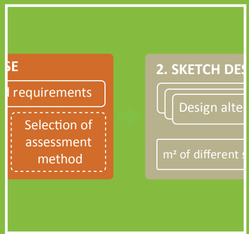
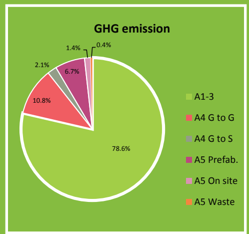
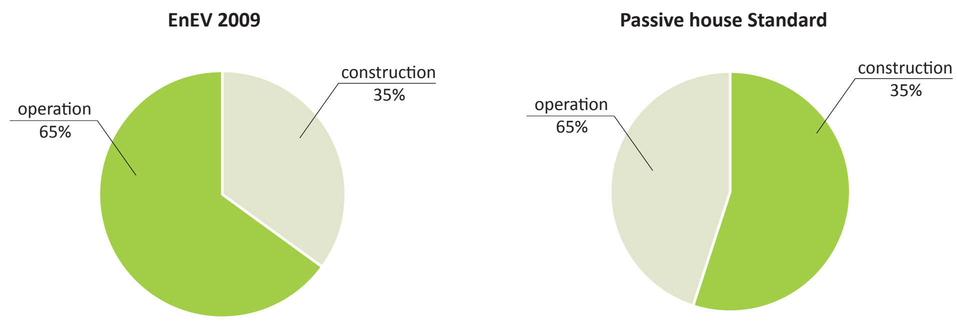
6. Good practices for carbon efficient wood construction





6 GOOD PRACTICES FOR CARBON EFFICIENCY IN WOOD CONSTRUCTION

F.6.1-1



6.1 Goal setting and requirements

A. Hafner, S. Ott, S. Winter

In this section, the scope of LCA and carbon footprint is to describe the environmental properties in the lifecycle of a building. It is done to improve the environmental performance of buildings. Therefore the borders of practical LCA as described in Section 4.5.2 are applied.

The use of wooden material for buildings involves some major advantages: the environmental impacts of wood are beneficial especially in terms of greenhouse gases and renewable primary energy. Also carbon is stocked in material and is regarded as a carbon sink. In terms of primary energy, renewable wood shows benefits. Here the embodied primary energy in material is a positive attribute for the end-of-life phase because it can be consumed. This can be shown through LCA and carbon footprint.

External benefits from such carbon efficient construction can include:

- Marketing for low carbon constructions;
- Improved reputation;
- Enable stakeholders to understand the true values of selected construction.

LCA calculation in lifecycle

Up to now, the operation phase has been regarded as the most dominant in the life cycle of buildings in terms of energy consumption resulting in greenhouse gas (GHG) emissions. Here the energy standard of the building envelope interacts with the energy consumption in the use phase and the used energy sources. Much attention has been paid on reducing energy usage in the operation of buildings, and several types of energy-efficient houses have been developed. As a result of decreasing the energy consumption in the operation phase, the other life cycle phases become more important (Figure F.6.1-1). Maintenance in the use phase is also important for calculations in the life cycle. Maintenance depends highly on the durability of materials and their exchange rate. For more information, see Chapter 7.

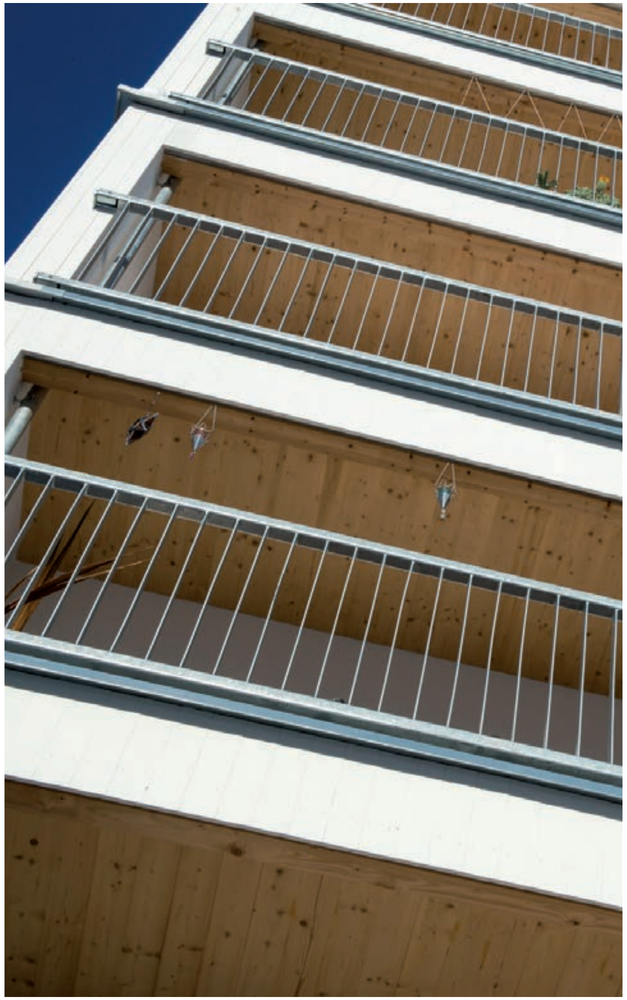
For buildings achieving a high energy standard, the impacts of module A can have an overall effect up to 50% or more. Therefore more attention needs to be given to the module A phase. And with that, the choice of building material comes into focus.

In module A, especially the production phase of building components (module A1-A3) has been discussed actively in connection with LCA of construction products. However, there have been few detailed assessments for construction work (module A4-A5). For more information, see Section 6.3.

Strategies for goal-setting

The preliminary goal-setting for sustainable building is done by the owner. Targets are outlined for building performance, environmental impact and economic impact. Building performance can be divided into the following elements: functional, technical and social qualities. Life cycle targets are also high-level targets that are important for sustainable buildings. When the project receives a positive decision, this stage ends up in the formulation of the target definition document. Environmental targets should be set with the help of core environmental indicators and contain at least carbon footprint, primary energy non-renewable and water. Detailed target setting needs information about relevant benchmarks. Benchmarks are already in development for sustainable buildings. This can be used as a possible reference.

When a competition program for sustainable building is created, it is necessary to define assessment methods and system boundaries



F.6.1-2

F.6.1-1 Dominance of construction and operation of different energetic standards in a life cycle analysis of an exemplary comparison
F.6.1-2 Detail of the facade from Augsburg – Grüntenstr. housing building

to achieve comparable assessment results. At the beginning of a project, it is vital for achieving carbon-efficient construction to set clear goals for the project. See also Figure F.6.1-2.

The goals can be the following:

1. Documentation of the carbon footprint
2. Internal quality control
3. External certification of the building
4. Optimization of environmental performance of the product

Goals can be reached for all phases of the life cycle. But not all goals can be reached at the same time.

- Documentation of the planning phase
- Documentation of the as-built state

For the documentation of carbon footprint performance, two main strategies are available, both influencing each other:

Quality control is related to goal-setting or benchmark use to reach a certain level of quality. Quality control can be done individually for each stage of the building project as shown in Figure F.6.1-2. It can also be part of an iterative process for monitoring the whole project. The achieved results are continuously compared to the set targets. When targets are not met, either corrective actions should be done or – in the case of justified reasons – the targets should be reformulated.

- Start goal-setting with the pre-design phase
- Use as a decision-making tool
- Optimization of the design phase
- Control of the production and prefabrication phase
- Documentation of quality

In various stages, quality control focuses on different issues:

External certification of the building is related to available systems on the market (BREEAM, LEED, BNB/DGNB, etc.). It has to follow the rules of these systems. The most recent systems take LCA calculations (DGNB, Openhouse) into account. In terms of optimizing construction based on ecological matters, there can be differences in the perception, as some systems only include GHG emissions and others use a wide range of indicators. It has to be noted critically that for a holistic understanding, it is not sufficient to assess only carbon footprint. Issues of resource- and water efficiency have to be considered.

Optimization of the product "building" throughout the whole development of building is the most advanced or demanding task. It is an iterative process. Several steps have to be made towards an optimized solution from defining first goals, alternative solutions, problem identification, improvements, etc.

This has to be done especially for all steps of the design process and also for the production process. It can or should cover all stages or phases of life cycle.

Requirements for practice

Design phase

- Strong influence on the primary structure (material) decision
- Definition of the required service life
- Energy demand goals
- End-of-life scenario choice

Pre-project stages allow the following:

Nowadays lifecycle assessment calculations often get commissioned during the planning process to be realized for buildings. With the results, the clients tend to decide which materials to use and then use the results for their marketing. Results and advantages of LCA need to be shown in a transparent and understandable way. If the results are not as promising, options for improvement should be shown. Up to now, improvements consist mainly in energy performance, as this still has the main influence. Improvements also can be made by reconsidering the durability of materials, as this influences the maintenance in use phase. Also adjustments in material choice for construction of buildings are possible. Here material choice and functional use of material are connected.

F.6.1-3

For example, foundations have a huge effect on share of primary energy and GHGs. Section 6.2 deals with the design of a low-carbon wooden house.

Production phase

- For producers of buildings: results help to optimize the production, lower energy demand and less GHG. Prefabrication processes can play a dominant role for wooden buildings. Chapter 5 discusses the sustainability aspects of the production phase.

- For the planner and client: Minimize the use of primary energy and GHG in the production and erection of a building. Here wood can show its advantages by storing carbon. For steps to fulfil the requirements, see Figure F.6.1-2.

Assessment can have various benefits – on the producer side as well as on the planner side.

6.2 Designing a low-carbon wooden house

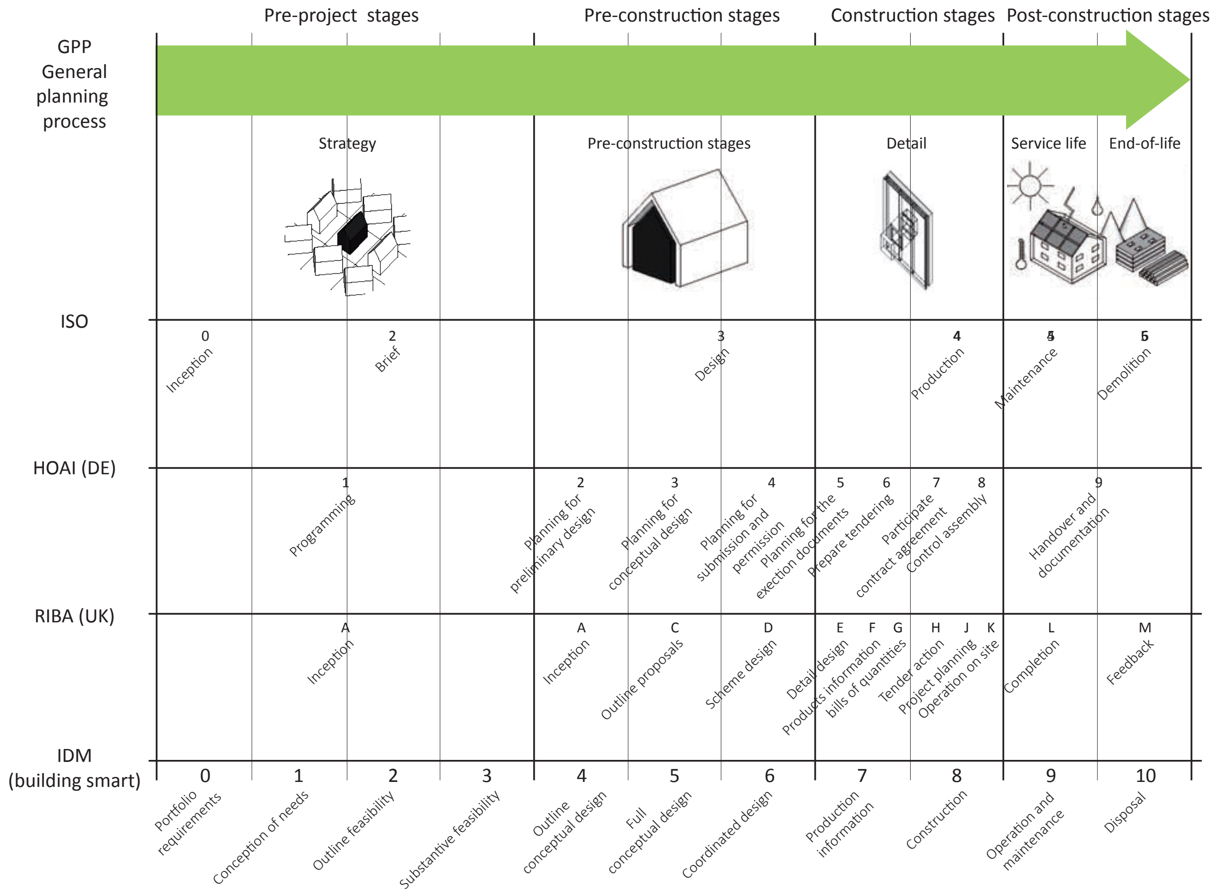
M. Kuittinen, T. Häkkinen

In the early design phase, there is often not enough information available that is required for making a life cycle assessment. In a standard-based LCA, it is allowed to cut off parts of the assessment that have less than 1% significance for the end result . Because this cannot be known without conducting an exhaustive LCA, it is formally very difficult to assess the carbon footprint in the early design stage.

The design of a building can be simplified into the following stages:

Phases

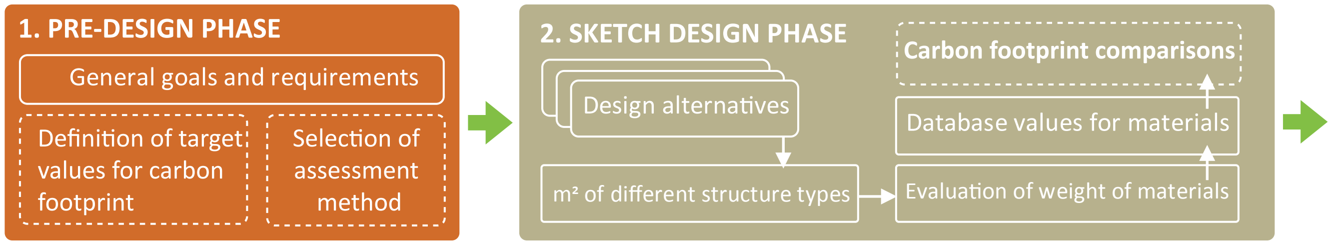
1. Pre-design
2. Sketch design
3. Final design
4. Working drawings
5. Tendering
6. Construction supervision
7. Final documentation



F.6.1-4

F.6.1-3 CLT school in Egglham, Austria
F.6.1-4 Strategies for goal setting and requirements

- Goal setting for carbon efficient buildings must be done by the owner at a very early stage.
- With the increase of energy efficiency in the use phase, the primary energy for construction becomes important.



F.6.2-1 Schematic diagram for the design process of a low carbon wooden house

In the following, the potential for designers to influence the carbon efficiency of the building is discussed.

Pre-design phase (1)

The pre-design phase should provide the designers and construction teams with goals and metrics for achieving the required carbon footprint levels in the building. Therefore the selection of the methodology for carbon footprint assessment is very important. Using normative technical standards – such as EN or ISO – is usually the most relevant approach since they are followed by industry and authorities. The possible reporting and documentation of CFP for other uses also needs to be considered so that all carbon footprint-related information can be gathered in the required format. Such uses can be requirements from authorities, possible green building certification schemes (LEED, BREEAM, DGNB) , public communication or marketing materials.

Furthermore, a clear functional unit for carbon footprint assessment should be decided upon. Typically, the relevant functional units are m^2 of gross or net floor area or m^3 of gross or net volume of the building.

The selection of goals and methodology should be done by the client or mandated to an experienced LCA or carbon-footprint assessor.

Sketch design phase (2)

Preliminary design seems to be the most important of all operative phases in meeting the required carbon footprint level. All major issues – such as size, shape and orientation of the building, construction materials, functions and energy concept – are solved in the preliminary design phase. The following design phases are usually bound to these decisions, and the later influence is deemed to have only an iterative nature.

Given the high importance of the preliminary design phase, it requires the well-planned cooperation of the design team from the beginning, as already recognised in near zero energy buildings design projects.

The preliminary design phase should also include a preliminary carbon footprint assessment. That can be based on comparing initial mass calculations – with the help of BIM – to general environmental data of construction materials and products. Such data is provided by construction federations or acquired from databases. Since material providers are normally not known at this phase, the preliminary carbon footprint can only give rough estimations. Still, it can show differences between design alternatives and is therefore valuable in decision-making. However, if more accurate carbon footprint figures are required in preliminary design phase, a correction factor should be used to normalise the results of preliminary carbon footprint estimation.

Final design (3)

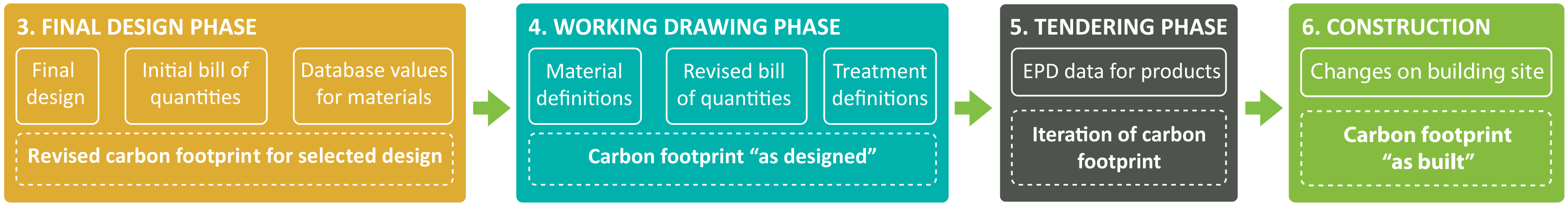
The final design follows the preliminary design proposals that have been accepted by the client or his representative. This acceptance should also include the acceptance of the practical means to reach the required carbon footprint level per selected functional unit.

For the acceptance, the design team should give a detailed carbon footprint estimation that is based on finished design, preliminary bill of quantities, and the energy certificate of the building.

If the building will be marketed, the carbon footprint estimation can be used along with green building certification pre-certificates, such as LEED, BREEAM or DGNB.

Working drawings (4)

Working drawings from each member of the design team enable a detailed assessment of the carbon footprint of the building, based on reliable technical information such as the environmental product declaration (EPD). Based on initial research findings, the



carbon footprint estimation at this stage will be relatively close to the final carbon footprint calculation at the construction stage.

The use of BIM is also recommended since the changes in design can be directly observed as changes in the bill of quantities, and its changes can be taken into the carbon footprint assessment. At this point, it is possible to calculate the carbon footprint for "building as designed". However, changes in the following phases can still alter the carbon footprint of "building as constructed".

From the designer's viewpoint, the easiest way to calculate buildings carbon footprint would be to rely on EPDs. In reality they are still not available for all products. However, there can be significant differences between the carbon footprint of a product manufactured by different companies because of different energy sources or transportation distances. If a designer wishes to ensure an easy comparison of materials' carbon footprint performance in later phases, there should be a claim in the building documentation about using or preferring products that have an EPD. Otherwise it will be time-consuming in practice to evaluate the carbon footprint effect of a change of product in the tendering and negotiation phases. So at this point at the latest, all database data that has possibly been used for carbon fooootprint estimations should be replaced with data from EPDs.

Tendering (5)

Typically, iteration in the tendering phase deals with finding alternative materials or treatment methods for certain products. From the carbon footprint viewpoint, this is a delicate issue since economic preferences tend to dominate and because material tendering is often given to competing construction companies. The design team and assessors seldom have a strong influence on their choices. Therefore the client should ensure a sufficient amount of consultation between construction companies, material providers and the design team or assessors in order to ensure that materials or working methods will not jeopardize the carbon footprint goals.

Construction supervision (6)

Supervision during the construction phase usually deals with solving encountered construction problems or detailing. In such consulting, material-related changes that might alter the carbon footprint balance are less likely than changes that are related to construction work. Changes in construction work may require deconstruction of wrongly built parts, repeated surface treatments, replacement of broken components or similar tasks. Although a designer might choose not to demand that a mistake be repaired in or to maintain keep the carbon footprint levels as planned, other functional, normative or technical reasons often force such changes to be carried out. Therefore, special attention must be paid to the supervision of the building site. Possible losses, surplus orders of materials, mistakes or accidents will inevitably lead to greater carbon footprint than planned.

Therefore the final carbon footprint of a building should not include the construction phase, because a strict carbon footprint level would lead to shortcuts on the building site. Especially rainy or cold construction conditions may significantly add to the energy demand on the building site, let alone possibly require re-casting of concrete with an accelerated drying time requirement with the help of chemicals and heat.

Supervision during possible repairs and renovations is comparable to a new construction project. Depending on the scale of the renovation, all previously described steps can be adapted if the carbon footprint goals are set for the renovation.

Final documentation (7)

Preparing a plan for changes and deconstruction is a recent proposal of environmentally conscious design. It is mostly a responsibility of the design team. Because very few examples of "design for deconstruction" exist to date, this task can be based on considering the construction steps in reverse order. If components of the building can easily be deconstructed with typical machinery, the carbon footprint in module C is likely to remain on a similar scale as in module A4-5.

The moisture content of deconstructed material that is aimed for re-use or energy recovery has to be optimized. If feasible, it would be advantageous to keep energy waste dry, so that its energy content would not decrease.

Towards carbon-conscious design

If the building sector wishes to contribute to the reduction of greenhouse gases and primary energy use, a systematic design process needs to be developed. As the operative energy use is reduced along with better energy efficiency, other parts of the life cycle increase their share in the emissions of a building's life cycle.

The motivation for reducing the carbon footprint of buildings is not yet financial. As long as there are no direct normative requirements for it in the EU, low-carbon house projects have so far remained on an experimental level and are based on ideological choices. If the legislation changes towards including emission taxation on construction products as well, economic reasons could start increasing interest in carbon-efficient design and construction.

To ensure that there is enough reliable data for designers, product manufacturers should start preparing EPDs in a comparable way. Construction associations or related organisations could collect that data and make it available.

Today, carbon-efficient design is a differentiating opportunity for designers and construction companies. Tomorrow, it is likely to be included in regulations. Pioneers will have the easiest adaptation periods and gain a competitive advantage.

6.3 Construction

A. Takano, F. Pittau

6.3.1 Introduction

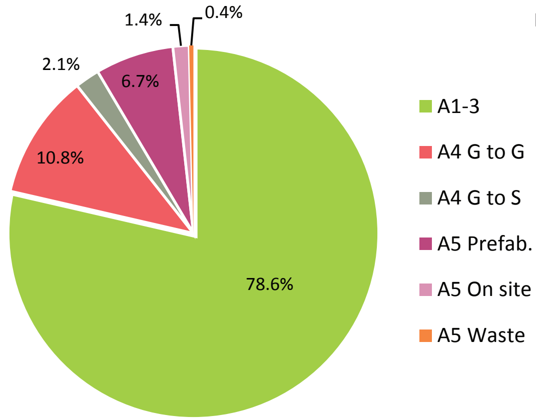
In this section, a feature of the environmental impact from the construction stage (module A4-5) is reviewed through literatures and case studies.

In a building LCA or carbon-footprint calculation, major attention has been paid to the use phase of a building due to its high share of environmental impact in a building life cycle. As a result of such effort, the impact from the use phase has been mitigated and the importance of the other life cycle stages has increased [1]. In general, the construction material production phase has been regarded as the next target of mitigation, and the other phases (such as construction, transportation and demolition) have not had priority because those phases normally account for a small proportion of the life cycle environmental impact [2]. It was reported that the construction phase contributes less than 10% of the overall life cycle impact of a building in many cases [3, 4, 5]. Therefore, the impacts from the construction phase have so far been ignored or just estimated in many studies [6].

However, recent research papers have mentioned that the construction phase has a relevant impact, and the trend of GHG emissions from construction equipment has increased significantly in the last decades [6, 7, 8]. They have claimed that the process should not be underestimated and they have attempted to establish the framework for environmental management during the construction phase. Although an optimization of the construction phase may not have a significant effect on the overall life cycle impact of a building, it would have a major impact at an industrial (aggregated) level. The environmental impact of the process should be known in order to optimize it for constructors and designers.

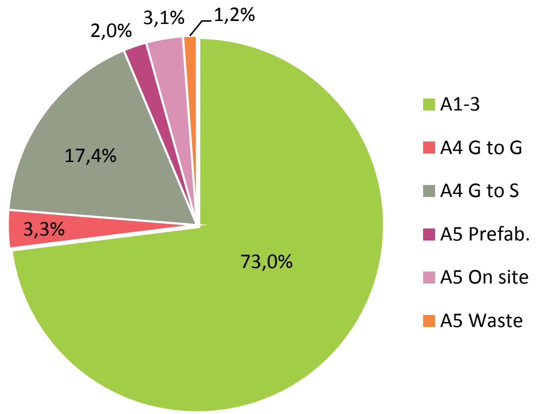
To review the environmental impact of the construction work, detailed data collection and the assessment for construction work have been conducted for three reference buildings: Mietraching (Germany), Joensuun Elli (Finland), and L'Aquila (Italy). Since the

F.6.3-1



GHG emission (kgCO_2-eq/m^2 of living area)					
A1-3	A4 G to G	A4 G to S	A5 Prefab.	A5 On-site	A5 Waste
171	23	5	15	3	1

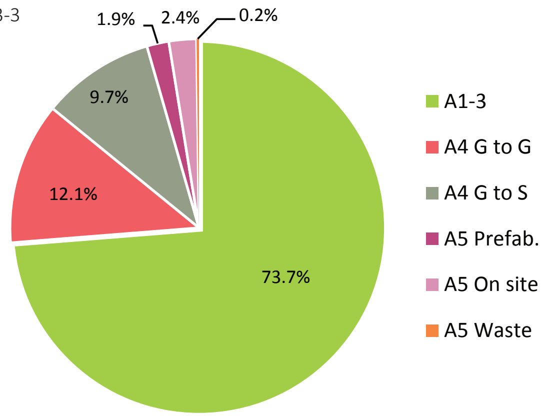
F.6.3-2



GHG emission (kgCO_2-eq/m^2 of living area)					
A1-3	A4 G to G	A4 G to S	A5 Prefab.	A5 On-site	A5 Waste
283,9	12,7	67,6	7,8	12,2	4,6

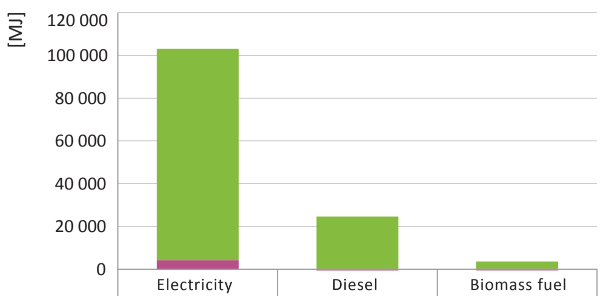
F.6.3-1 GHG emission during the production stage of Mietraching
F.6.3-2 GHG emission during the production stage of L'Aquila

F.6.3-3



GHG emission ($kgCO_2$-eq/m² of living area)					
A1-3	A4 G to G	A4 G to S	A5 Prefab.	A5 On-site	A5 Waste
275	45	36	7	9	1

F.6.3-4



	Electricity	Diesel	Biomass fuel
PE-nr	98888	24492	3427
PE-r	4189	95	119

F.6.3-3 GHG emission during the production stage of Joensuun Elli

F.6.3-4 Primary energy consumption during the prefabrication process of Mietraching (wooden building elements only) according to the consumed energy resources

specification of a basement differs significantly between the reference buildings and there are several uncertainties in non-wooden building element (e.g. prefabrication of steel staircase), the results shown in this section are limited to the material production and construction stage of the wooden building element of the buildings in order to make the results comparable. General information of the reference buildings, assessment condition, and LCA results with full inventories are described in Chapter 8: Case studies.

Based on the study results, possible improvement points, required documents for the assessment, uncertainties, and limitations of assessment are also discussed. The purpose of the study shown in this section is not to accurately quantify the environmental impact of construction work, but rather to understand the outline and to demonstrate LCA following a real construction process. Thus, the results are based on a limited condition of assessment and are not comparable with other study results.

6.3.2 Dominance of construction phase

Figure F.6.3-1 shows a dominance of each phase in the production stage (module A1-5) of the Mietraching building regarding GHG emissions. The material production phase (A1-3) and the construction phase (A4-5) account for approximately 80% and 20% of total GHG emissions, respectively, for the production of wooden building elements. In the construction phase, the transportation of products from the production gate to the prefabrication gate (G to G) and prefabrication process (A5) has a major impact.

Since the wooden building element of Mietraching has been fully prefabricated in the factory, including exterior cladding, windows, and doors, on-site assembly work has taken only about three weeks including all secondary work. This high level of prefabrication is reflected in the result. The waste management mainly consists of incineration of wood residues from prefabrication and on-site construction work. Therefore, GHG emissions are very low in this phase.

Figure F.6.3-2 shows the same issues with the L'Aquila building case study. The results show a different trend from Mietraching. While the material production phase still holds the most relevant share (73% of the total), the prefabrication process accounts for only 2% of the total, with on-site construction accounting for about 3%. The main difference can be seen at the on-site construction compared to Mietraching, since L'Aquila has a relatively low level of prefabrication within the wooden building elements. Also transportation plays a fundamental role, accounting for approximately 3% from gate to gate (G to G) and approximately 17% from prefabrication gate to building site (G to S). Waste management plays a less relevant role, with a minor influence on the overall result.

Figure F.6.3-3 presents the results of Joensuun Elli. The material production phase (A1-3) holds approximately 75% of the total emissions. One remarkable point is that the transportation process (A4) accounts for approximately 20% of the total, and actual construction work contributes very minor GHG emissions. This result originates from the very long transport distance of the main structural material and prefabricated building elements. (See Chapter 8: Case studies.) The on-site construction process has a very minor share in the total because of a high prefabrication level, as with the Mietraching building.

From these three results, it is understood that the material production phase (module A1-3) accounts for approximately three-fourths and the construction phase (module A4-5) holds approximately one-fourth of GHG emissions in the production stage of wooden building elements. Although there are some differences in each case, the trend is clear. In addition, it is remarkable that the transportation process, module A4, has a relevant impact. The L'Aquila case shows relatively higher GHG emissions in each phase than the other two cases because it was a renovation project in a stricken area.

6.3.3 Construction process: Prefabrication

From this section, each unit phase in the module A4-5 is reviewed individually.

In order to secure the accuracy and work efficiency of construction, prefabrication is the main construction method in northern and central Europe. Regarding LCA of prefabrication work, possible inventories are electricity consumption for a production line in a factory (e.g. construction machine operation, lighting, and ventilation machine operation), space heating/cooling energy, and fuel for operation of construction machineries. Basically it is not easy to collect these data accurately from a company due to lack of resources and time in the current situation of the industry. In addition, several projects are going at the same time in a factory. Therefore, the allocation of consumed energy and used material to each project needs to be considered.

One of the most important purposes of LCA in this phase for the industry would be to get a hint for the optimization of the process. Therefore, it would be more important to understand a dominant process in the production line and find out possible remedies rather than knowing an exact value.

As an example, Figure F.6.3-4 shows the primary energy consumption value for the prefabrication process of Mietraching according to the consumed energy resources. Electricity is dominant; it is consumed in machine operation, lighting and ventilation of the factory. Diesel is consumed in operating forklifts; and biomass fuel (wood residues from the prefabrication process), is for generating heat energy. Figure F.6.3-5 shows GHG emissions according to energy resource. From these figures, it is clear that optimizing electricity use during prefabrication is the first priority. The same trend could be seen in the prefabrication process in the Joensuun Elli case; about 95% of GHG emissions originate from electricity use (Figure F.6.3-6).

In principle, prefabrication work needs adequate floor area and space in a factory. Naturally the operation of such space consumes a large amount of energy. Space heating was the dominant energy consumer in both cases. However, as mentioned before, space heating energy is generated with process wood residues. Therefore, electricity use finally became the dominant factor for both primary energy consumption and GHG emissions during the prefabrication

A reduction in electricity use would be relatively easy. A good starting point would be optimization of the prefabrication process (e.g. proper process management and scheduling), optimization of a factory operation (e.g. adjusting the brightness of the factory according to the weather and adjusting the ventilation frequency according to the season and the work). Electricity use for the operation of a factory seems to be larger than the prefabrication machine operation, which would mean a greater potential for optimization.

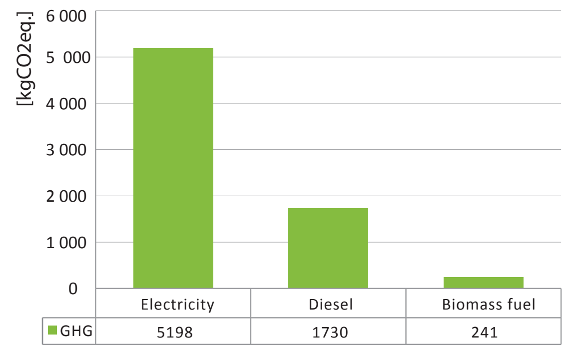
For the assessment, monthly electricity consumption, space heating/cooling energy consumption and bills for the fuel are a relevant information source. In order to allocate such energy consumption data into different projects running at the same time in a factory, the monitoring of working hours per project is helpful. This monitoring would also help to recognize which unit process consumes more energy and time in the production line. This distinction helps the optimization of the production process environmentally and economically. The physical basis (e.g. production volume or floor area of each section in a factory) can also be utilized for allocating consumed energy and materials. Direct monitoring of electricity use with a measuring instrument would be a relatively easy method as well and would provide more accurate results than the aggregated monthly data.

The assessment of this phase may tend to be rougher compared to the assessment of module A1-3 due to the current working situation in the industry (e.g., lack of resources). Due to a lack of information, this study also includes some assumptions based on the company's experience, the average value of the factory, and so on. A proper monitoring plan needs to be prepared in order to collect relevant data comprehensively. Further research and practice are required on this issue. The importance of managing prefabrication work from the environmental viewpoint will increase in the near future.

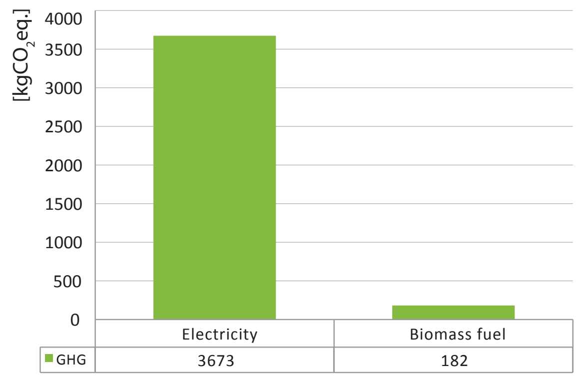
6.3.4 Construction: On-site work

Naturally the share of on-site construction work is affected by the level of prefabrication. When on-site construction work is only an assembly of prefabricated building elements, as in the case of Mietraching, the environmental impact from this phase is minor.

F.6.3-5



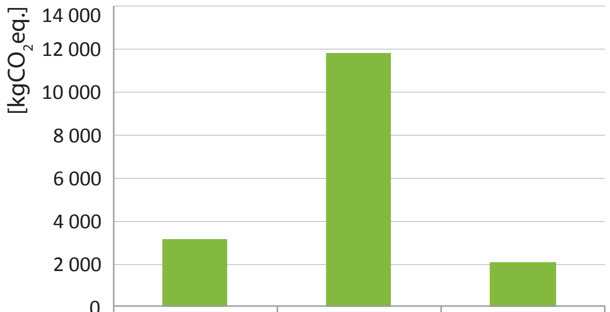
F.6.3-6



F.6.3-5 GHG emission from different energy source during prefabrication of Mietraching (wooden building elements only)

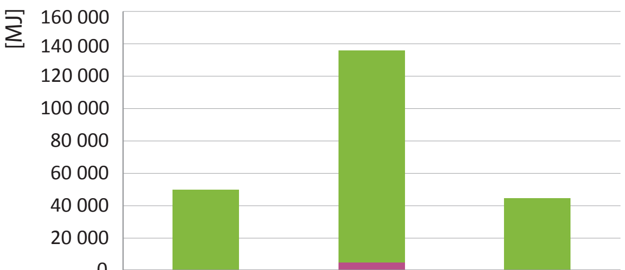
F.6.3-6 GHG emission from different energy source during prefabrication of Joensuun Elli (wooden building elements only)

F.6.3-7



	Diesel	Electricity	GPL
GHG-Fossil	3 121	11 820	2 110

F.6.3-8



	Diesel	Electricity	GPL
PE-nr	49734	131016	44716
PE-r	0	4835	0

F.6.3-7 GHG emission from different energy source during on-site construction work of L'Aquila (wooden building elements only)

F.6.3-8 Primary energy consumption from different energy source during prefabrication of Joensuun Elli (wooden building elements only)

Where there is less prefabricated building, the relevance of this process increases, such as in the case of L'Aquila.

Figures F.6.3-7 and F.6.3-8 show GHG emissions and PE consumption from on-site construction work for the wooden building elements of L'Aquila according to the used energy sources. GHG emission from electricity use is dominant, since most of the equipment used in this phase works with electricity. Nevertheless only a single electricity meter was installed on-site, the allocation of the consumed energy to the single process unit has been done considering the hours of use of the single machines. Electricity is also used for lighting during the construction process during the night and for heating workers' bathrooms and locker rooms. Diesel is mainly used for transportation (building elements and waste products) and excavators, while GPL (which is responsible for the lowest GHG fossil emissions) is used only for waterproofing.

Figures F.6.3-9 and F.6.3-10 show the same issue with Joensuun Elli. Here diesel use shows a much higher value than electricity use in both primary energy consumption and GHG emissions. It is assumed that this result is mainly due to the electricity mix and simply many used of diesel in the construction process. The used Finnish average electricity mix data includes large biomass fuel use, which would result in lower primary energy consumption and GHG emissions than fossil fuel use. These two case studies indicate that the use of electricity and diesel during on-site construction needs to be considered evenly.

Since there was single electricity meter on the construction site, it is difficult in this case to determine the most critical factor for electricity use during the on-site construction work. However, it can be assumed that the temporary construction office and the construction heater are the main electricity consumers, based on experience visiting the site. Diesel is consumed by crane and boom lift for assembly of the building elements.

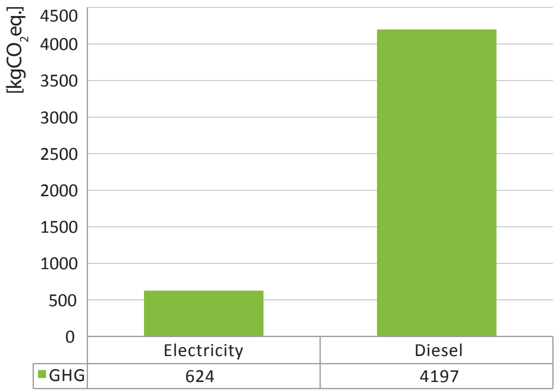
Data collection of on-site construction work is rather difficult. In fact, in addition to resources and time, special knowledge of construction may be required to monitor the on-site work. Since several sub-constructors are involved, it may be more complicate to monitor the work than prefabrication process in a factory. In the case of L'Aquila building, being a construction for emergency, a special agreement was signed between client and contractors. The contract forced the different construction companies to respect the stringent planned time schedule for the construction of the building (maximum 3 months). As a consequence, each sub-contractor planned preventively in detail every working activity in order to respect the timing constraints. The type of equipment, machinery, number of workers and hours of work per worker, temporary equipment, and transportation of materials are accurately evaluated in order to optimize the duration of the construction work. Therefore, it was possible to collect relevant data relatively easily.

In the Joensuun Elli case, a researcher has been stationed on the construction site and monitored the process everyday with the constructors, resulting in accurate data collection. However, this way of monitoring would be the exception. It is not realistic to station an observer for only such monitoring on the construction site. Detailed planning and monitoring by the constructor themselves, like in the case of L'Aquila, would be a relevant way for both the data collection and optimization of the process. This may also help to enhance a worker's mind toward the environmental efficiency of their work. A good planning of the construction activity leads to a saving of money, improvement in quality, and the optimization of environmental impacts.

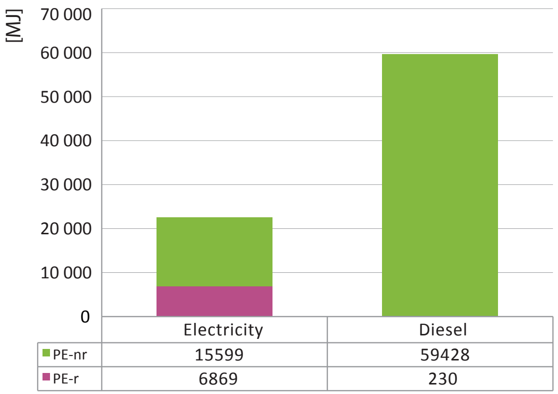
Monitoring of electricity consumption on a construction site could be easily conducted through the connection of a measuring instrument to electrical equipment. Nowadays there are different kinds of measuring devices available on the market, normally quite cheap, and some of them can directly share data on the Internet via a wireless connection. This kind of monitoring system provides more accurate results than the results from aggregated electricity consumption, allowing optimization of the most electricity consuming process or machine use.

The assessment of this phase tends to be more difficult compared to the assessment of prefabrication work. The result might include significant uncertainties. Detailed construction planning for environmental impact management (reduction of energy consumption and construction waste, etc.) is important, associating

F.6.3-9



F.6.3-10



F.6.3-9 GHG emission from different energy source during on-site construction work of Joensuun Elli (wooden building elements only)

F.6.3-10 Primary energy consumption during on-site construction process of Joensuun Elli (wooden building elements only) according to the consumed energy resources

with cost management in advance. For instance, some researchers have proposed the building construction planning model in order to minimize the global warming potential of construction work based on the expected construction machines, number of workers, duration of works, and so on [7, 9]. Development of a practical and realistic assessment method is required, as is combining this kind of estimation method and feedback from real construction work.

6.3.5 Transportation

The environmental impact of the transportation process is dependent on the distance, vehicle type and weight of deliverables. In the Mietraching case, many building components have been delivered from Germany by truck. Although it would be a normal situation in the construction industry in Europe, the dominance of transportation in the whole production phase is more than 10%, and it is the dominant process in the construction phase (A4-5). In the L'Aquila case, the distance for transporting CLT panels from Austrian manufacturers to the middle of Italy is relatively long, increasing the dominance of this phase up to approximately 12%. In the Joensuun Elli case, as mentioned before, the transportation process accounts for more than 20% of the whole. From these results, it is understood that the environmental impact of the transportation process is relevant and mitigation of this impact may have a higher priority than the actual construction work (A5) involving wooden building elements.

Normally, loadage is optimized for economical reasons. However, the transportation distance is not always proportionate to the price of a construction product. Therefore, sometimes a product is purchased from a distant country because of a cheaper price, even though the same product was available in a neighbouring city. In order to mitigate the carbon footprint of a building, it is significant to consider not only the cost, but also the transportation distance and environmental impact of manufacturing a product that will be delivered for a building construction. From an environmental point of view, it is naturally the worst case to import high impact products due to (for instance) inefficient manufacturing technology from afar because of a low price.

Data collection of this phase would be relatively simple. The required information is a combination of deliverables, transportation distance and vehicle type. Since the dominance of this phase is relatively high compared to the other process in module A4-5, detailed data collection and assessment shall be required. A transparent description of the process is important to lead the optimization of environmental impact.

6.3.6 Waste management

As shown in figures F.6.3-1 to F.6.3-3, the environmental impact from the management of construction waste is minor. However, this phase is important especially for wood construction because of the energy recovery from wood residues.

For instance, based on the amount of wood residue from prefabrication of the Mietraching building, approximately 200,000 MJ of heat energy could be generated, which could cover roughly one-third of the monthly space heating energy for the factory. In short, wood process residue is not waste, but an energy resource. Proper waste sorting is important to enhance the efficiency of waste reuse.

For the assessment of waste management, the required information is the type of waste, its amount and management method (recycle, landfill, etc.), and transport of those wastes. Basically this information is easily obtained. But it is difficult to collect the accurate data regarding waste amount from a specific project, since waste is collected in a container according to a sort from several projects. Detailed data collection may be required when an accurate LCA needs to be conducted in order to optimize the process. But an average number would be helpful for LCA in general.

6.3.7 Prefabrication vs. on-site construction

Although an environmental profile of different construction methods would be of interest for stakeholders from industry and government, there have been only a few scientific research studies this topic [10]. As an example, Quale et al. [10] compared the environmental impact of a modular construction system (prefabrication) and a conventional on-site construction system.

They collected needed information for assessing the construction process of a modular system from three residential modular companies, and based on that, made assumptions with five experienced professional homebuilders when the modular house is constructed on-site. The result shows an average of about 1.5 times more GHG emissions in the case of the on-site construction. However, there is also significant variation within each and some uncertainty in the calculation.

In order to tackle this topic, a tentative study was conducted. Referring the Mietraching building, a prefabrication-oriented construction system and an on-site oriented construction system are compared. Since the construction of Mietraching is highly prefabricated, the original data is used for the assessment of the prefabrication-oriented system. For the assessment of the on-site oriented system, the possible construction duration, number of workers, on-site construction machines and its working ratio, construction waste factor, and waste management method are assumed, based on the original data, literature, and interview with the builder.

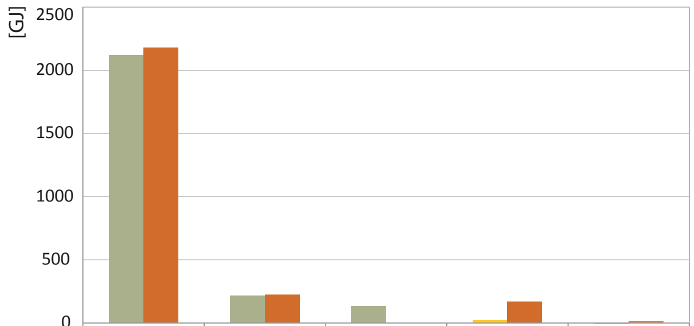
Figures F.6.3-11 and F.6.3-12 show the difference between the prefabrication-oriented system and the on-site oriented system regarding primary energy consumption and GHG emissions for the material production and construction phase of Mietraching. Normally, on-site construction work generates more waste than prefabrication, which means more building components are required for the on-site oriented system. This difference appeared in module A1-3, A4, and waste management.

In module A5: Prefabrication and module A5: On-site, the on-site oriented system shows a bigger impact than the prefabrication system. In the prefabrication process, the dominant energy resource is electricity. On the other hand, diesel is the main energy resource in on-site construction in this case. This study shows a result similarly shown in the literature [9]. Naturally it is impossible to conclude something from this study alone. However, from this result and the literature, it could be assumed that prefabrication is a more efficient construction method for environmental impact as well.

It is also assumed that the environmental profile of construction work is case-specific and affected by several parameters, such as location of the factory and construction site, size and facilities of the factory, and work efficiency of the builder. The construction work is not standardized as the material production process. Further research is required in order to clarify the features of different construction systems with a number of case studies.

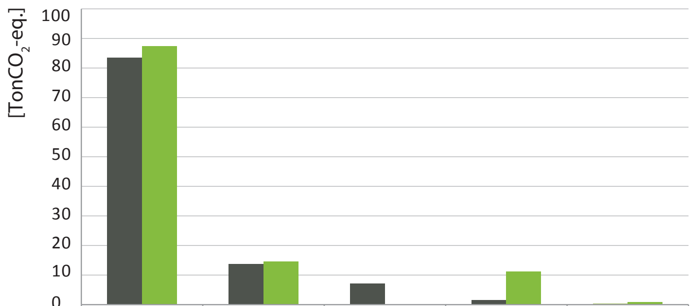
Regarding waste management, most waste from on-site construction is regarded as non-recyclable due to the inclusion of impurities. This would be one of the most critical differences between prefabrication and on-site construction. Especially when a benefit from construction waste is taken into consideration, the recyclability of construction waste would make a significant difference, as shown the example in Figure F.6.3-14. This comparison is based on the assumption that wood residue from the prefabrication process is fully recyclable, and 90% of the residue from on-site construction is regarded as non-recyclable waste and just disposed. Although this is an extreme simulation and varies case by case, it is clear that contriving to reduce the amount of waste and to raise the recyclability of waste needs to be considered, especially for on-site construction.

F.6.3-11



	A1-3	A4	A5 - prefab.	A5 - On-site	A5 - Waste
Prefab.	2122	214	131	21	4
On-site	2180	223	0	169	13

F.6.3-12

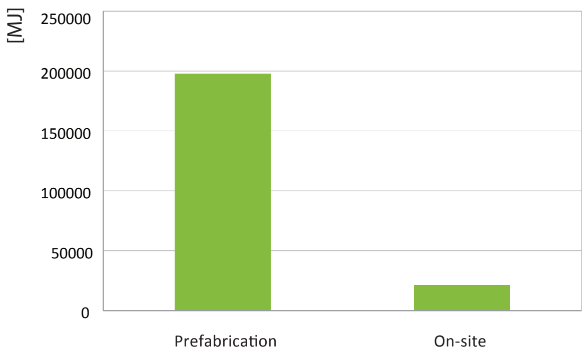


	A1-3	A4	A5 - prefab.	A5 - On-site	A5 - Waste
Prefab.	84	14	7	2	0.4
On-site	87	15	0	11	0.9

F.6.3-11 Tentative comparison of prefabrication oriented construction and on-site oriented construction regarding primary energy consumption during module A1-5 based on the case of Mietraching

F.6.3-12 Tentative comparison of prefabrication oriented construction and on-site oriented construction regarding GHG emission during module A1-5 based on the case of Mietraching

F.6.3-13 Progetto C.A.S.E, construction site, L’Aquila, Italy

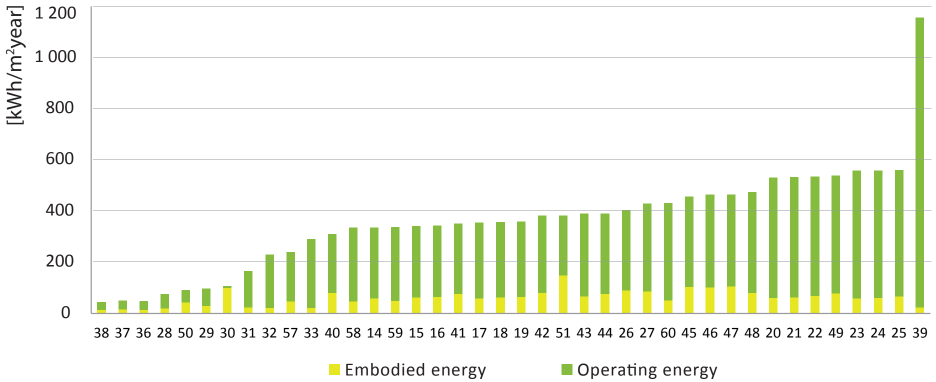


F.6.3-14 Tentative comparison of energy recovery capacity from wood residues generated from the two different construction systems in Mietraching

- Discussion in this chapter is only related to the construction phase of wooden building elements.
- Construction phase seems have minor environmental impact, but it is important to mitigate that at the industrial level.
- Transportation of building components and prefabricated building element has relevant impact.
- Reduction of electricity use during prefabrication process and of diesel use during on-site work is good starting point.
- Prefabrication seems be a more environmental efficient construction way compared to the on-site work
- Further research is required to develop practical and reliable assessment tool for construction work

F.6.4-1 Interior of the Villa Karlsson, Tidö-Lindö, Sweden

F.6.4-2 Primary energy consumption per m² of living area for different analyzed case studies [2].



6.4 Use and maintenance

E. De Angelis , F. Pittau, G. Zanata

In this chapter, the environmental impact from the use and maintenance phase (module B) is faced through case studies and literatures. The aim is to give practical recommendations in order to decrease as much as possible the environmental impacts in terms of GHG emissions of the building from this phase. Moreover, an overview of the relationship between this stage and the production and construction stage (module A) is conducted to clarify which kind of actions could be considered in order to avoid the simple shift of an impact from one phase to another.

6.4.1 Introduction

As shown in Section 6.1 (Figure 6.1-1), in the analysis of the life cycle of a building, the use and maintenance phase is normally the most relevant, mainly due to the long timeframe involved and the great amount of operational energy of building. This share can be optimized by increasing the energy efficiency of the envelope toward the new standard for Net-ZEB, aimed by the EU for the year 2020. Often, the actual service life of a building is not easily predicted, and this difficulty sets great limits to the assessment. According to EN 15978, activities in module B2-5 should include: B2 (maintenance, e.g. cleaning, painting), B3 (repairs), B4 (periodic component replacements), and B5 (refurbishments and renovations), and also B6 (energy use for operation, e.g. heating, cooling, ventilation), B1 (energy use for domestic activities, e.g. cooking, ironing, and washing) and B7 (energy use for operational water).

The need to reduce the energy consumption is due both to the difficulty in energy supply (Europe depends mainly on the rest of the world for its energy supply) and to pollution caused by fossil fuels. Reducing GHG emissions throughout the life cycle means making conscious design choices regarding the materials, construction techniques and equipment. The selection of materials with high durability and reliability may eventually control the risk of failure, and consequently decrease the amount of maintenance and replacements necessary to ensure the functionality of the building in its life cycle. In these terms, sustainability is also strictly linked to the service life of the building and its components. LCA facilitates understanding of whether the benefits from an activity compensate the environmental impact generated from the new inputs (resource consumption, GHG emissions, and waste production). In the use phase, several factors overlap: technological choices made upstream by the designer, the attention of the building occupants to properly manage the building in relation to the expected service life, and the possible functional and technological renovations. If, on one hand, proper maintenance allows an increase in the materials' service life by decreasing the number of replacements, on the other hand, the increasing required standard quality of a building element over time pushes the introduction in the building system of new products and new technologies in a different lifetime. The rapid evolution of technology (which leads to technical solutions with higher energy efficiency, e.g. higher efficiency and better performing doors, windows and installations) or the need for flexible buildings that require rapid changes in their use, involves the designers in considering proper strategies to simplify as much as possible renovation and replacement activities. In these terms, the use of BIM software may help to properly manage at the same time several critical issues connected to LCA. In fact, BIMs are able to create a single information node that simplifies updates and synchronisation mechanism among the actors of the same construction project. As a consequence, quantities or values stored in these properties can be extracted and reused as the source of information to perform calculations, analyses or simulations in order to define the best design and management strategies. TES EnergyFacade is a practical example of the potential of BIMs in the renovation for the improvement of the energy efficiency of the envelope of the existing building stock through the use of prefabricated timber modules. [1]

6.4.2 Influence of use and maintenance phase

As reported in Figure F.6.4-2, a recent study conducted on life cycle energy analysis of different conventional houses found that the operating energy in some cases may influence the energy balance up to 90–95%, accounting only for the energy amount for heating and the energy needs for materials production. [2]

On the contrary, when the energy performance of the building increases (high insulation of the building envelope and high efficiency of the heating system and ventilation), the influence of the production phase (A1-3) rises significantly, up to 60% of the overall energy need.

Figure F.6.4-2 compares the dominance of the production and construction phase (module A) with the use and maintenance phase (module B) for the L'Aquila building. As shown, the use phase (B6) accounts for a relevant share of the GHG fossil emissions (65%), while maintenance, repairs, replacement and refurbishment (B2-5) have a marginal influence (9%). The production phase (module A1-3) accounts for approximately 22% of total GHG emissions, while the construction phase (A4-5), in this case, accounts for only 4%.

These results indicate that the use phase (module B) accounts for approx. more than three-fifths and the production and construction phase (module B) accounts for approx. two-fifths of GHG emissions. Notice that for the L'Aquila building, the specific PE need for heating is roughly 43 kWh/m^2 per year, and the different performance of the envelope and services can significantly influence the results and the percentages.

6.4.3 Use and operational energy need and related GHG emissions

The greatest share of energy consumption of a building during this phase is normally given by heating and cooling systems and by the use of equipment needed for daily activities at home.

The efficiency of the appliances and their use over time significantly influence the annual energy balance. Figure F.6.4-3 shows the average dominance of the different electricity use in the residential sector in Europe (EU-15). In particular, electric heating systems, water use, lighting, refrigerators and freezers can contribute a significant share of primary energy consumption.

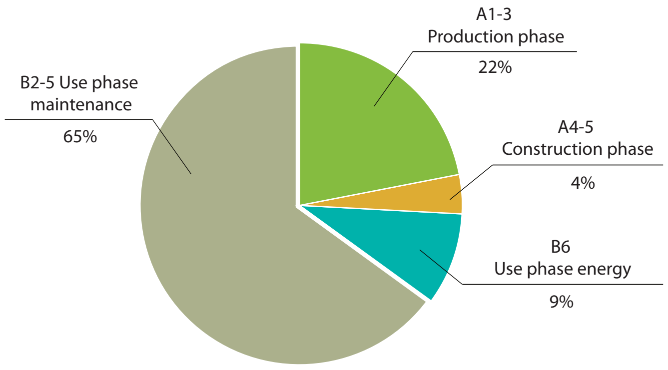
Unfortunately, it is impossible to assume that an appliance is properly used in a specific case because the use depends on the habits of the occupants. Recent studies demonstrate how the use of electric and electronic appliances (TVs, microwaves ovens, refrigerators, laptops, PCs, hot water boilers, etc.) contribute to a significant share of the total energy use in dwellings. In particular, recent studies in the UK show that almost 10% of the annual electricity need (roughly £50-90 per year) is consumed while in stand-by mode when the occupants are not using the appliance [3]. In order to save energy, some important indications can be gathered through the monitoring of the actual electricity and fossil fuel consumption in homes. This would enable control over the real efficiency of the appliances in time and their use, and, eventually the most energy consumer appliances can be replaced, once the technology introduces more efficient products on the market.

Particularly, demotic systems can give a very positive contribution in monitoring and saving energy, modifying the set-up of the system in case of anomalies and significantly decreasing the influence of the human factor.

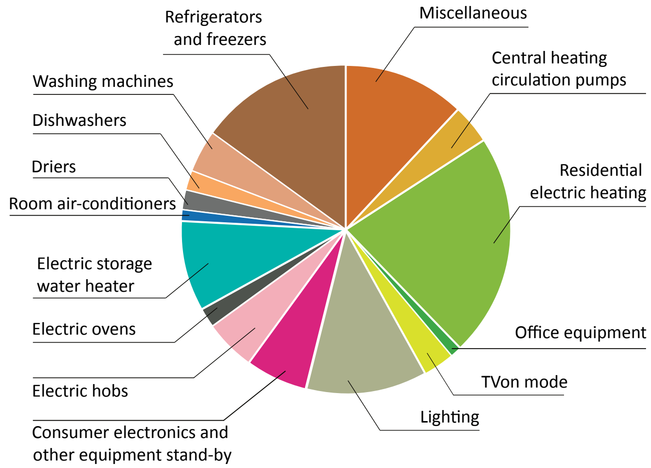
6.4.4 Maintenance and renovations

Maintenance and material replacement (B2-5) can have a significant effect on the life cycle of a building, and their impact can vary substantially, based on materials function. Therefore, they generally have to be included in LCA studies. Timber structures can have a life span of more than 50 years and basically no substitution need regardless of the structural system considered. However, different exterior or interior surface materials and some other building parts may have significantly different service lives or maintenance requirements.

F.6.4-3



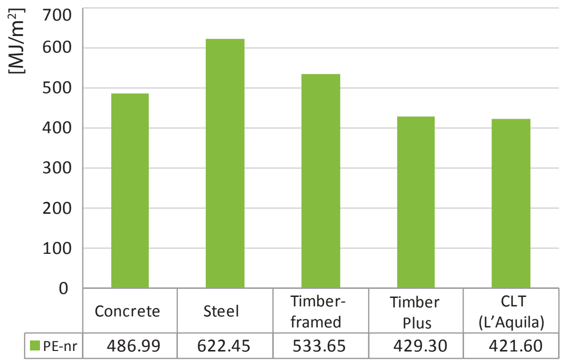
F.6.4-4



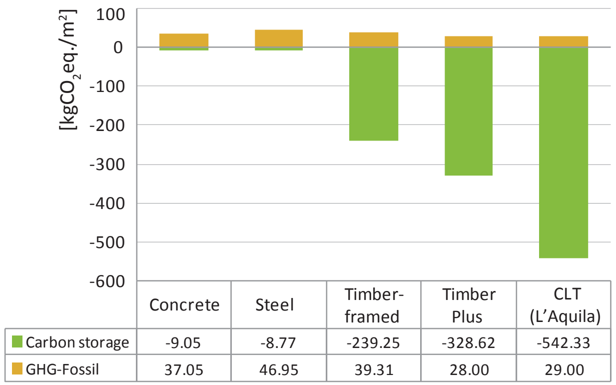
F.6.4-3 Relative dominance of use and maintenance phase in the L'Aquila building (GHG fossil emission).

F.6.4-4 Breakdown of electricity consumption among residential end-use equipment in the EU-15 from 2006 [6].

F.6.4-5



F.6.4-6



F.6.4-5 Non-renewable primary energy consumption for maintenance. Three alternative materials considered: concrete, steel and wood

F.6.4-6 GHG-fossil emission for maintenance. Three alternative materials considered: concrete, steel and wood.

On the basis of the energy efficiency standard of the building, retrofitting to a higher energy efficiency standard may provide significant benefits in terms of energy and CO_2 saving in the life cycle. Often, there is a great potential by improving energy efficiency in a large share of existing apartment buildings. Most studies on building energy retrofitting have focused on the final energy use during the operation phase of buildings. Fewer studies (e.g., the TES EnergyFacade Project [1]) have analyzed the life cycle primary energy implications of building energy retrofitting. In any case, the interaction between individual measures and the energy supply system needs to be carefully considered. In fact, the primary energy savings for the different energy efficiency measures depend on the energy supply system. Unfortunately, any actual prediction of the evolution of technologies for energy supply and the future energy strategies for each European country makes the effectiveness of the assessment very difficult to achieve.

In order to show the differences in terms of GHG fossil emissions and the non-renewable energy consumption of different materials, the results from an analysis of the impacts from the maintenance phase in the L'Aquila case study is shown comparing three alternative materials: concrete, steel and wood (timber-framed and CLT-based structures). The comparative calculation is made on the base of a tertiary building in New Zealand made of a timber-framed structure (press-lam) [4]. Then the results are compared with other representative residential building in L'Aquila made of CLT panels.

Figure F.6.4-5 shows the non-renewable PE consumed for each alternative for maintenance. In the analysis, some activities are taken into account: periodical cleaning, painting, checking and inspections, and partial substitution of some damaged parts per m^2 of living area. From these studies, increasing the use of wood in the structure (timber, plus it is still timber-framed but with a greater content of wood in finishing and cladding) leads to a decrease in the PE non-renewables used for this phase of the building's life cycle.

Similarly, Figure F.6.4-6 represents the relative amount of fossil carbon emission for each alternative structure. As shown in the figure, increasing the use of wood allows the storage of a great amount of carbon in timber products, with a positive effect on the environment in terms of carbon sequestration from the atmosphere. In both figures, steel results in the highest share of impact, mainly due to the superficial treatment to be restored periodically where the structural and non-structural elements are exposed. The estimated service life of the building normally may affect the result significantly. As shown in Figure F.6.4-8, the GHG emissions from maintenance and substitutions of material increase linearly over time for the L'Aquila building. Nevertheless, the reference service life of building products still remains very difficult to assume, mainly due to the lack of specific and validated databases.

Building elements

Considering the L'Aquila case study, it should be noted that wood does not undergo any degradation or decay of the mechanical properties over time, but it can be strongly subjected to biological degradation by fungi and xylophagous insects. For this reason, the life span of wood products is strongly influenced by the conditions of combined moisture exposure and temperature, conditions which may require careful maintenance. See Chapter 7: Service life and moisture safety.

The correct design of wood-based components is essential in order to avoid a premature degradation caused by an insufficient drainage of rainwater from critical surfaces. The ventilation allows the exportation of moisture and contributes effectively to keep the wooden surfaces dry. Moreover, a correct evaluation of the hygrothermal conditions of the timber structures in the critical seasons is strongly needed in order to choose the most effective airtightness. For this reason, more than for other alternative structures, it is important that the designers have valid know-how about good design practice in order to manage the most critical details of the construction.

Generally, the application of woodworm products, as well as fungicides or other preservative treatments, according to DIN 68800 and the European standard, is not allowed. Constructive wood protection must be considered first, and preservatives are allowed only if absolutely necessary. The use of these kinds of products for maintenance implies on the one hand the reduction of replacements, avoiding the consumption of natural resources and the emission of waste in the environment, but on the other hand the use of protective products with a significant environmental impact. As pointed out in an article by Werner and Nebel [5], the auxiliary products for maintenance of wood adversely affect the environmental impacts generated by the use of wood as a building material.

Unfortunately, some critical parts of timber components are placed in the internal part of the structure, and their operating status is impossible to check without an invasive inspection. For this reason, the use of humidity and temperature sensors in the most critical parts of the building (e.g., the connection between basement-foundations/external walls, windows/walls, roof/walls, etc.) should be adopted in order to ensure the best operative conditions in time, avoiding mould growth and degradation. A periodic check of the superficial temperature of the external/internal surfaces of the structures through the use of a thermographic camera allows one to qualitatively evaluate the operative conditions of the structures and see eventual increments of moisture content.

HVAC systems

Currently, not enough information on the environmental impact related to the maintenance of HVAC systems is available for an exhaustive LCA on buildings. EPDs are normally still rare for these kinds of systems, and if available, they do not include module B in the assessment. According to EN 15804, only module A1-3 is mandatory. Nevertheless, their influence in terms of GHG emissions in the use and maintenance phase could be significant. Especially for those systems containing liquids such as R22, R422d, R134a, R407c and R404 (normally used in machines for heating and/or cooling) could lead to a great impact in terms of GHG emissions. Nowadays, a new generation of liquids (e.g., R R410A, regenerated R22 or R422d) have a reduced impact on the global warming potential, so they are much more ecological than other liquids. Thus, the use of products and machines that adopt these liquids is strictly recommended in order to reduce their impact over time.

6.4.5 Recommendations

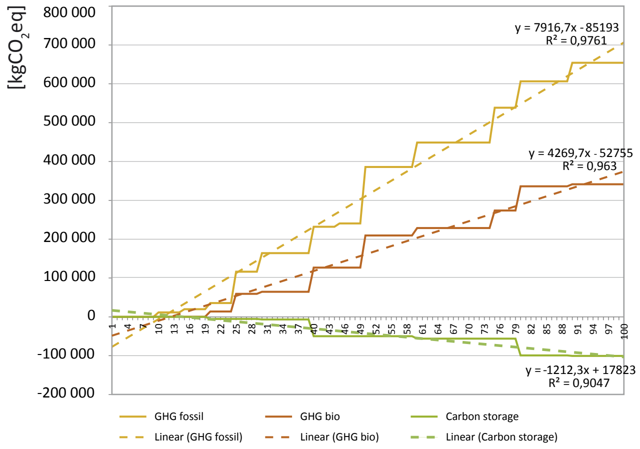
On the basis of the achieved results, the following conclusions can be summarized:

- The use and maintenance phase (module B) is in most of the cases still the most relevant phase in terms of the GHG emissions of a building. A share between 15% (low-energy houses) and 95% (conventional houses) is related to the energy spent for operational use and maintenance. The decrease of this share affects the impact from the production phase (module A). Thus, an optimization of the thermal performance of the building, according to the new in the boundaries of the assessment can give a valid contribution
  EU directive on energy efficiency, and a careful selection of the used materials is strictly needed;

- Occupants' habits and their appliance use during the use phase (B1) affect the results significantly. The mean European values or national consumption values for a "typical family" for each country may be assumed for the assessment of dwellings. Monitoring the actual electricity and fossil fuel consumption in homes allows control of the real efficiency of the appliances and their correct use. Especially home automation systems can be able to save a great share of energy, even if the education of the occupants in the use of the building still plays a fundamental role.

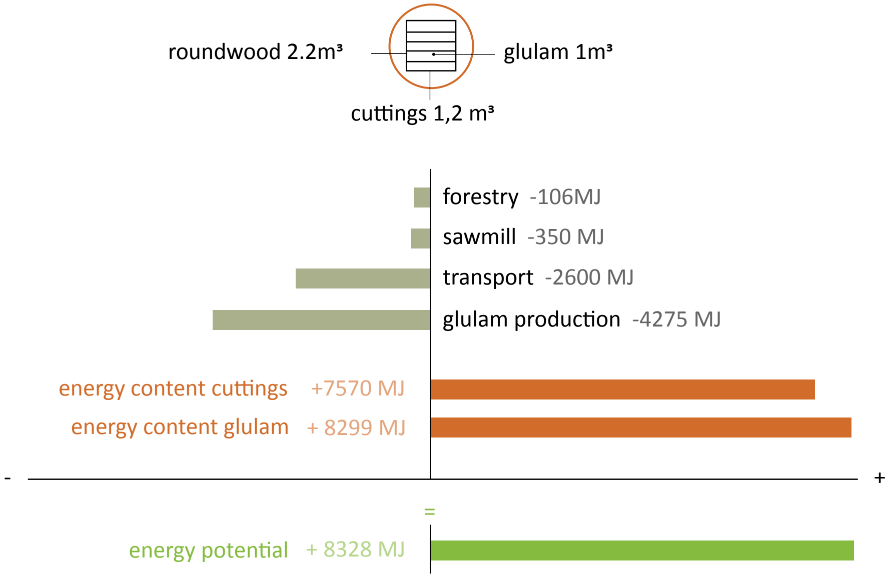
- Maintenance and material replacement activities have a significant effect on the life cycle of a building. The actual life span of the various materials is very difficult to estimate, mainly due to the lack of specific data. For the primary structure, normally the same life span of the building can be assumed, and different exterior or interior surface materials and some other building materials may have significant differences in terms of service life.

- The life span of wood products and the maintenance needed to preserve the functionality over time is strongly influenced by moisture content and temperature. The auxiliary products for maintenance of wood negatively affect the environmental



F.6.4-7 GHG fossil and biogenic emission and carbon storage over the time for maintenance (module B2) and replacement (B4) activities, L'Aquila building. The RSL of products were assumed from BLP Durability Assessment report [7] considering the k-factorial method for the prediction of the ESLs.

- Use and maintenance phase (mod. B) is, in most of the cases, still the most relevant phase in terms of GHG emission of a building.
- Maintenance and material replacement activities have a significant effect on life cycle of a building.



F.6.5-1 Material of 1 m³ of CLT stores biomass energy of 2313 kWh (8328 MJ) [2].

impacts generated by the use of wood as a building material. For this reason, the use of products with available EPDs is strongly recommended. Externally, the correct design of the technological details of wood elements (e.g. drainage, sufficient ventilation, rainwater protection, etc.) may increase the estimated life of the wooden products, decreasing the risk of failure.

- By using humidity and temperature sensors internally, the walls or floors can give a practical contribution in monitoring the physical conditions of the critical points, avoiding the risk of degrading wooden components. Even a periodic check of the temperature through the use of a thermographic camera allows monitoring the operating conditions of the structures.
- HVAC systems and the impact related to maintenance activities are often difficult to assess. Specific EPDs that include module B for an exhaustive LCA on buildings. The periodical substitution of some liquids for refrigeration could lead to a great impact in terms of GHG emissions. The use of products and machines that adopt new generation liquids with more ecological proprieties is recommended in order to reduce the overall impact over time.

6.5 Deconstruction and recycling, end-of-life

A. Hafner, S. Ott, S. Winter

6.5.1 General

Various papers have discussed the importance of the end-of-life phase for wood. For information on holistic understanding of this phase in the context of global considerations, see Chapter 3. This research project was mainly focused on the production phase and in parts on the use phase of buildings. Therefore, no detailed process recommendations and guidelines have been worked out yet for the end-of-life phase. This chapter shows general considerations on the end-of-life phase in relation to the use of wood. They are limited to the system of the practical LCA of buildings.

Deconstruction of a building, demolition and end-of-life scenarios are to be integrated in full LCA calculations. In the standards of EN 15804:2012 and EN 15978:2011, these phases are part of module C. Modules include deconstruction/demolition (C1), transport to the product’s waste processing (C2), waste processing for reuse, recovery or recycling, recovery and/or disposal (C3), disposal (C4); “including all transports, provision of all materials, products and energy, during the end-of-Life stage up to end of waste stage or final disposal.” [1]

To show the possible benefits and loads of materials beyond the product system boundary, a separate module D is also introduced. This means that in module D the recycling potential, the persistence of mineral building products, embedded renewable energy or carbon stored in the product can be shown. According to the standards, all benefits have to be separately shown in module D. This brings transparency to the calculations and helps to comprehend the included benefits and loads from the end-of-life scenarios modelled in the study.

Up to now for all wooden products, the end-of-life scenarios have consisted almost only in incineration and therefore energy recovery. The benefit of recovered energy then has to be shown in module D. With energy recovery, the energy content in wooden products then gets used and greenhouse gases are thereby emitted. The carbon stored in the product over the lifetime is released.

By growing trees in the forest, carbon gets stored in the material. Greenhouse gas emissions have a negative or minimal positive value in module A due to the carbon stored in the product. Here, calculations must sum up negative greenhouse gases (carbon storage) and emitted GHG during the production process. At the end-of-life, wooden material gets burned, so GHGs are emitted. Several LCA calculations regard wood as GHG-neutral.

This is only the case if calculations include the whole life cycle from production to end-of-life if the wood is not leaving the forest system and if these forests are not being harvested. LCA calculations done according to the standards of EN 15804 and EN 15978 do not give instructions for the handling of wood and sequestration of carbon. But according to these standards, the carbon and primary energy have to be accounted for separately in the different modules. This requires that the carbon balance is shown divided up in the modules. Hence wooden materials become a negative value in module A1 and a positive value in module C4, as can be seen in Figure F.6.5-1. Energy gains and the carbon stored in the product (if it is reused or recycled) have to be shown in module D. The overall carbon balance is still zero, but it can be divided among the different modules.

C1 – deconstruction and demolition

- *Starting point:* Building is not used anymore and will be demolished.
- *Content:* The building is replaced, dismantled and deconstructed. Includes all energy / emissions needed for deconstruction, demolition on site and for the general division in different fractions.
- *End:* Building is divided into different fractions according to European waste categories.
- *Role of wood:* The energy content / carbon stored in the wooden material still exists; material has its own backpack of emissions due to the product stage A to C1; a possible carbon credit can be accounted for in module D.

C2 – transport

- *Starting point:* The material input is sorted from the building in different fractions from C1.
- *Content:* All transport from the site to intermediate storage facilities and all transport to final disposal. If material is reused or recycled, the transport to the recycling plant is included (end = gate of plant). If material reaches its “end-of-waste” status, it is treated with all its burdens as a raw material supply (A1). For materials that leave the system as secondary material, stages C1 and C2 have to be calculated as end-of-life for the original product.
- *End:* Waste processing plant (recycling plant) or disposal is reached.
- *Role of wood:* energy content / carbon stored in the wooden material still exists; material has its own backpack of emissions due to the product stages A, C1 and C2; a possible carbon credit can be accounted for in module D.

C3 - waste processing

- *Starting point:* Building material fractions passing the gate of the waste processing plant.
- *Content:* This phase includes all processes that are necessary for reuse, recycling or energy recovery. “Waste processing shall be modelled and the elementary flows be included in the inventory.” [1, page 24]
- *End:* The material has reached the “end-of-waste” stage and is transferred to the product stage as secondary material.
- *Role of wood:* The energy content and carbon stored in the wooden material still exists; the material has its own backpack of emissions due to product stage A, C1, C2 and C3; a possible carbon credit can be counted in module D.

C4 – disposal

- *Starting point:* Final disposal or landfilling; includes all emissions.

“potential loads, (e.g. emissions) from waste processing in module C4 are considered part of the product system under study, according to the “polluter pays principle”. If however this waste processing gives rise to secondary fuels with an efficiency rate of <60% (and in institutions built after Dec. 31, 2008 <65%) such as heat and power from waste incineration or landfill gases, the potential benefits from the use of such secondary fuels in the next product system are assigned to module D and are calculated using current average substitution processes.” [1, page 24]

- *Role of wood:* Wooden material is burned, the embodied energy is used, the stored carbon is now zero, and the heating value can be assigned in module D.

D – Additional information

Module D is for information only and brings transparency to the benefits and burdens and the assumed scenarios. “When relevant, the informative module D is used to declare potential loads and benefits of secondary material or secondary fuel leaving the product system. Module D introduces the “design for reuse and recycling” concept for buildings by indicating the potential benefits of avoided future use of primary materials and fuels, while taking into account the loads associated with the recycling and recovery processes beyond the system boundary. Where a secondary material or fuel crosses the system boundary e.g. at the “end-of-life” stage and if it substitutes another material or fuel in the following product system, the potential benefits or avoided loads can be calculated based on a specified scenario which is consistent with any other scenario for waste management and is based on current average technology or practice. “ [1, page 29]

- *Starting point:* All declared benefits and burdens that have left the system boundary during stages A to C. This includes, for example, residues used as energy source, energy created by burning wood at end-of-life or carbon stored in a product for secondary use.

Possible categories (Wood)

- PE ren: Renewable primary energy for material use (in MJ). It is assumed that the material can replace (substitute) fresh wood. The material has reached the "end-of-waste" stage in module C3, reaching the point where it can replace other wooden raw material as input for wooden products.
- PE ree: Renewable primary energy for energetic use (in MJ). Here, the part of wooden material used for energy recovery is calculated.
- Sm: Secondary material (kg). This shows the amount of recycled material used as secondary in the production process used.
- MFR: Material for recycling (m³). This shows the amount of material which is usable for recycling, and should correspond with the energetic value in PE rem.
- MER: material energetic recovery (m³). This shows the amount of material that is usable for energetic recovery, and should correspond with the energetic value in PE ree.
- CRU: component recycling use (m³). This shows the amount of material that is usable for reuse without further processes.

According to the research report of [3], where life cycle assessment datasets for wooden building products were generated, these categories were outlined and calculated. They can make the possible reuse of wooden products visible and show a realistic division of the waste wood fractions, because not all waste wood is going to thermal recovery.

6.5.2 Legal framework

Material recycling, reuse and energy recovery are theoretically possible as end-of-life scenarios for wooden products. Different end-of-life options are useful for different cases. To explore these options, some general frameworks have to be shown, and then the different options are discussed.

Resource-efficient Europe Initiative

The aim is to increase resource efficiency by reducing the use of raw materials and lower CO_2 emissions. This reflects on building material and here also on recycling and reuse. [4]

Waste hierarchy

According to the EU Directive on waste [5], there is a waste hierarchy, which shall apply as a priority order to all material in waste prevention.

The EU directives as well as the national laws in many European countries aim at higher rate of reuse and recycling, which leads to reduced amounts of wastes to be landfilled. The basic principle in the European waste management directive is that materials should be primarily recovered for secondary use, and only as a secondary option, they can be utilized as energy. Landfill for wooden products is currently not allowed in Germany and other EU countries. Most probably energy recovery will not be regarded as recycling in the coming future.

For practical reuse, a classification of used wood is necessary. The aim must be to avoid bringing wood with preservatives back to recycling. As an example, four classification divisions in waste wood (German waste wood scenarios) are shown. The used wood is divided up into four categories in order to decide which wooden material is usable for which waste scenario,

a) Waste wood category A I:

Waste wood in its natural state or only mechanically worked that during use was at most insignificantly contaminated with substances harmful to wood.

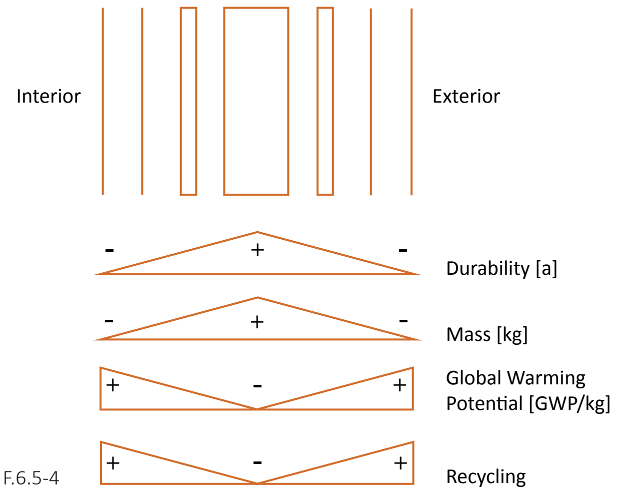
b) Waste wood category A II:

Bonded, painted, coated, lacquered or otherwise treated waste wood with no halogenated organic compounds in the coating and no wood preservatives.

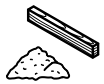
F.6.5-2

F.6.5-3

F.6.5-2 Piano pavillion, Lahti, Finland
F.6.5-3 Kierikki-keskus, Oulu, Finland



F.6.5-4

C1	C2	C3	C4	D
Deconstruction Demolition	Transport	Waste processing	Disposal	Benefits/loads
				+ -
Emissions from energy used for deconstruction	Emissions to intermediate storage facility and waste processing	Emissions for: • breaking up wood to chips • cutting e.g timber walls to beams	Incineration --> emissions (GHG)	Emergy (heating value)
Carbon storage	Carbon storage	Carbon storage	-	
PE-r	PE-r	PE-r	-	PE-ree

F.6.5-5

F.6.5-4 Sequence of technical and functional layers and weighted influence on the end-of-life impact. [10]

F.6.5-5 Allocation to different modules for energy recovery.

c) Waste wood category A III:

Waste wood with halogenated organic compounds in the coating with no wood preservatives.

d) Waste wood category A IV:

Waste wood treated with wood preservatives, such as railway sleepers, telephone masts, hop poles, vine poles as well as other waste wood which, due to its contamination, cannot be assigned to waste wood categories A I, A II or A III, with the exception of waste wood containing PCBs [6].

According to German laws, the term used wood (Altholz) means used wood from production and end user, as far as it is covered by the German life cycle Resource Management Act. There is also industrial wood, which includes all "manufactured wood products", wood from massive construction and wooden products with a mass percentage over 50%.

There are various studies (at least in the German market) ([7], [8], [9]), which quantify the usage of wood in market shares. Explicit calculations on recycling of wooden material in the building sector have not yet been done.

6.5.3 Building description and life cycle

While buildings are seen as a whole in the use phase, for end-of-life, it comes down to the specific construction and the materials they are made of. Building components can be decomposed into different layers to get a deeper understanding of their impact at end of life; compare Figure F.6.5-4. The layers of the building have different exposures, durability and therefore a different life span. In modern (timber) buildings, different layers are also common to fulfil a wide variety of technical requirements. There are technical/constructive layers and functional layers.

Technical layers:

- are part of the load-bearing structure,
- define resource use and material use,
- are relevant for the life span of the building part,
- are made to last for a long time.

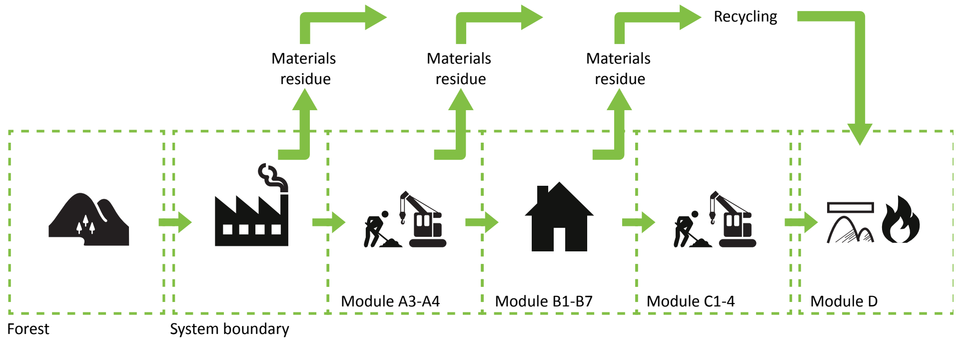
Functional layers:

- depend on usage,
- change resource consumption through reuse or recycling,
- are exchanged frequently, depending on exposure
- have to be material efficient
- durability should be chosen according to the usage.

The disassembly allows the identification of required service life of building parts and has to be considered in maintenance, inspection, and end-of-life scenarios. Figure F.6.5-4 shows the different layers of a façade divided in their technical and functional layers. The primary construction needs to outlast the whole life span; wooden primary construction has high mass and can store a large amount of carbon over this period. The other layers (e.g., cladding) will be replaced many times and therefore are relevant in terms of recycling potential and burdens/benefits at the end-of-life stage.

This can be used as design methodology for the improvement of environmental performance. Through the interdependency of use- and end-of-life scenarios, the different layers can be separately optimized more easily and then be designed for reuse. The jointing between layers and the frequency of renewal are additional criteria for the end-of-life phase, apart from the material impact.

C1	C2	C3	A1	D
Deconstruction Demolition	Transport	Waste processing	Raw material	Benefits/loads
				+ -
Emissions from energy used for deconstruction	Emissions to intermediate storage facility and waste processing	Emissions for: • breaking up wood to chip • cutting e-g timber walls to beams		
Carbon storage	Carbon storage	Carbon storage	Carbon storage	Carbon storage
PE-r	PE-r	Pe-r	-	Pe-rem, Pe-ree, SM, MPR, CRU
1. Life cycle			2. Life cycle	



F.6.5-6 (left) Allocation to different modules for material recycling
F.6.5-7 (right) Residues in the life cycle of buildings according to EN 15804 and EN 15978

6.5.4 Energy recovery

Energy recovery means that the material gets burned in incineration plants. Then the embedded primary energy stored in wooden products gets released and a heating value is generated.

For LCA calculations of buildings, emissions generated in the end-of-life stage also need to be allocated. The deconstruction of the wooden parts in the buildings, the collection in fractions and the shearing into small parts belong to modules C1 to C3. Module C4 contains the incineration process, while all the transport up to the incineration plant belongs to module C2. Module D lists the loads for energetic recovery (greenhouse gases) and states the benefits of usable primary energy.

Incineration with energy recovery is useful for various materials such as:

- Wood contaminated with paint/lacquer;
- Wood contaminated with toxic substances (like PCP, impregnation);
- Small wooden parts which are bound together with glue;
- Other materials that cannot easily be separated.

According to the German used wood categories described previously, energetic recovery is feasible for categories A III to A IV and in parts A II.

Calculations of how much energy is used in the process and how much emissions are generated must be done for the specific analyzed processes. Up to now for LCA calculations, the energetic recovery has been used as the end-of-life scenario for all wooden constructions. Landfilling is not allowed for wooden materials, while the possibilities of cascade use are not researched in detail yet and therefore are not widely applied in calculations. There are no figures existing yet for deconstruction (C1), which is very much dependent on the building site and its surroundings, and for waste processing (C3). The transport (C2) could be calculated for projects knowing the lorry size and distances from the site to the waste processing plant.

6.5.5 Material recycling

"Recycling" means any recovery operation by which waste materials are reprocessed into products, materials or substances; whether it is for its original or new purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" [5].

Material recycling can only be applied for wooden materials in category A I, and there must be a strict selection process to ensure that no contaminated material gets reused. Up to now the selected material for recycling gets used for softboard production. For example, massive timber construction is deconstructed and recycled by breaking the material into chips for chipboard. The material gets shredded to chips and is mixed with fresh material as input for softboard production only. The results of the usable percentage of recycling material has been worked on in the research project, DEMOWOOD.

A potential use of beams and joists of wide-span structures could be to saw them into parts and reuse them as beams for smaller constructions. Non-reusable materials (e.g. small corners) and residues can be burned, generating heating value.

From a life cycle perspective, this results in a longer period of carbon stored in products and a higher usage of secondary material which then implies less energy and emissions in the production phase A1.

6.5.6 Reuse (with low to no modification)

"'Re-use' means any operation by which products or components that are not waste are used again for the same purpose for which they were conceived." [5]

Reutilization: For example, massive timber construction is deconstructed and reused for the same purpose.

Subsequent use: For example, solid timber construction is deconstructed and then cut into parts to be used as beams for roofing. The compounds are down-cycled but the material still has some of its properties.

This reuse is only useful for wide-span structures and laminated beams that are have no material faults. For reuse, it is important that no preventive wood protection is applied to constructions, while for easy deconstruction it is beneficial to screw joints rather than nailing and clipping. This means that recommendations need to be made for design for reuse/recycling.

In general there are various possibilities to extend the life cycle of a product or material:

- Extend the life span of the building and the durability of the products.
- Keep information about an existing building through a building passport (or sustainability certification).
- Maintenance, repair, renewal of surfaces (exterior and interior).
- Modularity of the structural system from components to the structural system.
- Easy dismantling of the buildings (connecting devices).
- Design for reuse.
- Use screws instead of nails, clippings.
- Avoidance of composite materials.
- Avoidance of toxic substances.
- Use of waste wood fractions A I (only in parts A II).

The prefabrication in the wood process is an advantage for durability and the end-of-life phase, whereas the construction has to be designed in modular elements. The replacement of single layers is possible through straight joints, so recycling becomes much easier.

6.5.7 Conclusions

With the growing importance of wood as a significant biomass component of the renewable energy supply, there might be a shortage in the availability of wood in the future. The EU directives [5] and national laws in many European countries aim at a higher rate of re-use and recycling. The basic principle in the European waste management directive is that materials should be primarily recovered for secondary use, and not until a secondary option can they can be utilized as energy.

Therefore, the European Commission proposed to increase the efficiency in the production and the use of wood [11] and resource efficiency in general [4]. The overall goal must be to increase the long-term availability of renewable but at the same time limited resources for the wood cluster. The competition for raw materials between stakeholders in the wood cluster will be reduced and the wood utilization with immanent positive effects on climate protection will be optimized. An approach to higher resource efficiency is the implementation of material flow management in the entire process of timber construction.

The European Union has set an objective to develop itself as a recycling society, where waste generation is avoided, and wastes generated are utilized as a resource. The latest waste directive from 2008 [5] contains an article for the re-use and recycling of materials. Among other things, it requires that the member countries have to proceed with necessary actions to recycle materials and products. To fulfil the normative requirements, the industries and R&D should develop products that can be easily recycled. In the wood product sector, the waste hierarchy is so far largely underdeveloped. A lot of wood products that could be utilized in the secondary product life cycle are burned for energy.

This reduces the competitiveness of wood as a construction material not only from the environmental point of view, but also from the business point of view. On the other hand, it offers an obvious opportunity for innovative companies to create new business models, processes and products [12].

A better management of its renewable resources helps the wood sector to ensure a long-term availability of solid wood products at reasonable prices. This will allow preserving and also gaining market shares now and in the future.

In general, the demand for reclaimed wood products in the building sector will rise due to the fact that the thermal use of wood is the last option in the cascade of use. The preferred option has to be the reuse and the recycling of reclaimed wood. On this option the refinement of reclaimed wood for innovative products as well as the broadening and enhancement of the paths of reuse and recycling is strongly needed for the timber construction industry.

Long-term and a resource-efficient use of wood of premium quality (such as laminated wood, plywood, timber frame construction) is necessary to ensure sustainable construction with wood. In the process of planning wooden construction, the deconstruction, reuse and recycling of the products have to be considered, too.

Further research is needed in the availability of recycling material and also how to detect toxic substances in material for recycling. More research is also necessary in developing data for modules C1 and C3 for wooden products and C4 in general. Actual numbers from 2012 market observations show that the usage of wood for energy reasons has overcome the use of wood for the material use purpose for the first time in Germany. This underlines the necessity to promote reuse and recycling and furthermore, design for recycling in the wood sector.

6.6 Conclusions

Chapter 6 describes the environmental properties of Life Cycle Analysis and the carbon footprint in the life cycle of a building. The aim is to show the basic principles for carbon-efficient wood construction. This is done to improve the environmental performance of buildings. Providing a clear description of the assessment processes and results are fundamental requirements. The underlying fundamentals of the system boundaries for applied practical LCA are described in Section 6.4.2.

First, the general issues of goal setting and the requirements for it are discussed in Section 6.1. The processes of designing low-carbon wooden houses are outlined in Section 6.2. Beside product material, the construction process also has an ecological footprint. We evaluate the influence of the construction phase and compare the prefabrication versus on-site construction process with respect to ecological matters. The influence of transport and waste management are shown in Section 6.3. Then influences of the use and maintenance phase and related issues are discussed in Section 6.4. Finally, the end-of-life stage, deconstruction and recycling, with a focus on wooden material, are considered in Section 6.5.

The results are as follows. Goal setting for carbon-efficient buildings must be done by the owner at a very early stage in the process. A systematic design process needs to be developed so that the building sector can contribute to the reduction of greenhouse gases and primary energy use.

F.6.6 Construction site, L'Aquila building, Italy

Increasing energy efficiency during the use phase reduces the carbon footprint of this phase. Therefore, the primary energy consumption resulting from construction comes into focus. Generic data is used for making calculations during the design stages, whereas specific data is required for calculations done for real buildings.

The construction phase itself seems to have a minor environmental impact in comparison to the material side of operations, but it is still important to mitigate the impacts at the industrial level. The transportation of building components and prefabricated building elements has a relevant impact. Prefabrication (off-site construction) seems to be a more environmentally efficient way of building compared to on-site work.

Further research is required to develop a practical and reliable assessment tool for construction work. Our discussion is only related to the production and construction phases of wooden building elements.

The use and maintenance phases (mod. B) are in most of the cases still the most relevant phases in terms of the GHG emissions of a building. Maintenance and material replacement activities have a significant effect on the durability of a building.

The long-term and resource-efficient use of premium-quality wood (such as laminated wood, plywood, timber frame construction) is necessary to ensure sustainable construction when using wood. During the process of planning a wooden construction, the deconstruction, reuse and recycling of products must be considered as well.

F.6.7 Student housing in Kista, Sweden

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