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A guideline for material comparisons using LCA

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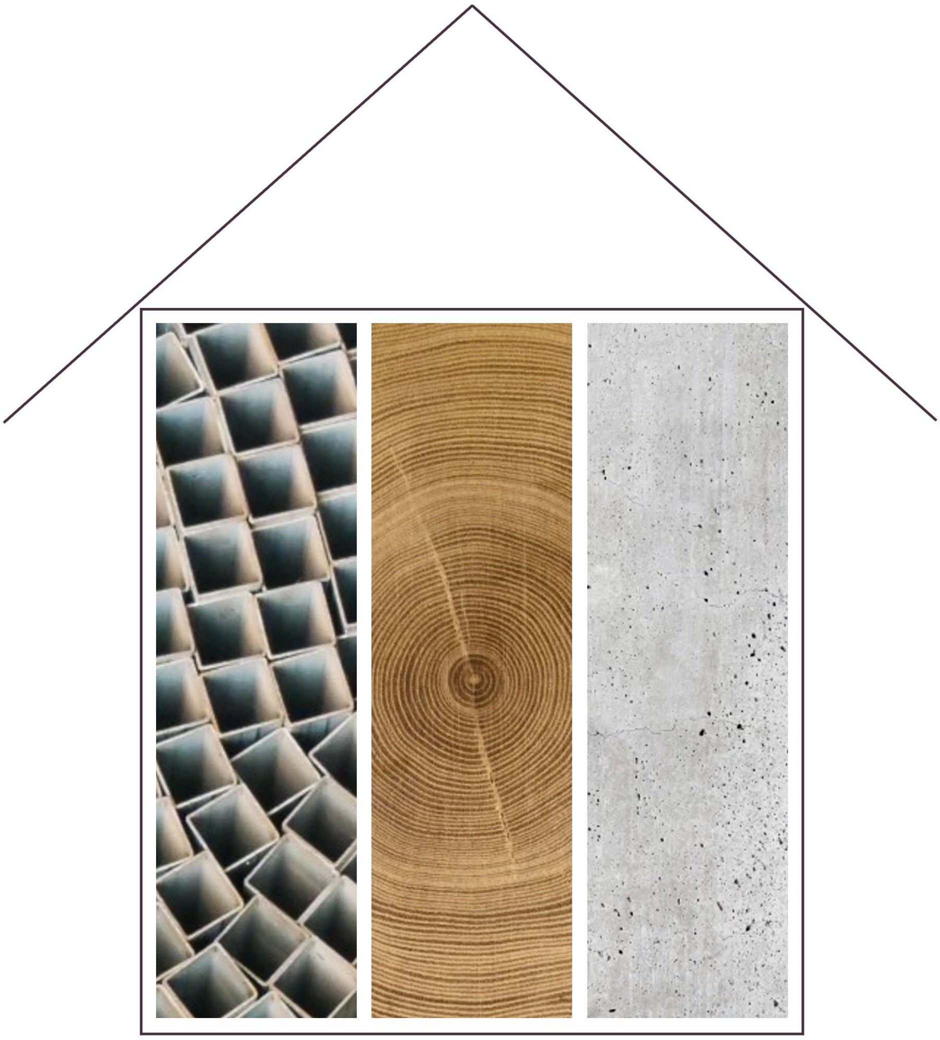

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A guideline for material comparisons using LCA

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SAMMENDRAG/SUMMARY:

Materialer som blir brukt i bygg og anlegg har en betydelig miljøpåvirkning, og denne effekten blir stadig mer tydelig ettersom energibehovet til bygninger fortsetter å synke. Det blir derfor stadig mer viktig å ta hensyn til miljøbelastningene knyttet til byggematerialer. Livsløpsvurderinger (LCA) og miljødeklarasjoner (EPD) er nyttige verktøy for dette formålet. Når man sammenligner resultatene fra flere LCA-studier av ulike byggematerialer, er ofte det vanligste spørsmålet: "Hvilket materiale er bedre for miljøet?". Svaret er imidlertid vanligvis ikke så enkelt – men hvorfor er det så vanskelig å avgjøre hvilket materiale som har lavest miljøpåvirkning? For å svare på dette må vi vurdere hva livssyklusanalyser er og hvordan en LCA blir utført. Rapporten dekker ulike faser av en LCA, fra å definere mål og omfanget av studien, til å skape livsløpsopplysninger (LCI), utføre livsløps konsekvensutredninger (LCIA), og rapporteringen og tolkningen av resultatene. I tillegg går rapporten i detalj inn på hvordan man kan håndtere publiserte LCA-studier, hvordan man kan arbeide med EPD-er og spørsmålet om karbonlagring i bygninger. I det siste kapittelet sammenlignes publiserte studier som evaluerer miljøpåvirkningen av ulike byggematerialer.

The materials used in construction have a significant environmental impact and this is becoming more important as operational energy requirements continue to fall. It is therefore becoming increasingly important to take into account the environmental burdens associated with materials used in construction. Life cycle assessment (LCA) and Environmental Product Declarations (EPD) are useful tools for this purpose. When comparing the results of numerous LCA studies of different construction materials, the main question is often ‘Which material is better for the environment?’. The answer, however, is usually not as simple – but why is it so difficult to decide which material has the lowest environmental impact? To answer this question, we have to consider what life cycle assessment is and how an LCA is undertaken. The report covers the stages of an LCA, from defining the goal and scope of the respective study to the creation of the life cycle inventory (LCI), the life cycle impact assessment (LCIA) to the reporting and interpretation of the results. Additionally, the report goes in detail into how to approach published LCA studies, how to work with EPDs and the much-discussed issue of Carbon storage in buildings. In the final chapter, the report assesses the comparability of published studies evaluating the environmental impact of different building materials.

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Preface

This report focuses on life cycle assessments (LCA) and the challenges involved in comparing published studies on this topic. LCA plays a vital role in understanding the environmental impact of products, processes, and systems throughout their life cycle.

We are grateful to the Norwegian Ministry of Agriculture and Food for their financial support to enhance knowledge about LCA and how to interpret the results. We hope the report will provide guidance to decision-makers, industry professionals, researchers and everybody interested in the environmental impact of building materials on interpreting LCA results and addressing the challenges of comparing studies.

Ås, 10.08.2023

Callum Hill, Stephen Amiandamhen, Katrin Zimmer

Content

1 Introduction

1.1 Background

The materials used in construction have a significant environmental impact and this is becoming more important as operational energy requirements continue to fall. Within the European Union, buildings currently account for 40% of total energy use and 36% of total GHG (greenhouse gas) emissions (Ramírez-Villegas et al. 2019). The emissions from the building sector rose to 9.7 $GtCO_2$ in 2018, while the building construction emissions accounted for a further 11 $GtCO_2$ (Ruttenborg 2020). The construction and use of our built environment account for 39% of global greenhouse gas emissions (Crawford 2021). Consequently, there must be special attention to reducing the whole life cycle impacts associated with the built environment.

Currently, two main approaches are used in the construction industry to reduce environmental impacts: 1) appropriate material selection (up-front impacts) and 2) optimization of energy use throughout the building's service life (operational impacts) (Rinne et al. 2022). Based on the EU's ambition to reduce GHG emissions from the building sector, the need to improve the environmental profile of buildings and energy efficiency for new and existing buildings is necessary.

1.2 Aim of the report

LCA is a complicated tool and material decisions based on LCA must be made with great caution and awareness of how an LCA is performed.

Therefore, our goal with this report is to go into the structure of an LCA and explain how to approach published LCAs and EPDs. The report will also discuss the potential for using the built environment for carbon storage. Finally, there will be an appraisal of the comparability of different published LCAs.

2 Structure of an LCA

When comparing the results of numerous life cycle assessment (LCA) studies of different construction materials, the first question that nearly everyone asks is ‘which material is better for the environment’. Unfortunately, even such a simple question does not appear to have a simple answer and the result is, often confusion. One study shows that this material is better, and another study says the opposite!

Why is it so difficult to decide which material has the lowest environmental impact?

In order to answer this question, we have to consider what life cycle assessment is and how an LCA is undertaken. Unfortunately, LCA is complicated, and it is not possible to give a simple description of the subject without over-simplifying.

Life cycle assessment is a tool which is used to determine the environmental impacts associated with a product (good) or process (service).

Conducting an LCA involves four well-defined stages:

- Defining the reason for the study (goal) and the system boundary (scope)
- Collecting information about inputs and outputs – the life cycle inventory (LCI)
- Determining the environmental impacts – life cycle impact analysis (LCIA)
- Interpretation and reporting

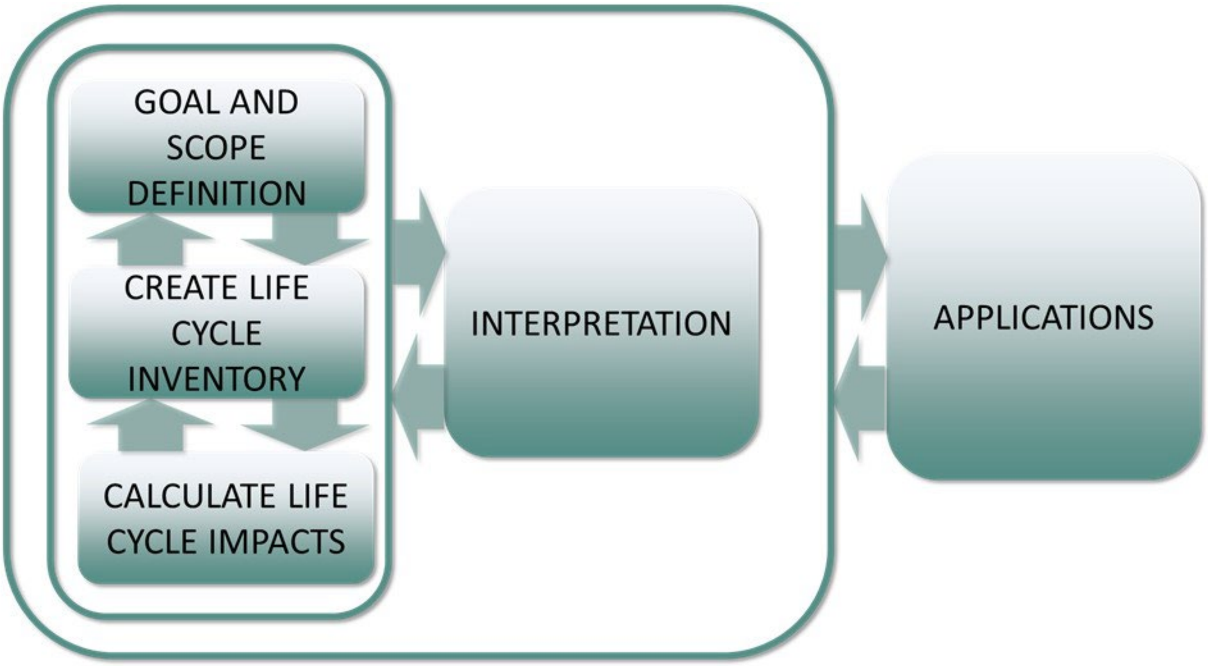

Figure 1. Overview of the steps or stages of an LCA with multiple feedback loops.

In practice, the process of conducting an LCA is iterative, with multiple feedback loops (Figure 1). For example, the collection of information for the life cycle inventory may lead to changes in the goals and scope or defining where the system boundaries lie.

2.1 Defining the goal and the scope of the study

Before starting the analysis it is necessary to state the reason for the LCA study (the goal). For example, the reason for the study may be to allow a manufacturer to better understand what are the major factors influencing the outcome of the study (known as an attributional LCA); this would allow the manufacturer to take action to reduce the environmental impact of a product or process. Alternatively, the purpose of the study might be to compare the consequence of choosing different materials for use in a product or process (known as a consequential LCA). At this stage, it is also important to define who the intended audience is. The reason for a clear definition of the goal of the study is to ensure that the LCA is transparent, which allows for the intended audience to be able to trust the outcomes of the study.

Once the goal of the study is stated, this is followed by a series of statements defining the scope of the study. The scope will state what the boundaries of the study are. For example, is the study looking at the manufacture of a product (cradle to factory gate), or is it considering the whole of the life cycle? What is the unit of the study? Is it reporting on a weight or volume, or area of a material (called a declared unit); or addressing something that has a defined function (such as a window or door, called a functional unit)? What else is included in the analysis? Does it include co-products or by-products? If the study is looking at the whole life cycle, then it must include maintenance, repair, replacement, and disposal. This might mean making assumptions about these activities if there is no robust data available.

Defining the system boundary is an essential part of the LCA. Does it only include production (cradle to factory gate, modules A1-A3), or also include other aspects of the whole life cycle? Ideally, for the purposes of an accurate comparison, it is necessary to include the whole life cycle (Figure 2, modules A, B, C, as defined in EN 15804).

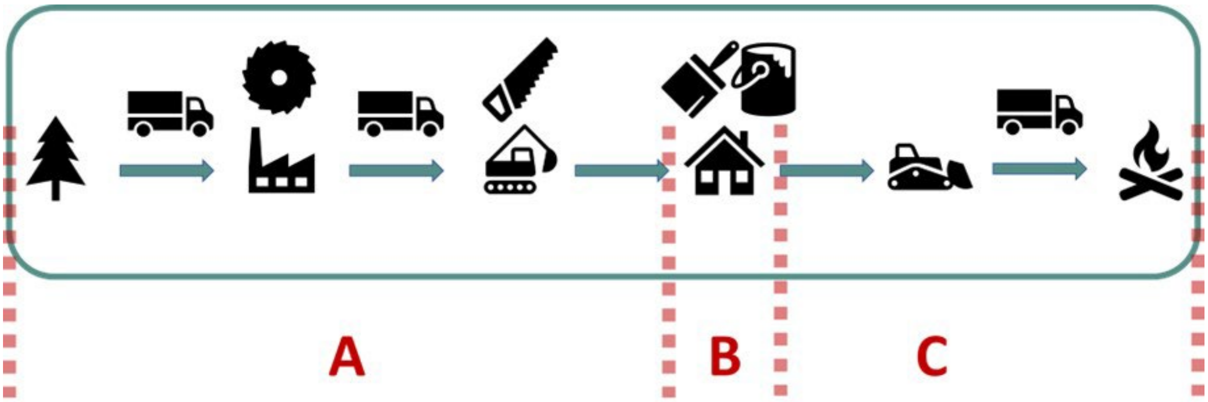

Figure 2. Scheme of the whole life cycle of the product, including modules A, B, C, as defined in EN 15804.

2.2 Creating a life cycle inventory (LCI)

Having specified the system boundary, the next part of the process is to collect information about the flows of materials and energy across that system boundary, both inputs and outputs (Figure 3). This data gathering is used to create what is referred to as a life cycle inventory. The ultimate aim of creating a life cycle inventory is to track all materials and energy sources back to the form which they occur in nature. The sort of information that is gathered includes:

- Materials inputs
- Utilities (electricity, gas, water, oil)
- Transportation (rail, road, ship, air)
- Waste outputs
- Products, co-products, and by-product outputs

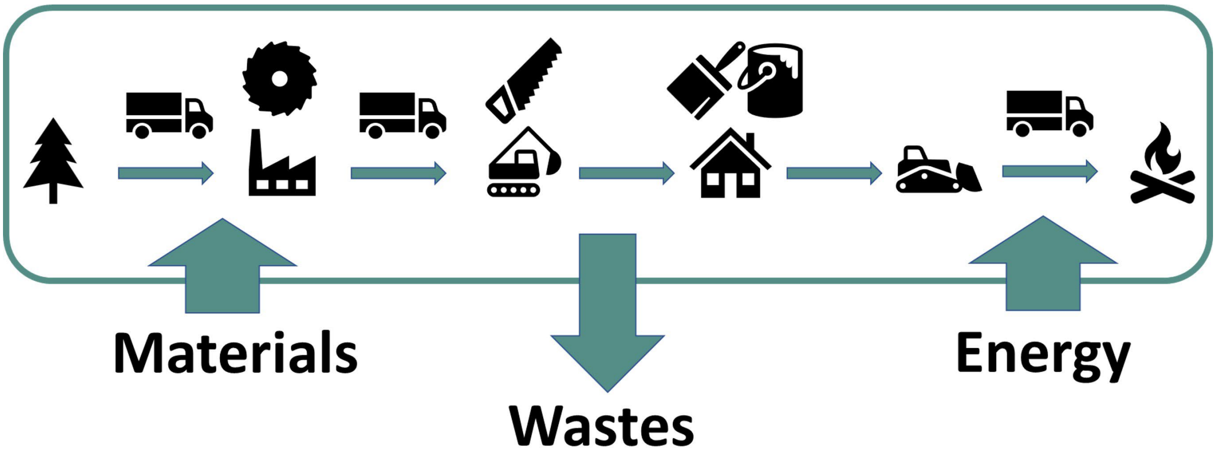

Figure 3. Scheme of input and output data for the life cycle inventory (LCI).

The main problems with data gathering are:

- Commercial confidentiality – The organisation that is making the product may be very uncomfortable with sharing technically-sensitive information with the LCA practitioner. However, it is vitally important that there is accurate information available in order to produce a valid study. This issue of commercial confidentiality is contrary to the requirement that LCAs should be transparent and verifiable. This will be discussed further later.
- Accuracy – Not all organisations keep records to the level of accuracy that is required for the LCA study, resulting in data gaps. How the LCA practitioner deals with data gaps depends upon what is missing and how important the information is. Another issue which is often encountered is determining the level of detail for data gathering, this leads to what is referred to as 'cut-off', where some information will be considered to be not sufficiently important to make the effort of obtaining the data worthwhile. This is something we will come back to when we discuss the sensitivity analysis.
- Complexity – With very complicated processes, it may be very difficult to obtain all of the necessary information. This applies especially when there are numerous subcontractors who are manufacturing components for a product.
- Allocation – If we are considering one product that is produced by a single factory then this is not a problem; but if there are multiple products (co-products) and we are considering only one of these, then we have to determine how to allocate energy and materials to the product that is being analysed. A typical example would be electricity use for a factory, where we would have to allocate some of that electricity use to a specific product. There are various ways of dealing with the 'allocation problem', which will be discussed later.

Although ideally, we can make a list of primary inputs from nature, in practice it is usually not possible to track all materials and energy sources back to their origin, since the organisation is often supplied with components or materials which have already been through other processes before they are used within the system. However, there are comprehensive databases that have done this part of the work, based on thousands of previous LCA studies. In this case, it is only necessary to create an inventory of materials and energy use that corresponds to entries in the background databases.

Two very commonly used industry-standard databases are GaBi and ecoinvent, although others exist (such as the Network for Transport Measures (NTM), ICE database, etc.). Some databases are free and some are expensive. The quality of databases varies considerably and will have an important influence on the results of a study. The important thing with using any database is to ensure that it is reliable and up-to-date (commercial databases are generally better in this respect since they have the resources to gather the data). However, databases evolve as new information is gathered. It is important to work with the latest versions and to be aware that older LCAs using older versions of databases are not strictly comparable with newer studies.

It can be problematic to create an inventory when the LCA information for some materials are not listed in the database. This is even more so when also manufacturing details are unavailable. This is very commonly found with chemicals, where there are huge numbers for which no LCA information exists. The LCA practitioner is then faced with several choices:

- Develop a model – is there sufficient information available that allows a model to be developed which is based upon already existing LCA data? This is the best approach, although the accuracy of the model depends upon the knowledge of the LCA practitioner and the availability of reliable information.
- Use a proxy – can something that already exists in the database be used as a substitute? The reliability of such an approach depends very much upon the knowledge of the LCA practitioner.
- Ignore it – a very risky approach; but in some cases, only small amounts of material may be used and this can therefore be excluded under the cut-off rules. However, it is very important to recognise that just because a small quantity of something is used, this does not automatically mean that the environmental impact will be correspondingly low.

The creation of the life cycle inventory also includes amassing data regarding the use of transportation; including distances, mode of transport and quantities carried. This information is then usually converted into units of tonne km, which is the quantity carried over a specified distance. For the early part of the life cycle (often called cradle to factory gate) it is quite usual for the transportation information to be readily obtainable. However, for later stages of the life cycle, (such as installation, maintenance, replacement, demolition, disposal) this information is either unknown, or varies depending on circumstances. These transport data may then very often rely on the creation of scenarios which require assumptions to be made. Generally, the information obtained for earlier stages of the life cycle tends to be more accurate and reliable than that obtained for later stages. This is especially true where there are a large number of options available (e.g., end-of-life – recycle/dispose/incinerate/re-use?). It is important that these assumptions are realistic and based upon current practice, rather than theoretical future scenarios.

Finally, there is the process known as cut-off. The collection of information for the inventory can get to the point where the data is not available, or may be considered trivial (e.g., how many envelopes were used in the office of an aluminium smelter!). It is therefore necessary to operate some form of cut-off, where the information is simply not gathered. This is often based on mass, e.g., if the quantity is less than 1% of the mass of the product then it can be ignored. Unfortunately, there are no reliable rules for how to operate cut-off and this often comes down to the experience of the LCA practitioner. Some materials may be present in very small quantities, but have a very large environmental impact (e.g., a computing chip in a mobile phone). One way of deciding on the importance of gathering the data is to use a sensitivity analysis (discussed later), where different quantities are added to the inventory (even if uncertain) and the effect on the outcome examined. If this exercise reveals that the component (chemical, material, etc.) does have a major impact, then it is necessary to devote extra resources into getting the accurate information. This is part of the iterative process mentioned earlier.

2.3 Life cycle impact assessment (LCIA)

Having assembled (as far as possible) a complete inventory of materials and energy for the life cycle assessment, the LCA practitioner then moves on to determining the environmental burdens associated with the materials, energy and processes, which were described in the LCI.

The environmental burdens are reported using what are referred to as impact factors, impact categories, characterisation factors, or some other term. Whatever the term used, the principle is the same; the impact is reported in terms of a unit and within a specific category. There are two main approaches to reporting on the environmental consequences and these are called mid-point or end-point impacts. A mid-point impact reports upon the consequence directly on the environment. Typical mid-point impact categories are:

- Global warming potential (GWP) (radiative forcing effects caused by greenhouse gases (GHGs), such as carbon dioxide and methane)
- Ozone depletion potential (ODP) of the stratosphere (the ozone layer, caused by release of ozone destroying chemicals such as chlorofluorocarbons)
- Eutrophication of freshwater, marine water, or terrestrial (algal blooms, deoxygenation of water-courses, caused by the release of phosphorus and nitrogen-containing compounds mainly)
- Photochemical ozone formation in the troposphere (atmospheric pollution at ground level, especially urban areas, caused by the emission of volatile organic compounds that react with oxygen in the presence of sunlight)
- Particulates in the atmosphere (especially 2.5 microns and smaller)
- Acidification (indicates acidification of soil or water due to deposition of acidic pollutants, such as sulphate and nitrate)
- Water use – water depletion of aquifers and other water bodies

There are over a hundred impact categories that can be used and the choice depends upon the requirements of the study. These impacts are calculated by a variety of methods (e.g., ReCiPe, ILCD, CML, etc.) and the results obtained using different methods do not always agree. With well-understood impact categories, such as GWP or ODP, the variation between calculation methods is not large, but with other categories, there can be quite big differences. Different calculation methods also may report the impact factors using different units and cannot be compared for this reason.

The most commonly reported impact category is global warming potential (GWP), and this will be examined in more detail, but the issues discussed here are typical of all impact categories. The GWP characterisation factor is reported in units of kg carbon dioxide equivalents [kg CO_2e], but there are many different GHGs, and these have different radiative forcing effects. Carbon dioxide has a GWP of 1, by definition, because it is the gas that is used as the reference.

However, methane is a much more powerful GHG compared with carbon dioxide, but methane slowly reacts with oxygen in the atmosphere to produce water and carbon dioxide, so the equivalent radiative forcing effect of methane changes over time. This means that the effect of the length of time that the pollutants exist in the environment has to be taken into account. By consensus, a time frame of 100 years is normally used for GWP, and this is usually shown by the symbol GWP_{100}. When the effect of the release of one kilogram of fossil methane into the atmosphere is accounted for over a 100-year period, then it has a GWP value of 29.8 kg CO_2 equivalents (this is according to the IPCC Sixth Assessment Report (2021)), this value is higher than stated in previous Assessment Reports because the scientific understanding of the effect of the release of methane is improving. However, this also means that direct comparisons between LCAs using different impact category calculations and characterisation methods may not be valid. The calculation methods get more accurate over time and for this reason it is important to ensure that the most up-to-date characterisation method is used. Older methods cannot necessarily be compared with newer methods.

It is also possible to report on the environmental burdens associated with a product or process by considering the consequences at the end of a chain of cause of effect and these characterisation factors are therefore referred to as end-point indicators. For example, these may report on effects on human life expectancy (disability-adjusted life years, DALY), or species loss, or some other consequential effect.

Sometimes, all of the environmental burdens are aggregated into a single score (e.g., ecopoints). End-point indicators and especially single score characterisation factors are much less reliable compared to mid-point categories, because there are many more steps in the chain of cause and effect and the science may not be completely understood. These end-point characterisation factors will not be discussed further.

As noted earlier, an issue that is often encountered when assigning environmental impacts to a product or process is what is often referred to as the 'allocation problem'. To explain what this means, consider the following scenario:

Let us suppose that we wish to determine the environmental impacts associated with the production of wheat straw for the purposes of making a straw bale building (Figure 4).

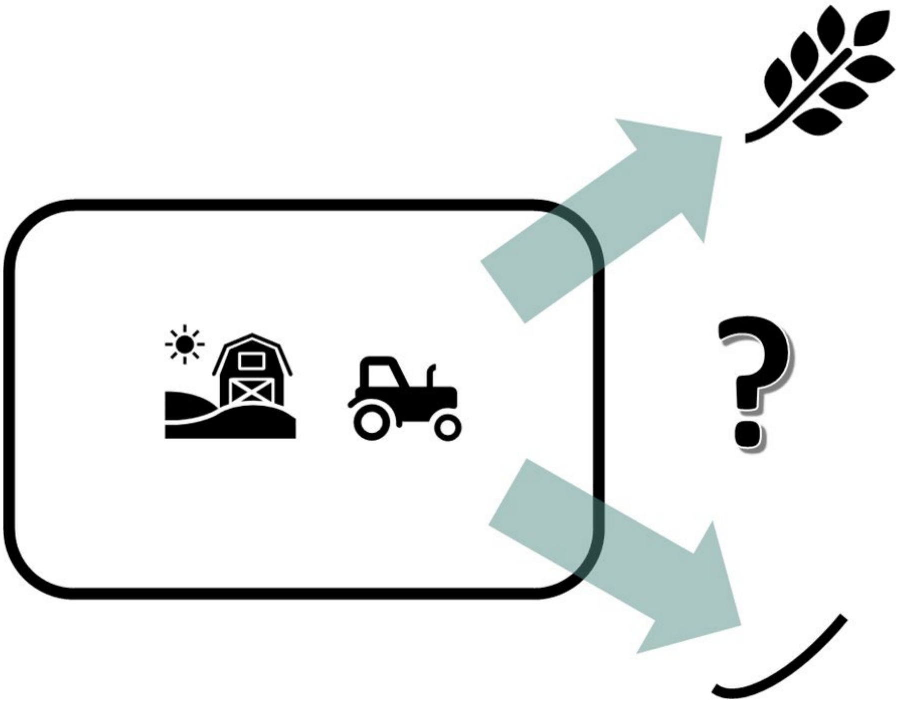

Figure 4. Example of an allocation problem: allocating the impacts for the production of wheat and wheat straw while determining the impacts for making a wheat straw building.

We can gather all of the necessary inventory information about the agricultural processes associated with the production of the straw. However, the primary purpose of a wheat crop is not to produce straw, but to produce wheat. How then are we to allocate the environmental burdens associated linked to the production of wheat and straw (the by-product)? We essentially have three choices on how to allocate:

- Allocation on an energy basis – we allocate the burdens based on the difference in calorific value between the wheat and the straw. Using this method is likely to be more useful if we are using the straw for energy production.
- Allocation on a mass basis – we measure the yield of the grain and of the straw and allocate the environmental burdens on that basis. This is a straightforward method but can result in a much larger impact being allocated to the by-product than is reasonable. After all, the purpose of growing the crop was to produce the grain, not the straw.

- Allocation on an economic basis – we allocate the burdens based on the ratio of the price of the grain and the straw. This is probably the most reasonable (in this case), but prices change, and this can affect the allocation.

No allocation method is completely satisfactory and using the wrong allocation can severely bias the results.

Because of the allocation problem, the standards and product category rules state that allocation should be avoided wherever possible. Where this is not possible, it is recommended that system expansion is used. This means that rather than consider the grain and the straw as separate systems, we have to look at the two as part of the same system (Figure 5).

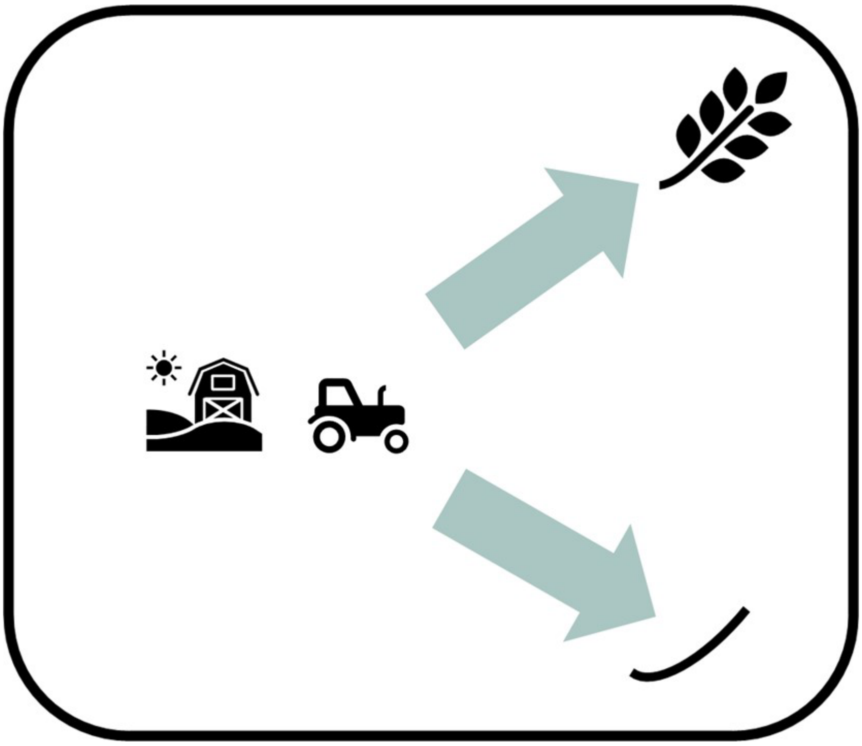

Figure 5. System expansion to avoid allocation of the impacts for the production of wheat and wheat straw while determining the impacts for making a wheat straw building. The grain production is now part of the analysis.

This is rarely a practical solution to the problem. If we wish to know the environmental burdens associated with the straw only, then we have to use allocation; there is no choice.

If allocation is used in the LCA study (it often is) – then it is important to check exactly how this was done, since incorrect use of allocation can have important consequences for the outcome of the study.

2.4 Reporting and interpretation

The next stage of an LCA is to report on and more importantly, interpret, the results. This stage should also include a sensitivity analysis, so that it is possible to understand the major factors influencing the outcome and how it is possible to make changes to reduce the impacts. Unfortunately, this is something that seldom features in most LCA studies.

A sensitivity analysis involves investigating what the effects of changing certain aspects of the LCA are – usually meaning changing parts of the inventory. The intention is to find out what the most important factors are that affect the outcome of the study. If the LCA proves to be particularly sensitive to changing an input, then it is clearly very important that this input is quantified very accurately. If this is not possible, then it is good practice to show what the effect of changing this parameter is.

It is unfortunate that LCA has become a tool that is often used for marketing purposes; especially so when considering the merits of using one material over another in reducing climate change. A very significant problem here is the issue of transparency and this is where a sensitivity analysis is extremely helpful when considering the environmental burdens associated with different materials. This important issue was highlighted previously (Hill and Zimmer, 2018).

- Does the study in question contain a sensitivity analysis?
- If not, why not?

Another important issue to consider when reading LCA studies is comparability.

If the aim of the study is to determine which material is the best choice from an environmental point of view, it is necessary to ensure that the comparison is fair and representative. In such a consequential LCA it is important to consider the following:

Is the unit of comparison representative and fair? For comparing materials used in construction, it is likely that only a whole building comparison over the entire lifetime of that structure is likely to reveal which is the best material choice. Such a study would include all of the variables; including lifetime energy use, maintenance, replacement, deconstruction, disposal, etc. When considering potential climate change impacts/mitigation, then such a study is referred to as a whole-life carbon analysis. These studies are very complicated and can involve a lot of assumptions about energy performance of the buildings, service lives of materials, maintenance requirements, fates at end-of-life, etc. The information provided in such studies should be sufficient to allow for an understanding of how these variables affect the outcome (sensitivity analysis) and how the calculations were performed (transparency). Unfortunately, it is very unusual to find any study that can be interpreted at a sufficient level of detail to be considered fully transparent.

To some extent, the issue of comparability of different products has been made easier by the introduction of international standards that define product category rules (PCRs), which ensure that different LCA studies are produced using the same methodology. LCAs made using agreed product category rules can be used to produce environmental product declarations (EPDs), which (in principle) do allow different products to be compared, providing they use the same functional unit or declared unit. One such example is the European Standard EN 15804 which defines PCRs for products used in construction.

3 How to approach published LCA studies

Things to consider when attempting to analyse LCA studies are:

- What is the goal and scope?

The first thing to note whenever a study appears is who has paid for the study and what is the goal and scope? This is not to say that a study is invalidated by who has paid for it, but the outcome of any comparative study that is funded by an industry body is unlikely to publish findings that do not support the products of that industry!

- Is the unit of comparison fair and reasonable?

Figure 6. Is the unit of comparison fair and reasonable?

In this report, we are considering the various factors associated with what are called 'comparative assertions'. Simply put, a comparative assertion is a statement that one product is better than another from an environmental impact perspective.

When comparing the results of different LCA studies, it is vitally important that the same unit of comparison is used. Where we are considering materials for buildings, it is important to use the same functional unit (Figure 6). An example of a functional unit is a window of certain dimensions or with impact reported per m^2 of fenestration.

If the intention is to decide whether timber or concrete is a better construction material from an environmental perspective, there are many things that must be considered. Is the unit of comparison defined in the scope the correct one to answer the question stated in the goal of the study? If the intention is to decide on the best material for use in a building from an environmental perspective, then the only sensible unit of comparison (functional unit) is a building at the same location. The comparison should be for the whole life of that building and include all the maintenance and operational aspects. Furthermore, the comparison should also include a consideration of the end-of-life fate of the material in question. In a later section of this report, we will look into this in more detail.

In any LCA study, it is important that the system boundaries (the goal and the scope) are very clearly specified. The system boundary describes what the subject of the study is and what is outside the scope of the study.

Is the study only going to look at one aspect, such as climate change, or include other environmental indicators? If other environmental indicators are included, then what is the purpose, and what is the conclusion if different indicators show greater or lesser impacts (some may be better for one product and some may be worse)?

Clearly, such a study is going to be complicated, and it may involve lots of claims and assumptions, where verifiable data does not exist, or is uncertain.

Problems with this approach inevitably arise when the comparison study is not fully transparent, and the assumptions that are made are not supported with appropriate well-quantified data sets. These may include claims made about maintenance requirements, lifetimes of materials (hence the need for repair or replacement), energy demands of buildings constructed using different materials, ultimate fates of materials at end-of-life, etc.

In order to circumvent these issues of complexity, one approach is to simplify the study, but this may have the effect of invalidating the results if the model that is used is too simple.

Unfortunately, the purpose of some studies is not to conduct an unbiased and independent analysis of different materials; but rather, to show the merits of one material compared to alternatives and for this reason, assumptions may be made that tend to favour one material over another. The requirement to conduct a sensitivity analysis, in order to determine the influence that various assumptions have upon the outcome of the study, is seldom considered. The main result is confusion – one study says this and the next one says the opposite.

One way of dealing with this problem is to conduct a literature review or meta-analysis, and this was the purpose of the study of Hill and Zimmer (2018).

Hill and Zimmer (2018) emphasised the role of uncertainties and variabilities in the data and how this affected the outcome of LCA studies.

The report came to the following conclusions:

- Only consequential LCA can be used when comparing different materials for use in construction.
- The functional unit should be the same. If two buildings are compared in a scenario, they should have the same energy performance in terms of heating and cooling requirements. System expansion is necessary to include the building plus the generation of energy in order to take account of the recovered energy from waste wood.
- It is necessary to consider the whole life cycle of the materials using realistic assumptions regarding maintenance cycles and end-of-life scenarios.
- Uncertainties need to be studied in greater detail using sensitivity analysis.
- The LCAs should be transparent and employ appropriate sensitivity analyses to show the effect that different assumptions have on the outcome. Very few studies meet these requirements, often for reasons of commercial confidentiality.
- An appropriate set of physical and temporal system boundaries needs to be chosen. The whole life cycle of the building needs to be considered. There may be arguments for extending the LCA beyond the life of the material, to consider recycling, or incineration with energy recovery. The comparison of timber with other building materials requires consideration of the energy recovery that is possible from timber thinning, processing residues and also the timber from the structure at end-of-life. It is also necessary to make appropriate allocations of environmental burdens or use system expansion correctly. This is particularly important when the energy from timber residues is taken into account and compared with materials which have no inherent energy content. There is also the issue of concrete carbonation to be considered, although this is not as significant at end-of-life as is sometimes stated. Concrete carbonation in real-life situations is not fully understood and assumptions regarding carbonation at end-of-life require justification. These uncertainties need to be explored.
- Appropriate allocations need to be made with respect to timber co-products. This can be very complicated for timber products, since the system boundary also includes the forest and forest operations from planting to harvest and may also include the next rotation with energy credits arising from thinning and carbon sequestration by the growing biomass. This is a complex issue and can have a significant influence on the results. Allocations can

be made on the basis of mass, economics or energy content; each usually giving different results. A sensitivity analysis should be employed to illustrate this.

- The assumptions that are made regarding the whole life cycle of the building and materials can have a very profound influence upon the associated environmental impacts. There needs to be an open transparent presentation of the assumptions made. Furthermore, in order to back up the decisions made regarding those assumptions, it is necessary to perform a sensitivity analysis.

The deciding criteria as to what constitutes a lower overall environmental impact depends upon a value judgement. Different environmental impacts can have greater relative importance, depending upon the temporal and spatial scale considered.

4 EN 15804 and working with EPDs

Because of the huge variability and complexity in LCA studies there has been a need to develop product category rules to define how the LCA should be conducted and reported. The intention is to use these product category rules (PCRs) to produce environmental product declarations (EPDs), which (in theory) allow for comparability between different products and materials.

In Europe, the PCRs for construction products are defined in a European standard EN 15804. As of December 2022, the most recent version of EN 15804 is: EN 15804:2012+A2:2019/AC:2021 'Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products'.

This standard was first published in 2012 and revised in 2019 to align the methods and reporting categories with the EU Product Environmental Footprint (PEF) Product Category Rules. Subsequently, a minor change was made in 2021 to the freshwater eutrophication potential reporting characterisation factor in order to correct an error in the reporting units.

The standard provides a description of how to conduct an LCA in order to produce an Environmental Product Declaration (EPD) for products, or services for the built environment. The EPD can report the environmental information as a declared unit (a weight, volume, or quantity of material with specified dimensions), or as a functional unit (quantified performance of a product/service system for use as a reference unit).

The purpose of providing a standard that defines core product category rules describing how to conduct an LCA and report on the outcomes is to provide verifiable and consistent data for an EPD, based on LCA; as well as verifiable and consistent product-related technical data, or scenarios, for the assessment of environmental performance.

The purpose of the EN 15804 standard is to allow for communication of the environmental information of construction products/services from business to business; and, subject to additional requirements, for the communication of the environmental information of construction products/services to consumers.

At first sight, the information contained in EPDs can be quite intimidating, so this section of the document will provide some basic principles for understanding and getting the best out of an environmental product declaration.

The following examples are not given for the purpose of comparison of different products, but to illustrate some of the problems that make such a comparison problematical.

The main environmental indicator of interest is global warming potential (GWP) which is reported in units of kilograms carbon dioxide equivalents (kg CO_2e). In earlier versions of EN 15804 there was one entry for GWP, which is reported for all the different parts of the life cycle. The cradle to factory gate part of the life cycle is EPD modules A1-A3 (Table 1).

In the EPDs of many building products, it is possible to find out the climate change impact associated with manufacturing the product by adding the values in modules A1-A3. Quite often, this is already done, or sometimes all three modules are aggregated and just reported as A1-A3, rather than separately. As an example, we can examine the Norwegian EPD Foundation EPD number NEPD-1419-466-EN for a product called BASIS® cement. This gives GWP values for each of the modules A1, A2, A3 and an aggregated score of 745 kg CO_2e for modules A1-A3 for the declared unit (1000 kg of cement) (this is often referred to as the embodied carbon of the product). This EPD has been produced to the EN 15804 standard, but since the EPD was published in 2016, it will not have been produced to the latest (+A2) version of that standard. This EPD only declares the modules A1-A3 and can be used as the basis for products made from that cement, hence the use of a declared unit rather than a functional unit.

Table 1. Different life cycle stages as defined in EN 15804.

Module	Life cycle stage	Description
A1	Production	Raw material supply
A2	Production	Transport
A3	Production	Manufacturing
A4	Construction	Transport
A5	Construction	Construction/installation
B1	Use	Use
B2	Use	Maintenance
B3	Use	Repair
B4	Use	Replacement
B5	Use	Refurbishment
B6	Use	Operational energy use
B7	Use	Operational water use
C1	End-of-life	De-construction/demolition
C2	End-of-life	Transport
C3	End-of-life	Waste processing
C4	End-of-life	Disposal
D	Beyond building life cycle	Reuse/recovery/recycling

By comparison, an EPD for a timber product (NEPD-307-179-EN) for sawn and dried timber of spruce or pine, is examined. The GWP impact for modules A1-A3 for this product is given as -672 kg CO_2e for the declared unit of 1 m^3 of sawn dried timber. This EPD was published in 2015, meaning that it also followed the product category rules specified in the older (+A1) version of EN 15804. The reason for the negative number is that the GWP includes both the impact associated with the GHG emissions associated with transport and processing, but also includes the sequestered atmospheric carbon that is stored in the wood (which is shown as a negative number). Reading through the EPD we find that the sequestered atmospheric carbon that is stored in the wood is stated as -715 kg CO_2e per m^3. It is now straightforward to calculate the GWP impact of processing one cubic metre of timber (-672-(-715) = 43 kg CO_2e per m^3). Based upon the density used for the calculations that is stated in the EPD (390 kg/m^3) it is possible to calculate the impact for producing 1000 kg of timber = 110 kg CO_2e.

This is considerably lower than the 745 kg CO_2e recorded to produce 1000 kg of the cement product, so does this mean that wood is the better choice? The answer is that it is not possible to make any such comparison based upon these declared units. The only way to make comparisons (comparative assertions) is to look at the same functional unit (something that can be directly substituted because it has the same function).

Before we go onto considering how it is possible to make these comparisons, it is necessary to look at the changes that have been made to EN 15804. For the purposes of this document, only GWP will be discussed, although there have been other changes made, including new characterisation factors (impact categories).

- One of the most obvious changes for the latest version of EN 15804 (+A2 version), is the dividing of the global warming potential characterisation factor into fossil, biogenic and land use and land use change (luluc) categories. There are also specific requirements when reporting the biogenic GWP category for materials which contain sequestered atmospheric carbon (e.g., timber products). These are important changes, and it is necessary to examine the new rules in more detail.

- The GWP-biogenic indicator accounts for GWP from removals of CO_2 into biomass from all sources except native forests, as transfer of carbon, sequestered by living biomass, from nature into the product system. This indicator also accounts for GWP from transfers of any biogenic carbon from previous product systems into the product system under study.
- Any carbon exchanges in native forests are declared in the category GWP-luluc. Native forests exclude short term forests, degraded forests, managed forest, and forests with short term or long-term rotations. Any carbon exchanges associated with land use change are also included.
- For timber products it is no longer allowed to report only for the life cycle modules A1-A3 (cradle to factory gate), but must also include modules C1-C4 and module D.
- It is not permitted to consider the storage of atmospheric carbon (biogenic carbon) as being permanent. It states in the standard (Section 6.3.5.5): *'The degradation of a product's biogenic carbon content in a solid waste disposal site shall be declared without time limit. The emission is treated as an emission of biogenic carbon dioxide.'* This means that the biogenic carbon content, which is reported as a negative value in module A1, must be reported as a positive value in module C4. This means that the sum of biogenic carbon storage over the whole reported life cycle is zero.
- Biogenic carbon in the declared product should be treated separately from biogenic carbon in the packaging and these two values are declared in a separate table in the EPD.

These are the requirements that are specified in EN 15804 when dealing with biogenic carbon, but some EPD program operators also have additional requirements.

Although the rules are quite specific in describing how biogenic carbon should be reported in an EPD, there are still potential problems when it comes to interpreting the declared values. Some of these are listed below.

Many EPDs show the sequestration of atmospheric carbon into the timber in the forest in module A1 (where this is reported separately). However, this is not reported the same way in different EPDs. The most common way of reporting the sequestered carbon is to calculate the quantity of stored carbon in the declared unit (taking account of moisture content). In EPDs where the stored carbon is declared separately (as is now a requirement), it is therefore relatively straightforward to calculate the GWP impact associated with processing from the declared GWP total for modules A1-A3 (Figure 7). This can be done by subtracting the amount of carbon stored in the declared product (in kg CO_2e) from the GWP total value.

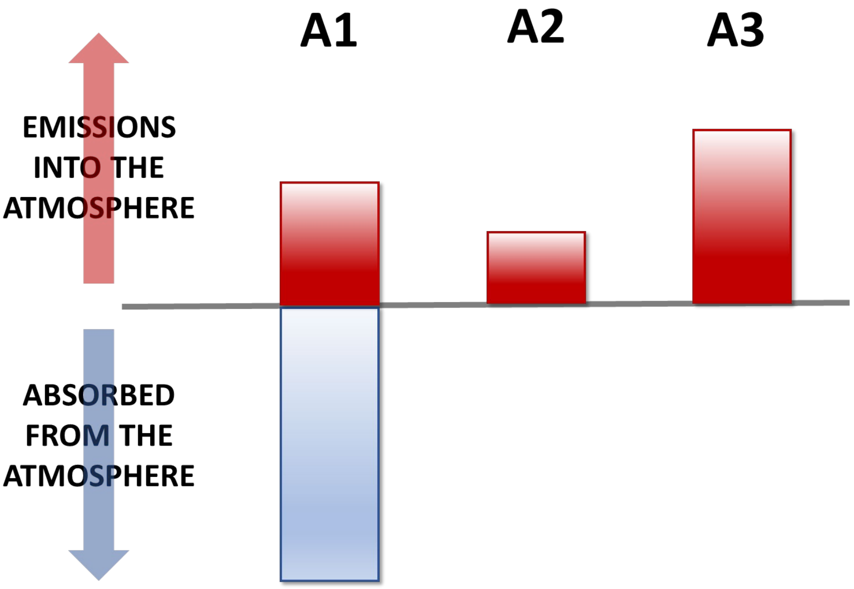

Figure 7. Sequestered atmospheric carbon is shown in module A1, emissions associated with processing, transport etc., are shown in modules A1, A2 and A3. The total GWP impact for manufacturing the product is the sum of emissions minus the quantity of sequestred atmospheric carbon stored in the product (all in kg CO_2e). For timber products, this always results in a negative GWP total. Many EPDs aggregate the A1, A2 and A3 values to give a 'cradle to factory gate' total value. (Please note this is for illustration only and the relative heights of the bars are not connected with real values).

However, in older versions of EN 15804 where the stored atmospheric carbon in the declared unit is not declared in the EPD, it is possible to calculate this value by using the method stated in the standard EN 16449 '*Wood and wood-based products — Calculation of the biogenic carbon content of wood and conversion to carbon dioxide*', assuming that the density and moisture content of the declared unit are stated. This second method cannot be considered as reliable as the first. This should no longer be a problem with EPDs following the new (A2) version of EN 15804.

In some cases, the value declared for the A1 module for the GWP biogenic carbon is much higher than that stored in the declared unit. This is because the EPD is reporting on the biogenic carbon in the timber before it is processed, which can be very confusing for the reader. Where sawn timber is produced from raw wood, the volume efficiency of conversion may be 60% or lower, which introduces a considerable difference in the calculated stored atmospheric carbon between the wood before and after processing. In some cases, the processing residues may be incinerated to provide energy at the sawmill, in which case this would be shown as an emission of biogenic carbon in module A3 (where A1-A3 is aggregated, this means the net value is zero and only the sequestered value for the declared unit gets reported, figure 8).

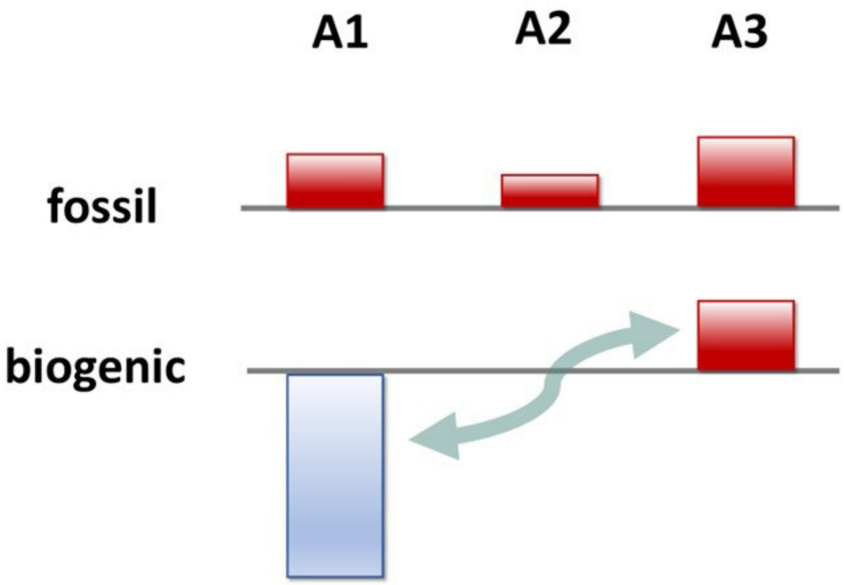

Figure 8. In the latest (A2) version of EN 15804, the fossil and biogenic carbon is reported separately. Atmospheric carbon that is stored in the tree before harvesting is shown in module A1. Emissions of biogenic carbon can occur in other modules, such as in A3 where (for example) chippings and bark may be used as a fuel source for providing heat for drying kilns.

As noted earlier, although the sum of A1, A2, A3 for timber products produces a negative value, because the amount of sequestered carbon in the timber exceeds the GWP emissions (when measured in kg CO_2e), it is mandatory to report the emission of this biogenic carbon in module C4 (without time limit, figure 9). This emission may also include other losses of biogenic carbon within the product system and does not necessarily equal the amount of stored carbon in the product (it might, but it also might not!). This loss of carbon from the system is reported as a positive value because it is an impact.

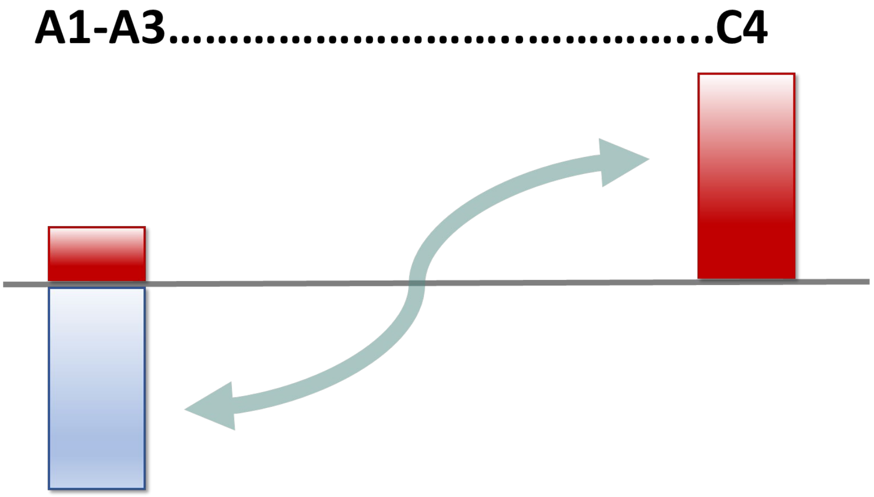

Figure 9. The atmospheric carbon stored in the product (a negative value) in modules A1-A3 must be shown as an emission to the atmosphere (a positive value) in module C4.

In other cases, the wood residues may be sent from the sawmill to other product systems (e.g., particleboard) and consequently, the stored carbon is not reported as a flow to the atmosphere (positive value), even though it has left the system (Figure 10). The loss of this carbon to the atmosphere now belongs in a different system (for particleboard) which is not part of the system of the declared unit (the sawn timber).

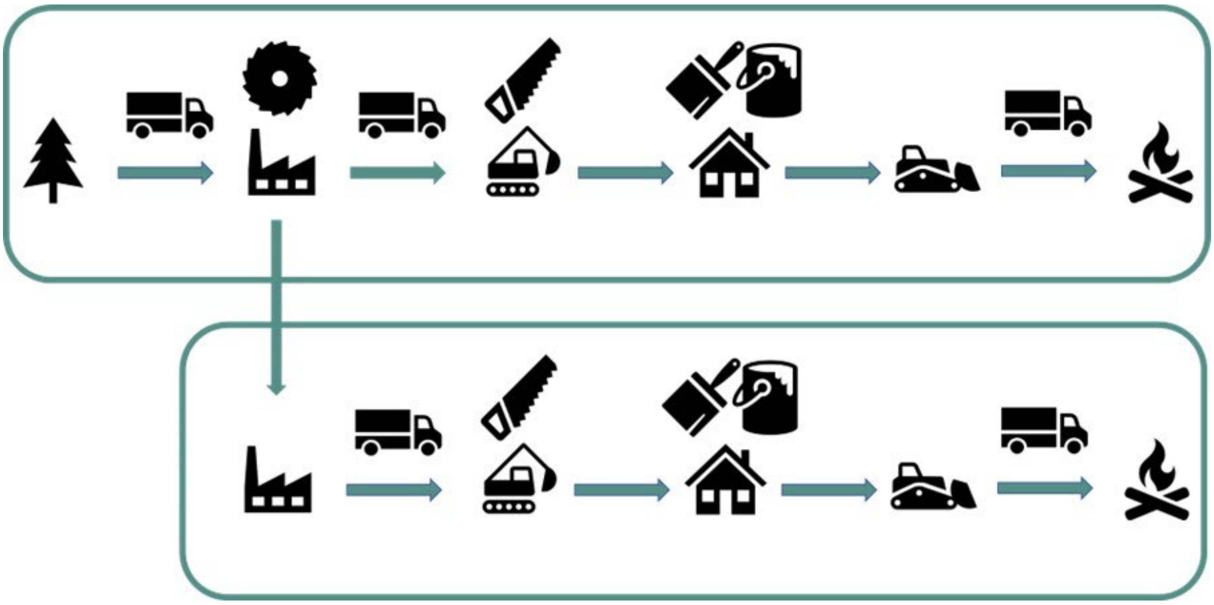

Figure 10. Some of the biogenic carbon stored in the wood is lost from the sawmilling system as waste wood and sawdust, but exported to another system which is devoted to particleboard manufacture and use.

In the latest version of EN 15804, this loss of biogenic carbon must be reported somewhere, and the only place to do this is in module D (this may or may not happen in the EPD). This method for carbon accounting, where the stored atmospheric carbon in the wood before processing is declared, adds complication to an already complicated subject. Another way of dealing with this is to use system expansion, which is acceptable for an academic LCA study, but an EPD is for one product only.

Yet another complication can arise where biomass is used to provide energy to the processing facility, but this emission of biogenic carbon (positive value in GWP-biogenic) is not associated with processing residues but is a flow of biogenic carbon into the system (e.g., wastes from another process). If properly accounted for, the inflow of the biogenic carbon and the outflow due to combustion should be accounted for and result in a zero effect when A1-A3 are aggregated.

The net result is that in EPDs which deal with biogenic carbon it can be quite difficult to work out what the GHG emissions are and what the quantity of sequestered carbon in the declared unit is (which is what most people want to know!). Fortunately, most EPDs only consider the biogenic carbon stored in the product and this rather complicated piece of text is only included to explain why some inconsistencies may be encountered.

With EPDs following the latest version of EN 15804, the stored atmospheric carbon in the declared unit must be stated in a table, separately from any stored atmospheric carbon in the packaging. However, explicitly stating the GHG emissions associated with processing is not, at the time of writing, a requirement in the standard. Many EPD program operators now require that the GWP value is stated in the EPD without any reference to stored biogenic carbon. For example, epd-norge (the Norwegian EPD Foundation) states that: *'In order to facilitate simplified carbon footprint calculations from cradle-to-gate, the climate change indicator with instantaneous oxidation of biogenic carbon (GWP-IOBC) shall also be reported in the EPD'.* (Product category rules NPCR Part A: Construction products and services. Version 2.0.)

The stored atmospheric carbon in biogenic products, such as wood, is calculated according to the method described in the European Standard EN 16449, as follows:

$$P = (44/12) \times (cf) \times [(\rho_w \times V_w) / (1 + (w/100))]$$

Where:

- P is the biogenic carbon content reported in units of carbon dioxide equivalents (kg CO_2e). The factor 44/12 converts carbon equivalents into carbon dioxide equivalents.
- cf is the carbon fraction of the woody biomass (oven-dry basis), with the default value being 0.5 if not known.
- w is the percentage moisture content of the material.
- ρ_w is the density of the woody biomass at that moisture content (in kg/m^3).
- V_w is the volume of the solid wood material as that moisture content (in m^3).

For example, a 1 m^3 volume of timber having a density of 500 kg/m^3 at 12% moisture content has a biogenic carbon content of:

$$(44/12) \times (0.5) \times [(500 \times 1) / (1 + 12/100)] = 818.5 \text{ kg } CO_2e/m^3$$

In EN 15804 the table reporting the biogenic carbon content uses the units of kg C, rather than kg CO_2e, the conversion between these two is as follows:

$$1 \text{ kg } CO_2e = (44/12) \times \text{kg C}$$

Having established the importance of being able to unambiguously separate the GWP impact from sequestered carbon, we now turn to the issue of how to make comparative assertions between products made from different materials but representing the same functional unit.

As an example, we have analysed windows with frames made from different materials (Figure 11). A survey was conducted of environmental product declarations which have been published for various window products. EPDs for over 250 window systems were analysed and the declared GWP impact for 1 m^2 of window was obtained. The data for opening (not fixed) windows is presented below for different framing materials.

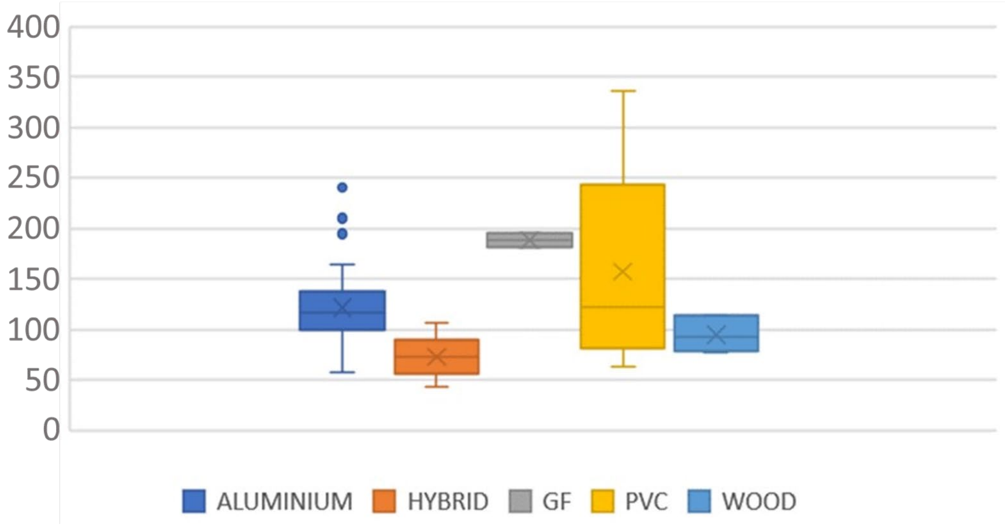

Figure 11. The graph shows the declared GWP for opening windows of different framing materials, where the EPDs of 250 window systems were analysed. GF=glass fibre, PVC = poly(vinyl chloride)

The information presented in the graph is not to show that one framing system is better than another (this requires a more in-depth analysis), but rather to show the spread of values that is found when such an analysis is undertaken, making it very difficult to perform simple comparisons with confidence. To give an example, the hybrid window systems are composed of wood frames with aluminium outer sheathing and consequently might be expected to exhibit GWP values between the wood and aluminium frame systems, but they do not. To understand why, it is necessary to examine each EPD in more detail and especially, to examine the assumptions that were made when conducting the study.

5 Carbon Storage in Buildings

A much-debated topic is the issue of using timber buildings as a long-term store of atmospheric carbon in the built environment. There is no agreed mechanism within LCA to account for the issue of time of storage in harvested wood products (HWPs) although there have been many attempts to do this (e.g., Tellnes et al. 2017). EN 15804 states that although atmospheric carbon storage can be included in EPDs of products such as wood, this can only be done if the whole life cycle is included and the emissions of atmospheric carbon are included for later parts of the life cycle, irrespective of the actual final fate of the product. There is provision for an unambiguous inclusion of stored atmospheric carbon in the biogenic product, however.

The Inter-governmental Panel on Climate Change (IPCC) gives guidance on how to deal with carbon storage in HWPs. However, there are four approaches detailed in the GHG reporting guidance (stock change, production, atmospheric flow, simple decay) and these can produce different results (Rüter et al. 2019). Nonetheless, this does provide a mechanism whereby the time of storage of timber products within the built environment can be shown to directly influence the quantity of atmospheric carbon that is stored at a national, or sector, level.

Producing this information requires accurate data on the GWP impacts of timber processing, atmospheric carbon storage and the quantities of timber entering and leaving the built environment HWP carbon pool. It is also essential to have accurate inventory information on the amount of carbon stored in forests, both above-ground and below-ground.

- Can the built environment be used as a sink for atmospheric carbon dioxide?

The answer is yes, but only while the store of carbon in the built environment is increasing.

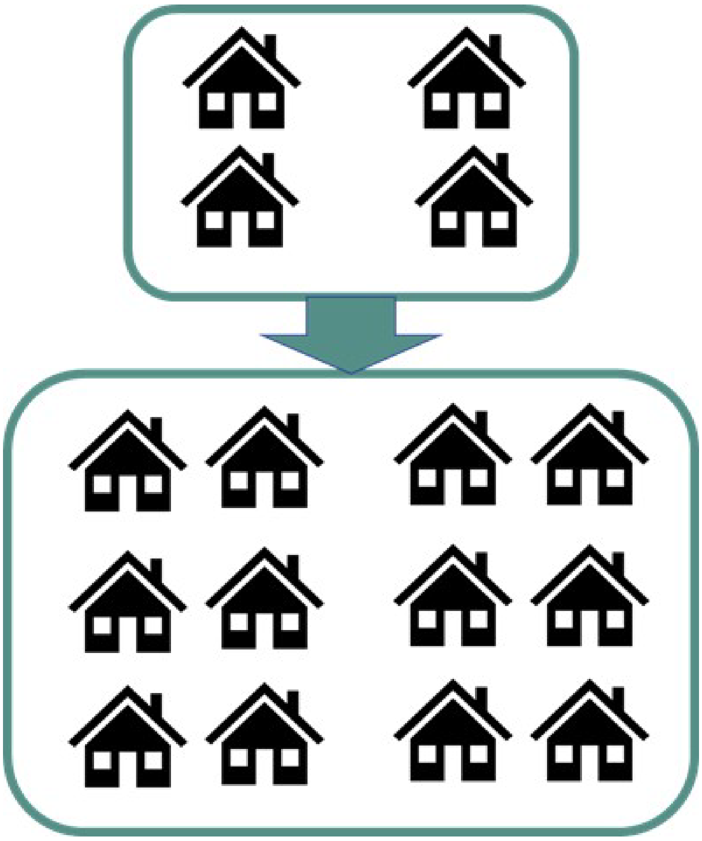

Figure 12. The built environment can be used as a sink for atmospheric carbon dioxide as long as the store of carbon in the built environment is increasing.

Note that a carbon sink is a C-pool that is increasing in size (Figure 12), whereas a carbon store is one where the size (stock) of the C-pool remains constant. Since we are dealing with a dynamic system, with flows of carbon into and out of these pools, we can write these definitions:

- carbon sink is one where the flow of carbon into the C-pool exceeds the flow out of the pool (the carbon stock in the pool is increasing).
- A carbon store is a C-pool where the flows of carbon into and out of the pool are equal (the carbon stock in the pool is constant).
- A carbon source is a C-pool where the flow of carbon out of the pool exceeds the C-flow into the pool (the carbon stock in the pool is decreasing

The use of timber in the built environment can be used as a climate change mitigation measure, but only if the volume of timber is increasing year-on-year. This can be done by encouraging the use of timber in construction and by increasing the lifetime of timber products.

At some point in the future, the quantity of timber entering the built environment will equal the amount exiting and the built environment then acts as a carbon store rather than a carbon sink. This is assuming that the carbon stored in the timber is turned into carbon dioxide (through burning) at the end-of-life. Alternative scenarios are possible, where the wood is re-used in another product, such as by cascading to particleboards. Ultimately, we assume in the models that all of the atmospheric carbon in the wood will be returned to the atmosphere.

We can represent the atmospheric carbon flow through the system in the following system diagram (Figure 13).

Figure 13. System diagram representing the atmospheric carbon flow through the system.

This shows that the atmospheric carbon enters the forest carbon pool, is passed to the built environment carbon pool until end-of-life, where (in this scenario) it is burnt and the carbon re-enters the atmosphere.

Clearly, although it is possible to use the built environmental carbon pool as a store/sink for atmospheric carbon, it is essential that the forestry carbon pool is also maintained or increased, otherwise, there is not a benefit.

One common criticism of using harvested wood products (HWPs) as a potential carbon storage pool, is that the overall carbon accounting effect is zero, because as much carbon enters the atmosphere as leaves the atmosphere. However, this view is over-simplistic.

It is very important that the time of carbon storage in the different pools is taken account of because this has a very important influence on the stocks of carbon in those pools and the dynamics of carbon storage. A relatively simple analysis of the relationship between stocks and flows and residence time in the carbon flow shows that doubling the residence time will double the size of the stock (assuming the flows in and out remain constant).

A common objection to the use of timber products in the built environment as a potential climate change mitigation strategy is that this might compromise the ability of forests to act as carbon stores. It is true that if forests are not managed properly, then they can act as carbon sources and that reducing the size of the carbon stock in the forest is counterproductive. There is no benefit gained by increasing the carbon stock in the built environment at the expense of the carbon stock in the forests.

It is vitally important, therefore, that no more timber is taken out of the forest in any one year than can be replaced by the growth of new timber in that year. This is not simply a matter of working out how much new timber will be added each year and that is the amount that can be removed. It is also important to take account of various factors that lead to the loss of timber, such as pests, diseases, extreme weather events, etc. These two parameters are referred to as the gross annual increment (GAI) and the net annual increment (NAI).

- The gross annual increment is the total amount of woody biomass created in a forest in one year, taking no account of natural losses.
- The net annual increment is the volume of wood that is produced in the forest annually minus losses due to the natural mortality of trees.

For harvesting in a forest to be sustainable, the volume of wood taken in any year should never exceed the NAI.

In order to take into account sequestered atmospheric carbon in the woody biomass in EPDs, it is a requirement that the timber is certified, requiring sustainable forestry practices.

6 Comparison of studies and the climate impacts of timber and concrete structures

6.1 Environmental impact of timber

For timber products, the production includes the whole of the forestry cycle from planting through to harvesting, transportation to a primary processing facility (sawmill) processing to form a primary product, which may be used directly, or secondary processing to form a building material such as cross-laminated timber. Arguments for the preferred use of timber in construction are that the production of timber has a lower environmental impact compared with most other materials (substitution effect) and that timber is made from atmospheric carbon dioxide (in part) and that using timber in long-life buildings can act as a carbon store (sink effect).

As already mentioned, carbon neutrality, which is usually ascribed to timber is a direct result of the ability of trees to store carbon. The carbon in trees, referred to as biogenic carbon absorbed from the atmosphere when the tree grows is released back into the atmosphere when the tree decays or is incinerated (Amiandamhen et al. 2020). However, carbon imbalance usually occurs when timber harvest exceeds reforestation, thereby reducing the biogenic carbon pool. In an intensively managed forest, the biogenic carbon pool is assumed to be constant. It is important to know that even if timber production is carbon neutral, GHG emissions will continue during different stages of timber manufacturing. Consequently, whilst the net carbon dioxide emission may be zero, the net effect on the radiative forcing can be either positive or negative, depending on the time difference between carbon release into and sequestration from the atmosphere (Skullestad et al. 2016). LCA accounting for biogenic carbon assumes that carbon dioxide emissions are climate neutral. This assumption, however, underestimates the potential benefit of long-term storage of carbon in timber buildings compared to the benefits of short-term storage as bioenergy sources. NS 3720:2018 requires that the biogenic carbon be included in the module where binding or emission of carbon takes place. However, many LCA studies simplify their calculation by accounting the biogenic carbon contribution as climate neutral, although it has been documented that biogenic carbon has a climate effect (Ruttenborg 2020).

6.2 Environmental impact of concrete

Cement production is responsible for the major source of energy use and GHG emissions in concrete manufacturing. The cement industry is a major contributor to global emissions of greenhouse gases. About half of these emissions come from the fuel used in combustion and the remaining comes from the direct calcination of limestone. To some extent, the emissions of carbon dioxide from fuels used in clinker production can be reduced by changing the type of fuel. However, the heating of limestone to create quicklime inevitably releases fossil carbon into the atmosphere. Contrary to timber products, concrete undergoes a process where some of the carbon dioxide emitted during production of cement is rebound in hardened concrete in a time-dependent carbonation. Carbonation occurs throughout the life of concrete and the rate depends on several conditions including amount of pure clinker in the concrete, density of the concrete and the surface area of the concrete exposed to air (Skullestad et al. 2016). The environmental performance of concrete is improved by the addition of materials which are mostly always side streams of other industrial processes, and the climate contribution of such materials is usually assumed to be zero. Industrial residues such as fly ash, and ground granulated blast furnace slag can also be used to replace limestone to a much greater extent. In addition, demolished concrete can be re-used as aggregates in road construction and the manufacture of new concrete, thereby recycling carbon to the built environment. NS-EN 16757 requires that carbonation must be included in the calculations for the modules B1, C3, C4 and D.

6.3 Comparison of the climate impacts of timber and concrete structures

What is the best choice of materials for construction from an environmental perspective? What do the different Nordic studies studying the environmental impact of buildings conclude? And what are the factors influencing the environmental impact of buildings?

To understand the factors affecting the environmental impact of buildings, the whole life cycle needs to be considered along with conceptual parameters which have an impact on the total emissions of a building.

In 2018, Norwegian standard NS 3720:2018 for GHG calculations in buildings was published. It describes a methodology for GHG emissions connected to the lifetime of a building for the purpose of comparison of the results across different tools and models. It also describes rules for both complete GHG calculations and for various partial calculations and stipulates that a basic overall GHG calculation for a building without location must include emissions from the site, materials, and energy in operation. The scope of NS 3720 is to assess how different building materials, energy-efficient renovation strategies, and end-of-life scenarios affect the environmental profile of a building in the Nordic region.

Recent studies have focused on the development of building materials with low GHG emissions that can mitigate climate change, either by reducing the emissions or storing carbon in the long term. Consequently, wooden buildings have been characterized as low-carbon constructions compared to non-wooden buildings, and wooden construction represents a lower embodied energy consumption than concrete (Petrovic et al. 2019; Rinne et al. 2022).

Such studies should include a whole building for an entire life cycle including maintenance, replacement, operating energy requirements, end-of-life, and disposal. Options should include possible scenarios for beyond end-of-life (re-use, recovery, recycling). In the following, the environmental impacts of a number of Nordic studies are given comparing timber and concrete structures.

The environmental impacts of a 5-storey hybrid apartment building were compared to timber and reinforced concrete counterparts in a whole-building LCA (Rinne et al. 2022). All stages of the product and construction (A1-A5), use (B1-B6), end-of-life (C1-C4), and recovery (D) were assessed. The functional unit used was kg CO_2e. The results found that the timber apartment had the lowest carbon footprint (28% less than the hybrid apartment) for modules A1-A3, whilst the carbon footprint was even lower in module A4 (55% less than the hybrid apartment). However, in modules B1-B5, the carbon footprint for the timber apartment was greater by about 20%. In modules C1-C4, the concrete apartment had the lowest emissions of about 35061 kg CO_2e whilst that of timber was highest with about 44627 kg CO_2e. In module D, timber was the better material owing to the options of recycling.

Hegeir et al. (2022) performed a comparative LCA of timber, steel and concrete portal frames in modules A1-A4. Portal frames with variable spans were designed to meet similar load-bearing capacity, with reinforced concrete in the foundation of all frames. Steel dowels and bolts were used in the connections of timber frames. All frames were assumed to be subjected to a uniform live load of 0.4 kN/m^2 at the roof and the columns were pinned to the foundations for all building frames. The functional unit was set to kg CO_2e/m^2. The system boundaries were set to product stage in modules A1-A4. The results showed that steel frames had a total global warming potential per square meter (GWP/m^2) that was higher than concrete frames and much higher than timber frames. Timber frames had a negative net GWP/m^2 although concrete was used in the foundation. The study concluded that timber had better environmental impact than concrete due to the carbon stored in the wood but did not account for whole-life carbon.

One study was conducted on two residential buildings that are functionally identical, and dimensioned to the same fire, acoustic and load conditions (Ruttenborg 2020). The system boundary considered in the study was the product stage (A1-A3). The calculations were for a glued laminated timber and concrete construction. Both buildings were assumed to have a service lifetime of 60 years and that none of the building members are replaced during the lifetime. Using two different data sets (Arda and EPD), the results showed that the total emissions from the wooden building was about 354 242.3 and 185 768.4 kg CO_2e, respectively. Total emissions from the concrete building were found to be 354 644.5 and 302 290.4 kg CO_2e, respectively. Sensitivity analysis showed that both materials are crucial for the results obtained and that they contribute more than 40% of the total emissions in both buildings and for different calculation methods.

Another study looked at different structural solutions based on the same architectural drawings and requirements (Malmqvist et al. 2019). Three concrete solutions including 1) cast-in-place concrete slabs, external and internal walls, 2) cast-in-place concrete slabs, load-bearing internal walls and external lightweight walls reinforced with steel and steel pillars in the façade and 3) soundproof concrete hollow core slabs with Granab flooring system. Two timber solutions were also considered including 1) prefabricated volume elements in wood b) external soundproof walls and slab in solid glued laminated timber elements. The study included product stage modules (A1-A3), manufacturing stage (A4-A5), use stage (B1-B6) and end-of-life stage (C1-C4). The five structural solutions were designed with an operational energy use of 41 kWh/m^2 ·A_{temp}. The results showed that timber solutions had lower emissions overall, compared to concrete solutions and the product stage is the critical factor. The results for the product stage were 176 and 167 kg CO_2e/m^2 ·A_{temp} whilst that of the concrete solutions were 279, 234 and 218 kg CO_2e/m^2 A_{temp}.

Other comparisons were made for wood and concrete structures for buildings with 4, 8 and 16 floors (Rønning and Tellnes 2018). Three different scenarios were made for the concrete and only one was made for the timber structure. Whilst EPDs of cross-laminated timber and glued laminated timber were used for the timber products, data were obtained from concrete manufacturers. The comparison showed that the timber structure had the lowest emissions for buildings with 4 floors, whilst concrete structures had the lowest emission at 16 floors. The difference between the best concrete solutions and the timber solutions was minimal for the 8-floor high building. The total emissions from the concrete building with 8 floors were between 65 and 85 kg CO_2e, whilst that of the wooden building was about 70 kg CO_2e. In a single-family house LCA, Petrovic et al. (2019) showed that concrete slab and thermo-treated wood had the highest environmental impact whilst untreated wood-based materials including cellulose insulation and wooden frame had the lowest impact.

Using timber from sustainably managed production where biogenic carbon is assumed to be constant, Skullestad et al. (2016) used LCA to compare the climate impact for building heights of 3 – 21 storeys. LCI data on timber were obtained from Norwegian forestry and timber producers. Emissions in the forest supply chain were calculated from fossil fuel used by machines and trucks, as well as from electricity consumption. The study used three calculation approaches and scenarios and found that timber structures caused lower climate impact compared to concrete structures. The functional unit in the study was kg CO_2e per building and system boundaries within the product stage A1-A3. Whilst concrete had an environmental impact between 4 471 874 – 1 010 788 kg CO_2e for the 7-storey building, timber building had an environmental impact between 174 522 – 220 415 kg CO_2e. By applying attributional LCA, timber structures were found to cause a climate change impact that is 34-84% lower than that of reinforced concrete. When we observe per square meter floor area, the climate change saving by substituting a reinforced concrete with a timber material decreases slightly with building height up to 12 storeys but increases from 12 to 21 storeys (Skullestad et al. 2016).

Emissions from timber structures to concrete and steel material solutions were compared in another study (Hofmeister et al. 2015). The timber structure was dimensioned to the same load, fire, and sound condition as the concrete structure. Modules included in the LCA consisted of the product stage (A1-A3), end-of-life phase (C3-C4) and product recycling and energy recovery phase (D). The functional unit represented in the study was 1 m^2 of a total of 1 980 m^2 heated floor area over a period of 60 years. The results showed that the timber structure has lower GHG emissions for all approaches and scenarios, with a value of 1.8-2.1 kg CO_2e/m^2/year compared to 3.2-3.5 kg CO_2e/m^2/year for the concrete and steel structure.

6.4 Comparability of the studies

Usually, you would not want to rely on one study when comparing the environmental impact of building materials, or more specifically how concrete performs compared to timber in buildings. Then, the available studies must be compared very carefully.

Table 2 compiles cases from recently published literature from the Nordic countries and can be useful for comparing the studies on the environmental impacts of buildings constructed or projected with these two building materials. Older studies have been reviewed in Hill and Zimmer (2018).

Table 2. Summary table of the technical details of the studies comparing the climate impact of building structures.

Author(s)		Country	Building material(s)	Case subject	Type of building	System boundary	Functional units	Biogenic carbon
Andersen et al. 2022		Norway	Wood, steel, concrete	Buildings with 5 and 8 floors	Residential	All stages	kg CO_2e/m^2	Yes
	Remarks	The lifespan of the building was modelled as 100 years. Operational energy use was modelled based on electricity and exact data was not available.						
Hegeir et al. 2022		Norway	Wood, steel, reinforced concrete	Portal frame	Office	A1-A4	kg CO_2e/m^2	NA
	Remarks	Reinforced concrete was used in the foundation of all frames. The study did not examine the energy performance/maintenance, etc., or end-of-life issues and therefore does not report on whole-life carbon.						
Rinne et al. 2022		Finland	Concrete, wood, hybrid	Building with 5 floors	Residential	All stages	kg CO_2e/m^2	NA
	Remarks	The analysis was done for the environmental impact from building materials of assemblies, construction, and end-of-life treatment of 50 years.						
Ruttenborg 2020		Norway	Wood, concrete	Building with 8 floors	Residential	A1-A3	kg CO_2e	No
	Remarks	The calculations were for a glued laminated timber and concrete construction. Both buildings were assumed to have a service lifetime of 60 years and that none of the building members are replaced during the lifetime. The analysis did not include heating, ventilation, and other power consumptions.						
Malmqvist et al. 2019		Sweden	Wood, concrete	Slabs and walls	Office	All stages	kg CO_2e/m^2	No
	Remarks	Three concrete- and two wood solutions were studied, all five designed with an operational energy use of 41 kWh/m^2. This was assumed to be the same for all structures over the building lifetime.						
Rønning and Tellnes 2018		Norway	Wood, concrete	Buildings with 4, 8 and 16 floors	Office	A1-A3	kg CO_2e	NA
	Remarks	Three different scenarios for the concrete and only one scenario for the wood were considered. While EPDs of cross-laminated timber and glued laminated timber were used for the timber products, specific data were obtained from concrete manufacturers.						
Skullestad et al. 2016		Norway	Wood, concrete	Buildings with 3, 7, 12, 21 floors	Office	A1-A3	kg CO_2e	Yes
	Remarks	The study did not examine the end-of-life issues and therefore does not report on whole-life carbon.						
Hofmeister et al. 2015		Norway	Wood, steel, concrete	Building with 4 floors	Office	A1-A3, C3-C4, D	kg CO_2e/m^2	NA
	Remarks	The timber structure was dimensioned to the same load, fire, and sound condition as the concrete structure. Due to lower weight, the foundations and basement walls were downsized in the wood scenario.						

From Table 2, it is evident that it is almost impossible to make useful comparisons between studies for the two building materials under investigation. For example, where similar materials have been analysed within the same system boundary and functional units, it is still possible to observe differences in the case subject and/or type of buildings. The energy requirements of a residential building are different from those of an office building. Where two or more similar building types have been studied, the case subject may differ significantly. The GHG emissions calculations for the same building height may differ due to the material design and assumptions in the study. Different engineered wood products have different GHG contributions.

LCA is an established tool for evaluating the environmental impact of buildings, but the use of different functional units and system boundaries significantly affects the results in a consequential LCA. The choice of materials has a critical impact on GHG emissions in a life cycle perspective. Timber and concrete products have their characteristic climate impact, which is either underestimated or overestimated due to several factors including methodology, data credibility and study rationale. Differences in included building elements and system boundaries make comparison difficult because equal boundaries are critical for comparison of studies. The GHG premiums for the two structural alternatives depend on the structural premiums and reflect how the structural material quantities per square meter increase or decrease with building height.

From the foregoing, there are several reasons why the timber structure outperforms the concrete structure with respect to environmental impact in this study. The major consideration is that timber structure consists of materials with lower emission factors, hence timber structures caused lower environmental impact than concrete structures. However, contextual parameters and system boundaries highly impacted the results of those studies. To simplify the LCA comparison, most of the studies included the main structural elements of a building instead of the whole building LCA. This was done based on the assumptions that all the other building components have the same environmental impact, which may not be practical. It is notable to mention that finetuning the design of materials and using recycled materials or those with low environmental impacts will have a significant effect on the GHG emissions. In addition, many of the studies did not examine end-of-life scenarios, which can also have an impact on the GWP of the product. Consequently, the effect of changing the building materials is thus not conclusive.

7 Glossary

Abbraviation	English term	Norwegian term
LCA	life cycle assessments	livsløpsvurdering, livssyklusanalyse
LCIA	lifecycle impact assessment	livsløps konsekvensutredning, livsløpseffektvurdering
LCI	lifecycle inventory	livssyklusopplysninger, livssyklusinventaret
ALCA	attributional LCA	ofte også på norsk: attributional LCA
CLCA	consequential LCA	ofte også på norsk: consequential LCA
kg CO_2e	kg carbon dioxide equivalents	kg karbondioksid ekvivalenter
GHG	greenhouse gas	drivhusgass, ofte også klimagass
GWP	global warming potential	global oppvarmingspotensial
ODP	ozone depletion potential	potensialet for ozonnedbryting
PCRs	product category rules	produktkategoriregler
EPD	environmental product declaration	miljødeklarasjon
luluc	land use and land use change	arealbruk og arealbruksendringer
HWP	harvested wood products	treprodukter
IPCC	Intergovernmental Panel on Climate Change	FNs klimapanel
GaBi	common industry-standard database	ofte brukt database
Ecoinvent	common industry-standard database	ofte brukt database

declared unit: weight, volume or area of a material	deklarert enhet: vekt, volum eller areal av et material
functional unit: product with defined function (such as a window or door)	funksjonell enhet: produkt med definert funksjon for eksempel vindu eller dør
goal: reason for the study	mål, hensikt til studien
scope: the system boundary	omfanget av studien

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