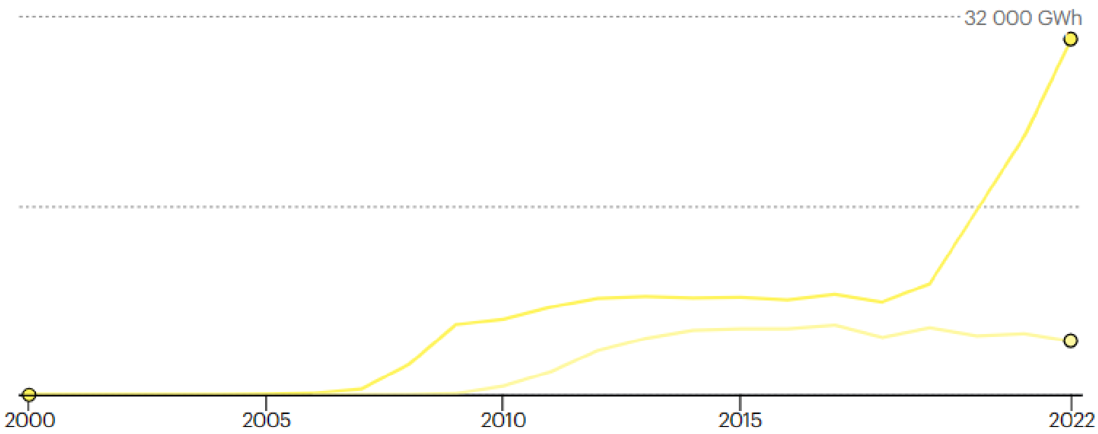

Figure 17. Evolution of electricity generation sources in Spain since 2000. Source: IEA

6.3 Product Design Impacts on Supply Chain Design

In the building materials sector, it has been seen how the integration of product design and the supply chain affect the impact. Therefore, the management and coordination of these functions, although difficult to quantify in some cases, allows the reduction of emissions.

All this makes it possible to identify opportunities for improvement, although one of the impediments is often the difficult access to all the information. This leads to the assessment of strategies among the participants to achieve a higher level of transparency.

It can be argued that the elaboration of LCAs of a product allows the company to make its product better known and even differentiate it from others. This represents a change in the promotion of the product, since it makes consumers part of the global benefits that these changes would have. And in many cases, for the decision-making process the LCAs are taken into account for the selection of the products (Subal, Braunschweig and Hellweg, 2024).

In addition, it allows to know in which stages it could be studied to reduce the impact, even to make comparisons for the same product on the different stages. This allows the company to affirm that they are aware of how their products and their supply chain management impact emissions.

By including all this information in the elaboration of the EPDs, the clients who manage the work and are in charge of product selection can know this information. For this, ISO 14040/44 or EN standards must be met, approved by a third party in charge of verifying that everything is correct for certification and publication. Thus, allowing to differentiate the project while obtaining certain certificates that guarantee minimum environmental standards for end customers who will make use of the housing. With the largest study of LCA in construction products, it is possible to advance in order to take advantage of the potential that this sector has in the mitigation of emissions (Dsilva, Zarmukhambetova and Locke, 2023).

6.4 Competition

Obtaining EPDs for Uponor's products gives them a significant competitive advantage. This is because it increases the transparency of their products' emissions, reinforcing their commitment to sustainability. This is especially attractive today, as more and more customers are becoming more environmentally conscious, influencing their purchasing behavior in a positive way. In addition, society is increasingly pushing for more sustainable alternative products.

Moreover, governments through regulations and sustainability policies promote the use of these certifications to allocate projects. This is directly related to one of Porter's forces. As complying with regulations not only helps them to avoid sanctions and changes, but also opens the door to new market opportunities and enhances the company's reputation (Khurram, Hassan and Khurram, 2020).

7. Conclusions

The last chapter of the thesis contains the conclusions of the work carried out in the master's thesis. The limitations of the work are included, as well as suggestions for future work on the treated topics in order to continue improving knowledge and transparency.

An answer has been sought to how the elaboration of the LCA based with specific data was aligned in the elaboration of certifications. With this, the supply chain may undergo variations to meet environmental requirements better. After knowing the problems faced by a company in the construction sector, it is possible to analyze the different aspects to be improved for the future.

The main objective to study in the work was to know how the difference in the choice of materials for a product affected the LCA study. For this it was important to understand the requirements for the development of the LCA, since for each type of product the specifications are different. It has been possible to observe how the integral study of the product design with the supply chain are key to its improvement. This is because it allows a deeper understanding of the consequences of the decisions made at the beginning of the process when doing its implementation (Barbhuiya and Das, 2023).

Since these issues have been gaining importance over the last few years, as seen in the moment of the research for information. With the increased use of the tool, it is possible to increase the knowledge of the information, promoting greater transparency (Dsilva, Zarmukhambetova and Locke, 2023).

Moreover, this also prompts to study how to create a circularity around a product. Thus managing the waste that will be created at the end of the building's life cycle. Although this is a case of the future, it advocates discovering and promoting initiatives to link the end of the chain with the initial moment (Bisinella *et al.*, 2024).

7.1 Limitations

For the study of what are the current problems for the elaboration of EPDs, only the construction sector has been taken into account with the additional discussion of another sector. Therefore, a further study with other sectors could change with respect to the regulations that are required or the advances in the harmonization of the elaboration of certain certifications to improve the environmental information of their products. Moreover, It could also support the results from the interview from Uponor in the case that there were not significant differences between them.

On the other hand, the work for the thesis has been carried out on the specific materials for the installation of underfloor heating in a general way. It could have been done also on other products that change material to have a broader view. However, it is sufficient to see that this change has consequences later on for the supply chain.

As for the impacts studied for the elaborated LCA, only those related to the type of material, transport and EoL have been observed. This excludes its energy use for later analysis since it was of another magnitude. Since the use of energy used in these systems may vary according to the building, due to its origin and location. Regarding the calculations, for both final cases, the additional calculation of the panels has been added to the pipes. Since in both cases the same panel would be used.

7.2 Future Work

The construction sector has a great impact on emissions, either from the materials used or the services that are increasingly improving. It is of great importance to come up with solutions and practices that can improve these aspects. Therefore, studying the LCA of the products that are part of the system either by the materials they use or by how they improve energy efficiency is key. This motivates the search to learn more about the benefits of studying the LCA for further study and use.

With the preliminary responses of the current challenges with respect to EPDs, it has been possible to check with the literature review the improvements that should be made for the future. With this, a better understanding of the phases and coordination with the industry could improve the transparency of emissions.

Although socially these changes are well seen, there should also be a greater push to promote that looking at the sustainable aspect is better in the long run. Moreover, in terms of the SDGs, there are several of them that can be improved by studying LCA in the construction sector.

With other sectors, LCAs are more advanced, and it is only recently that interest in LCAs in construction has increased. As it is a sector with difficulties to monitor each of the aspects that have impacts, it is suggested that its study should be increased more and more. And for this, there are certain phases close to the EoL in which assumptions are made that do not have to be entirely correct or that facilitate the robustness of the LCA (Dsilva, Zarmukhambetova and Locke, 2023).

In conclusion, for future research it would be interesting to increase the information about the environmental impact of products. With this information it is possible to know the stages in which improvements can be made. In the analysis, changes in the supply chain are shown, partly thanks to the changes and processes of the materials used. In addition, further studies on the assessment of EoL scenarios can guarantee that the material's future is accurate (Bisinella *et al.*, 2024). And for this, greater transparency and coordination are needed.

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9. APPENDIX

RQ1- General and Regulation questions

1. Name
2. Company
3. Position in the company
4. What are the main challenges you face in the elaboration of Life Cycle Assessments (LCA)?
    - Lack of reliable data
    - Complexity in data analysis
    - High costs
    - Changing regulatory requirements
    - Other
5. How important is to have correct information for the success of an LCA, and how do you ensure its accuracy?
    - Very important: Internal audits and data verifications
    - Important: Use of recognized databases
    - Moderately important: Cross-validation with other sources
    - Slightly important: Relying on professional experience and judgment
    - Other
6. How does your company approach regulations and certifications in the context of LCA?
    - Strict compliance with local and international regulations
    - Implementation of certified management systems (ISO 14001, etc.)
    - Collaboration with external certifying bodies
    - Continuous monitoring and updating of internal procedures
    - Other
7. What challenges do you encounter with the analysis methods and data templates in LCA?

- Difficulties in standardizing methods
- Lack of industry consensus
- Complexity in integrating different data formats
- Limitations of available software tools
- Other

8. How do you choose the Product Category Rules (PCR) for your LCA, and what challenges do you face in harmonizing these rules?
    - Based on current regulations and international standards
    - Consulting with subject matter experts
    - Considering applicability and relevance to specific products
    - Difficulty in interpreting and uniformly applying the rules
    - Other
9. How has compliance with Sustainable Development Goals (SDGs) affected your operations and practices, and how have you adapted to new regulations?
    - Implementation of new sustainable processes
    - Increased transparency and sustainability reporting
    - Investment in green technologies
    - Training and awareness-raising among staff
    - Other
10. How do you ensure the accuracy of data obtained from Environmental Product Declarations (EPDs) used in LCAs?
    - Third-party verification
    - Use of standardized data collection methodologies
    - Periodic review and updating of EPDs
    - Implementation of rigorous quality controls
    - Other
11. How do legal restrictions and environmental regulations influence your choice of sustainable materials?
    - Selection of certified and approved materials
    - Prioritizing materials with lower environmental impact
    - Adapting products to specific market regulations

- Development of new materials in collaboration with suppliers
- Other

12. What challenges do you face when comparing Environmental Product Declarations (EPDs)?
    - Differences in methodologies and calculation approaches
    - Variability in data quality and accuracy
    - Lack of harmonization in EPD formats
    - Complexity in interpreting comparative results
    - Other
13. Would you like your responses to be anonymous?
    - Yes
    - No

RQ2- Product Design questions for Uponor

1. How flexible is the supply chain for the analysis?
2. Does the supply vary depending on the country to which the product is destined?
3. What is the location of the factory?
4. What is the material per m^2, recycled content, mass, and end-of-life for each type of material (normal and blue)?
5. What is the type of transport is it used from the factory to Madrid?
6. What is the product's lifespan in years?
7. What is the product's energy consumption, including nominal power, days of use per year, and daily hours?