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Life Cycle Analysis and Life Cycle Costing of an innovative lightweight drywall system - Comparison with conventional cases.

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«Δηλώνω υπεύθυνα ότι η συγκεκριμένη μεταπτυχιακή εργασία για τη λήψη του Μεταπτυχιακού Διπλώματος Ειδίκευσης στη Διοίκηση Επιχειρήσεων, έχει συγγραφεί από εμένα προσωπικά και δεν έχει υποβληθεί ούτε έχει εγκριθεί στο πλαίσιο κάποιου άλλου μεταπτυχιακού ή προπτυχιακού τίτλου σπουδών, στην Ελλάδα ή στο εξωτερικό.

Η εργασία αυτή έχοντας εκπονηθεί από εμένα, αντιπροσωπεύει τις προσωπικές μου απόψεις επί του θέματος. Οι πηγές στις οποίες ανέτρεξα για την εκπόνηση της συγκεκριμένης μεταπτυχιακής αναφέρονται στο σύνολό τους, δίνοντας πλήρεις αναφορές στους συγγραφείς, συμπεριλαμβανομένων και των πηγών που ενδεχομένως χρησιμοποιήθηκαν από το διαδίκτυο».

Ονοματεπώνυμο **Υπογραφή**

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Abstract

In recent years, the growing necessity to save material and energy resources, along with an increasing concern over the environmental issues and the uncertainties on the evolution of the economy have impelled the authorities to take radical actions in most industries. Building industry is one of the most significant drivers of social and economic development but at the same time its share to the environmental footprint and resources depletion is also remarkable. The United Nations with the 2030 Agenda for Sustainable Development has defined a plan of actions to build a world in which consumption, production and use of natural resources will be sustainable. Hence the sustainable development in its three dimensions social – economic – environmental has become subject to scrutiny through the implementation of Life Cycle Management tools.

The current study presents the environmental impacts and the economic viability of three alternative external wall cases. The first one is a nano-enhanced lightweight steel skeleton/dry wall system with improved thermal, vibration/seismic and fire performance which is called ELISSA panel. The other two external wall systems are common types of external brick wall applied in North/Central Europe and South Europe (CONV1 and CONV2 respectively). The structure of the study encompasses:

a) The introduction
b) The literature review
c) The LCA analysis (according to international standards)
d) The LCC analysis

It aims to examine the sustainability of the ELISSA panel towards the environmental and economic pillar. For that reason it is compared to the most common alternative cases. The analysis is performed through the implementation of the Life-Cycle Assessment tool (LCA) in order to calculate the environmental impacts and the Life-Cycle Costing analysis tool (LCC) in order to estimate the economic viability. Both LCA and LCC are examined the product systems throughout the 50 years of their service life. However, they differ in their system boundaries. The LCA analysis extended from “cradle to grave” without taking into consideration the operational phase. On the contrary the LCC analysis covers the full life cycle of the respective

walls except from the End of Life stage which is difficult to estimate after 50 years from now.

The LCA results confirm an unambiguous superiority of ELISSA panel towards the GHG emissions due to the use of recyclable materials. The same results appear for the POPC. On the contrary, it seems that the innovation of ELISSA panel i.e. the use VIP panels as insulation material, the metal studs and the intumescent paints for fire protection are responsible for the high scores at EP, AC and ODP indices comparing to the conventional cases. Also the lightweight technology provides a benefit in the transportation burdens in comparison to CONV1 and CONV2 panels. However, the VIP panels and the steel studs of the ELISSA panel are produced from an energy intensive process which increases the life cycle primary energy requirements. The recycling of steel and VIP’s at the end of life improves the embodied energy index but the total primary energy demands of the ELISSA panel are still high.

The environmental benefits of prefabrication are expressed only through the benefit of reducing the construction waste. The ELISSA panel was examined both as a prefabricated building component and as a typical wall constructed on site. The results show that prefabrication improves the environmental performance of the wall.

Finally, the net present value of the ELISSA panel throughout the 50 years of its service life seems to be greater than both conventional cases and that is because of the high initial cost of the construction. Undoubtedly the operational expenses for heating and cooling of a building with an ELISSA type envelope are less than the conventional cases (due to the improved thermal insulation). Nonetheless the high discount rate of 7,67% (which was calculated through the CAPM model) together with the assumption of 2.01% of annual increase of electricity prices make the ELISSA case the least preferable case of all. Because of the high uncertainty of the economic factors, the LCC analysis should be performed for a specific country in a more detailed manner.

Glossary of terms

Product system

A product system is a collection of unit processes connected by flows of intermediate products which perform one or more defined functions. A product system description includes unit processes, elementary flows and product flows across the system boundaries and intermediate product flows within the system.

Primary steel

Refers to the steel manufactured primarily from iron ore in a Blast Furnace (BF), which is subsequently processed in the Basic Oxygen Furnace (BOF).

Secondary steel

Refers to the recycling route and is typically the Electric Arc Furnace (EAF) process which converts scrap into new steel by re-melting old steel.

Recycling rate (RR)

The fraction of steel recovered as scrap during the life time of a product and includes any scrap that is generated after manufacturing the steel product under analysis

Metallic yield (Y)

The process yield of the EAF. It is the ratio of steel output to scrap input.

Inert Waste

Waste that does not undergo any significant physical, chemical or biological transformations. Inert waste will not dissolve, burn or otherwise physically react, biodegrade or adversely affect other matter with which it comes into contact in a way likely to give rise to environmental pollution or harm human health. The total leachability and pollutant content of the waste and the ecotoxicity of the leachate must be insignificant, and in particular not endanger the quality of surface water and/or groundwaster. [Council directive 1999/31/EC – Article 2]

Post-consumer waste

Waste that arises from the installation or removal of a building material in its application. It includes both construction and demolition waste.

1. Introduction

Since the very start of economic discipline, it had been a matter of debate, whether the economic growth can be sustain in a finite natural environment[1]. This question endures until our time when the unprecedented social and economic growth provokes devastating global effects. The depletion of natural resources in conjunction with the increased pollution levels of air, water and land, as a result of the continuous social and technological development, are major concerns of developed countries around the world.

One of the most significant drivers of social and economic development is building industry, whose share to the environmental pollution and resources depletion is also crucial. Buildings are long term assets useful for at least 50 years and more than two thirds of buildings standing today are expected to endure until 2050[2]. The clear majority of them is located in urban areas and they are responsible for providing a suitable indoor environment for the inhabitants, which, however, involves to an enormous consumption of natural resources and energy during construction operation and maintenance. Many studies argue that building sector is responsible for 30-40% of the total energy use and approximately 40-50% of greenhouse gases emissions, globally [3,4]. Additionally, it is estimated that building sector consumes 60% of the overall raw materials extracted from the Earth and the subsequent transformation of raw materials into construction materials is responsible for the 50% of the GHG emissions in the atmosphere[5], whilst Construction and Demolition Waste (CDW) accounts for 25-30% of all waste generated in European region. Identifying these issues, contemporary policies and researches currently focus on the attempt to achieve sustainable development of urban environment [6].

But, what is the actual meaning of sustainable development? In 1987, the World Commission on Environment and Development gave an accurate definition about sustainable development as "*the development that meets the needs of the present without compromising the ability of future generations to meet their own needs*". This definition was enhanced by the 2030 Agenda for Sustainable Development and its framework of 17 Sustainable Development Goals (SDGs) adopted by the United Nations General Assembly in September 2015. Through the latter, the global community is committed to achieve sustainable development in its three dimensions i.e. Environmental, Economic and Social, "*in a balanced and integrated manner*" [7]. Nonetheless, the interrelationship between these dimensions leads to contradictions to each other making the task of achieving sustainable development quite a challenging one. However, Godshalk suggests that the primary aspect of sustainable development are environmental and economic, while social aspect has secondary impact in urban planning [8].

Sustainable development can be analyzed, managed and assured through the implementation of Life Cycle Management tools; Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) and Social Life Cycle Assessment (SLCA). In the current study the former two dimensions of sustainable development (environmental and economic) are examined by employing the LCA and LCC tools.

However, compared to other "products" the implementation of a LC tool in a building is a challenging process for the following reasons. They are large in scale, complex in materials and function and temporally dynamic due to limited service life of building components and changing user requirements. Their production processes are much less standardized than most manufactured goods because of the unique character of each building. There is limited quantitative information about the environmental impacts of the production and manufacturing of construction materials, or the actual process of construction and demolition [9].

1.1. Policies and trends

Europe is considerably aware of the climate change phenomenon and especially the consequences of building sector to the regional and the global climate. European buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in the EU. Comparatively, the energy consumption between a new and an older European building varies significantly with an older building to consume up to 20 times more energy per square meter than a new one. Currently, about 35% of the European building stock is over 50 years old which exacerbates the overall energy profile. Identifying the situation, EU has issued the 2010 Energy Performance of Buildings Directive (EPBD)[10] and the 2012 Energy Efficiency Directive[11] in order to reduce the energy consumption of buildings. However this legislation deals only with the use phase of buildings without taking into account the total building life cycle [12]. Similar to the EPBD and the Energy Efficiency Directive, the EU has also issued the Construction Products Regulation[13], the EU Emissions Trading System[14], the Industrial Emissions Directive[15], the Waste Framework Directive[16] and the Landfill Directive[17] which yet focus on different resources and specific parts of life cycle and they are not designed to provide an overall life cycle approach.

In a life cycle point of view, building sector is one of the most resource consuming sectors in the EU. Considering the whole life cycle of a building, from the extraction of materials, the manufacturing of building materials, the construction of the building, the use and maintenance until the final disposal or disassembly, buildings are responsible for:

- 1/2 of extracted materials
- 1/2 of energy consumption
- 1/3 of water consumption
- 1/3 of waste stream generation

All these stages of building life cycle contribute to the environmental performance of buildings the assessment of which is essential for obtaining a sustainable environment. EU has already identified the negative impacts of EU building stock market and has issued initiatives in order to alleviate the situation and promote a more efficient use of resources consumed by new and renovated commercial, residential and public buildings and to reduce their overall environmental impacts throughout the full life cycle.

Firstly, in 2014 the European Commission adopted the Communication on "Resource Efficiency Opportunities in the Building sector"[18] whose main objective was the reduction of the environmental impact of buildings by improving the overall resource efficiency. This initiative provides reliable information to decision-makers (designers, manufacturers, contractors, authorities) for the assessment of the environmental performance of buildings and enhances the related competitiveness of construction businesses. Also, it sets the guidelines of establishing "common framework of core indicators" which enable the comparison between different environmental assessment projects. These indicators should be flexible in their use so that they could potentially be incorporated into new and existing assessment schemes, or be used by a diverse range of stakeholders, including public authorities, design teams and property investors.

Later, the European Commission's 2015 Communication introduced the Circular Economy Action Plan [19]. In this plan, which is very essential for the buildings due to their long service life, design improvements for environmental impacts reduction and durability and recyclability of building materials were encouraged. This package contains measures for converting waste products into valuable new ones covering the whole product life cycle: from production and consumption to waste management and the market for secondary raw materials through greater recycling and re-use. It must be underlined that EU has set some clear targets for reduction of waste and establish an ambitious and credible long-term path for waste management and recycling:

- A common EU target for recycling 65% of municipal waste by 2030;
- A common EU target for recycling 75% of packaging waste by 2030;
- A binding landfill target to reduce landfill to maximum of 10% of municipal waste by 2030;
- A ban on landfilling of separately collected waste;
- Promotion of economic instruments to discourage landfilling ;
- Simplified and improved definitions and harmonized calculation methods for recycling rates throughout the EU;
- Concrete measures to promote re-use and stimulate industrial symbiosis - turning one industry's by-product into another industry's raw material;
- Economic incentives for producers to put greener products on the market and support recovery and recycling schemes (e.g. for packaging, batteries, electric and electronic equipment, vehicles).

From the economic perspective, many studies from France and UK allege that, today, the construction cost of a sustainable residential building has been reduced approximately to the same level of a conventional building. In detail, a study carried out by QUALITEL (France) proved that the extra cost of a sustainable building was 10% more than that of a standard building in 2003 and today it is less than 1%. [20]

1.2. Life Cycle concept

1.2.1. Life Cycle Assessment

Life Cycle Assessment, or LCA, is an acknowledged decision making support tool for performing analyses of engineering designs (i.e. products, processes or activities) and identifying and quantifying the associated environmental burdens. The results of an LCA study let someone know about the environmental footprint of the design, as well as the regions in which certain emissions take place and contribute the potential actions to be taken in order to reduce the harmful environmental outputs.

The LCA concept started in the late 80's when many different products were analyzed "from cradle to grave". It is a science-based, comprehensive and standardized environmental assessment methodology similar to cost benefit analysis and risk management. According to International Organization for Standardization (ISO 14040) LCA is the "*compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle*".

Typically, an LCA study investigates parts of or the whole life of a product over the environmental impacts. The product's Life Cycle (LC) phases are divided into: upstream phases (e.g. extraction of raw materials, production, transportation and construction), use of the product and downstream phases (deconstruction/demolition and disposal, waste handling). The examination involves the balancing of inputs (e.g. raw materials, use of resources, energy etc.) and outputs (e.g. waste, emissions, by products etc.) for each LC phase of the examined product system, thus practitioner must collect data from a wide range of sources in order to compile an inventory and then to translate the available information into environmental impacts

The most important type of an LCA study is the "Cradle-to Grave" analysis which provides a holistic approach towards the environmental outputs. This is because the final consumption of products, as one of the key indicators that moves the economy, exhibits core opportunities for indirect environmental management across the chain or network of unit processes related to a product. Also, a holistic approach provides a complete view of the product's life, avoiding shifting the unfavorable impacts to another LC phase of the product. For instance, Blengini et al. conduct an LCA analysis on a low energy family house in Northern Italy and they concluded that by implementing energy reduction approaches (e.g. thicker insulation) the winter heat demand was reduced significantly by a ratio of 10:1 comparing a standard house but the LC energy and carbon footprint was reduced only by 2.1:1 and 2.2:1 respectively [21]. This is because the environmental burdens were shifted from the use phase to the upstream phases and maintenance of the product system.

The basic structure of an LCA study consists of four individual steps: the Goal and Scope Definition, the Life Cycle Inventory (LCI), the Life Cycle Impact Assessment (LCIA) and the subsequent Interpretation of the results.

1. The **Goal and Scope Definition** illustrates the objectives and the working plan of the entire LCA and it is considered as the source of guidance of the subsequent phases. In this step, the goal of the study, the intended use of the results, as well as the intended audience is specified. Additionally, the scope of the study refers to the temporal, geographical and technological specifications of the LCA content. All the assumptions and limitations are comprehensively depicted in this step, as well as the boundaries of the system (System Boundaries) and the Functional Unit.
2. The **Life Cycle Inventory (LCI)** is the step in which the product system is described. This is the most time-consuming and costly phase due to the enormous amount of data to be collected. Data can be found either in commercial databases (e.g. Ecoinvent 2.2) and libraries (which is called background data) or specific data for the exact product under study (which is called foreground data). In practice, the data used in the LCA is a combination of both types of data.

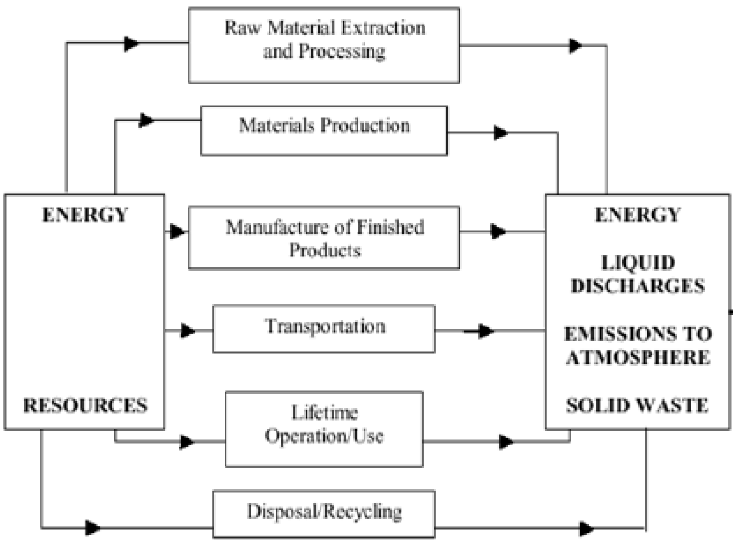
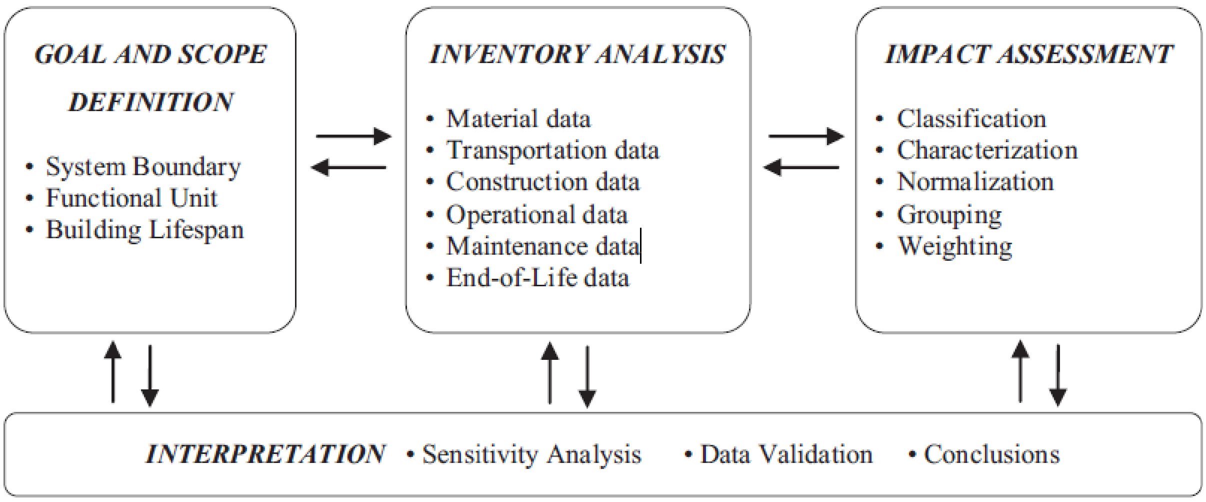


Figure 1: A graphical representation of Inventory analysis step**[22]**.

3. The **Life Cycle Impact Assessment (LCIA)** is the step in which the set of results of the inventory analysis is depicted in terms of environmental impacts. Using a list of impact categories (based on the objectives mentioned at Goal

and Scope Definition step) the LCIA translates the emissions from a given product into impacts on various human and terrestrial eco-systems. Examples of Impact categories are: Global Warming Potential (GWP), Ozone layer Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Oxidation (OPCP), Embodied Energy (EE).

4. The **Interpretation** is the step in which the results are presented in the form of graphs and tables which is very useful in case of comparisons between two or more products. The outcome of the interpretation is the extraction of useful conclusions which lead to environmental friendly decisions in order to alleviate the environmental burdens. The potential changes in the proposed design should then be taken into consideration in the LCI (step 2) in order to extract new results. This fact makes the LCA an iterative process as illustrated in the following figure:



1.2.2. Life Cycle Costing

The second pillar of sustainable development is the prosperity/profitability aspect which is analyzed by the Life Cycle Costing (LCC) analysis. This is a valuable financial methodology for estimating and comparing different product systems or different design strategies in a long term perspective in terms of economic viability[23]. The basic idea of LCC is the assessment of all costs associated with the life cycle of a product system (from initial construction through maintenance and operation) obtaining a deeper understanding of costs during the life cycle for different design strategies. It is defined as a comparative cost assessment technique which is applied for a specific period of time taking into consideration all the relevant economic factors related to the initial and future costs. By comparing the life cycle costs of various design configurations, LCC can explore trade-offs between low initial costs and long term cost savings, identify the most cost effective system for a given use and determine how long it will take for a specific system to pay back its incremental cost.

The complexity and long life duration of buildings make the LCC methodology the appropriate financial decision making tool for a stakeholder. The analysis displays many benefits as it processes a huge amount of information in terms of economic values using a common unit (currency) and provides valuable information considering strategic options in a life cycle perspective. However, it can (and must) be criticized as it is based on the estimation and valuation of uncertain future events and outcomes(time value of money, the project specific discount rate, inflation). The subjective factors involved in the analysis may affect the results and mislead the decision making process[6].

1.3. The ELISSA concept

The ELISSA (Energy Efficient Lightweight-Sustainable-Safe-Steel Construction) project is a European collaborative project in which modular buildings using lightweight steel skeleton and dry wall systems are examined. These buildings can be constructed very quickly, are flexible and economical, with good energy performance and they fulfill all EU building regulations. The basic construction material is plasterboard, a widely used commodity of drywall panels and the load bearing structure is based on metal studs of various geometries. The building envelop is insulated using mineral wool and Vacuum Insulation Panels (VIP), an innovative inorganic nanomaterial which provides improved thermal performance. The nano-enhanced lightweight steel drywall elements reach the highest achievable degree of energy efficiency, safety and sustainability. Also the prefabrication of the building elements provides lower construction cost due to standardized procedures, reduces the construction waste and minimizes the construction time. The anticipated improvements are:

- Lower operational energy costs
- Safe construction
- Less weight
- Greater flexibility
- Reduced project financing
- Low cost of alternations

- Less building spoil and lower costs of disposal

The projected lifetime of an ELISSA construction is assumed 50 years and a typical single-family dwelling can advance far enough within only 3-4 days to allow work on the interiors to begin.

1.4. Problem statement

The purpose of this study is to assess the sustainability of an innovative external wall configuration, which was examined in the context of the ELISSA project. This wall is compared to two alternative cases implemented in the Europe (one in the north and one in the south Europe) which are considered as the dominant cases in the respective regions. The innovative wall is still in the embryonic stage trying to enter the market of building construction industry. It exhibits many significant advantages like flexibility, considerable reduction of the construction time, environmental friendly material usage, exceptional energy performance and high recyclability when it reaches the end of life stage. Also it is a prefabricated product constructed at an off site prefabrication plant 30 km away from the construction site. The sustainability is expressed through the environmental and economic aspect using the Life Cycle Management tools described above. The LCC and LCA analyses are carried out separately to cover both the environmental and the economic aspect of the products under study. The system boundaries of the analyses are clearly stated and all the estimations and the inevitable assumptions and limitations adopted are thoroughly described for further investigation and criticism.

2. Literature Review of LCAs

2.1. LCA methodologies

The basic concept of an LCA study is to calculate the environmental impacts during the life cycle stages of the examined product system. It is a structured procedure based on a model viewing the product system as a network of basic building blocks called unit processes. Each unit process represents an activity or a group of activities and records:

a) The intermediate exchanges from and to the technosphere i.e. inputs of energy and raw materials and outputs of products and waste
b) The exchanges with the environment i.e. input of natural resources and output of emissions. [24]

After gathering all the relative data for each unit process, the model evaluates the environmental impact of the specific unit process under study. Afterwards the relative impacts of the involved unit processes are aggregated in order to calculate the total impacts of the examined product system over a specific phase of its life cycle. Finally, the life cycle impact is obtained from the sum of the impact of each relative LC phase.

$$I = I_{extraction} + I_{manufacturing} + I_{on-site} + I_{operation} + I_{demolition} + I_{recycling} + I_{disposal}$$

Where I represents the environmental impact (e.g. Embodied energy, greenhouse gases etc) and I_j represents the environmental impact of jth building phase [25]. The appropriate data needed to perform the inventory analysis and finally to solve the equation above is a labour and time intensive process. The inputs (i.e. energy and natural resources) and outputs (i.e. emissions to land, water and air, waste) considering each building phase have to be compiled and calculated so that the two subsequent steps of an LCA (impact assessment and interpretation) to be carried out.

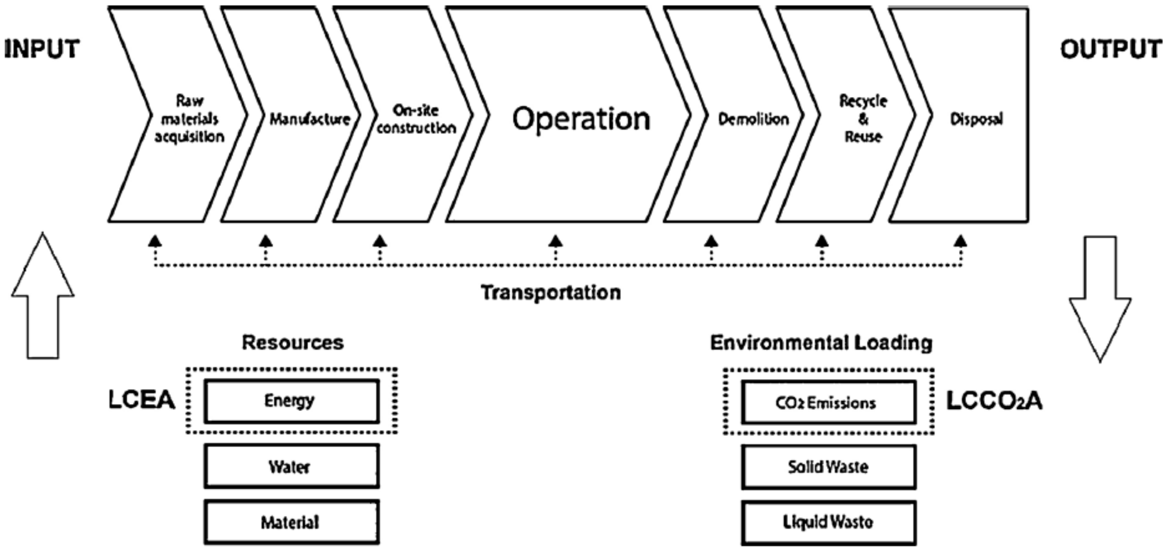


Figure 2: Basic model of an LCA. Here the LCEA[1] and $LCCO_2A$[2] models are depicted **[25]**.

The accuracy and extend of an LCI is dependent on which of the main analysis methods is chosen. Process based and economic Input-Output are the two traditional LCI methodologies which will be analyzed bellow.

Process-based analysis

In the process-based LCA, the practitioner uses various data from individual manufacturers or suppliers to calculate the environmental impacts. The data refers to materials, fuels and energy resources inputs and emissions and waste outputs for each step required to produce a product. [22] This approach requires the examination of each process in detail. The accuracy of the process analysis method can be high but it is only relevant to the particular system considered and can be subject to considerable variability. Additionally, due to a lack of available data, truncations are inevitably occurred leading to significant truncation errors[26]. Different types of process-based LCA methods are:

- ‘’Cradle-to-Grave’’
- ‘’Cradle-to-Gate’’
- ‘’Cradle-to-Cradle’’
- ‘’Gate-to-Gate’’

The majority of the LCA studies are applying process-based methodology.

Economic Input-Output analysis

[1] LCEA (Life Cycle Energyfocuses on the energy inputs to a system.
[2] $LCCO_2A$ focuses on the CO_2 equivalent emissions released form a system.

The economic Input-Output analysis (EIO-LCA), developed by Wassily Leontief the Nobel prize winning economist, combines sector-based financial data in order to determine the environmental performance of a product or service. Unlike process-based method, EIO-LCA quantifies the interrelations among activities of all industry sectors giving a more holistic view of a process or product. It relies on sector-level averages that may (or may not) represent a subset of the sector relevant to the particular product. [22,26] This method has a systematically complete system boundary but it generally used as a black box with little understanding of the values being assumed in the model for each process.

In the following table, the advantages and disadvantages of each LCA method are illustated:

	Process based LCA	EIO LCA
Advantages	Results are detailes, process specific Alloes for specific product comparisons Identifies areas for process improvements, weak points analysis, Provides for future product development assessments.	Results are economy-wide, comprehensive assessments Allows for system-level comparisons Uses publicly available, reproducible assessments, Provides information on every commodity in the economy.
Disadvantages	Setting system boundary is subjective, Tend to be time intensive and costly, Difficult to apply to new pracess design, Use proprietary data, Cannot be replicated if confidential data are used, Uncertainty in data.	Product assessments contain aggregate data, Process assessments dificult, Must ling monetary values with physical units, Imports treated as products created within economic boundaries, Availability of data for complete environmental effects, Difficult to apply to an open economy with substantial non-comparable imports, Uncertainty in data.

2.2. Previous studies

The LCA methodology has already been used in a wide range of applications from several sectors of the economy, including the building sector. The studies shed light on the impacts related to the different building phases and the material selection and the construction techniques followed by the stakeholders. An LCA analysis can provide useful information for decision makers such as architects, engineers, investors, consumers, governments etc. in order to determine and mitigate the environmental impacts in the early stage of a construction project designing and promote sustainability in building industry.

However, applying an LCA in the building sector is a difficult task not only due to the complexity of the buildings but also because of:

- The long life duration (often more than 50 years) which makes it difficult to predict the life-cycle impacts

- The building changes in its form and function during its life span.
- Buildings are large in scale encompassing lots of materials many of which have limited service life.
- Most of the environmental impacts occur during the operational phase and the outcomes depend on occupants behavior.
- There are many stakeholders in the building industry (designers, material producers, residents etc)
- There are limited information about the construction and demolition energy requirements and the associated environmental impacts.

Each building is a unique case study and it is designed as such. So there is very little standardization comparing to most products which fact requires specific handling.

What is generally included in an LCA study of buildings is the embodied energy and the environmental impacts of the materials and building components combination. The scope of an LCA study in building industry usually includes the raw material extraction and the processing into building materials, the transportation of materials and building components to site, the use of the building, the waste materials, maintenance and replacement, the demolition/disassembly of the building and the transportation of waste to the treatment site. On the contrary, the transport of equipment to site along with the construction phase and the construction waste generation are not usually included at the scope of the studies.

As far as the LCA results, most LCA practitioners conclude that the operational phase of the building is the one with the largest environmental impact because of its extensive duration. The emissions produce during the use phase is related to fossil fuel combustion for electrical generation and for space heating and cooling to maintain the appropriate temperature[27]. It has been estimated that the use phase in conventional buildings represents approximately 80% to 90% of the life cycle energy use while the 10% to 20% is consumed at the material extraction and production phase and less than 1% is consumed at the end of life [28]. Nevertheless, it must be mentioned that the location of the building has an important role in the total energy consumption and as a consequence in the overall embodied energy and life cycle environmental impacts. The high contribution of the use phase to the life-cycle environmental performance of a building explains the significance of mitigating the impacts of this phase by designing a so-called low-energy building[3]. On the contrary, the implementation of a low energy design in a construction, swifts the energy loads from the use phase to the pre-use phase in a life cycle perspective. In other words, a low energy design strategy can provide both a net benefit in operational energy but it increases the embodied

[3] Low energy building is a building built according to a special design criteria aimed at minimizing the buildings operation energy.

energy of the pre-use phase[21,29]. The literature suggests that there is a potential for reducing embodied energy requirements by using recyclable materials, so the initial choice of building materials and construction techniques is a significant factor for obtaining the acceptable level of sustainability.

The outcomes of an LCA study are quantifiable environmental indicators which are described in the initial goal and scope definition. The most commonly studied impacts are global warming, acidification, eutrophication, ozone depletion and embodied energy[22,27,28]. Blengini and Di Carlo[21] suggested that the selection of indicators is a subjected process and it must be consistent with ISO recommendation for impact assessment method.

Various studies have been carried out displaying the environmental impacts of different structure systems. Othman S. Alshamrani et al. [30]examined some types of structure such as concrete, steel, masonry and wood over a 75 years lifespan about the environmental impacts and the material and resources they consume. They concluded that concrete and masonry buildings dominate in energy consumption and GHG emissions during certain life cycle phases such as manufacturing, construction and demolition but they perform lower energy demands in operation phase.

Su Xing et al. [31] compared two different office buildings, a steel-structured and concrete-structured, over a 50 years lifespan. They concluded that the steel-structured building performs significantly better than concrete-structured building accounting for 24.9% less life-cycle energy consumption of the materials it consists of and 48.1% less CO_2 emissions per area than the latter. Simultaneously the mineral consumption of steel-framed building is only 21.5% as that of concrete-framed building.

The necessity of saving material and energy seems to be achieved by changing the construction practices form heavyweight structures and static partition walls to lightweight drywalls and steel structured buildings. Ricardo Mateus et al. [32] analyze ten lightweight partition wall technologies comparing them with two conventional heavyweight and lightweight technologies. They found out that the reference plasterboard wall along with lightweight sandwich membrane wall type 9 and 10 have least GHG emissions accounting for 17, 6.75 and 16.9 $kgCO_2$-eq respectively. On the contrary, the heavyweight technology contributes to 44.3 $kgCO_2$-eq.

2.3. Lightweight vs Heavyweight construction technologies

Reality shows that when it comes to the initial type of construction, the designers prefer heavyweight technologies mainly due to client’s higher functional perception about these technologies comparing to the alternative lightweight ones. However lightweight technologies can satisfy similar functional performance level and can have some advantages at the level of other key sustainable construction issues.

At first, a relevant advantage of a lightweight wall is its lower thickness when compared with the heavyweight conventional system. This property allows maximizing the net floor area of the building. Secondly, from a thermal analysis perspective, lightweight walls can have similar or better performance than heavyweight ones since their thermal insulation can be improved by placing an adequate insulation material in the space between the two surfaces of the wall. Additionally, lightweight walls need less material at the construction process. They mostly consist of plasterboard which is a totally recyclable, light and easy to use material, whereas heavyweight walls are made of hallow bricks and Portland-cement based mortar having a specific weight near 150kg/m^2. As a consequence, heavyweight technologies perform worse than lightweight one in transportation costs and the relevant environmental burdens, materials loss factors during construction and maintenance phases, flexibility during operation or refurnishing, reuse potential and recycling potential. Previous studies conclude that lightweight plasterboard walls are better than heavyweight masonry walls in terms of environmental performance and its less material and energy per square meter. Finally the lightweight construction technology allows seasonal or annual transformations of the housing units that increase the adaptability to the user and its changeable needs[33].

2.4. Prefabrication

Construction industry is one of the oldest industries with no remarkable innovation and improvements over the last 40 years. Additionally, the industry is characterized as labour-intensive, wasteful and inefficient because of its on site construction approach [34]. Prefabrication is an alternative construction technique that has been developed since the 1970s. It refers to structures built at a location other than the location that they are going to be used.

Comparing to conventional in-situ construction, prefabrication provides a lot of benefits:

1. Cost reduction due to repetitive and standard modular production
2. High levels of quality assurance
3. Reduce the necessity of labour work on site as most of the construction elements are prefabricated in the factory
4. Reduces the construction time up to 12%.
5. Reduces significantly the construction waste stream (up to 84.7% can be saved)
6. Easy to manage, more standardized work resulting in safer working environment.

7. However, it is inflexible to the design changes compared to the much more flexible in-situ construction method.[35]

According to Mao Chao et al. [36] there are three levels of prefabrication. The simplest of all is the semi-prefabrication method in which some parts of the building is constructed in-situ while the rest are constructed at the prefabrication site. The second level of prefabrication is called comprehensive prefabrication and it refers to building elements that are independently manufactured in the prefabrication site and then they are transported on site in order to be joined together. The third method is the volumetric modular building according to which the entire building is produced in the factory.

3. Goal and Scope Definition

3.1. Goal of the study

The main goal of this study is to evaluate the environmental performance of an external prefabricated lightweight steel skeleton/dry wall system with its innovative internal insulation materials implemented in the European Collaborative Project ELISSA. The integrated construction system is compared with two conventional brick wall cases applied in South and Central/North Europe.

The study quantifies the relevant environmental impacts of the configurations associated with the production of their building materials and the final disposal of them. For doing so, Life Cycle Analysis (LCA) methodology is utilized according to the ILCD Handbook [37] and the ISO 14040 and 14044 standards [38] for each case (innovative and conventional walls). LCA is a structured, comprehensive and internationally accepted method of evaluating the relevant primary energy demands, the gaseous emissions and the resources depletion related to the service or product being studied. The main parts of the LCA analysis are: the Goal and Scope definition, the Inventory analysis, the Life Cycle Impact Assessment (LCIA) and the Interpretation of the results.

The LCA is conducted at the Product Level which means that it is referred as a compilation of materials which are assembled together into the final products [39]. The products analyzed here are particularly three wall systems:

1. an innovative prefabricated lightweight wall structure incorporating nano-enhanced materials for thermal insulation and fire resistance (**ELISSA panel**)
2. a conventional brick wall structure, constructed on site, which includes common insulation materials and is applied to Central/North Europe (**CONV1 panel**).
3. a conventional brick wall structure constructed on site which includes common insulation materials and is applied to South Europe **(CONV2 panel)**

The analysis is extended from ‘’Cradle to Grave’’ taking into account the raw material extraction, the production of the appropriate building components, the assembly and the end of life treatment whilst the use phase is excluded. The intended audiences include various stakeholders such as construction industry, policy makers, architects, service providers, investors and others.

3.2. Scope of the study

3.2.1. Product systems

The product systems under study are considered as three configurations of external building wall. They are consisted of different kinds of building materials assembled together forming walls with different layers. The walls incorporate no type of transparent part (such as a window or a door). The conventional cases represent the most common configurations found in European region with the appropriate insulation level according to the climate conditions of each region. The ELISSA panel is made of steel covered with dry wall materials and incorporates three innovative elements which will play a significant role in the overall analysis:

- Prefabricated load bearing steel structure
- Vacuum Insulation Panels (VIP)
- Intumescent paints

The study take also into consideration the benefits derived from prefabrication as a construction process. A detailed description of each wall panel is presented below.

3.2.2. System boundaries

The external wall systems will be examined during their life cycle, from “cradle to grave”. The analysis involves three major stages:

1. the initial manufacturing of building materials extended from the extraction of raw materials until the manufacturing of the finished product,
2. the construction process, and
3. the End of Life (EoL) treatment of the waste material.

The intermediate transportations are also taken into account. Additionally, the characteristics of the applied construction method of each wall panel are considered. In particular, the ELISSA panel contains prefabricated wall structure, hence the building materials were transported from their manufacturing plants to the wall manufacturing center in order to be assembled into major wall components. These major assemblies were subsequently transported to the construction site for the final assembly. On the other hand, the building materials contained in the conventional cases were directly transported to the construction site. Finally, the waste materials (either construction waste or post-consumer waste) are leaded to the waste treatment facilities for the final disposal. A schematic description of the applied system boundaries is shown in Figure 3.

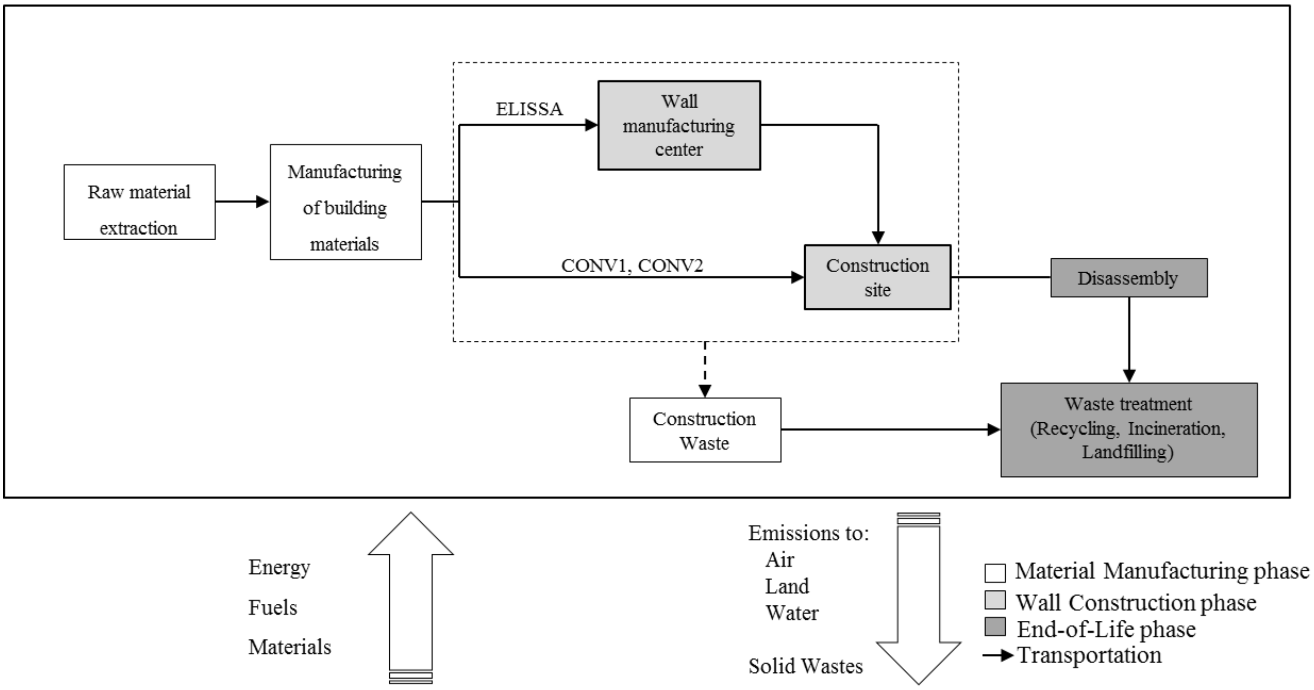


Figure 3: System boundaries of the analysis

The EoL phase of the walls contains not only the burdens arisen from the waste processing, but also the potential benefits or loads from the afterwards use of the waste by substituting virgin material.

3.2.3. Functional Unit

The base upon which the comparison between the wall systems under study is occurred is **1 m^2 of external wall at 100% opacity**. In this square meter almost all building materials are included except of those introduced in the Inclusions and Exclusions bellow. For the sake of consistency all the wall panels contain both load bearing and non-load bearing elements, depending to the construction type, so that they provide the same characteristics in terms of structural design. The examined life time is 50 years. The compilation of building materials included in the examined wall systems vary for each system. A comprehensive description of the materials is given bellow at Section 2.

3.2.4. Inclusions/ Exclusions

The building elements that take part in this study are designated as major contributors to the environmental performance of the wall component. The choice of these elements is based on the quantities of mass and the general LCA practice associated with the building industry. For that reason, metal nails, screws and fasteners, as well as the external and internal paints are neglected from the analysis as it is assumed that their contribution is relatively low comparing the proportion of their mass to the total mass of the functional unit. Particularly it is estimated that the sum of their mass does not exceed the 1% of the system’s mass. Additionally, the insulation membrane is also excluded from the scope of the analysis due to the lack of specific information and its relatively low mass per square meter of the wall.

In general, the elements included in the analysis are:

- The insulation materials
- The internal and external cladding
- The metal structure (both load and non-load bearing)
- The vertically perforated clay units
- The reinforced concrete
- The internal and external renders

3.2.5. Assumptions and limitations

The following limitations and assumptions have been adopted in the LCA study. Firstly it is assumed that the same construction methods and materials are followed for the next 50 years. Although it is difficult to forecast the waste treatment approaches as well as the recycling rates after 50 years, the end of life model was based on current practices. A detailed description of the EoL model is given bellow. Also the energy mix and intensities are considered constant over the next 50 years. The energy mix that is utilized is the average European energy mix. Due to lack of information, the energy and fuel consumption during the construction and demolition processes are not included into the scope of the study. The waste stream generated in each life cycle phase of the configurations (either construction or demolition waste) is assumed to be treated by the same approach related to the type of the building material. In this concept, no distinction has been made regarding the specific characteristics of the state of the waste e.g the level of contamination of the post-consumer waste.

4. Overview of the wall systems

This section describes in more detail the bill of materials contained in the wall systems.

4.1. ELISSA panel

ELISSA panel is a nano-enhanced lightweight steel skeleton/dry wall system with improved thermal, vibration/seismic and fire performance. It is consisted of multifunctional prefabricated elements with improved thermal properties resulting in reducing energy consumption during the operational phase of the building. Also it provides less waste disposal due to the prefabrication and the use of re-usable/recyclable building materials.

The skeleton of the wall is called ‘’Transformer’’ (Figure 4). It is a prefabricated load-bearing steel structured system consisted of thin-walled, cold-formed U- and C-formed hot-dip galvanized steel profiles in steelgrade S320GD+Z or DX51D+Z275 [40]. The profiles are coated with a 1.9mm thickness layer of Intumescent paint to increase the fire performance. A 15mm layer of gypsum plasterboard (KNAUF Diamant) is attached to each side of the ‘’Transformer’’ while in the inside void a 147mm layer of Mineral wool is situated. The interior side of the wall incorporates 20mm layer of Vacuum Insulation Panel (VIP), a 50mm layer of Rockwool and two layers of 15mm KNAUF Diamant. The inside surface is attached on a non-load-bearing steel structure made by galvanized cold-rolled runners and studs. Table 1 and Figure 5 illustrate the configuration of ELISSA panel, the types of materials used, their thickness and their amount per square meter of wall panel.

Figure 4: COCOON “Transformer”

Table 1: The bill of materials employed in the ELISSA case.

a/a	Material	Layers	Thickness [mm]	Density [kg/m^3]	kg/m^2
1	External render	1	15	1800	27

3	KNAUF Diamant 1x15mm	1	15.0	1030	15.5
4	Structure COCOON C147/50/1.5mm centered at 625mm	-	1.5	7800	13.96
5	Intumescent paints	-	1.9		1.03
6	KNAUF insulation mineral wool FCB 035,	1	147.0	50	7.35
7	KNAUF Diamant 1x15mm	1	15.0		15.5
8	Vacuum Insulation Panels 20mm	1	20.0	200	4
9	KNAUF profile CW50/0.6mm centered at 625mm	1		7800	2.61
10	KNAUF Insulation mineral wool, 50mm,	1	50.0	50	2.5
11	KNAUF Diamant 2x15.0mm	2	30.0	1030	31

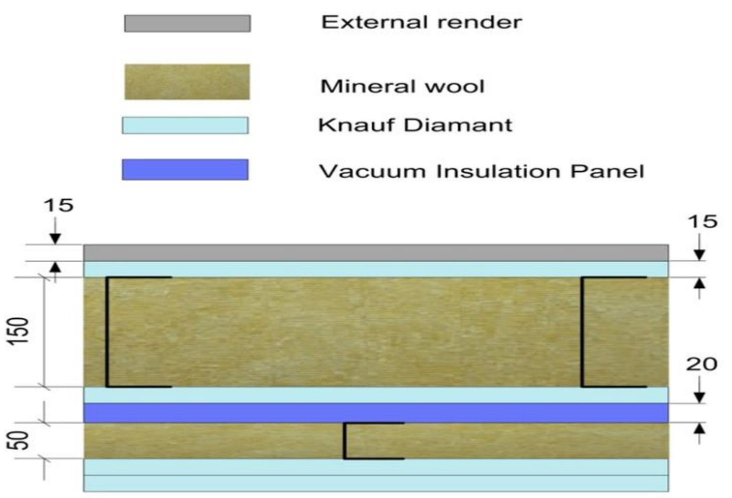


Figure 5: Cross-sectional view of ELISSA panel.

The mass per square meter of each construction element was calculated from data derived from the technical datasets and Deliverable Reports of ELISSA project.

The steel structure of ELISSA panel is divided into two segments:

1. Prefabricated load bearing COCOON “Transformer” system
2. KNAUF C- and U- formed profiles

Both types of steel are Cold-formed Hot dipped galvanized.

The calculation of the amount of steel of COCOON Transformer system contained in a square meter is based on the AW002 façade (ANNEX 1) which was taken as a reference. In particular, the total amount of structural steel sections measured from the architectural drawings, was divided by the wall area, so as to calculate the equivalent amount of mass contained in a square meter. According to the drawings, the COCOON's structural profiles and their quantity are presented below along with the equivalent steel mass:

Table 2: COCOON profiles and their quantities.

a/a		Pieces	Length [mm]	Tot Length [m]	kg/m [4]
1	C profile 147/50/1.5	6	2275	13.650	3.3
2	U profile 150/40/1.5	2	2387	4.774	3.3
3	DT1 profile 2xC 146/50/1.5	1	2275	2.275	6.6
			Total weight of AW002 (kg)		75.81
			Wall area (m^2)		5.43
			Total weight (kg/m^2)		**13.96**

As far as the non-loadbearing structure is concerned, the construction of the metal grid proposed by KNAUF requires the metal studs (CW-profiles) to be placed vertically with 625cm spacing between them. So the examined façade should contain 5 pieces of studs and 2 pieces of runners at the bottom and the upper side of the panel. The same methodology is implied here, firstly the total mass of non-loadbearing metal structure contained inside AW002 façade is calculated and then it is divided with the corresponding wall area.

Table 3:KNAUF profiles and their quantities.

a/a		Pieces	Length [mm]	Tot Length [m]	kg/m [5]
1	CW profile 100/50/0.6	5	2275	11.375	0.918
2	U profile 100/40/0.6	2	2387	4.774	0.779
			Total weight of AW002 (kg)		14.16
			Total weight (kg/m^2)		**2.61**

The ELISSA panel contains four layers of KNAUF Diamant gypsum board. According to the manufacturer, their mass is 15.5kg/m^2 so the total amount of Diamant gypsum board contained in a reference m^2 is **62kg/m^2.**

ELISSA panel contains also two layers to mineral wool, 147mm and 50mm thickness respectively. It is assumed that the density is 50kg/m^3 so the total amount of mineral wool is **9.85kg/m^2**.

[4] According to Deliverable 3.1: Structural analysis of COCOON Transformer.
[5] Derived from technical datasets provided by KNAUF

Finally, according to D6.1: Life Cycle Analysis [41], the COCOON steel sections are coated with a 1.9mm layer of Intumescent Paint. The total amount of the paint that corresponds to the equivalent loadbearing steel content of a square meter of ELISSA panel is **1.03kg/m²**.

4.2. Conventional panel: CONV1

The conventional panel CONV1 refers to typical external wall located in North and Central Europe. It is considered as the most common configuration in this region. It includes a layer of 350mm vertically perforated clay unit 5.7/1.6, followed by a layer of 150mm mineral wool insulation that covers the whole wall area. Both the internal and external surface of the wall is covered by renders. In the internal surface there is a 15mm lime based mortar, whereas in the external surface there is a 15mm cement based mortar respectively.

The configuration encompasses also the loadbearing structure made by reinforced concrete which consists of two columns situated in either side of the masonry and a beam on the upper site of it. It is assumed that the reinforced concrete structure takes the 24% of the whole façade area, whilst the masonry wall takes the 76%. Also, the thickness of the load bearing structure is 30cm and the reinforced steel content is estimated to be 4.5% of the concrete mass. Table 4 and Figure 6 summarize the configuration of CONV1 panel, the types of materials used, their thickness and their amount per square meter of the examined wall panel.

Table 4: The bill of materials employed in CONV1 case.

a/a	Material	Layers	Total Thickness [mm]	Density [kg/m³]	kg/m²
1	External render	1	15	1800	27
2	Mineral wool	1	150	50	7.5
3	Vertically perforated clay unit 5.7/1.6	1	350	750-1150	252.7[6]
4	Internal render	1	15	1000	15
5	Concrete	1	300	2380	171.36
6	Reinforcing steel	-	-	7800	7.71

[6] The amount of vertically perforated clay units was calculated using the average density of the range i.e. 950kg/m³.

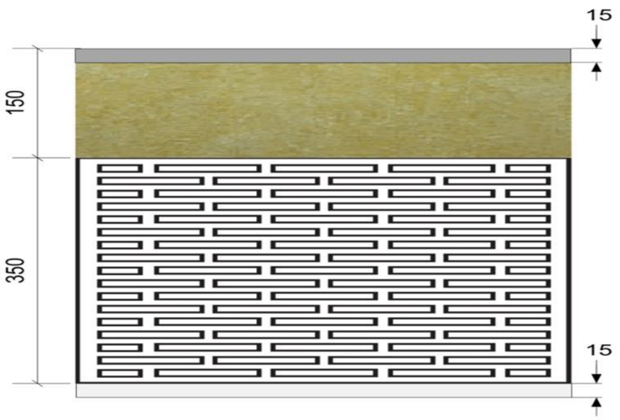


Figure 6: Cross-sectional view of CONV1 panel.

4.3. Conventional panel: CONV2

Conventional panel CONV2 is similar to CONV1 and it refers to a typical external wall located in South Europe. It is considered as the most common configuration at this region and it includes two layers of vertically perforated clay unit 2.8/4.1 with a 200mm total thickness and a layer of 65mm mineral wool insulation that covers the whole wall area. The internal and external surface of the wall is covered by lime based and cement based renders of 15mm thickness each respectively.

Like CONV1, the CONV2 configuration encompasses also a loadbearing structure made by reinforce concrete which consists of two columns situated in either side of the masonry and a beam on the upper site of it. The amount of concrete and reinforcing steel is the same as the previous case since the same assumptions were adopted. Table 5 and Figure 7 summarize the configuration of CONV2 panel, the types of materials used, their thickness and amount per square meter of wall panel.

Table 5: The bill of materials employed in CONV2 case.

a/a	Material	Layers	Thickness [mm]	Density [kg/m^2]	kg/m^2
1	External render	1	15	1800	27
2	Mineral wool	1	150	50	3.25
3	Vertically perforated clay unit 2.8/4.1	2	350	840-1435	172.9[7]
4	Internal render	1	15	1000	15

[7] The amount of the vertically perforated clay units was calculated using the average density of the range i.e. 1137.5kg/m^3.

5	Concrete	1	300	2380	171.36
6	Reinforcing steel	**-**	**-**	7800	7.71

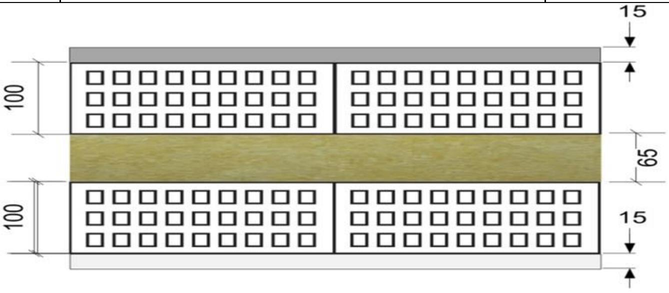


Figure 7: Cross-sectional view of CONV2 panel.

5. Inventory

The wall systems are produced by a combination of building materials. The aim of this section is to provide the appropriate data and information applied to this analysis in order to model the environmental performance of each wall. Data associated with the specific material production processes, the construction methods, and the end-of-life approaches are presented as well as all the necessary assumptions. The data is derived primarily from Ecoinvent database, the available literature and the Manufacturers participating in the ELISSA project.

5.1. Production phase of building materials

This phase includes all the manufacturing processes from the raw material extraction to the production of the finished material as well as the intermediate transportations. It represents the ''Cradle-to-Gate'' stage of LCA.

5.1.1. Structural steel

The utilized steel portion for each configuration is considered as low-alloyed primary steel which means that it is produced via Basic Oxygen Furnace route (LD converter) in an integrated steel plant. In this manufacturing route the main raw material inputs are pig iron and steel scrap (known as recycled content of steel making process) for temperature adjustments. The recycled content is considered 125g per kilogram of primary steel whereas the incorporated pig iron content is 900g per kilogram of primary steel. The output of this process is a semi-finished casting product (ingots, slabs, billets or blooms) which is subsequently processed in rolling mills and product finishing lines in order to be prepared for the market [42].

The hot rolling process follows the casting process and includes the processes of scarfing, grinding, heating, descaling, rolling and finishing. The repeatedly compressing procedure between several electrical powered rollers forms the semi-finished product into a hot rolled structural steel section. If further quality is required, the hot rolled section is processed in cold rolling mills attributing high quality surface finish and precise metallurgical properties [43].

For galvanized steel the semi-finished steel product outputs from cold rolling mills whose shape doesn't change anymore, are continuously passed through molten zinc. An alloying reaction between the two metals takes place, leading to a good bond between coating and substrates [43]. According to [44], the steel grade of COCOON "Transformer" system is DX51D+Z275 meaning that its surface incorporates 275g of zinc per square meter.

In this study two types of steel are analyzed:

1. the steel reinforcing bars made by hot rolled primary steel utilized by CONV1 and CONV2 cases in order to strengthen concrete
2. the hot dipped galvanized steel sections which refer to COCOON Transformer and KNAUF profiles used at the ELISSA panel.

The reinforcing steel was modeled based on data derived from Ecoinvent 2.2 database according to the following table 6:

Table 6: Inventory of Hot rolled primary steel

Model	Inputs	Amount	Description
Hot rolled steel section, BOF route, at plant/RER U	*Steel, converter, low-alloyed, at plant/RER U*	*1 kg*	Primary production of steel
	Hot rolling, steel/RER U	*1 kg*	Hot rolling process

The hot dipped galvanized profiles follow the same production route as reinforcing bars with an additional process at a cold rolling mill and the zinc coating. The inventory of hot dipped galvanized steel is depicted in Table 7.

Table 7: Inventory of Hot-dip galvanized steel

Model	Inputs	Amount	Description
Hot dipped galvanized steel, BOF route, at plant/RER U	*Steel, converter, low-alloyed, at plant/RER U*	*1 kg*	Primary production of steel
	Hot rolling, steel/RER U	*1 kg*	Hot rolling process
	Sheet rolling, steel/RER U	*1 kg*	Cold rolling process
	Zinc coating, coils/RER U	*0.064m^2*	Zinc coating (275g/m^2)

5.1.2. Mineral wool

Mineral wool is an insulation material output of Glass industry. It is produced by the coke filed hot blast cupola technique which may be compared to a steel making blast furnace in operation. It is produced by melting a combination of alumino-silicate rock, blast furnace slag and limestone or dolomite. More information about the production process can be found at [45,46]. In the current study, the Ecoinvent 2.2

database in which the packing process is included (Ecoinvent Database: *Rock wool, packed, at plant/CH U)*

5.1.3. Gypsum boards

Gypsum boards are used in all areas of interior construction as cladding in premium drywall systems with increased demands on sound insulation, fire protection and/or increased demands on robustness as well as in moderate wet rooms. They are manufactured through a continuous process production line in which the components of plasterboards are suspended in water and spread on a continuous sheet of board liner. Beforehand, the board liner is cut on the sides for edge shaping. The slurry is covered with a second sheet of board liner in the forming station and the edges of the visible face board liner are flipped upwards. On the subsequent board line the gypsum is setting continuously and is dried in a multi-level drier to the permitted residual moisture level. Drying is followed by the cutting of the boards to the desired lengths.

In order to calculate the environmental burdens attributed to KNAUF Diamant board, the issued Environmental Product Declaration (EPD) [47] is utilized. In this study the Life Cycle environmental impacts of a 12.8kg of KNAUF Diamant are evaluated using European datasets especially for the provision of electricity and thermal energy. The following table summarizes the results of the given evaluation from “cradle-to-gate” adjusted for 1 kg of KNAUF Diamant.

Table 8: Environmental impacts form the production of 1kg of KNAUF Diamant.

Impact Category	Unit	KNAUF Diamant A1-A3
GWP	kg CO2 eq.	3.09E-01
ODP	kg CFC-11 eq	1.63E-11
AP	kg SO2 eq	6.54E-04
EP	kg PO4--eq	1.38E-04
POPC	kg C2H4	4.80E-05
EE	MJ Primary	6.76E+00

5.1.4. Vacuum Insulation Panels

The Vacuum Insulation Panels (or VIPs) are insulation plates with a considerably low thermal conductivity of 0.004-0.007W/mK, providing a thermal resistance of about 8-10 times that of conventional insulation material with the same thickness. They are made of pressed fumed silica (82% w), opacifier (14% w) and polyester fiber fleece (4% w) [41]. Their manufacturing process includes the hydraulic pressing of a mixture of raw materials that compose the VIP core. After the pressing, the panel is cut to size and dried at a temperature between 60 and 150°C and wrapped in a fabric. Then a metalized film covers the core and seals it since the required pressure has been reached [48]. VIPs are produced in a highly energy-consuming manner, primarily with electricity, resulting in significantly high levels of primary energy demands comparing to the conventional insulation materials [49]. It is estimated that 90% of the life cycle evaluation comes from that area (silicon processing industry) [50]. According to [41], the manufacturing process of 2.8kg of VIP requires 0.81kWh of electricity.

The LCA data related to VIP manufacturing process is derived from [41]. Given the values of each impact category for the three main constituents of VIP, the following table is created:

Table 9: Environmental impacts attributed to each constituent material that forms a 4kg VIP.

Impact Category	Unit	Pyrogenic silica powder	Opacifier	Polyester fibre fleece	Electric energy required for manufacturing	VIP
GWP	kg CO2 eq.	2.35E+01	4.14E+00	1.20E+00	5.80E-01	2.94E+01
ODP	kg CFC-11 eq	1.94E-05	4.66E-07	7.16E-08	2.95E-08	1.99E-05
AP	kg SO2 eq	1.01E-01	2.22E-02	4.82E-03	2.24E-03	1.30E-01
EP	kg PO4--eq	4.05E-02	9.64E-03	2.89E-03	1.68E-03	5.47E-02
POPC	kg C2H4	6.75E-03	1.07E-03	2.27E-04	1.73E-04	8.22E-03
NRE	MJ Primary	3.82E+02	9.28E+01	2.66E+01	1.28E+01	5.14E+02

According to D6.1, the relative mass of the aforementioned materials that is needed to form a 4kg VIP is given below:

Table 10: The composition of the materials and the required electric energy that produce a 4kg VIP.

Materials		Amount	Unit
Vacuum Insulation	Pyrogenic silica	3.28	Kg

Panel (4 kg)	powder		
	Opacifier	0.58	Kg
	Polyester fibre fleece	0.14	Kg
	Electric Energy	1.16	KWh

5.1.5. Intumescent Paint

Intumescent paint is a painted steel coating that provides increased thermal protection to the loadbearing steel structure of ELISSA panel in the case of fire. It prevents the arisen of the steel temperature to reach a critical point at which steel loses its load bearing capability with drastic consequences for the stability of the building. The LCA data used for intumescent paint were adopted from [41].

Table 11: Environmental impacts of 1.04kg of Intumescent Paint.

Impact Category	Unit	Intumescent Paint
GWP	kg CO2 eq.	3.39E+00
ODP	kg CFC-11 eq	8.19E-05
AP	kg SO2 eq	3.09E-03
EP	kg PO4--eq	1.36E-02
POPC	kg C2H4	6.31E-03
NRE	MJ Primary	6.68E+01

5.1.6. Concrete structure

The concrete is applied to the conventional panels as described above. The LCA data were derived from Ecoinvent 2.2 (Ecoinvent Database: *Concrete, normal, at plant/CH U*)

5.1.7. Vertically perforated clay units

They cover the 76% of the conventional panels' area. They modeled as common bricks (Ecoinvent Database: *Brick, at plant/RER U)*

5.1.8. External render/Internal plaster

As far as the external and internal coatings, they modeled as concrete based and lime based renders respectively. The LCA data were derived from Ecoinvent 2.2 as follows:

- External render: *Cement mortar, at plant/CH U*
- Internal plaster: *Lime mortar, at plant/CH U*

5.2. Construction phase

In this section, the conventional construction method and the off-site pre-fabrication are analyzed. The construction burdens arisen from the electricity consumption of power tools and lighting as well as diesel fuel used by heavy equipment at the construction site are excluded due particularly to lack of relative information. However, the burdens attributed to construction waste are considered.

The examined wall systems are built based on two different construction practices:

1. Off-site prefabrication: The building materials are transferred in a factory or other manufacturing site, assembled to a wall system and transported to the construction site as a complete wall system. This method is applied to the ELISSA panel
2. Conventional construction practice: The building materials are transferred directly to the construction site where the assembly is carried out. This method was applied to the CONV1 and CONV2 panels.

5.2.1. Construction wastage

Construction wastages and losses are arisen during the construction, refurbishment and renovation of a building as a result of wasteful design, off-cuts from the construction, damaged material and over-ordering. Kellenberger et al.[51] underlined that the influence of the construction waste is less than 4% for the total Eco-indicator 99[8] and the non-renewable CED[9] (from fossil and nuclear). In this study the construction waste will be included according to the relative quantities derived

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[8] Eco-Indicator 99 is a single score indicator which assess the effects of resource use and emission on human health, ecosystem quality and resource quality.
[9] CED : Cumulative Energy Demand

from literature. [51–54] The construction waste factors are expressed as a fraction of the total material quantity.

Table 12: Percentages of wastage that have been assumed

Materials	Wastage (%)
External/Internal render	5
Hot-dip Galvanized steel	4
Mineral wool	3
Gypsum board	5
Intumescent paints	7
VIP	0
Clay units	6
Concrete	3
Reinforcing steel	4

These percentages are added to the previously gauged requirements of building materials contributing to increased environmental impacts. The VIP wastage is zero due to the fact that they cannot be cut or modified at the construction site. They are mounted on the wall as compact panels in that form produced by the manufacturer.

5.2.2. Prefabrication

There is a growing propensity to reduce wastage generation of the construction industry by implementing methods such as prefabrication. Prefabrication is a manufacturing process taken place at a specialized factory in which various materials are transported and joined together in particular component parts of the final installation[55]. In general, prefabrication can be categorized as three types, namely, semi-prefabrication, comprehensive prefabrication and volumetric modular building. A detailed description of each type can be found on [56]. In the ELISSA concept the comprehensive prefabrication method is implied meaning that all building elements are independently designed and manufactured at an off-site construction facility and then they transported on site to be assembled to the final building. Here it is assumed that all building materials are transported to KNAUF facilities. According to [57] prefabrication can provide significant waste reduction due to the quality control system of the manufacture company. By this system the waste stream generation of the major materials is strictly supervised and controlled. In many cases, stakeholders estimate the implementation of prefabrication method reduces to nearly zero the wastage generation [54,57]. In this study, a reduction of 85% of the construction waste comparing to that generated from the conventional construction method is adopted.

Additional benefits from prefabrication, which cannot be highlighted in the current study are the improved quality control, safer working environment, improved environmental performance and the reduction in labour requirements [58]. What is more, prefabrication provides the ability of disassembling the building components at the end of building's life and managing the construction elements in a more sustainable way (recycling or reusing) than simply disposing to landfill. This can reduce the demands for additional virgin materials [59].

In summary, the bills of materials for each case are illustrated in the Table 13, Table 14 and Table 15 taking into consideration the percentages of the construction wastes and the benefits of prefabrication.

Table 13: Quantities of building materials of ELISSA panel

a/a	Building material	Amount (kg/m^2)	C.W. (%)	Reduction of C.W. (%)	Total amount(kg/m^2)
1	External render	27.00	5	85	27.20
2	KNAUF Diamant	62.00	5	85	62.47
3	Mineral wool	9.85	3	85	9.89
4	Hot-dip Galvanized steel profiles	16.57	4	85	16.67
5	VIP	4.00	0	85	4.00
6	Intumescent paints	1.03	7	85	1.04

Table 14: Quantities of building materials of CONV1 panel

a/a	Building material	Amount (kg/m^2)	C.W. (%)	Reduction of C.W. (%)	Total amount(kg/m^2)
1	External render	27.00	5	0	28.35
2	Mineral wool	7.50	3	0	7.73
3	Vertically perforated clay unit 5.7/1.6	252.70	6	0	267.86
4	Internal plaster	15.00	5	0	15.75
5	Concrete	171.36	3	0	176.50
6	Reinforcing steel	7.71	4	0	8.02

Table 15: Quantities of building materials of CONV2 panel

a/a	Building material	Amount (kg/m^2)	C.W. (%)	Reduction of C.W. (%)	Total amount(kg/m^2)
1	External render	27.00	5	0	28.35
2	Mineral wool	3.25	3	0	3.35
3	Vertically perforated clay unit 2.8/4.1	172.90	6	0	183.27
4	Internal plaster	15.00	5	0	15.75
5	Concrete	171.36	3	0	176.50
6	Reinforcing steel	7.71	4	0	8.02

5.2.3. Transportation

Figure 8 illustrates the transportation routes followed by the wall system cases in question. It is clear that the prefabricated components are burdened with a complementary transportation from the prefabrication plant to the project site where the assembly process is occurred. The studied distances are assumption-based and they may differ significantly from the actual ones. The considered mean of transportation is Lorry 20-28t. The environmental burdens attributed to the transportation process include not only the operational burdens but also the production, maintenance and disposal of the vehicle along with the construction, maintenance and disposal of the road adjusted to the transportation of each material. The transport dataset was derived from Ecoinvent Database: *Transport, lorry 20-28t, fleet average/CH U.*

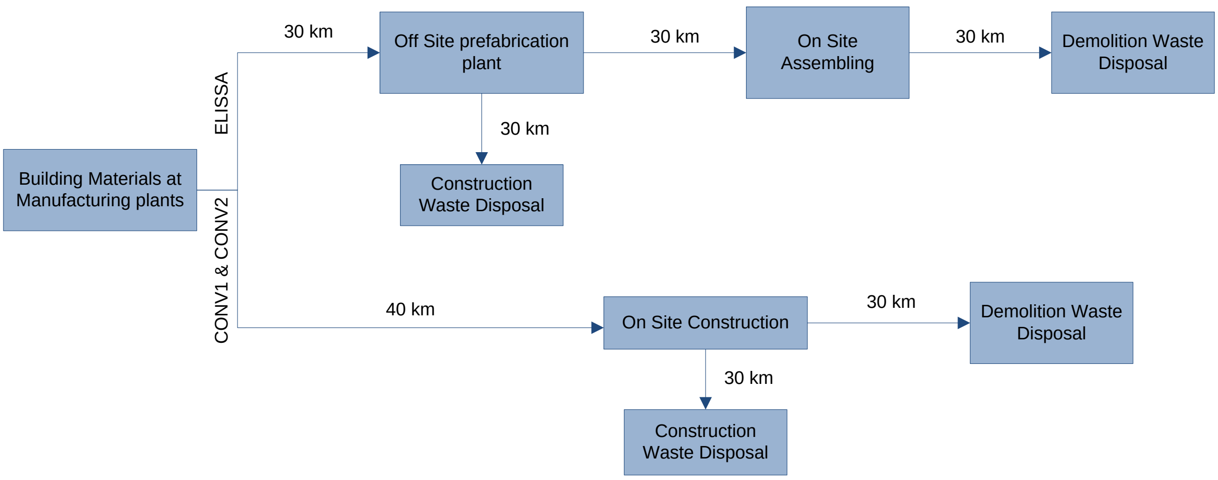


Figure 8: The projected transportation routes for Prefabrication (ELISSA panel) and Conventional (CONV1 and CONV2) construction methods.

The applied load factor[10] is assumed the same as that employed in the Ecoinvent Database which is derived from average values of load. In the case of lorry 20-28t the average load is 5.8t [60]. The prefabrication plant was assumed to be KNAUF factory, so the transportation distances of KNAUF Diamant boards and KNAUF insulation mineral wool are zero as KNAUF is the manufacturer of these materials.

5.3. End-of-Life stage

In this section the waste treatment approaches are studied for the environmental point of view. Due to the fact that it is quite difficult to foresee the applied waste treatment processes at the end of the product's life after 50 years from now, the study is constrained by calculating the environmental impacts of the contemporary practices. The EoL model starts when a material reaches the EoL stage either during the construction phase (as construction waste) or at the end of the projected life cycle. The potential benefits and loads from the use of the processed waste (e.g. after being recycled) although they referred to another product system, beyond the examined system boundary, they are taken into consideration. This processed waste is considered as products/materials which substitute other materials or fuels in another product system (e.g. as secondary materials and energy carriers).

5.3.1. Waste treatment: Steel

After its service life is completed, steel scrap is collected and re-melted in a Electric Arc Furnace (EAF) to produce new products from secondary steel. Given that there is no change in its inherent properties, steel recycling can be considered as closed loop. The methodology used for modeling EoL treatment of steel was employed by Wordsteel and is based in "Closed material Loop Recycling".

In this study, it is assumed that steel scrap is the only metal input of EAF and the production of 1kg of secondary steel requires 1.105kg of steel scrap, thus the Metallic Yield (Y) of EAF is equal to 0.905. On the other hand, the metal content of Blast Furnace is divided into 0.125 kg of iron scrap and 0.9kg of pig iron (considering the production of 1 kg of low-alloyed steel). A typical Recycling Rate (RR) of steel used at construction industry is 85% [61]. That is, 85% of steel is recovered as steel

[10] Load factor is the ration of the average load to total vehicle freight capacity expressed in terms of vehicle kilometers

scrap and is recycled through EAF route and 15% of steel is disposed to landfill. The methodology and the equations for calculating the environmental impacts of recycling are represented in Appendix 10 of Wordsteel Methodology report.

5.3.2. Waste treatment: Gypsum Board

Gypsum is considered to be "fully and eternally recyclable" by the gypsum industry although only the production and construction waste is currently recycled in some extend. The recycling rate for demolition gypsum waste is low in many European countries given that selective deconstruction is required which is an expensive process. Additionally, the collected gypsum boards from demolition projects can be contaminated with other materials (paints, screws, fastenings, insulation materials etc) rendering recycling difficult. In the context of GtoG[11] project, Eurogypsum has listed the acceptance criteria for gypsum board recycling per country for the recyclers participating in the project.[62]

The main environmental issue associated with gypsum waste management is the production of the toxic hydrogen sulphide gas (H_2S) when plasterboard waste is disposed to inert landfills. When the gypsum board exposed to rain, in an anaerobic environment and mixed with organic waste H_2S will be released which is lethal in high concentrations. For that reasons, European Union legislation requires specific cells in inert landfills to avoid H_2S emissions[63].

In the context of this study, the dataset of EPD [47] is used assuming that 95% by weight of the board is recycled and 5% is disposed to landfill. The result of recycling process can be used for the production of new gypsum based building materials. The dataset of EoL stage of KNAUF Diamant adjusted for 1 kg of product is listed in Table 16.

Table 16: EoL environmental impacts of 1 kg of KNAUF Diamant board.

Parameter	Unit	Recycling process	Disposal of non-recyclable material	Benefits form recycling
GWP	kg CO2 eq.	6.16E-03	8.05E-04	-1.34E-01
ODP	kg CFC-11 eq	6.13E-13	1.30E-14	-9.77E-12
AP	kg SO2 eq	1.00E-05	4.91E-06	-3.10E-04

[11] GtoG project aims at transforming the European gypsum demolition waste market to achieve higher recycling rates of gypsum waste.

EP	kg PO4--eq	1.31E-06	6.74E-07	-2.45E-05
POPC	kg C2H4	7.53E-07	4.61E-07	-2.88E-05
EE	MJ Primary	1.07E-01	1.21E-02	-9.06E-01

5.3.3. Waste treatment: Mineral wool

Mineral wool is an insulation material capable of being recycled and reused in new insulation products at the end of its life. In 2006, the Danish Environmental Protection Agency released a report which concluded that it could be technically possible to recycle a significant portion (90%) of the collected and shorted mineral wool. However the current practice is not recycling but disposal to inert landfills [64]. Mineral wool waste is classed as non-hazardous waste in the European list of waste products. It consists at minimum of 95% inert material whereas the remaining 5% is made up of binder components [45]. In this study, mineral wool is assumed to be disposed to inert material landfill.

5.3.4. Waste treatment: VIP

Many studies argue that Vacuum Insulation Panels are fully recyclable products unless they damaged or contaminated in a great degree [48,49,65]. However, very few LCA studies [66] give an overview of the environmental impacts (or credits) at the end of their service life, estimating that the recycling of VIP core can provide a significant reduction at the overall life cycle impacts related both to the gaseous emissions and the primary energy consumption at the production stage. In the current study, the LCA data provided by [41] is utilized in order to simulate the recycling process of VIP panels and the subsequent benefits from it.

5.3.5. Waste treatment: Intumescent paint

At the end of life, intumescent paint is assumed to be removed from the metal surface using manual equipment and it is disposed to landfill. The LCA data was derived from [41].

5.3.6. Waste treatment: Inert materials

The lithoid fraction which is mainly referred to the CONV1 and CONV2 cases encompasses the concrete structure, the bricks and the external and internal renders.

Those materials are assumed to be treated as infilling materials avoiding the extraction of virgin aggregates such as gravel.

6. Impact Assessment

The life cycle impact assessment presents the results of the inventory analysis in different impact categories. Two impact assessment methods have been chosen; the CED (Cumulative Energy Demand) method to evaluate the embodied energy (EE) requirements and the EPD (Environmental Product Declaration) method to evaluate the following impact categories with the associated abbreviations:

- Global warming (GWP)
- Ozone layer depletion (ODP)
- Acidification (AP)
- Eutrophication (EP)
- Photochemical Oxidation (POPC)

Global Warming index-refer to the gases contributing to the global warming phenomenon due to the greenhouse effect. They are aggregated according to their impact compared to the carbon dioxide with is used as the reference gas. The impacts are expressed in kg CO_2 equivalent.

Ozone layer Depletion (ODP) index-refer to gases that contributes to the depletion of the ozone layer like chlorofluorocarbons. The impacts are expressed in kg CFC-11 equivalent.

Acidification (AP) index- refer to the air acidification potential through the emission of acidifying gases such as SO_2, NO_x, HCl, HF and NH_3 on the basis of the number of hydrogen ions that can be produced per mole of a substance, using SO_2 as the reference substance. The impacts are expressed in kg SO_2 equivalent.

Eutrofication (EP) index-refer to those substances that have potential for causing nutrification. This index is a measure of the capacity to form biomass compared to phosphate (PO_4). The impacts are expressed in kg PO_4 equivalent.

Photochemical Oxidation (POPC) index-refer to gases contributing to the formation of smog. They are aggregated according to their relative photo-oxidation potential compared to ethylene as the reference gas. The impacts are expressed in kg C_2H_4 equivalent.[67]

Embodied Energy (EE) index- refer to the sum energy requirements for the production, transportation and end-of-life treatment attributed to a specific product system. The impact is expressed in MJ of primary energy.

Table 17: Environmental impacts of ELISSA panel

	Materials	Unit	External render	Knauf Diamant	Mineral wool	Hot-dip Galvanized Steel	VIP	Intumescent paints	Prefabricated components	Total
Production phase	**Amount**	kg/m^2	27.20	62.47	9.89	16.67	4.00	1.04	-	121.27
	GWP	kg CO_2 eq.	5.18E+00	1.93E+01	1.11E+01	4.86E+01	2.94E+01	3.43E+00	-	1.17E+02
	ODP	kg CFC-11 eq	1.89E-07	1.02E-09	6.65E-07	3.07E-06	1.99E-05	8.28E-05	-	1.07E-04
	AP	kg SO_2 eq	8.16E-03	4.08E-02	7.26E-02	3.56E-01	1.30E-01	1.37E-02	-	6.22E-01
	EP	kg PO_4 eq	2.27E-03	8.64E-03	1.82E-02	1.52E-01	5.47E-02	6.38E-03	-	2.43E-01
	POPC	kg C_2H_4	1.67E-03	3.00E-03	1.18E-02	4.28E-02	8.22E-03	3.12E-03	-	7.07E-02
	EE	MJ Primary	4.16E+01	4.22E+02	2.15E+02	7.72E+02	5.14E+02	6.75E+01	-	2.03E+03
Transportation	**GWP**	kg CO_2 eq.	3.17E-01	3.64E-01	5.76E-02	1.94E-01	4.66E-02	1.21E-02	7.01E-01	1.69E+00
	ODP	kg CFC-11 eq	4.53E-08	5.20E-08	8.24E-09	2.77E-08	6.66E-09	1.73E-09	1.00E-07	2.42E-07
	AP	kg SO_2 eq	1.67E-03	1.92E-03	3.04E-04	1.02E-03	2.46E-04	6.39E-05	3.70E-03	8.93E-03
	EP	kg PO_4 eq	4.52E-04	5.19E-04	8.23E-05	2.77E-04	6.65E-05	1.73E-05	1.00E-03	2.42E-03
	POPC	kg C_2H_4	4.87E-04	5.59E-04	8.85E-05	2.98E-04	7.15E-05	1.86E-05	1.08E-03	2.60E-03
	EE	MJ Primary	5.34E+00	6.13E+00	9.71E-01	3.27E+00	7.85E-01	2.04E-01	1.18E+01	2.85E+01
End-of-Life phase	**GWP**	kg CO_2 eq.	-7.66E-02	-7.96E+00	7.02E-02	-2.04E+01	-2.83E+01	7.40E-03	-	-5.67E+01
	ODP	kg CFC-11 eq	-7.35E-09	-5.71E-10	1.85E-08	-2.67E-07	-2.17E-05	1.95E-09	-	-2.20E-05
	AP	kg SO_2 eq	-4.40E-04	-1.84E-02	3.99E-04	-6.83E-02	-1.31E-01	4.19E-05	-	-2.18E-01
	EP	kg PO_4 eq	-1.56E-04	-1.40E-03	1.02E-04	-4.52E-02	-5.11E-02	1.07E-05	-	-9.78E-02
	POPC	kg C_2H_4	-9.81E-05	-1.72E-03	1.59E-04	-1.69E-02	-8.10E-03	1.67E-05	-	-2.67E-02
	EE	MJ Primary	-2.03E+00	-4.92E+01	1.96E+00	-2.71E+02	-4.99E+02	2.05E-01	-	-8.18E+02

Table 18: Environmental impacts of CONV1 panel

	Materials	Unit	External render	Mineral wool	Vertically perforated clay unit 5,7/1,6	Internal plaster	Concrete	Reinforcing steel	Total
Production phase	**Amount**	kg/m^2	28.35	7.73	267.86	15.75	176.50	8.02	504.21
	GWP	kg CO_2 eq.	5.40E+00	8.70E+00	6.38E+01	9.46E+00	1.94E+01	1.89E+01	1.26E+02
	ODP	kg CFC-11 eq	1.97E-07	5.20E-07	6.39E-06	2.88E-07	5.63E-07	7.86E-07	8.75E-06
	AP	kg SO_2 eq	8.50E-03	5.67E-02	1.32E-01	1.29E-02	3.02E-02	6.42E-02	3.05E-01
	EP	kg PO_4 eq	2.37E-03	1.42E-02	4.61E-02	3.33E-03	8.07E-03	4.31E-02	1.17E-01
	POPC	kg C_2H_4	1.74E-03	9.25E-03	4.62E-02	2.74E-03	5.77E-03	1.72E-02	8.29E-02
	EE	MJ Primary	4.34E+01	1.68E+02	7.58E+02	5.67E+01	1.07E+02	2.89E+02	1.42E+03
Transportation	**GWP**	kg CO_2 eq.	3.85E-01	1.05E-01	3.64E+00	2.14E-01	2.40E+00	1.09E-01	6.85E+00
	ODP	kg CFC-11 eq	5.51E-08	1.50E-08	5.20E-07	3.06E-08	3.43E-07	1.56E-08	9.79E-07
	AP	kg SO_2 eq	2.03E-03	5.54E-04	1.92E-02	1.13E-03	1.27E-02	5.75E-04	3.61E-02
	EP	kg PO_4 eq	5.50E-04	1.50E-04	5.20E-03	3.06E-04	3.42E-03	1.56E-04	9.78E-03
	POPC	kg C_2H_4	5.92E-04	1.61E-04	5.59E-03	3.29E-04	3.68E-03	1.67E-04	1.05E-02
	EE	MJ Primary	6.49E+00	1.77E+00	6.13E+01	3.61E+00	4.04E+01	1.84E+00	1.15E+02
End-of-Life phase	**GWP**	kg CO_2 eq.	-7.99E-02	5.48E-02	-7.54E-01	-4.44E-02	-4.97E-01	-9.82E+00	-1.11E+01
	ODP	kg CFC-11 eq	-7.66E-09	1.45E-08	-7.23E-08	-4.25E-09	-4.77E-08	-1.28E-07	-2.46E-07
	AP	kg SO_2 eq	-4.59E-04	3.11E-04	-4.33E-03	-2.55E-04	-2.85E-03	-3.29E-02	-4.05E-02
	EP	kg PO_4 eq	-1.62E-04	7.97E-05	-1.53E-03	-9.00E-05	-1.01E-03	-2.18E-02	-2.45E-02
	POPC	kg C_2H_4	-1.02E-04	1.24E-04	-9.66E-04	-5.68E-05	-6.37E-04	-8.13E-03	-9.77E-03
	EE	MJ Primary	-2.12E+00	1.53E+00	-2.00E+01	-1.18E+00	-1.32E+01	-1.30E+02	-1.65E+02

Table 19: Environmental impacts of CONV2 panel

	Materials	Unit	External render	Mineral wool	Vertically perforated clay unit 2.8/4.1	Internal plaster	Concrete	Reinforcing steel	Total
Production phase	**Amount**	[kg/m^2]	28.35	3.35	183.27	15.75	176.50	8.02	415.24
	GWP	kg CO_2 eq.	5.40E+00	3.77E+00	4.36E+01	9.46E+00	1.94E+01	1.89E+01	1.01E+02
	ODP	kg CFC-11 eq	1.97E-07	2.25E-07	4.38E-06	2.88E-07	5.63E-07	7.86E-07	6.44E-06
	AP	kg SO_2 eq	8.50E-03	2.45E-02	9.05E-02	1.29E-02	3.02E-02	6.42E-02	2.31E-01
	EP	kg PO_4 eq	2.37E-03	6.15E-03	3.15E-02	3.33E-03	8.07E-03	4.31E-02	9.45E-02
	POPC	kg C_2H_4	1.74E-03	4.01E-03	3.16E-02	2.74E-03	5.77E-03	1.72E-02	6.30E-02
	EE	MJ Primary	4.34E+01	7.26E+01	5.19E+02	5.67E+01	1.07E+02	2.89E+02	1.09E+03
Transportation	**GWP**	kg CO_2 eq.	3.85E-01	4.55E-02	2.49E+00	2.14E-01	2.40E+00	1.09E-01	5.64E+00
	ODP	kg CFC-11 eq	5.51E-08	6.50E-09	3.56E-07	3.06E-08	3.43E-07	1.56E-08	8.06E-07
	AP	kg SO_2 eq	2.03E-03	2.40E-04	1.31E-02	1.13E-03	1.27E-02	5.75E-04	2.98E-02
	EP	kg PO_4 eq	5.50E-04	6.49E-05	3.56E-03	3.06E-04	3.42E-03	1.56E-04	8.06E-03
	POPC	kg C_2H_4	5.92E-04	6.98E-05	3.82E-03	3.29E-04	3.68E-03	1.67E-04	8.66E-03
	EE	MJ Primary	6.49E+00	7.66E-01	4.20E+01	3.61E+00	4.04E+01	1.84E+00	9.50E+01
End-of-Life phase	**GWP**	kg CO_2 eq.	-7.99E-02	2.38E-02	-5.16E-01	-4.44E-02	-4.97E-01	-9.82E+00	-1.09E+01
	ODP	kg CFC-11 eq	-7.66E-09	6.27E-09	-4.95E-08	-4.25E-09	-4.77E-08	-1.28E-07	-2.31E-07
	AP	kg SO_2 eq	-4.59E-04	1.35E-04	-2.96E-03	-2.55E-04	-2.85E-03	-3.29E-02	-3.93E-02
	EP	kg PO_4 eq	-1.62E-04	3.45E-05	-1.05E-03	-9.00E-05	-1.01E-03	-2.18E-02	-2.40E-02
	POPC	kg C_2H_4	-1.02E-04	5.38E-05	-6.61E-04	-5.68E-05	-6.37E-04	-8.13E-03	-9.54E-03
	EE	MJ Primary	-2.12E+00	6.63E-01	-1.37E+01	-1.18E+00	-1.32E+01	-1.30E+02	-1.60E+02

Table 20: Life cycle environmental impacts per type of wall panel.

Impact Category	Unit	ELISSA Panel	CONV1 panel	CONV2 panel
GWP	kg CO_2 eq.	62.02	121.29	95.23
ODP	kg CFC-11 eq	0.000085	0.0000095	0.0000070
AP	kg SO_2 eq	0.41	0.30	0.22
EP	kg PO_4 eq	0.15	0.102	0.079
POPC	kg C_2H_4	0.047	0.083	0.062
EE	MJ Primary	1242.31	1372.18	1022.89

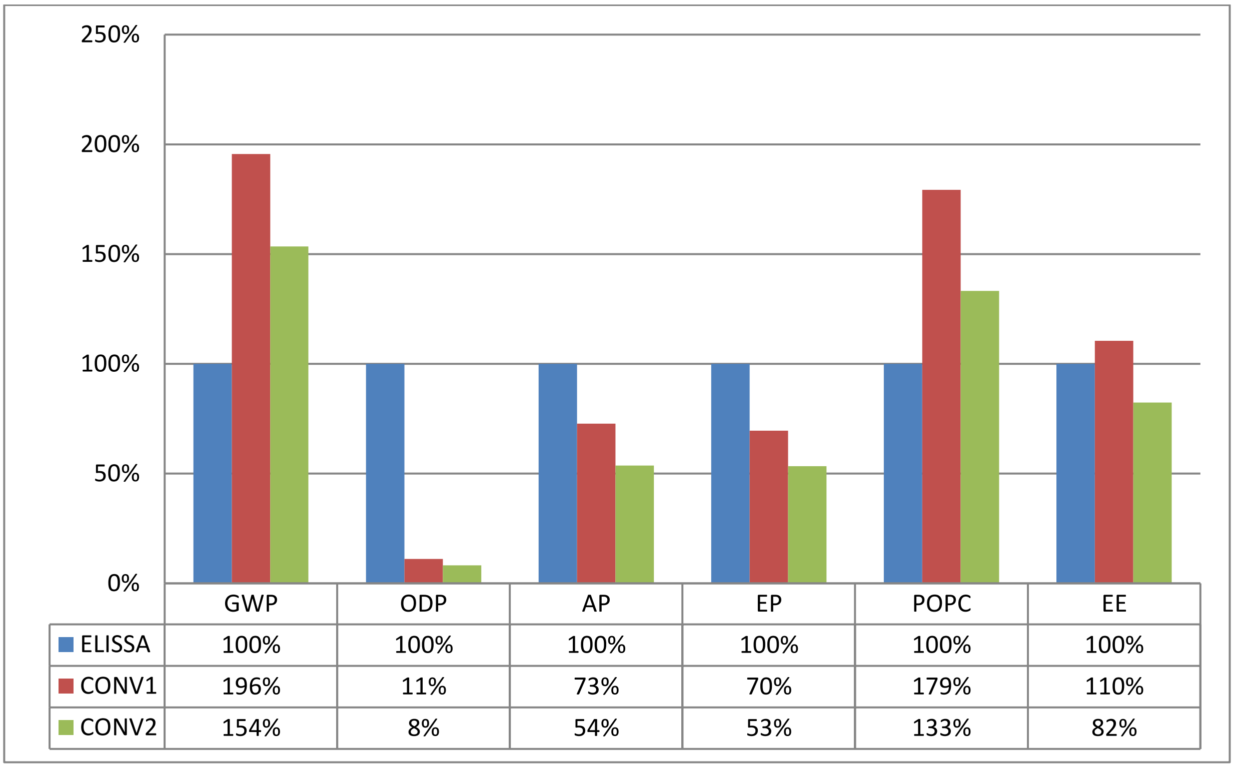
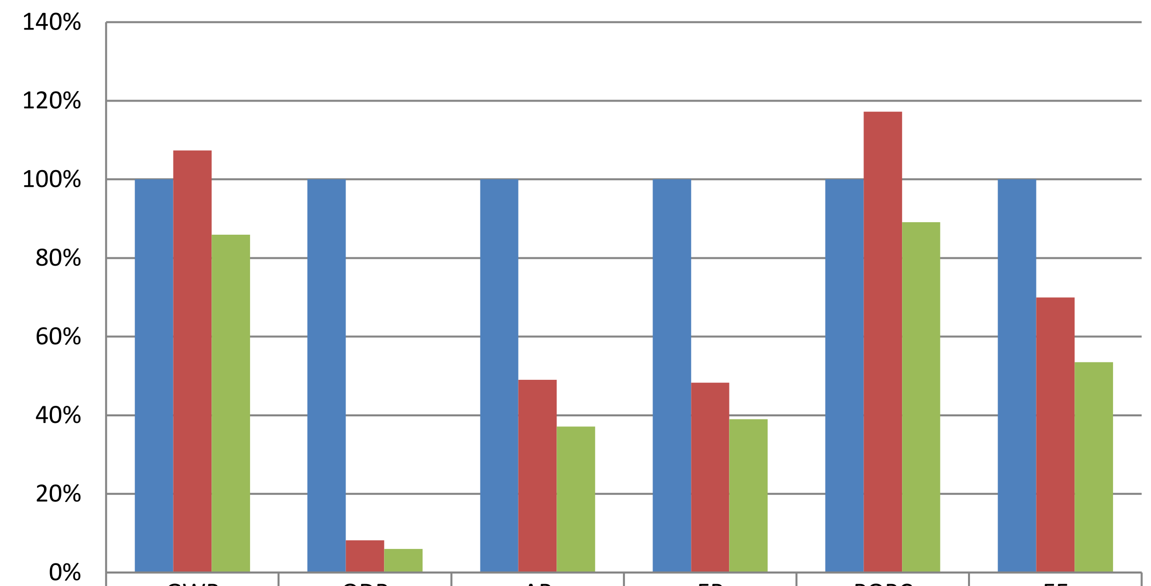
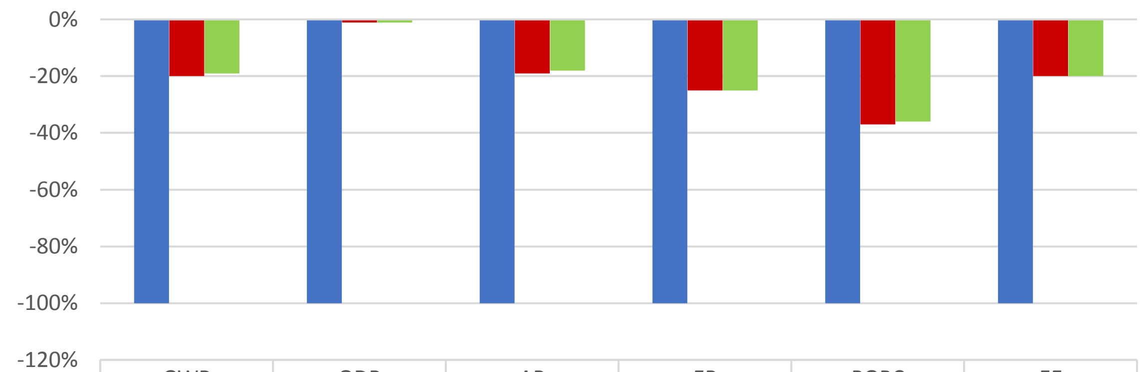


Figure 9: Normalized comparison of the life cycle environmental impacts of ELISSA case and Conventional cases.



	GWP	ODP	AP	EP	POPC	EE
ELISSA	100%	100%	100%	100%	100%	100%
CONV1	107%	8%	49%	48%	117%	70%
CONV2	86%	6%	37%	39%	89%	54%

Figure 10: Normalized comparison of the Production stage environmental impacts of ELISSA case and Conventional cases.



	GWP	ODP	AP	EP	POPC	EE
ELISSSA	-100%	-100%	-100%	-100%	-100%	-100%
CONV1	-20%	-1,12%	-19%	-25%	-37%	-20%
CONV2	-19%	-1,05%	-18%	-25%	-36%	-20%

Figure 11: Normalized comparison of the EoL environmental impacts of ELISSA case and Conventional cases.

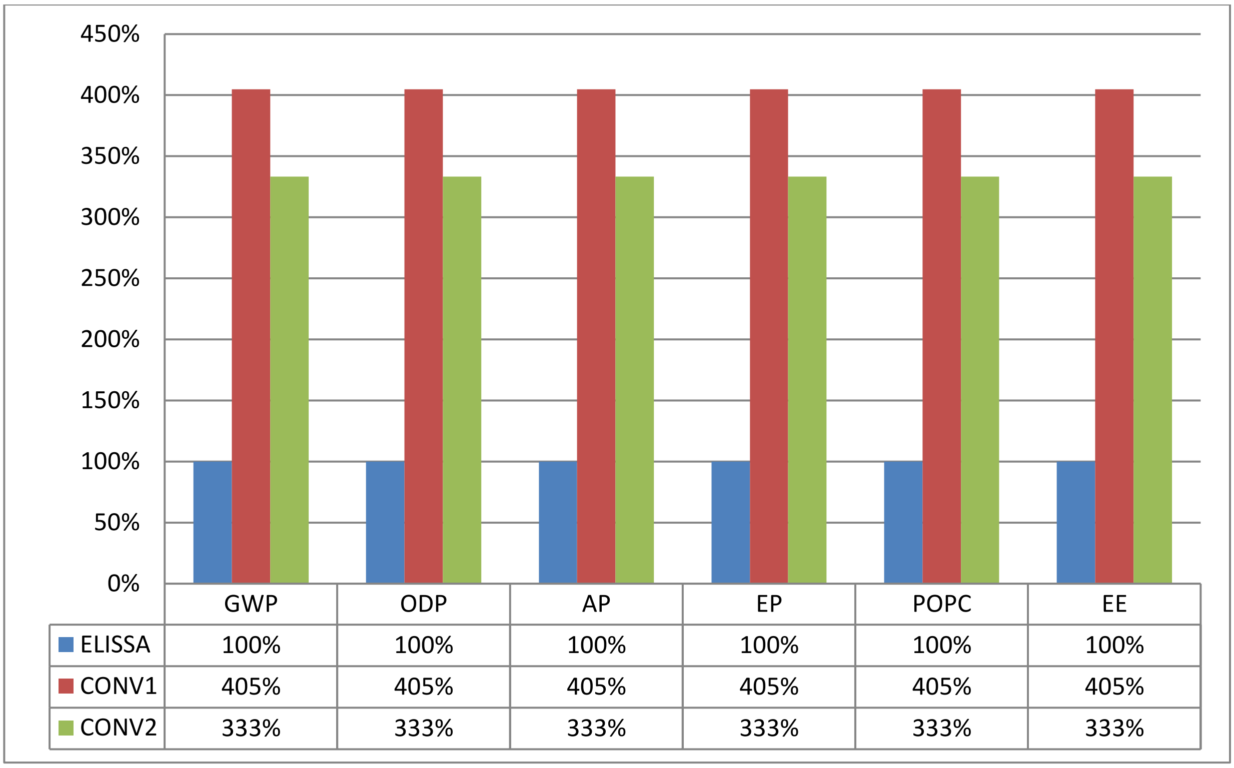


Figure 12: Normalized comparison of the total Transportation environmental impacts of ELISSA case and Conventional cases.

7. Interpretation and conclusions

This study investigates the life cycle environmental impacts of ELISSA panel comparing to two conventional cases implemented in Europe. The assessment was referred to an equivalent square meter of wall panel in which both loadbearing and non-loadbearing structure elements are included.

The study sought to compare the environmental impacts of ELISSA wall case as an alternative of the conventional cases across Europe, focusing on the production phase impacts as well as the burdens or credits associated with the end-of-life waste treatment. The specific characteristics related to the construction method (particularly prefabrication method) were also taken into consideration. The ELISSA panel is characterized as prefabricated lightweight drywall system incorporating Vacuum Insulation Panels and Mineral wool as thermal insulation. On the other hand, conventional wall panels CONV1 and CONV2 are typical heavy constructed brick walls which incorporate reinforced concrete as their loadbearing structure and Mineral wool as thermal insulation.

7.1. Comparing the alternative cases

From a life cycle perspective, the results show an unambiguous superiority of ELISSA panel regarding the Global Warming Potential index in comparison to the CONV1 and CONV2 panels. According to Figure 9 the CONV1 and CONV2 panels emit approximately 96% and 54% more greenhouse gases (GHG) than the ELISSA case. Given that the GHG emissions level owing to the ELISSA production stage (Figure 10) ranges roughly at the same level with the alternative cases (CONV1 emits 7% more CO_2 whereas CONV2 14% less than ELISSA), this fact is due to the high recyclability of the ELISSA building materials whose treatment provides considerable credits at the end of its service life. In more detail, the benefits of recycling at the ELISSA wall case are 5 times greater than CONV1 and CONV2. However, it has to be noted that as far as the GHG emissions are concerned, waste treatment approaches utilized in the context of this study reduce the total CO_2 equivalent emissions of all cases in some extend. Additionally, the transportation burdens, which slightly affect the outcomes, are significantly higher in the Conventional panels due to their weight in comparison to the ELISSA panel (Figure 12). CONV1 and CONV2 weighs approximately 3,4 to 4,2 times more than the ELISSA panel which increases the total transportation burdens in the same degree. The additional transportation process from the off-site prefabrication plant to the construction site has no change in the results.

When it comes to Ozone Depletion impact category (ODP), ELISSA panel is definitely the most violent case for the Ozone layer. It accounts for 0.000085 kg CFC-11 equivalent comparing to the CONV1 and CONV2 cases which account for 0.0000095 kg CFC-11 equivalent and 0.0000070 kg CFC-11 equivalent respectively, or in terms of percentage the conventional cases emit 11% and 8% of the ELISSA's gaseous emissions respectively. The increased chlorofluorocarbons emissions of ELISSA panel are attributed mostly to the intumescent paint for enhancing the fire resistance of COCOON steel structure although its quantity is relatively small comparing to the mass of the wall (its mass accounts for a mere 0.86% the mass of the ELISSA wall).

Additionally, ELISSA panel is inferior to CONV1 and CONV2 panel both regarding acidification and eutrophication indices. The conventional cases score 73% and 54% comparing to the ELISSA panel in terms of AP index and 70% and 53% comparing to the ELISSA panel in terms of EP index respectively. The main contributor of the increased impacts in both indices seems to be the galvanized steel portion of ELISSA wall being responsible for the 58% of AP related emissions and the 61% of EP related emissions. However, the EoL approaches implemented in the ELISSA case provide a notable net benefit of 0.218kg SO_seq (roughly 35% of the production stage related impacts) regarding the AP index and 0.0978kg PO_4 eq(roughly 40% of the production stage related impacts) regarding the EP index.

On the contrary to the AP and EP indices, ELISSA panel performs better than the conventional panels regarding the photochemical oxidation index. In particular, the emissions related to POPC are increased by 79% and 33% vis-à-vis ELISSA ones for CONV1 and CONV2 respectively. The vast majority of the emissions are related to the production phase during which CONV1 panel emits 0.083kg C_2H_4 equivalent whereas the CONV2 and ELISSA panels emit 0.063 and 0.071kg C_2H_4 eq respectively. The transportation process seems to have a considerable influence in the final results of the conventional cases since the total burden as a percentage of their life cycle impact ranges between 13 and 14% far greater than the transportation burden associated with the ELISSA case which accounts for 6%.

Finally, as far as the Embodied Energy index is concerned, ELISSA panel is better than CONV1 but worse than CONV2. Particularly, CONV1 wall embodied energy is roughly 10% more than ELISSA wall whereas CONV2 is 18% less in life cycle point of view. The production of ELISSA building materials accounts for 2032 MJ of primary energy comparing to the CONV1 and CONV2 which account for 1422 MJ and 1088 MJ respectively. These noticeable differences in the magnitude of EE between the wall cases are eliminated at the EoL stage due to the high recycling rate and the benefits of the afterwards use of the recycled materials. EoL treatment of provides 818 MJ net reduction whereas in the CONV1 and CONV2 cases the associated reduction is barely 165MJ and 160MJ respectively. The high energy demands of ELISSA panel are attributed to the production of VIP and Hot-dip Galvanized Steel sections as the aforementioned materials are characterized as energy-intensive ones.

It must be noted that this study does not take into account the operational energy due to the thermal characteristics of each wall case since the Use phase is considered out of the scope of the analysis. The operational energy demands for heating and cooling are directly proportional to the U_{value} of each wall case. According to [41] the U_{value} of the ELISSA panel is 0.14W/m^{2}K, the U_{value} of the CONV1 panel ranges between 0.14 and 0.16W/m^{2}K and the U_{value} of the CONV2 panel ranges between 0.35 and 0.42 W/m^{2}K. Thus, it is obvious that the ELISSA panel has an additional advantage comparing to the conventional cases which may be significant considering the accumulated annual demands over the 50 years of the projected lifetime.

7.2. Comparing the construction methods

In order to compare the two construction methods, prefabrication and conventional construction, an additional calculation of the environmental impacts of ELISSA panel was conducted as if it was constructed on site. For that purpose, any reduction of construction waste was eliminated hence it was assumed that the construction waste proportion of ELISSA case is that depicted in Table 12 for each building material. Also the transportation route was assumed the same as CONV1 and CONV2 panels. The results are illustrated in Table 21.

Table 21: Comparison between Prefabrication and Conventional construction method. The life cycle impacts belong to the ELISSA wall

Impact category	Unit	Prefabrication	Conventional const method	Reduction due to prefabr.
GWP	kg CO_2 eq.	62.02	64.17	3.3%
ODP	kg CFC-11 eq	0.0001	0.0001	5.6%
AP	kg SO_2 eq	0.4129	0.4266	3.2%
EP	kg PO_4--eq	0.1472	0.1520	3.2%
POPC	kg C_2H_4	0.0466	0.0482	3.1%
EE	MJ Primary	1242.31	1286.45	3.4%

The reduction of life cycle impacts owing to the implementation of prefabrication as construction method is presented in Table 21. This reduction seems relatively small but it is consistent with literature [56,68]. The small reduction may be due to the lower level of prefabrication which fact could be changed if a higher degree of prefabrication was implemented.

7.3. Production phase related impacts

Focusing on the production phase of each wall panel, Figure 13 and Figure 14 illustrate the GHG emissions and the associated primary energy demands. It is obvious that the production of the materials that constitute the ELISSA panel emits less greenhouse gases comparing the CONV1 panel but more than CONV2 panel. On the contrary, ELISSA requires significantly more primary energy than the conventional cases at this phase. This is because of two specific materials: the hot-dip galvanized steel and the VIP panels.

To begin with, steel structure is the main contributor to ELISSA production impacts. It accounts for 42% of the GHG emissions and 38% of the primary energy requirements related to the production phase of ELISSA panel. It is well known that steel industry is a highly energy-intensive one[69]. Also the primary production route provokes higher related impacts as virgin iron is used to produce the semi-finished steel slab. According to [70] the impacts in question can be reduced if virgin iron is substituted with steel scrap so applying the primary production route (Basic Oxygen Furnace route) in this study, the total impacts related to GWP and EE are increased.

Moreover, the steel structure is made of hot-dip galvanized steel the zinc coating process of which exacerbates the outcome. According to the previous study, the reasons why the impacts related to hot-dip galvanized steel are so high are the inputs of steel, energy and zinc.

VIP panels are the second most influential material contributing roughly 25% in both GHG emissions and primary energy requirements. The manufacturers claim that 95-99% of all impacts are owed to the production of the core material [48]. The GHG and EE impact of VIP are much greater of those of mineral wool which is in line with Schonhardt et al. [49] who contend that the EE impact of VIPs is about the double of that of mineral wool.

On the other hand, the highest proportion of GHG emissions as well as the EE in conventional cases belongs to vertically perforated clay units. That is because their amount (268kg and 183kg for CONV1 and CONV2 respectively) is almost half of the total wall mass in each case. The concrete structure contributes to 30% of GHG emissions in terms of CONV1 panel and 38% in terms of CONV2 panel, whilst as far as the EE index is concerned it contributes to 28 and 36% respectively. However, the amount of reinforced concrete is strongly depended on the specification of the building so its relative contribution in a square meter of a wall panel may differ significantly. In this study, the amount of the incorporated reinforced concrete is based on estimations.

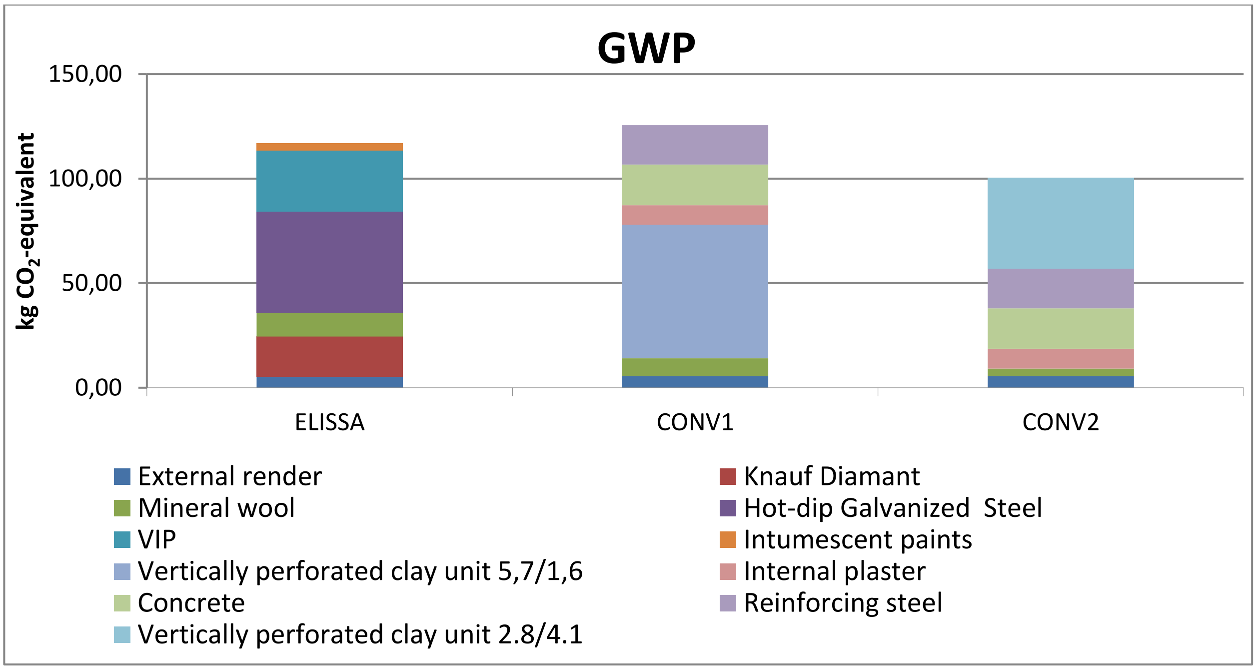


Figure 13: GHG emissions during production phase

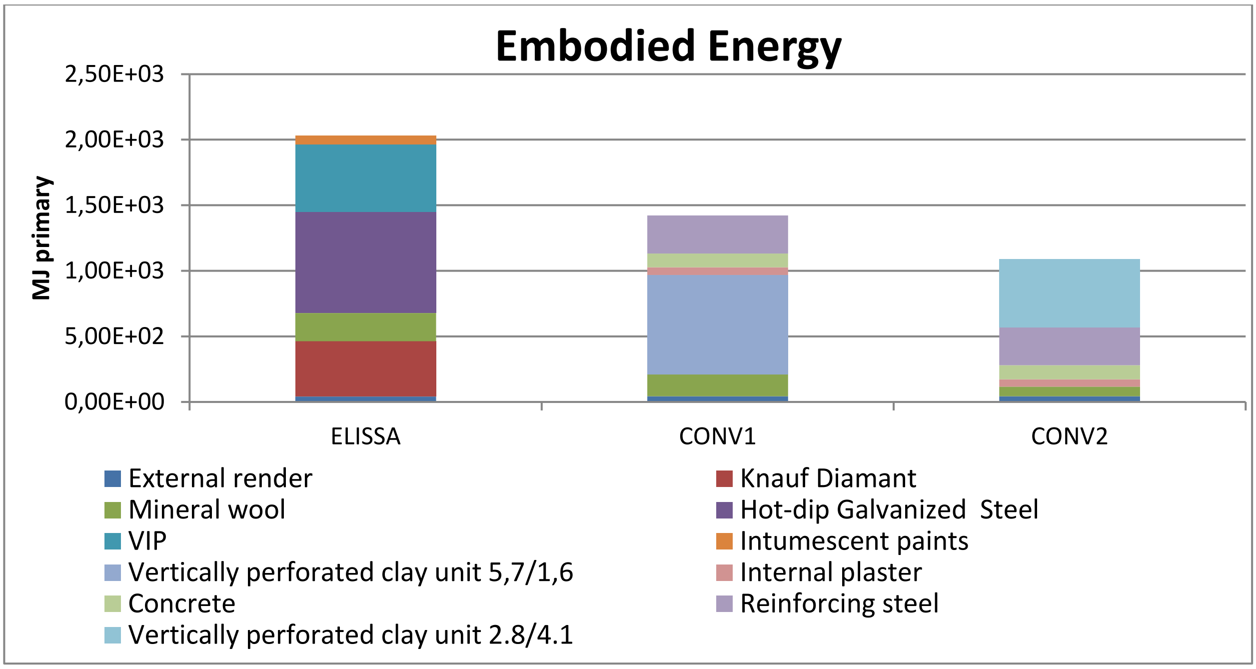


Figure 14: Primary energy requirements of the production phase

7.4. Transportation related impacts

As it has been already mentioned, the burdens arisen from the transportation of building materials from the manufacturing plant to the construction site and the afterwards transportation of waste material to the disposal facilities are by far greater at the Conventional cases than the ELISSA case. Indeed, this difference is as high as 405% in the case of CONV1 and 333% in the case of CONV2 panel according to Figure 12. This is explained by the mass of each examined case. CONV1 panel weighs 504.21kg/m^2, CONV2 415.24kg/m^2 and ELLISA panel weighs barely 121.27kg/m^2 taking also into consideration the construction wastage of each case. Given that the transportation burdens are directly proportional to the mass of the freight (the transportation process is expressed in ton-kilometers which means the transport of 1 ton over 1km or 1kg over 1000km), the results are reasonable. It must be noted that the transportation distances are based on estimations which may differ significantly from case to case burdening even more the impacts related to the materials with high amount of mass.

7.5. End-of-Life related impacts

According to Figure 15 and Figure 16, which illustrate the score of each case towards the GWP and EE indices at the EoL phase, it is concluded that the waste treatment approaches of all cases provide a net credit in their life cycle impacts but ELISSA panel is undoubtedly superior to the conventional cases. In particular to the latter, the recycling of waste VIP panels can provide a reduction equal to 24% in terms of GHG emissions and 25% in terms of primary energy demand related to the production phase of the wall. Similarly, the recycling of the steel portion of the wall reduces the production phase related impacts by 17% regarding the GHG emissions and 13% regarding primary energy demand. The recycling of gypsum board panels provides also a quite significant reduction of 7% regarding the GHG emissions and 0.1% of the EE. The high recyclability of building materials employed in the ELISSA case can compensate for the production phase related impacts in some extend. The aforementioned building materials (VIP panels and galvanized steel) can contribute to the production of new products substituting virgin materials. On the one hand VIP core can be collected and recycled into new VIP panels by avoiding the production of silicon carbide, fumed silica and cellulose fiber [66]. On the other hand, galvanized steel can be recycled through EAF route to produce new semi-finished steel products like ingots and slabs.

Regarding the conventional cases, the vast majority of building materials are disposed as infilling materials avoiding the production of virgin aggregates such as gravel. However, this approach has little impact on the reduction of the total life cycle burdens. On the contrary, the recycling of reinforcing steel bars shows a significant reduction accounting for 8 and 10% in terms of production phase GHG emissions and 9 and 12% in terms of production phase EE for CONV1 and CONV2 respectively. In this study the benefits of carbonation attributed to concrete and concrete based mortars were not considered due to the exclusion of use phase in which the majority of CO_2 reabsorption is occurred [71,72] .

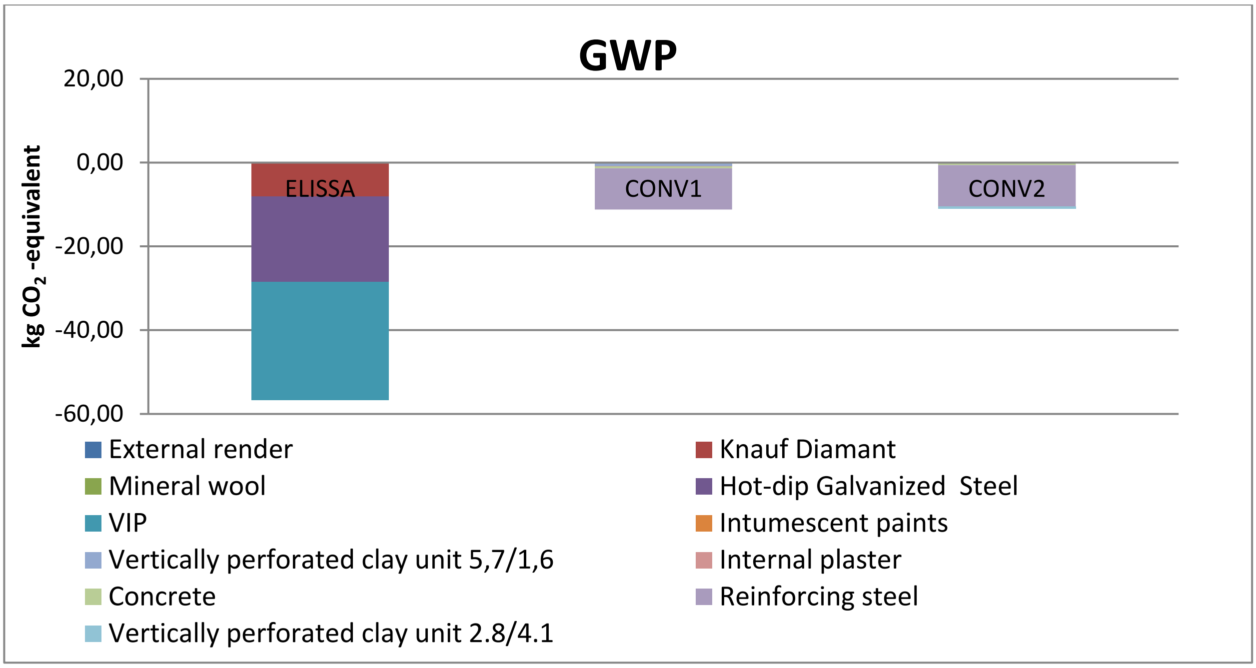


Figure 15: Burdens/Credits related to GWP at the EoL phase

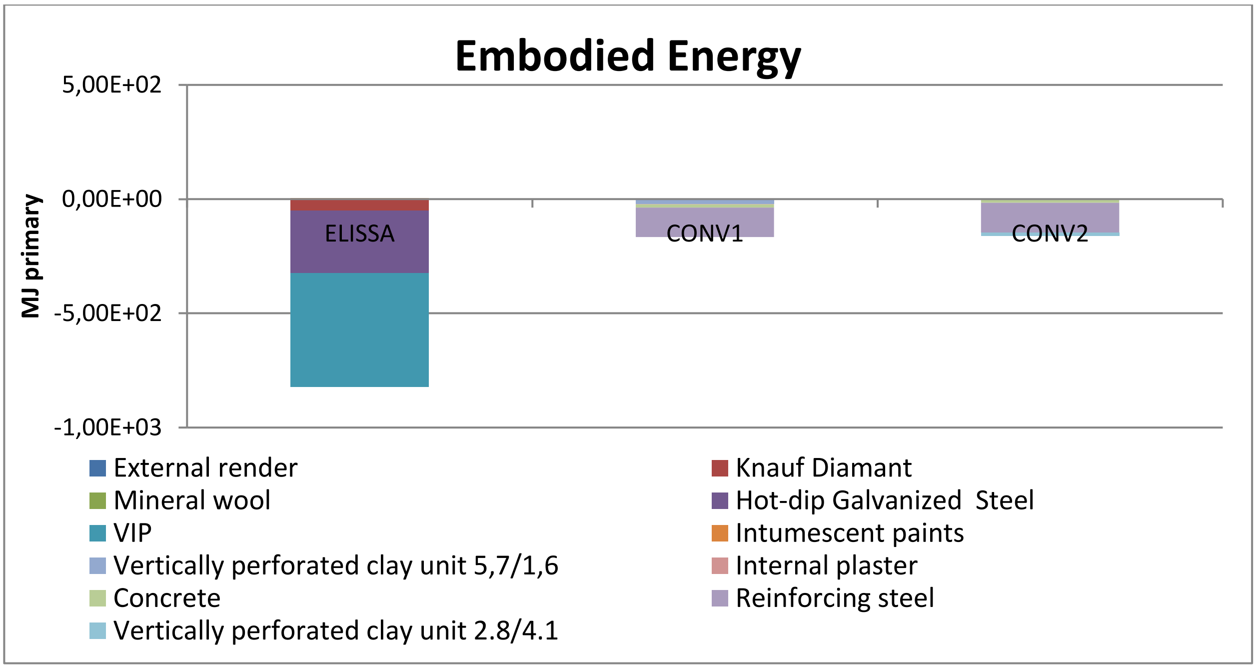


Figure 16: Burdens/Credits related to the EE at the EoL phase

8. Life Cycle Costing

The life cycle analysis is complemented by a life cycle cost analysis. In order to compare the different alternatives, a derived indicator consisting of net present cost of all relevant life cycle costs is calculated. The LCC analysis encompasses the total cost of the external walls of a residential building and the annual cost of energy for maintaining the appropriate indoor environment. The total net present cost refers to 50 years of building operation and it is defined as €/m^2 of net building area (standardized Method of Life Cycle Costing for Construction Procurement ISO15686, 2008, Chapter 5 metrics).

The life cycle costing is divided into the construction and the use phase assessment. In the construction the initial investment cost is calculated. This cost includes the raw material extraction phase, the manufacturing phase, the intermediate transportations and the installation of the product in site. In the use phase assessment, the energy consumption was estimated along with the annual cost of energy. Additional economic factors were applied based on subjective estimations and literature data.

For each wall panel, the net present value of overall life cycle cost is computed over 50 years. The equation of calculating NPV is presented below:

$$NPV_p = \sum_{0}^{50} \frac{(\Delta Capex_y + ES_y)x(1 + CPI)^y}{(1 + r)^y}$$

where NPV_p is the net present value of panel P over 50 years of lifespan in EURO; y is a specific year, $\Delta Capex_y$ is the capital expenditure in year y or the investment for the considered wall panel on the specific year y in EURO; ES_y is the energy consumption for heating and cooling (the operating costs of the building) for the considered case which has been allocated to the aforementioned functional unit in year y, in EURO, CPI is the considered inflation rate 2.01% which is computed as the average of the consumer price index (CPI) from 1991 until 2016 in the Euro area [73] and r is the discount rate.

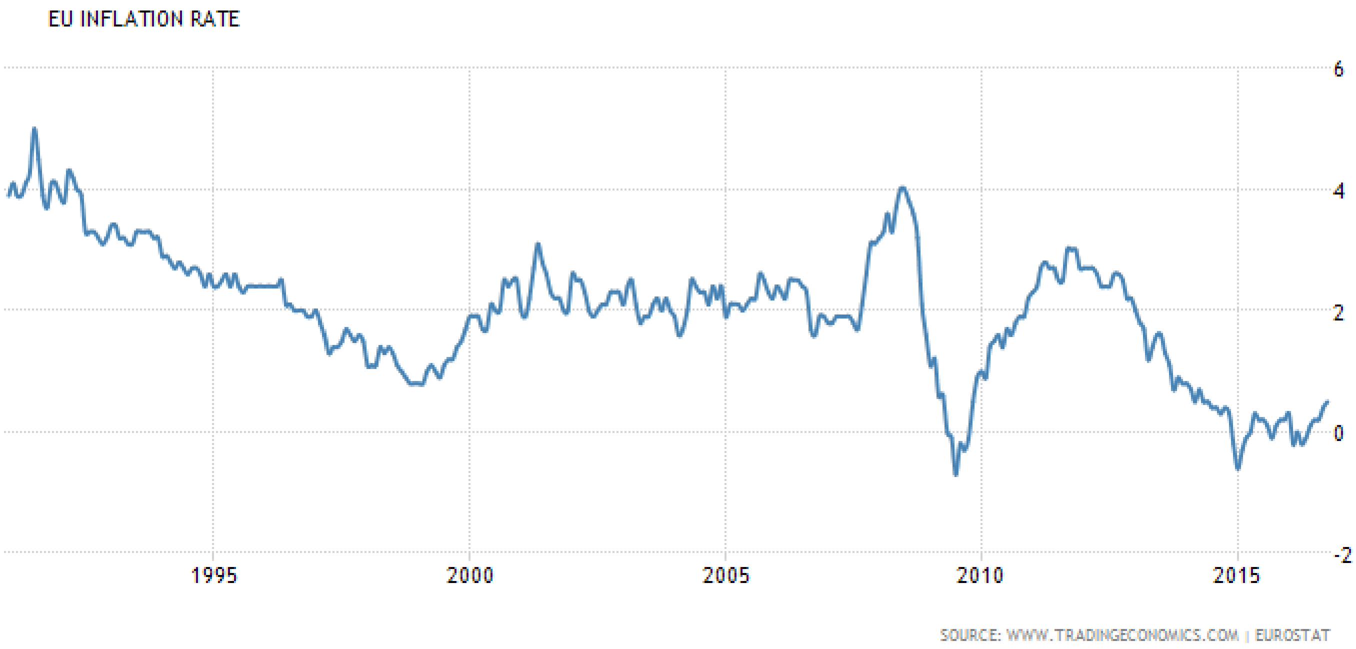


Figure 17: Inflation rate in Europe.

8.1. Discount rate calculation

The discount rate is a rate that reflects an investor's opportunity cost of money over time, meaning that an investor wants to achieve a return at least as high as that of his next best investment. Hence, the discount rate represents the investor's minimum acceptable rate of return. It is calculated using the Capital Asset Pricing Model (CAPM) as it has been analyzed by Berk and DeMarzo[74]. According to this model, the expected return on any investment should come from two components:

1. A baseline risk-free of return that we would demand to compensate for inflation and the time value of money, even if there were no risk of losing our money.
2. A risk premium that varies with the amount of systematic risk in the investment.

Under the CAPM assumptions, the discount rate can be computed using the following equation:

$$r = r_E \frac{E}{E + D} + r_D \frac{D}{E + D}(1 - \tau_D)$$

Where r is the discount rate; r_E is the cost of equity; r_D is the cost of debt; E is the projected equity value; D is the projected debt value and τ_D is the effective tax rate.

The cost of equity (r_E) can be computed also using the CAPM model:

$$r_E = r_f + \beta(r_M - r_f)$$

where r_f is the risk free rate of return; r_M is the market return; and β (beta) is the investment risk premium compared to the market.

The values of the economic factors that used at the aforementioned equations vary significantly from country to country. Even among the countries of the European Union the outcomes of the equations could considerably differ, thus the analysis should be specified to a country or countries with the same economic performance. In this study, average European values were taken into account. Hence, the risk free rate of return was taken as the mean spot yield on 10 year Germany government bond extended from 1981 to 2016. According to [75] the risk free rate is approximately equal to 5.5%. Additionally, the systematic risk of the investment, expressed by β (beta) factor, was taken equal to 0.87 as the beta for the European Real Estate (Development) Sector [76]. The market risk premium or equity risk premium is a quantitative measure of the additional return demanded by market participants for increased risk. It is assumed equal to 8% as the mean value of the five biggest European countries in terms of population (Germany, France, Spain, Italy and United Kingdom)[76].

Based on the CAPM model and the values of the economic factors, the cost of equity (r_E) is equal to 12,5%.

The tax rate in Euro zone for corporate income is assumed as 28.92% the mean value of the corporate income tax rate from 1995 until 2015[77].

The average corporate cost of borrowing (r_D) in Euro area from 2003 until 2016 is assumed 4%. For further information see [78].

The proportion of debt and equity (E and D) in real estate sector in Europe was difficult to be found. Thus it is assumed that 50 % of the investment was made by private capital and the other 50% by corporate loan.

In light of the above values, the CAPM model generates a discount rate value (r) of 7.67%.

8.2. Selected wall panels

As described in the LCA analysis the wall panels under study are the innovative ELISSA wall panel, the Conventional panel (CONV1) and the Conventional panel (CONV2) which are applied in North/Central and South Europe respectively. In this session the economic characteristics are reported regarding the cost of ownership of building materials and the average cost of the construction and installation process. All the data were derived from various stakeholders and market research.

Table 22: Cost per area of ELISSA wall panel.

ELISSA wall			
U – value [W/m²K]	Total thickness [mm]	Weight per area [kg/m²]	Cost per area (€/m²)
0.14	295	109	169.58
Materials	Density [kg/m³]	Thermal conductivity $\lambda_{10,dry}$ [W/mK]	Cost (€/m²)
External render	1800	0.89	7.52
Diamant board	1030	0.3	26
Mineral wool	50	0.035	24.52
Vacuum insulation panel	220	0.007	40
Steel stud Cocoon KNAUF CW	7800	60.5	22 3.43
Installation cost			46.11

Table 23: Cost per area of CONV1 brick wall panel.

Brick wall – Central/North Europe (CONV1)			
U – value [W/m²K]	Total thickness [mm]	Weight per area [kg/m²]	Cost per area (€/m²)
0.14 – 0.16	530	312 - 452	135.53
Materials	Density [kg/m³]	Thermal conductivity $\lambda_{10,dry}$ [W/mK]	Cost (€/m²)
External render	1800	0.89	7.52
Mineral wool	50	0.035	18
Vertically perforated clay unit 5,7/1,6	750-1150	0.14-0.19	22.89
Internal plaster	1000	0.39	5.68
Reinforced Concrete			14.4[12]
Installation cost			77.04

[12] Concrete's density is estimated 2380 kg/m3. In order to calculate the load bearing structure of the conventional cases, the 5.34 m² AW002 façade of ELISSA panel is taken as a reference. Assuming that 24% [4] of the referenced wall area is covered by 30 cm thick reinforced concrete, the overall volume of the concrete structure is 0.39m³ or 0.072m3/m². The reinforcing steel content is estimated to be 4.5% of concrete mass. The total cost of materials and the installation is 200€/m³ of reinforced concrete.

Table 24: Cost per area of CONV2 brick wall panel.

Brick wall – South Europe (CONV2)				
U – value [W/m²K]	Total thickness [mm]		Weight per area [kg/m²]	Cost per area (€/m²)
0.35 – 0.42	295		213 - 332	99.68
Materials	Density [kg/m³]	Thermal conductivity $\lambda_{10,dry}$ [W/mK]		Cost (€/m²)
External render	1800	0.89		7.52
Mineral wool	50	0.035		6.52
Vertically perforated clay unit 2.8/4.1	840-1435	0.22-0.45		15.26
Internal plaster	1000	0.39		5.68
Reinforced Concrete				14.4
Installation cost				50.3

The values above represent the Capital expenses (CAPEX) of the investments. In addition, the Operational expenses (OPEX) throughout the 50 years of life span have to be added. The OPEX encompass only the annual cost of energy required to maintain the appropriate temperature inside the house, while the cost of maintenance is assumed to be negligible.

The cost of heating and cooling is considered a significant annual expense which should be taken into account in the LCC analysis. In order to calculate the annual energy consumption, a 100m² residential building (apartment) was considered and it is depicted in Figure 18. The annual energy loads for heating and cooling were calculated by TRNSYS and they are considered constant over the 50 years of study. It is assumed that the annual loads are covered by air-to-air heat pumps, which are electrical operated devises, so the final consumption of energy is in the form of electricity.

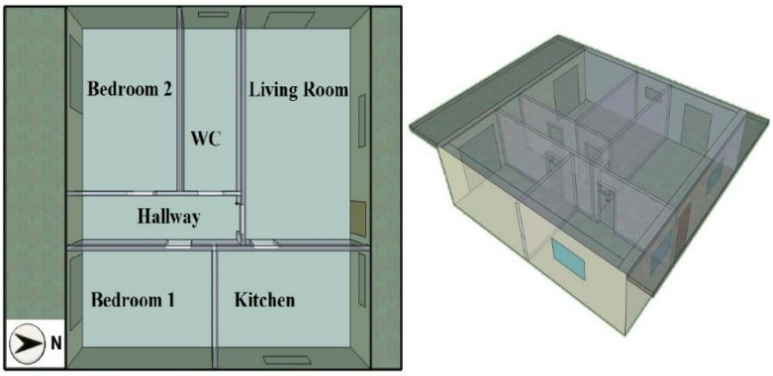


Figure 18: The design of the investigated apartment.

Building Characteristics

Type of building	Residential building (apartment)
Place	Geneva
Net Building area	100 m^2
Opaque area	96 m^2
Transparent area	18 m^2
Electricity consumption (CONV1)	4943 kWh
Electricity consumption (CONV2)	5996 kWh
Electricity consumption (ELISSA)	4920 kWh

The price of energy in the EU depends on a range of different supply and demand conditions, including the geopolitical situation, import diversification, network costs, environmental protection costs, severe weather conditions, or levels of excise and taxation. In Figure **19** the evolution of electricity prices of EU-28 is illustrated. The average price of electricity in Europe is currently 0.219 EUR/kWh with a growing propensity [80]. It is assumed that it is increased according to the inflation rate.

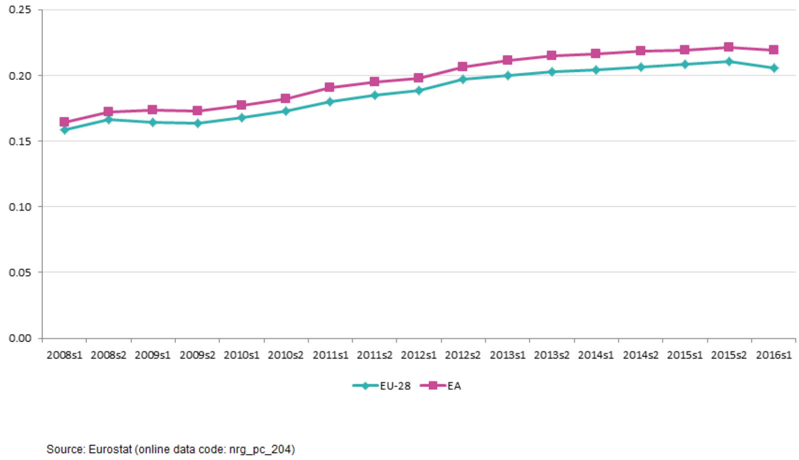


Figure 19: Evolution of EU-28 and EA electricity prices for household consumers.

The value of the waste at the end of life stage is difficult to be estimated due to the long life duration of the walls, hence in the current study, it is excluded from the analysis.

8.3. Conclusions

The life cycle costing analysis of the wall systems was examined over the 50 years of their projected lifespan in which both capital expenses (in the form of initial cost of building materials and construction process) and operational expenses (in the form of annual cost of energy) were included. The cost of demolition/deconstruction as well as the residual value of building materials of the building at the end of its life was not taken into account. According to the average European data and the predictions explained above, the calculations concluded to the following diagrams:

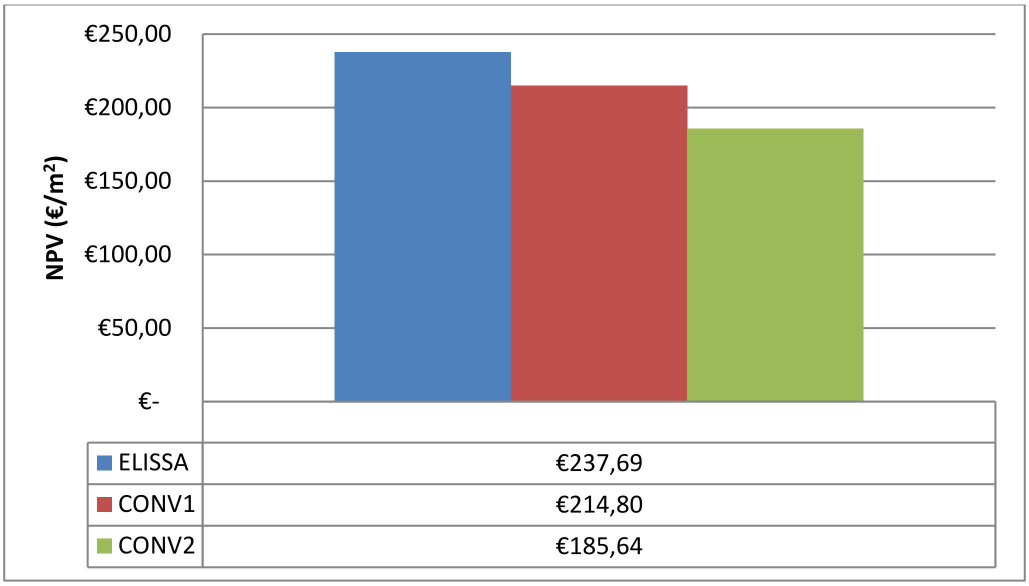


Figure 20: Life cycle cost of each case.

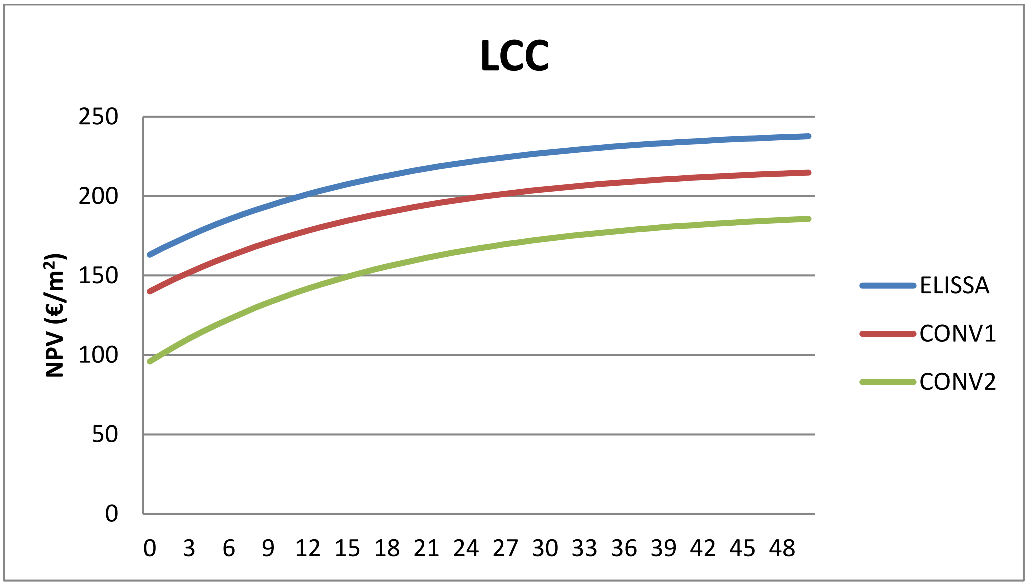


Figure 21: Cumulative life cycle cost.

The results show clearly that the life cycle cost of the ELISSA case is greater than the cost of both conventional ones. This is particularly due to the higher initial cost of the wall, as the ELISSA wall is 17% more expensive than CONV1 and 70% than CONV2. The low thermal conductivity of the ELISSA wall, as a result of the implementation of the innovative insulation materials, provides a significant energy saving over the 50 years of building operation. However, it seems that it is not enough and the LCC equivalent of ELISSA case scores 11% greater than CONV1 case and 28% greater than CONV2 case.

As far as the building operation, Figure 22 depicts the cumulative cost of energy for each wall case. It is concluded that 50year cost of energy is greater in CONV2 wall whereas ELISSA and CONV1 perform almost the same operational expenses.

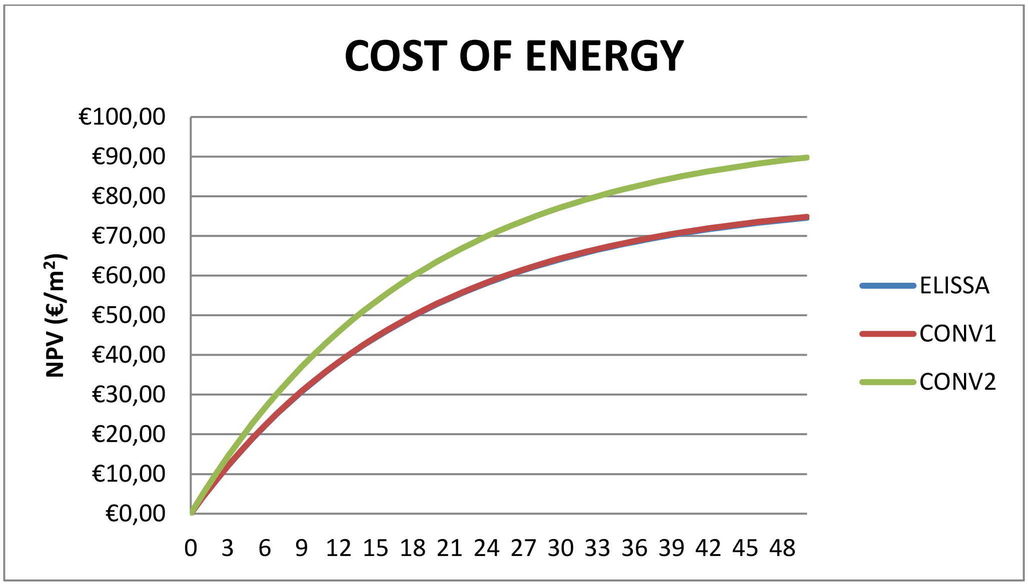


Figure 22: Cumulative cost of energy.

The aforementioned results are susceptible to changes in discount rate and electricity prices. In the current study it is assumed a discount rate of 7,67% and an annual increase in electricity price equal to the inflation rate. However, these factors include subjective assumptions which may mislead the choice of a potential investor as they have great impact on the present value and LCC will affect the optimal solution. For instance, the electricity prices were increased up to 45% between 2006 and 2013 which is equal to a 5,45% annual rate. Also some LCC studies use a discount rate equal to 5% or less. Finally, the geographic location is another significant factor which affects the outcomes by changing the annual heating and cooling loads. By changing these factors, the ELISSA wall becomes the cost-optimum choice due to the fact that its benefit lies in the lower operational energy needs throughout the 50 years of service life.

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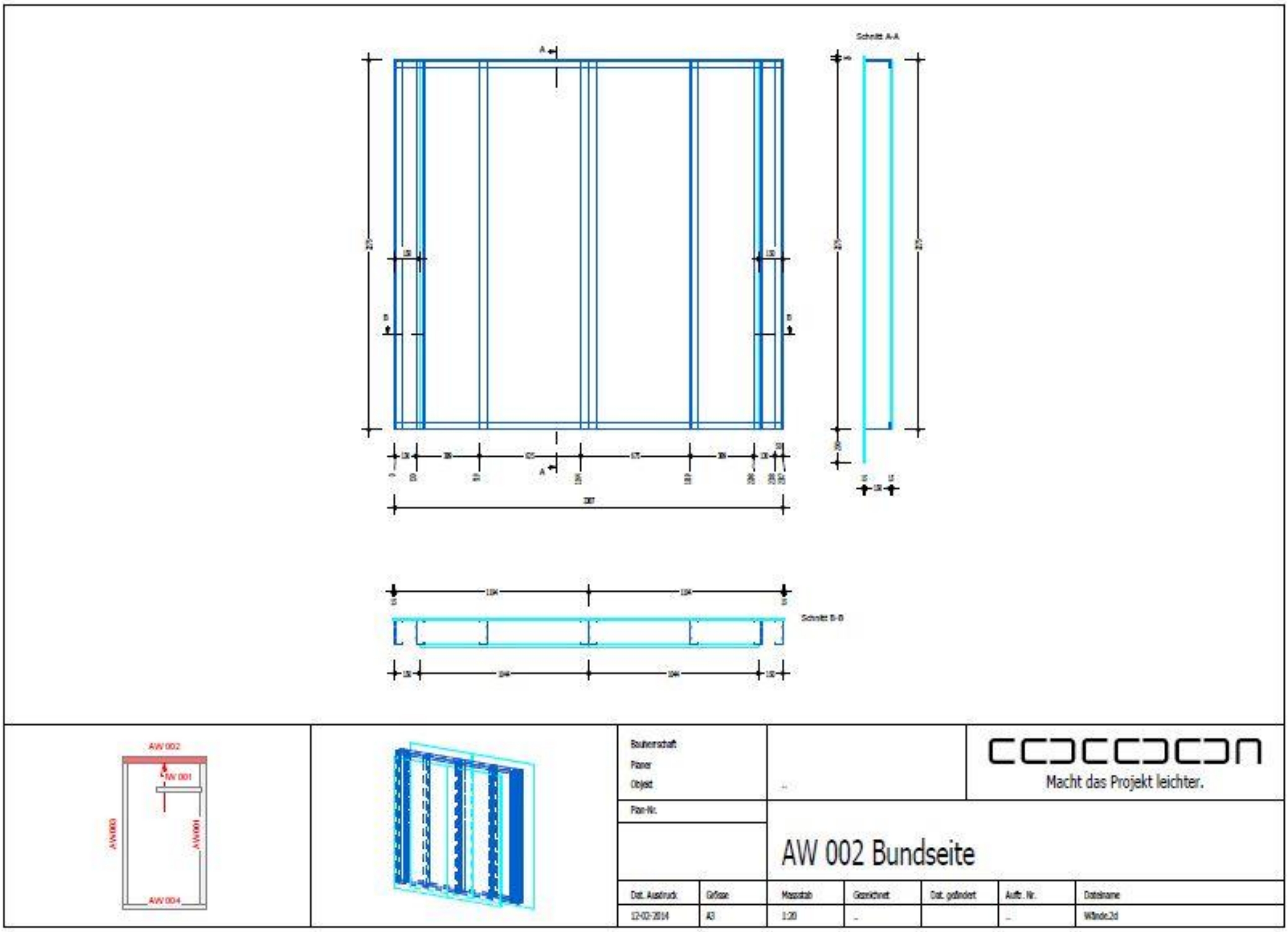
10. ANNEX 1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Schnitt B-B
AW 002
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Bauherrschaft
Planer
Objekt
Plan-Nr.
Macht das Projekt leichter.
AW 002 Bundseite
Dat. Ausdruck
Grösse
Massstab
Gezeichnet
Dat. geändert
Auftr. Nr.
Dateiname
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