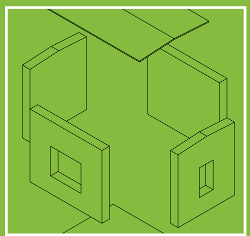
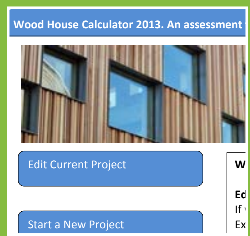
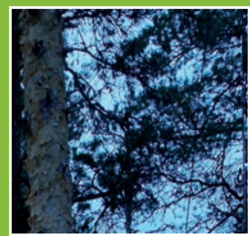
4. Carbon footprint calculation methodology







4 CARBON FOOTPRINT CALCULATION METHODOLOGY

4.1 Introduction

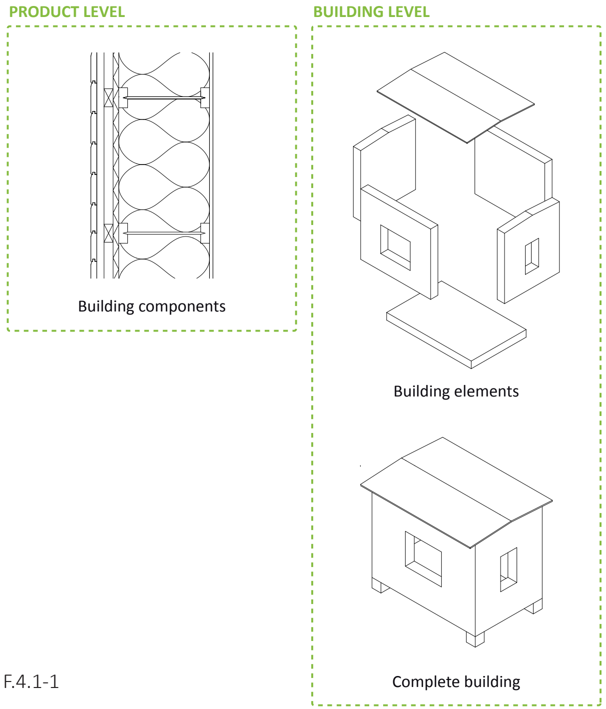
A. Takano

This chapter introduces basic methodologies for carbon footprint calculation of wooden products and building. The contents in this chapter are applied to two environmental impact categories: carbon footprint and primary energy demand.

A building is a very complex system, as it consists of plenty of materials and equipment. Building components, building elements, and the whole building could be analyzed using the LCA methodology. The assessment of building components corresponds mainly to the production stage of building materials. For instance, dominance analysis of building material types used in a building can be done at this level. Building elements is an aggregate of building components, and issues such as the construction stage, prefabrication processes, and building physics are often analyzed at this level. In addition, dominance analysis of building elements are done in order to see which part of a building has a high environmental impact. Finally, a complete life cycle assessment can be conducted for the whole building.

According to EN standards, LCA of construction works is divided into two levels: product level and building level. EN 15804 focuses on the product level, i.e. Environmental product declarations (EPDs) - Core rules for the product category of construction products, while the EN 15978 focuses on the building level, i.e. assessment of environmental performance of buildings. In this chapter, the methodologies are explained following this level definition with the practical division mentioned above in mind.

The LCA of a building is a complex task to handle. Nevertheless, general rules have been set up by the standardization authorities. For instance, comparability of the assessment results is one of the critical issues in practice. In many case, an assessment result is based on the specific methodologies according to the purpose of the assessment. Therefore, the results cannot be directly compared with each other. This is the same even at the product level. Especially wooden materials can be regarded from diverse aspects because of its specific properties, which most other materials do not have (i.e. carbon storage property, variable properties based on a species, variable moisture content, usability of waste, etc.). The difficulty of handling LCA for the practical user is also an issue to consider.



F.4.1-1

F.4.1-2

F.4.1-3

Therefore, one of the most important goals of this project is to discuss relevant methodologies for calculating the carbon footprint of wooden products and building in practical use. The methodologies must be based on sound scientific grounds and in line with the related standards. At the same time, it needs to be explained simply, clearly and realistically as possible and utilized easily.

According to such intentions, the practical methodologies are introduced, traversing several related topics. Simplification of the methods may finally lead to a critical misunderstanding due to the complex nature of building LCA. However, having understood those situations, the aim here is to show a clear and reasonable starting point for practical implementation.

F.4.1-1 Definition of building level and product level
F.4.1-2 Sörgård school in Vaggeryd, Sweden
F.4.1-3 Flyinge Kungsgård in Flyinge, Sweden

4.1.1 Biogenic carbon emissions

D. Peñaloza

The Greenhouse Gas Protocol defines "biogenic" as a product that is produced from living organisms or biological processes, but not from fossilized processes or fossil sources [1]. The carbon neutrality of bio-based products and biomass energy production is a much debated topic, which will be discussed in this section of the book for wood-based construction products.

The biogenic carbon emissions directly attributed to a wood-based product result either from the use of biomass energy during the production phase or from the combustion of the product after the end-of-life stage. These emissions are equal to the amount of carbon sequestered in the growing tree, which provides the biomass for the wood or the energy used. Furthermore, the forest re-growth driven by re-planting harvested trees is also in balance with such emissions. All of this is assuming that the carbon stocks in the forest are not decreasing, a ground rule for sustainable forestry and a common requirement in European forestry practices.

These emissions and sequestration phenomena may be seen as part of an accelerated natural carbon cycle. This is why, if biogenic emissions are to be accounted for in the carbon footprint of a product, the carbon flows in the forest system should also be included in order to cover the full life cycle of the product.

This would increase the level of complexity when calculating the carbon footprint and the final result would not be affected, provided that the biomass originates from forests where the carbon stock is constant over time. In Europe, the total standing forest biomass has increased steadily over many decades, which means that the notion of "carbon neutrality" is a conservative assumption. This is why, for simplicity sake, it is recommended that researchers not account for biogenic carbon sequestration and emissions when calculating the carbon footprint.

In addition, there is a temporal effect from the storage of carbon in wood products that is associated with the atmospheric dynamics of greenhouse gases (see Chapter 3).

4.2 Standards related to carbon footprint

M. Kuittinen, T. Valtonen

Carbon footprint in standards and specifications

The international normative document that is exclusively dealing with carbon footprint is ISO/TS 14067 - Carbon footprint of products. It gives recommendations for assessments regardless of product type. Therefore its instructions are general in their approach. This specification sets rules for system boundaries, input and output data as well as alternative communication formats, depending on the use purpose of the assessment.

A more specifically wood-related standard is drafted in prEN 16449-Calculation of sequestration of atmospheric carbon dioxide. It contains calculation rules that can be applied for calculating the carbon footprint of wood material. It is only applicable to wood material, not wood-based construction products that include other materials as well.

Environmental product declaration

Standard EN 15804 regulates the content and structure of environmental product declarations (EPDs) of construction products in general. Product category rules are developed based on this horizontal standard. They take into account the specific features of different construction materials and thus make it easier to compare the EPDs within the same category. For example, prEN16485 is developed for specifically wood-based construction products.

Impact on global warming is an essential part of an EPD

The ISO carbon footprint standard can be applied to produce a single environmental impact assessment of a wooden product, whereas the EPD includes the assessment of several impact categories. The choice of the approach ultimately depends on the scope and goal of the assessment.

Product Environmental Footprint (PEF)

The European Commission is developing a harmonised methodology for environmental footprint studies covering all goods and services and allowing generation of comparable assessment results. It is based on ISO standards and recognised methodologies such as the International Reference Life Cycle Data System (ILCD). The PEF methodology [1] is likely to be referred to in political instruments as directives and public procurement rules.

Standardized carbon footprint calculations for wooden buildings and construction products

The carbon footprint assessment of building can either use the common LCA methodology (EN 15978 for building and EN 15804 for products) or limit the approach to only a carbon footprint assessment (ISO/TS 14067:2013). Again, the scope and goal of the study define which approach is most relevant.

4.3 Assessment procedure and assessment tools and their use

T. Häkkinen

The environmental assessment of a building requires that information is available on the following:

- qualities and quantities of materials needed for the building;
- environmental impacts of the production of these materials, including extracting, transporting and refining raw materials;
- energy demand of the building to fulfil the required building performance;
- energy supply solutions (electricity, district heat, district cooling, fuels); and
- environmental impacts of the energy supply solutions.

To assess the environmental impacts through the whole life cycle, information is also needed about the design service life, renovation and end-of-life scenarios.

LIFE CYCLE ASSESSMENT

ISO 14040 Environmental management - Life cycle assessment - Principles and framework

ISO 14044 Environmental management - Life cycle assessment - Requirements and guidelines

ENVIRONMENTAL PRODUCT DECLARATIONS

ISO 21930 Sustainability in building construction - Environmental declarations of building products

EN 15804 Environmental product declarations - Core rules for product category of construction products

prEN 16485 Product category rules for wood and wood-based products for use in construction

CARBON FOOTPRINT

ISO TS 14067 Carbon footprint of products

prEN 16449 Calculation of sequestration of atmospheric carbon dioxide

SUSTAINABILITY OF BUILDINGS

ISO 21929 Sustainability in building construction - Sustainability indicators

ISO 21931 Sustainability in building construction - Framework for methods of assessment for environmental performance of construction works

EN 15643-1 Sustainability assessment of buildings - General framework

EN 15978 Assessment of environmental performance of buildings - Calculation method

F.4.2-1 Standards for Life Cycle Assessment

	CO_2	CH_4	N_2O
	g/MJ	g/MJ	g/MJ
Anthracite	98.3	0.300	0.0015
Bituminous coal	94.6	0.300	0.0015
Lignite coal	101	0.300	0.0015
Coke	107	0.010	0.0015
Natural gas	56.1	0.010	0.0006
Heavy fuel oil or residual fuel oil	77.4	0.01 0	0.0006
Light heating oil, diesel or distillate fuel oil	74.1	0.010	0.0006
Wood or other solid biomass	112*	0.300	0.004

* Biomass related CO_2 emissions.

F.4.3-1

CO_{2ee}	302,01 g/kg
CO_2	301,93 g/kg
CH_4	0,0033599 g/kg
N_2O	6,9708E-06 g/kg

F.4.3-2

F.4.3-1 Emission factors for stationary combustion in the category residential. Values are given in net calorific value basis. Data is based on IPCC Guidelines/ Stationary combustion (IPCC 2006). When calculating the CF of the heating energy of a building, the efficiency factor has to be considered additionally

F.4.3-2 Environmental data for the production of diesel oil (density 835 kg/m3) based on the ELCD database

In practice, the environmental assessment procedure requires that applied tools are available. Otherwise the collection of information is too time-consuming to be carried out during any normal design process.

This section introduces principal solutions for the assessment procedure and discusses the significance of different factors for the final assessment result. The focus of the discussion is on carbon footprint assessment.

Data bases – carbon footprint data on building materials and energy

The most important prerequisite for the assessment of embodied carbon footprint of a building design is that information is available on the carbon footprint of building materials.

Environmental product declarations worked out according to a standardized process (EN 15804 and EN 15942) present information on the carbon footprint and other environmental aspects based on the life cycle approach.

To provide comparable information, EPDs must have the same product category rules. The information should also be relevant for the case. EN 15942 tries to support the usability of information in different use situations by defining a structure for the information and thus also by requiring data transparency.

An example of a comprehensive collection of EPDs is published by the German IBU. [1]

INIES [2] is the French database for the environmental product declarations of building products made by product manufacturers and professional associations. The format of data meets the NF P01-010 standard requirements.

In Finland, rather comprehensive data on carbon footprint for building materials is available in the connection of ILMARI tool [3].

Free LCA data is available in the European reference Life Cycle Database (ELCD) [4]. ELCD is a database of the JRC of the European Commission. It contains more than 300 datasets in ILCD format on energy, material production, disposal and transport. However, the number of building materials is quite low.

ELCD lists databases for search and use [5]. For example, the GEMIS database [6] covers processes for energy (fossil, nuclear, renewable), materials (for example metals, minerals, food, plastics), and transport (person and freight), as well as recycling and waste treatment processes.

Many countries still lack adequate information on the carbon footprint of building materials. Thus, generic and commercial databases such as those published by GaBi [7] and EcoInvent [8] are often used. Because of its general good availability, German data on building products is also much represented in both free LCA databases and in commercial databases. However, as stated earlier, the use of specific information relevant for the case is recommended. There may be a big difference in the CF of products produced in different countries with the help of different manufacturing processes and energy carriers. Good examples of factors affecting the CF of sawn timber are given in Chapter 5.

Generic information on the carbon footprint of energy carriers is given by IPCC [9] (Table F.4.3-1).

The information of IPCC does not include pre-combustion values. However, these have to be considered in a life cycle approach. Information on the pre-combustion values of energy carriers is given by ELCD [10]. The following table gives an example for diesel oil.

ELCD also gives LCI information about electricity. In principal, the carbon footprint information of electricity and heat can be calculated with the help of International Energy Agency (IEA) statistics [11]. The following table gives an example calculated by VTT for Finnish electricity and district heat in the accordance with both energy and benefit sharing methods and as an average for 5 years (2006 – 2010) [12].

CO_2 emission from a sustainability managed forest is normally regarded as zero in LCI calculations. The current draft for product category rules for wood-based products (prEN 16485) [13] presents that GHG emissions should be measured on a net basis, equalling emissions to the atmosphere minus removals from the atmosphere, over a given time horizon. In practice, even sustainable forests, where the carbon balance of forest land is basically neutral over the full rotation, are not absolutely climate neutral. This is because the rotation length or re-growth time is typically much longer than the urgent timetable of emission reductions, thus creating a carbon debt with respect to the no-use baseline [14]. In addition, a change in land management practices can reduce the terrestrial carbon stocks. For example, intensified utilization of forest harvest residues leads to declining stocks of dead wood and soil carbon at the landscape level [15]. IPPC gives guidelines for the assessment of land use related emissions, but these are not normally considered in LCIs. However, when land use is considered in the system boundary, the reference situation for forest land use has to be defined appropriately, describing the development in the absence of the studied system.

As described in this section, the limited availability of relevant and comprehensive data on building materials is still a problem in a number of European countries. Another problem is that – although data was available – its ease of use is weak when data has to be manually collected and allocated to the information on the bill of quantities of a design. Applied tools and solutions are needed to enable the assessment of the carbon footprint of alternative solutions and building designs.

Assessment tools

The design phase lacks effective assessment tools [16]. The existing sustainable building (SB) rating methods provide indicators for designers. LCA tools, energy consumption estimation methods and service-life prediction methods are also available, but all these methods entail significant amounts of extra work. The problem is not only about the access to data but also the availability of powerful calculation procedures. Design for sustainable buildings needs integrated methods that provide the process with product information and enable the comparison of design options easily or with reasonable extra work also in the early stages of design. [17]. At present, the assessment process is usually carried out when the design of the project is almost finalized. Environmental matters need to be considered in the early stage of design, because alterations to the brief may be expensive. The assessment tools should also be reconfigured so that they do not rely on detailed design information before that has been generated by the designer. Environmental and financial issues also need concurrent consideration as parts of the evaluation framework.

Different kinds of assessment tools are already available for the environmental assessment of buildings. The usefulness of assessment tools is mainly based on two issues: the inclusion of environmental data for relevant materials and support for calculation processes. An essential issue is whether the determination of material qualities and quantities is taken place separately or whether the environmental data can be directly linked to the design-based information on the bill of quantities.

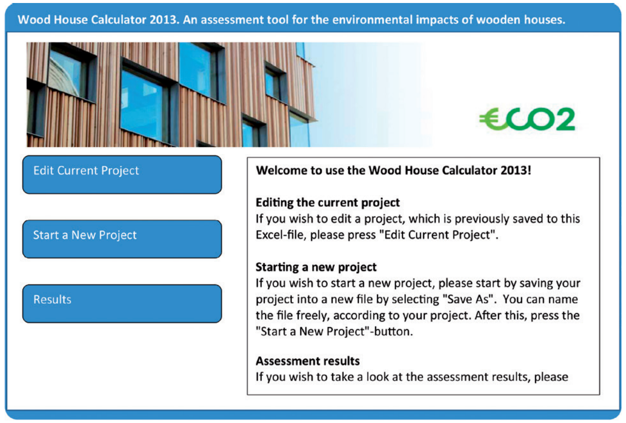
The most typical example of a simple assessment tool is an Excel-based tool that supports the definition of building structures, calculation of material quantities, and finally the calculation of the environmental impact by combining the environmental data of materials with the quantity data. The Finnish Log House Calculator is an example of this kind of tools [18] (Figure F.4.3-4).

The SuPerBuildings project [19] studied the possibilities and potential of integrating sustainable building assessment methods with Building Information Models (BIMs). Interoperability and openness of different tools were assessed in terms of data import and data export. For data import, this evaluates whether the tool only enables entering data through its user interface or whether it has the capacity to import data. Several file formats were considered: CAD format, TXT format, XML-based format, IFC). For data export, this evaluates whether the tool offers different ways to store and report the results obtained different possibilities were considered: Report, File Export with formats like Office format, TXT, XML, IFC). The result of this analysis showed that none of the chosen software solutions are sufficient to perform a comprehensive sustainable analysis with the help of core indicators [20], but a number of software programs have a connection to the BIM and are therefore able to retrieve information from it. For the moment, most of the tools are able to retrieve technical information in order to perform some calculation and edit a report.

	Benefit [1]		Energy [1]	
	Electricity	District heat	Electricity	District heat
CO_2 fossil, kg/MWh	309	236	222	273
CO_2 biogenic kg/MWh	121	134	67.5	160
CH_4 kg/MWh	0.821	0,364	0.709	0,424
N_2O kg/MWh	0.000654	0.000397	0.000523	0.000448
GHG kg/MWh	330	245	240	283

1) The energy method allocates the emissions according to the produced energies. The benefit distribution method allocates the emissions to the products relative to their production alternatives.

F.4.3-3



F.4.3-4

F.4.3-3 LCA based environmental profiles for average Finnish electricity (considering net imports)

F.4.3-4 An example of a simple Excel-based calculation tool, which enables the definition of structures and calculation of embodied impacts for log houses.

Recommendations were developed in order to take advantage of the BIM approach [21].

Comparability of assessment results

The comparability of the assessment results depends on the calculation principles. It is impossible to define rules that are unambiguously correct in all situations because relevant rules depend on the scope of the assessment. When LCI or a carbon footprint assessment is required (for example, in the design competition), it is necessary to define the rules (when possible by referring to a standard that actually gives the calculation rules). EN 15978 defines a calculation method for the environmental assessment of buildings. However, this standard alone does not enable fully comparable assessment results because it does not define detailed principles for the carbon footprint assessment of an energy supply.

The following text summarizes the most important factors that affect the assessment results and which should be defined when comparable CF assessment results are required.

Carbon footprint database for building materials

The most recommendable data are EPDs of building products relevant in the country in question and prepared with the same category rules. When this is not possible, relevant data should preferably be provided specifically for the case (for example, by the organizer of the design competition).

System boundary

The system boundary in terms of a building's life cycle stages can be defined by referring to the stages defined in EN 15804 (Section 6.2) and EN 15978 (Section 7.4).

The coverage of the assessment in terms of building-related constructions and technical equipment can be defined with the help of the list given in EN 15978 (Section 7.5).

The main structures of a building (here including the foundation, floors, exterior and interior walls, roof, and balconies) typically account for a very significant share of the overall carbon footprint of a building (stages A1 – A5). According to a parametric study carried out by VTT, the share is typically roughly 70% in residential blocks of flats [22], while windows, doors, glazings, equipments, fittings, floorings and coating materials form the main part of the rest when all embodied carbon of the building is calculated for the investment stage. The consideration of renovation materials may remarkably increase the calculation result (by roughly 30% during a 50-year period compared to the investment stage only). Although the significance of technical equipment is normally low, it may increase a lot when solar cells, solar collectors and air conditioning are used. These may increase the sum by 15–30% during a 50-years period, compared to the base case without this equipment. The share of material-related processes (building, installation, renovation, demolishing) may be roughly 10–15% of the total embodied carbon during a 50-years period. In addition, the construction of building on-site may significantly increase the production-related impacts in the worst cases when the site must be stabilized. In those cases, the order of magnitude of the carbon footprint of a site construction may the same as that of the whole building [23]. All numerical examples are based on the Finnish parametric case study referred to above

Parameters of carbon footprint

Especially regarding wooden building products and biofuels, the parameters of carbon footprint have to be defined. Especially the consideration of sequestered carbon has an essential impact on the comparability of the results. The following list outlines the essential parameters to be considered:

- CO_2 fossil
- CO_2 biogenic
- CH_4
- N_2O
- Other GHGs as listed by IPCC [24]
- CO_2 sequestered

To maintain the transparency of the calculation result and because of the significance of sequestered CO_2 on the calculation outcome, it is recommended that this parameter is kept separate when it is considered.

Electricity and district heat calculation

An important source for the potential differences in calculation results is the calculation method for the environmental impacts of electricity and district heat, especially in those countries where combined heat and power generation is typical and where electricity and district heat are common methods for the energy supply of buildings, as shown in Table F.4.3-3.

In addition to the calculation method (such as energy or benefit), there are other methodological issues that significantly affect the calculation outcome when electricity and district heat are used. Especially when the environmental impact of alternative energy solutions in retrofitting projects is assessed, it is important to define whether average or marginal/seasonal values are used for electricity. For example, the assessed values for GHG values in Finland (in g/kWh) would be 330 for average electricity (see Table 4.3-3) and 970 for coal-based condensing power. The selection of the calculation basis significantly affects the results.

In addition, the consideration of future scenarios for energy supply is important to define. The share of fossil fuels may significantly decrease and thus the carbon footprint of energy supply solutions will also decrease during the coming decades. As shown, for example, in the MECOREN project,[25] the consideration of future scenarios (the consideration of the expected changes in the emission values of electricity and heat) has a very significant effect on the calculation results. When it is taken into account, the relative significance of material-related impacts normally increases compared to building operation related impacts.

Conclusions

This section gives information about the tools and databases for calculating the LCA of the embodied carbon and carbon footprint of a whole building. To assess the carbon footprint of a building,

F.4.4-1

information is needed on the quantities and qualities of materials being used as building products, on the environmental impacts of products, on the energy demand of the building, on the energy supply solutions and on the environmental impact of the energy supply. In addition, information is required about the service life and estimated renewal periods of the different products and building parts.

Different kinds of databases and tools are available for calculating the environmental impact of buildings. The assessment should always ensure that as relevant data as possible is used. There are large variations between the different databases. The variations may be based both on actual differences in production processes and on energy supply solutions. There may also be differences because of the system boundaries (including geographical boundaries and time boundaries).

With respect to wooden products, the system boundaries and principals used to calculate the carbon footprint can significantly affect the assessment results. In particular, the consideration of sequestered carbon and biogenic CO_2 has an important effect on the results (see also Chapter 3).

4.4 Product level

F. Dolezal, Lauri Linkosalmi, H. Mötzl & D.Peñaloza

Modelling the life cycle of a building starts at the product level. Buildings are a complex system, where products with very different background systems take part, bringing different kinds of uncertainties and challenges.

In this section, these challenges will be discussed with a focus on wood and forest products.

4.4.1 Goal and scope definition

The definition of the goal and scope is the first step of any life cycle study, as it sets the baseline for all the work ahead. The importance of the goal definition is highlighted in every standard, as every methodological choice shall be made based on the study goal, so the results may provide an answer to the questions which drove its commissioning. As the driving forces are particularly different for every study, the goal definition can be regarded as case-dependent, and the aspects they depend on are discussed in this sub-section.

The first key aspect to consider when defining the goal and scope of any LCI-LCA project is the driving forces behind it. The commissioner of the study and what are the results going to be applied for are key issues, and the goal of the study shall be defined based on these. The goal must clearly determine what is the question or problem that the study is meant to solve, so the methodology is tailored to provide the results required to answer it.

At the product level, it is usually building products manufacturing companies who commission LCA studies. It is possible that companies want to learn more about the environmental implications of their manufacturing systems, and so the study is meant to find environmental hotspots and potential for improvement. But even if this is the case, developing Environmental Product Declarations (EPDs), public procurement and product information are on the table as mid/long-term goals.

The commissioner of the study is one thing, but another relevant aspect that must be clearly stated in the goal definition is the intended use of the study. Defining the intended use will have a strong influence in further stages, especially those regarding methodological choices, data collection, reporting and documentation, and reviewing schemes. This is of high importance at the product level, as sometimes commissioners begin with accounting or decision-support a study, and later intend to use these results for EPDs and marketing. The differences of requirements for these uses may prove significant.

This leads to another key aspect to consider, which is identifying the intended audience. Sometimes the intended audience and the commissioner of the project are the same, but it is not always the case. However, the intended audience must be identified at the same time as the goal and scope, so the displaying of results can be planned well in advance.

The International Reference Life Cycle Data System (ILCD) handbook [1] requires the goal, purpose, intended use, commissioner and intended audience to be clearly stated during the goal and scope definition. Additionally, the handbook classifies studies according to their intended use and if they shall be used for decision-making, and it divides all of its provisions according to this classification. ISO 14044 [2] has the same general requirements to be stated in the goal with a clear statement on whether the results of the study will be used for comparison and if these will be communicated to the public.

All the aspects described above should be stated and taken into account when defining the goal. However, other things must be stated at this first stage, such as the functional unit used. It is common to use material amounts as a functional unit in the product level. Volume or mass units may be used as long as assumptions or values related to density or specific weight are provided with the result. Density values provide a way to relate volume and mass amounts, so there is a way to convert the results of the analysis from one functional unit to the other. It should be mentioned that moisture content should be taken into account when performing this kind of calculation, as it can influence the density and energy content values of wood products.

Nevertheless, sometimes the function provided by similar amounts of different materials can be different, which means material amounts might not be adequate functional units. A good example to illustrate this issue is the choice of insulation materials, which might have different conductivity, because the same amount of different materials could have different insulation capacity. This would directly affect the function of the material, and cannot be directly related to the material amount. This is why the functional unit must be chosen carefully, depending on the kind of material under study.

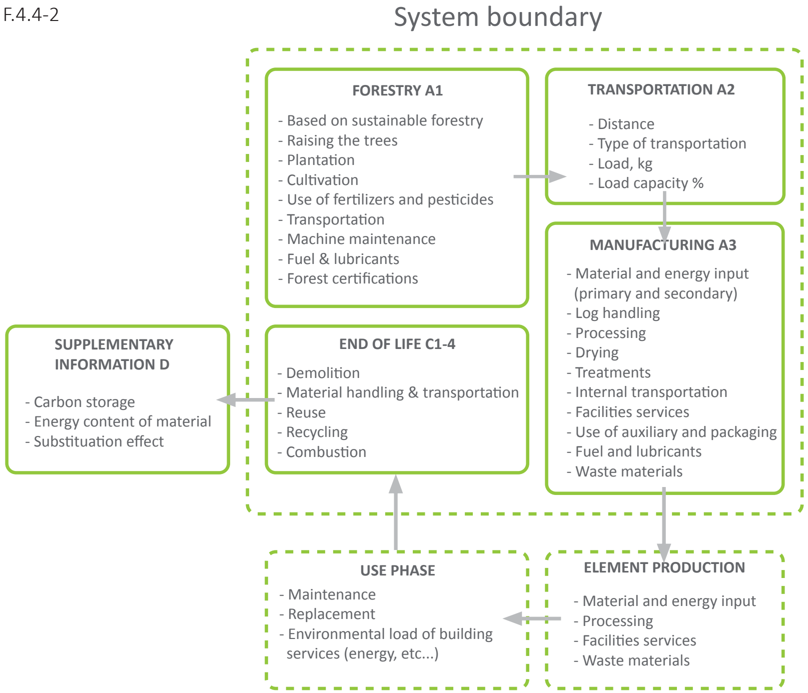
The reference flow must be also clearly identified at this stage. It is defined by ISO 14040 [3] as the measure of the output(s) of the process(s) required to provide the function identified as the functional unit. The role of the reference flow gains importance when the results should be used for comparison between systems, as this comparison should be done only in terms of this reference flow.

There are other aspects that must be clearly defined at this stage as a way of planning how the LCA will be performed. Issues such as the allocation method, the system boundaries, the data requirements, the chosen cut-off criteria, the main assumptions and the uncertainties and limitations of the study should be clearly identified at this stage as part of the scope of the study. They are further discussed in the coming sections.

4.4.2 System boundary for wood based products

The system boundary defines the borders for the study, as it specifies which unit processes are part of the studied product system and which processes are excluded. The boundaries of a product system separate it from natural systems and other technosphere systems, which are always out of the boundaries. According to different standards [4, 5], the system boundaries should describe the main elements of the physical system. The product system should be modelled in such a way that all the

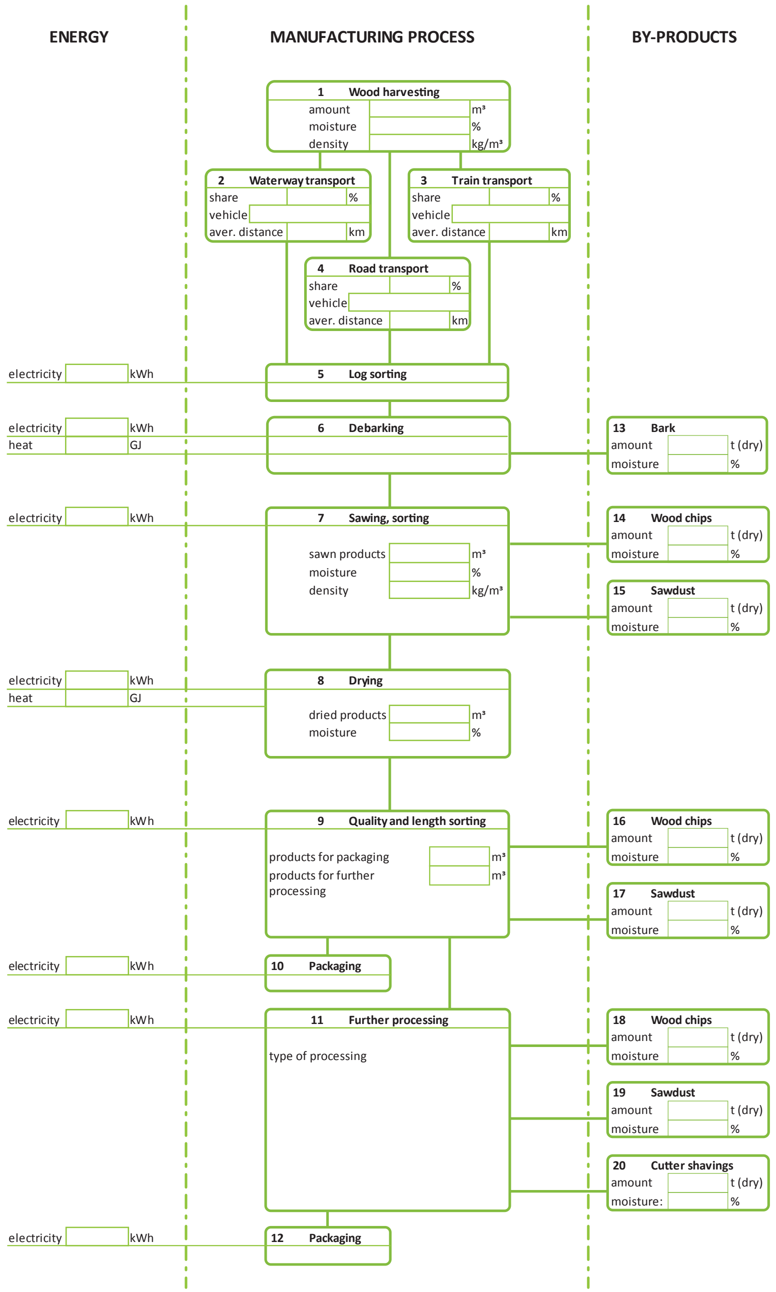
F.4.4-2



Input	Raw materials	m^3 or kg
	Electricity	MJ or kWh
	Heat	MJ or kWh
	Fuels	kg, l or MJ
Output	Materials	m^3 or kg
	Waste	m^3or kg

F.4.4-3

F.4.4-1 Detail of the facade from the Student housings in Kista, Sweden
F.4.4-2 System boundary of wood based construction materials
F.4.4-3 Inventory data for unit process



F.4.4-4 Manufacturing flow for the sawn timber

input and output flows are elementary flows within the boundaries.

According to ISO 14040 [3], the following unit processes or flows should be taken into consideration:

- acquisition of raw materials;
- inputs and outputs in the main manufacturing/ processing sequence;
- distribution/transportation;
- production and use of fuels, electricity and heat;
- use and maintenance of products;
- disposal of process wastes and products;
- recovery of used products (including reuse, recycling and energy recovery);
- manufacture of ancillary materials;
- manufacture, maintenance and decommissioning of capital equipment;
- additional operations, such as lighting and heating.

In the specific case of building materials and their manufacturing phases, modules A1-A2-A3 [4] must take into consideration raw material extraction and processing, transportation of raw materials and manufacturing processes. Furthermore, it must include all materials, products and energy, as well as waste processing up to the end-of waste phase or disposal of final residues. All this information could also be stated as one aggregated result for modules A1-A3. Figure F.4.4-2 shows a typical system model for wood construction materials.

Raw material extraction (A1)

Forestry is the main source of raw materials for wooden building materials. Some of the co-products are recycled during the process, but this might differ for different regions in Europe. When recycling of co-products takes place and recycling loops appear, it should be dealt using physical allocation. A basic assumption in the raw material acquisition process modelling is that it is based on sustainable forestry. The forestry process should take into consideration the cultivation and plantation of trees, as well as the use of fertilizers and pesticides. All machinery work should be considered, as well as infrastructure, transportation, maintenance and harvesting processes in the forest.

Transportation (A2)

The transportation of the raw materials from the acquisition place to the processing place needs to be included as well. Every transportation mode used like road, rail or ship should be reported including the transported distance (km) for each, as well as the respective load (kg), filling factor (%) and type of vehicle.

Manufacturing (A3)

The production phase includes gate-to-gate data; all material and energy inputs to the production site must be included, as well as waste materials. Manufacturing activities such as sawing and planning usually generate co-products such as sawdust or chips. These by-products are usually used for energy production, creating recycling loops, or allocation issues that should be handled using physical allocation.

End of Life (C1-C4)

The end-of-life module includes the processes of demolition, transportation, waste processing and disposal. The end-of-life module is of high interest, as different materials have very different disposal processes that may be changed for different locations and time boundaries. The environmental benefits from disposal processes or substitution effects should not be included in these modules and shall be included in the following module (D) instead.

Supplementary information (D)

Benefits and loads beyond the system boundary should be shown as a separate number in the supplementary information module D [4]. These kinds of benefits or loads for the wooden building products may be carbon storage, the energy content of material, recycling benefits or re-use potential, including substitution effects. These benefits and loads must only be shown in this module and should not be aggregated in the total carbon footprint of the product.

4.4.3 Data inventory

In Life Cycle Assessment, the most crucial issue is the system boundary; moreover, the quality and coverage of data is an important aspect. Data can be monitored from the studied process system, or generic data can be monitored from databases or environmental product declarations.

All data which is used in Life Cycle Assessment shall be listed and documented. Data inventory and sources should be transparent and possible to verify later on. General data can be used when it is justified according to goal and scope decisions; case-specific data should be used when it is studied certain system. Table F.4.4-3 shows the basic idea of data inventory for one unit process.

Inventory data for a whole system can be present as a flow chart. Figure F.4.4-4 shows an example of sawn timber manufacturing. All phases of manufacturing are taken into consideration in this flow: material, energy and by-product flows.

4.4.4 Allocation of environmental impacts

Manufacturing processes in the wood working industry often produce multiple products. Those products can either be main products or by-products, and the environmental burden of the process is distributed among these multiple products. It is recommended to divide the unit process to be allocated into two or more sub-processes or to expand the product system to include additional functions related to the co-products. In some cases, it is not possible to use a wider approach; in that case, allocation within the manufacturing process needs to be used.

Wherever possible, according to ISO 14044 [2], allocation must be avoided. Allocation means partitioning input or output flows from a process or a product system between the product system under study and one or more other product systems.

If a process must be divided but data is not available, inputs and outputs of the verified system should be divided by its products or functions in a way that the separation shows basic physical relations among them. This is what allocation is about.

If related co-production processes are not independent and can't be separated, allocation has to consider the primary purpose of processes and assign it to all relevant products and functions adequately. The scope of the production site and related processes, usually shown in concession, should be considered. Processes with a very low contribution to the revenue can be neglected. A contribution to the revenue of 1% or less is considered very low.

According to EN 15804 [4], if the processes cannot be sub-divided, allocation of a related co-production has to be carried out as follows:

- Allocation has to be based on physical properties (mass, volume) if the difference in the revenue generated by these co-products is low. A difference of 25% in revenue from the co-products is regarded as high.

- In all other cases, allocation has to be based on economical values.

Physical allocation

Physical allocation means that physical properties of the different flows are used to allocate the environmental loads from the process. Mass and volume are usually used for physical allocation, but other physical properties (such as energy or exergy) could be used as well.

Economic allocation

Percentages for economic allocation are identified by given prices or price-relations of products. Economic allocation might be seen as a kind of mass or volume allocation, but weighted by the economic value. The main problem of economic allocation is that, compared to mass or volume, prices are not as stable and depend on and vary heavily with market conditions and fluctuations. For economic allocation of wood, volume should be considered instead of mass values.

Discussion

The use of economic allocation factors changes the weighting of products compared to simple mass or volume allocation. Therefore, in a second step, these changes have to be adjusted by calculating allocation corrections for each product.

Co-products from the same process may have different moisture contents, which could directly affect the physical relations, when allocation is based on such as mass and volume. This is why they should be approximated using available information such as ecoinvent database modules for wood [5] or from the literature. Utilize economics values; they can be varied according to the end use of products and time. Sometimes even economic values are not available, or price can be an internal one within the company. In this case, percentages of price relations have to be claimed. Experience shows that these relations usually can be provided immediately. In most cases, mass or volume are not appropriate figures to describe the technical value of a product, as they do not reflect the main characteristics of the product. With mass allocation, large burdens are attributed to low-value products if they are produced in large amounts, e.g., rock as a side product of gold production.

Emission measurements of boilers and cogeneration plants are taken into account if data is provided by producers and applied to the production. Afterwards, the main product is modelled in a second module, where allocation is applied on the product. Additional inputs that are only related to the main product (such as packaging) are considered at this stage.

It should be mentioned that the choice of allocation method has a strong influence on the results of life cycle assessments and carbon footprint. Considering the example of gold production, relations can vary heavily due to different allocation methods.

Recommendation for allocation

In principle, the selection of allocation method is case-dependent. When deciding which method to apply, the circumstances of the specific process and co-products should be evaluated. Nevertheless, given the variability in economic value of co-products, physical mass allocation is recommended for wooden products as the default methodology. Since environmental impact is a physical phenomenon, it should not be affected by fluctuations in the social and economic situation.

4.4.5 Interpretation of results

The final stages of every LCA study should always take practitioners back to its goal. All the work involved during this stage strives to find whether or not the purpose of the study was fulfilled. This section will cover the identification of the relevant aspects from the results and conclusions, as the following section covers the checking of the robustness of results.

Identifying highly significant processes or “hot spots” is often relevant because of their strong influence on the total environment impact of a product. This is even more relevant for accounting studies, as their purpose is to identify processes where there is higher potential for environmental improvement for the studied product.

In studies where the goal does not include an environmental impact assessment, the interpretation of results is less relevant. For this kind of study, the main objective is to model and inventory the system for a specific product or material, and delivering only a set of comprehensive data is required. This is often the case in EPD development, where the challenge is fulfilling the requirements for a public EPD defined in the standards and presenting the results in a way that all public stakeholders can understand.

These requirements are important for the concrete case of EPD development. The core rules for the product category construction works EN 15804 [4] establish a set of requirements for reporting and documentation. It also includes requirements for verification of the validity of the EPD, as well as the documentation required for this verification. Furthermore, the EN 15942 [6] standard establishes a communication format for EPD. All these requirements must be revised and fulfilled if the results of the study are to be used for public information.

Transparency of the results is very important for any life cycle study. The sources of background data must be very clear, as well as how it was obtained or inventoried, what kind of process and technology it represents, what is included in the data, and possible sources of uncertainty regarding specific data sources.

Some data can be cut-off. Cut-off criteria and rules are used to exclude some inputs and outputs in an LCA study. The use of cut-off criteria within a study needs to be clearly understood and well described, as it should not be used to hide data or results. All excluded inputs and outputs must be comprehensively justified and documented in the final report. Standard EN 15804 [4] describes specific rules and criteria for the cut-off. Different cut-off criteria should be used to determine which inputs are to be included in the assessment, criteria regarding, for example, mass, energy and environmental significance. To cut off inputs according to only one factor may cause the omission of some important results. Therefore, decisions to cut off any flow need to consider preferably the mass and energy contribution as well as the environmental significance [2].

The conclusions drawn from the study shall be consistent with the study goal. The interpretation of results should lead to the fulfilment of the original study goal, whatever it is. The questions that the commissioners raised by performing the study shall be clearly answered by the results, otherwise the methodology and the system model shall be revised.

4.4.6 Uncertainties and limitations

Every LCA study must identify and state the uncertainties and limitations of its results. This is important not only for studies intended to be used for information and marketing, but also for every study because it affects the reproducibility of the results by other practitioners. It is also possible to assess the robustness of the results if it is required or planned in the goal and scope stage. In this final section, the most common sources of uncertainty will be discussed, including some ways to deal with these uncertainties.

First, it is important to distinguish between two different concepts in this regard: uncertainty analysis and sensitivity analysis. **Uncertainty analysis** deals with the uncertainties in the data used and the assumptions made to obtain this data. **Sensitivity analysis** deals with the sensitivity of the results to changes in the methodological choices used in the study.

Imprecise data is what uncertainty analysis deals with – imprecisions which appear when processes can have different environmental impacts if they operate under different conditions or when processes are modelled using different assumptions [7].

At the product level, a comprehensive way to deal with this is to present an interval instead of an average result. If a dataset or a process brings uncertainty to the results and it proves to have a significant contribution to the environmental impact of the products, the results can be presented as an interval of potential environmental impact from the product. This would give the audience a full and realistic picture of the environmental potential from the specific product. This is a comprehensive way to deal with uncertainty, but also requires more resources as practitioners need to obtain or inventory further data.

One usual source of sensitivity for any LCA study is the **excluded processes**. It is easy for any kind of audience to have a view of the processes that are included in the study, as this is usually described in the system boundaries section and diagrams. Nevertheless, the excluded processes are not as straightforward to see, and practitioners who intend to use the study results might bring uncertainty without realizing it.

It is not clear how much the environmental impact from these processes will affect the results of the study. It is difficult to know if this influence is high or low, as the only way to know this for certain is to actually include these processes. The reasons for their exclusion are often justified by previous findings that show a minimal influence on the result or a lack of relevant data to model these. Anyhow, it will affect the completeness of the results.

The best way to deal with this issue is to perform a sensitivity analysis where these processes are included in the model, making some basic assumptions such as transport distances or modes, material requirements, emission factors, and technology used. The effect of this change must be analysed in a comparative way, assessing how much the overall results would change if these processes are excluded or not.

The robustness of results might also be sensitive to the **representativeness of data**. At the product level, the data is often inventoried by a specific manufacturer. Sometimes it is possible to include several sites, but it is possible that manufacturers have only one production site. Production sites represent only one kind of technology they use, which might be out of date or modern. Production sites can also represent a common technology in a specific country, while the electricity system in each country may also greatly influence the results.

This means that the results obtained at the product level are often not very representative of a product type. They represent the specific technology of the manufacturer, which represents a specific time period or a specific time of year. They also might be representative of a country, a region, a company or even just a production site. If results are not representative, other LCA practitioners would not be able to reproduce them easily because averages or simply other types of data might often be preferred.

The best way to deal with this issue is to gather representative data from the beginning, inventorying as many different processes, technologies and sites as possible. Then average and specific results would be available, and the representativeness limitation would be avoided. This requires additional resources for the project, so it may not always be possible. As with all other methodological choices, this choice will depend on the study goal and purpose.

It can also be argued that most of the LCA studies performed at the product level aim to represent the production system of a specific company, a specific site or a specific process, especially if the LCA is carried out as part of the development of an EPD. For these cases, representativeness would not be an issue, and would rather be a normal thing to have a very specific result.

Sometimes LCA practitioners find surprising results, or simply doubt some of the methodological choices made. **Variation analysis** is a good alternative in these cases when a variation in the methodology is explored and alternative scenarios are calculated based on a single assumption, data choice or calculation done differently [7]. If the results do not change much, it means that this particular choice would not influence the results, so the study may go on. If the results change significantly, the methodology shall be revised.

Wood products usually have uncertainties regarding the selected allocation method. Since multi-output processes and recycling loops are quite common, the way in which allocation issues are dealt with often brings uncertainty to the results. The best way to deal with this is to do a variation analysis and test other allocation methods in processes that influence the results the most.

The choice of data for electricity or heating systems is often a very influential one, and wood products are no exception. Often production facilities use a great deal of biomass by-products to produce energy for their own process, but additional electricity or heat is always required. Modelling electricity systems is always challenging, as many variables affect the outcome, such as assumptions regarding technology, fuel, and energy carrier. Furthermore, whether to use average mixes, local specific data, marginal data or a specific technology influence the results as well. The best way to deal with these uncertainties is a variation analysis, where different scenarios using different energy models are modelled and the implications of this choice are comprehensively described.

Standards deal with uncertainties in similar ways. The ILCD handbook for LCA recommends a completeness check (to see if the cut-off criteria are met), a sensitivity check (to test the accuracy and precision of results) and a consistency check (if the results are consistent with the study goal) [1]. Furthermore, ISO 14044 [2] has the same recommendations, while emphasizing the importance of choosing evaluation techniques that are consistent with the goal and purpose of the report, especially as different uses imply different levels of robustness and verification.

Finally, the results of the uncertainty and sensitivity analysis may have different outcomes. On one hand, it might be observed that the uncertainties from the data used and the method followed do not affect the results. If this is the case, the results of the study will be more reliable. On the other hand, the results might turn highly sensitive to changes in method and data. This would mean that more reliable data or a more relevant or more complete system model is needed.

- Key aspects about the goal and scope definition stage are functional unit.
- Reference flow and purpose of the study
- Both economical allocation and physical allocation method have merit and demerit.
- Mass-based physical allocation is recommended for wood-based products

4.5 Building level

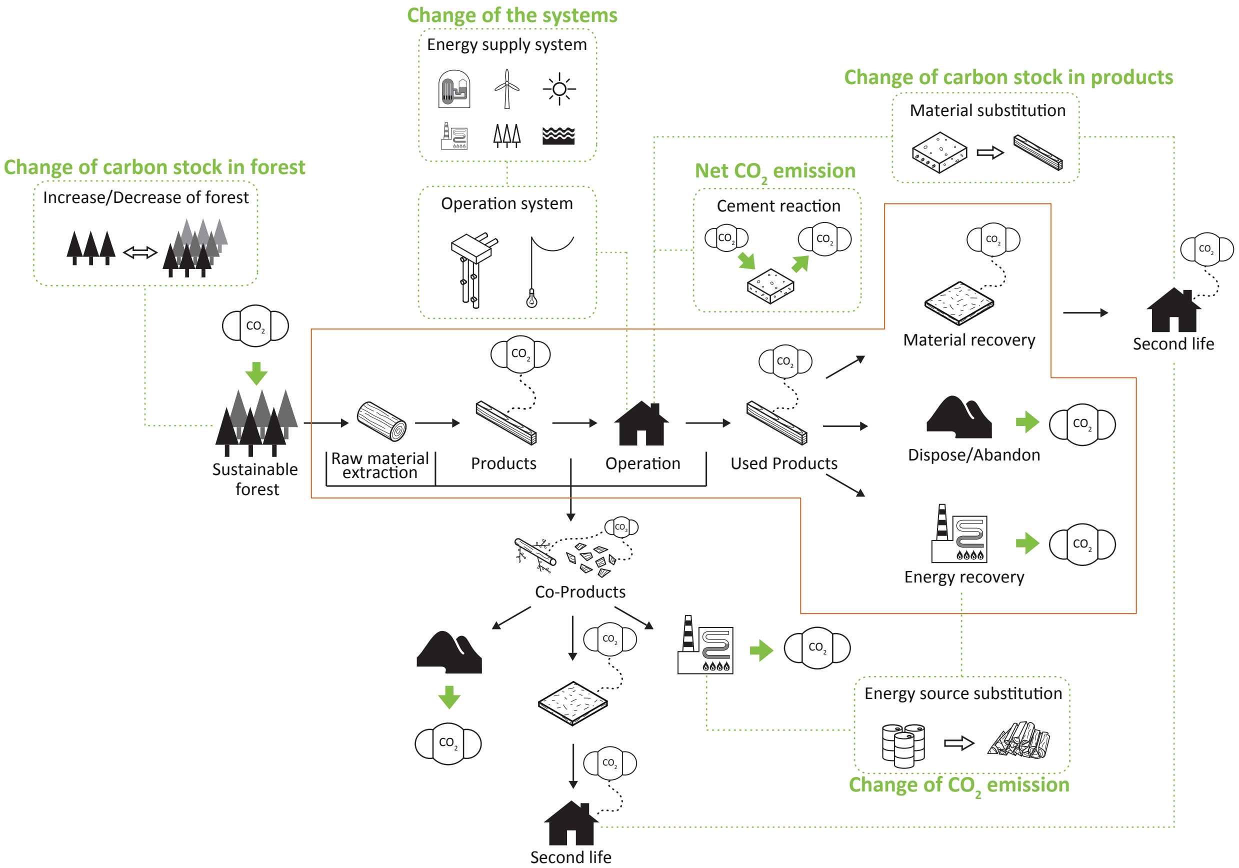
4.5.1 General issues – System boundary condition

A.Takano, A. Hafner, S. Ott, S. Winter & A.Dodoo

Carbon footprint analysis of buildings is more complex than that of many other products due to the following: the long lifespan of most buildings, with impacts occurring at different times during the life cycle; the possible changes in form or function during the lifespan of the building; the multitude of different actors, including designers, builders and users, that influence the life cycle impacts of the building; and the lack of standardization of building design and construction, making each building unique [1]. Furthermore, buildings are complex systems of multiple components and functions and are dynamic due to their different life cycle stages, which are interlinked with energy supply activities. For wood-based systems, carbon footprint analysis should take into account all the inputs and outputs over time across every stage of processing, from forest regeneration and management, harvesting, product processing, product use, maintenance and final disposal of the wood.

Figure 4.5-1 shows the activities and flows linked to the life cycle of a wood-based building. An analysis of this system provides information about the consequences of changes in the level of production of a product and may include effects both inside (direct) and outside (indirect) the life cycle of the product. This wide system boundary is important to draw conclusions on the full carbon flow connected to a building, as the system includes a wider scope and time frame.

On the other hands, practical simplification of the system boundary may be required, for instance, where the purpose of assessment focuses on system building as such. The red line in Figure F.4.5-1 shows a simple system boundary for practical implementation of a carbon footprint analysis as an example. An assessment of this system provides information about the impacts of processes to produce, consume and dispose of an average single unit of a product, but does not include induced effects from changes in outputs, such as shifts in production and emissions from other products that are displaced by the product being assessed. This approach aims at describing environmental properties of a building in its life cycle. Different carbon footprint analyses can be



F.4.5-1 Holistic picture of carbon footprint related to a wood-based building system and simplified system boundary (red line) for the system building including only direct environmental effects.

Description	Carbon dioxide emission
Production /retrofitting phase	Fossil fuel use for material production and building construction.
	Net cement reaction (calcination)
	Wood residues
	Carbon stock changes in forest.
Operation phase/ Service life	Fossil fuel for building operation (space heating, tap water heating, electricity for ventilation and for household and facility management)
	Carbon uptake in re-growing forest.
	Net cement reaction (carbonation)
End-of-life phase	Fossil fuel for end-of-life activities- material demolishing, transportation, recovery.
	Wood residue recovery
	End-of-life benefits of materials e.g. concrete, steel etc.
	Net cement reaction (carbonation)

F.4.5-2 Main activities and flow in a complete carbon footprint analysis of a wood or non-wood-based buildings

compared across differing technologies or different co-products of a process with the same system boundary.

The system boundary condition is an issue that needs to be considered according to the scope and goal of the assessment. A different system boundary requires fulfilling slightly different methodological issues. Regarding the two different system boundary conditions mentioned before, the methodological points are discussed in the following sections of this chapter.

4.5.2 Full carbon footprint analysis

A. Dodoo, R. Sathre

General guidelines for carbon footprint analysis are outlined in ISO/TS 14067 (ISO, 2013). According to the technical specification, a scientific approach should be used to assess a carbon footprint with emphasis on relevance, completeness, consistency, accuracy, and transparency for the entire life cycle of a product. According to the International Standards Organization [2], ISO 14067 builds on existing standards in the ISO 14000 category and is consistent with the ISO standards for life cycle assessment.

Holistic analysis of the carbon footprint of wood vs. non-wood based building systems is a complex issue. Wood substitution raises two important questions: (1) what would happen without the substitution (the performance of the reference system)?, and (2) how will the substitution system perform? In principle, marginal changes will occur in both the reference system (the non-wood product system) and the substitution system (the wood product system). Gustavsson and Sathre [3] discussed key issues to address to accurately analyze the carbon footprint of building and construction systems. These issues include a definition of appropriate functional units, establishment of effective system boundaries in terms of activity, time and space, and choice and quality of data.

Unit of analysis

Defining an appropriate unit of analysis or functional unit for comparing different systems is an essential step in carbon footprint analysis. Different functional units have been used in the carbon footprint analysis of buildings [4]. These units include the complete building or unit area (m^2) of a building's gross, living or heated floor area. Functional units based on material volume, mass, or isolated structural characteristics of building components are inadequate as the function of different materials cannot be directly compared and materials may often fulfil more than one function (e.g. structural support and thermal insulation). A robust functional unit must reflect the complex interactions between multiple system components and functions. This is done by considering the complete building.

System boundaries

System boundaries of carbon footprint analysis must be broad enough to include all significant impacts. The ISO/TS 14067 technical specification on carbon footprint analysis states that a study shall "consider all stages of the life cycle of a product when assessing the [carbon footprint], from raw material acquisition to final disposal" and to "include all GHG sources and sinks together with carbon storage that provide a significant contribution to the assessment of GHG emissions and removals arising from the whole or partial system being studied" (ISO 2010). Analysis of carbon footprint of buildings in a life cycle perspective should include "all the upstream and downstream processes needed to establish and maintain the function(s) of the building, from the acquisition of raw materials to their disposal or to the point where materials exit the system boundary either during or at the end of the building life cycle" [5]. All CO2 flows and stocks linked to buildings (Table F.4.5-2) need to be considered in a life cycle optimization. Activities, temporal and spatial aspects of the system boundaries should be considered in a carbon footprint analysis.

Activities-related system boundaries

Activities-related system boundaries encompass building production, operation, end-of-life, and all related energy and material processes required during the building life cycle.

Production phase

The production phase of buildings encompasses extraction of raw materials, transport and processing of raw materials into building materials, fabrication and assembly of materials into a ready building. Biomass residues obtained from forest thinning and harvesting, wood processing industries and construction sites must be taken into account [6].

For those materials extracted directly from natural deposits (mineral ores, for example), an appropriate system boundary for the calculation of the carbon footprint begins at the point of extraction. For biological materials that are cultivated (for example, wood from sustainably managed forests), the analysis includes the technological (i.e. human-directed) energy used for biomass production. This includes the GHG emissions from fuels used for the management of forest land, the harvesting of timber, and the transport and processing of wood materials.

Energy input is required to extract, transport and process building materials, and this may result in GHG emission. In cases where the type of fossil fuel is known (e.g., end-use fuels used for material production in well-documented industrial processes), the CO_2 intensity of that fuel is used in carbon footprint calculations. In cases where there is some uncertainty as to the appropriate choice of fuel (e.g., the fuel that is used to produce marginal electricity), a "reference fuel" can be employed to determine the significance of the carbon intensity of the fuel that may be used [7]. Coal and fossil gas are two potential reference fossil fuels, representing the high and low ends, respectively, of the range of carbon intensity (kg C emitted per GJ heat energy released) of fossil fuels, thus indicating the range of uncertainty introduced by the fossil fuel used.

To estimate the carbon footprint implications of building production, the total material mass inputs for buildings (including waste on construction sites) should be accounted for. The amount of building waste typically varies between materials and also varies between construction sites. In the absence of specific data, waste material generated during construction of the buildings may be estimated by increasing the material quantities in the finished buildings by specific percentages that are representative for each material. For example, Björklund and Tillman [8] estimated material waste percentages for Swedish construction sites. Examples of these values are 1.5% for concrete, 7% for insulation, 10% for plasterboard and wood, 15% for steel reinforcement, and 5% for most other materials. These values may vary depending on whether the assembly is on-site or prefabricated.

The carbon dynamics of cement-based products include calcination and carbonation. CO_2 is released during the production of Portland cement due to the calcination reaction, when calcium carbonate is heated and broken down into calcium oxide and CO_2. Carbonation removal is less than the calcination emission, thus the net process reaction emissions can be a significant part of the carbon footprint of cement products [9].

Different physical processes can be used to produce the same material, each process with unique requirements and effects on the environment [10]. This may result in significant differences in the carbon footprint for the same type of material. Recent ISO specifications on carbon footprint calculations state that data "shall be representative of the processes for which they are collected" [11].

In the building construction stage, diverse materials are put together into a complete building. Several factors may affect the primary energy used for building construction, including the method of construction and the type of building materials [12]. In contrast to site-built systems, modular building systems are typically prefabricated off-site as volume elements, and then transported on-site and assembled on site-built foundations. The GHG emission for building construction may also vary, depending on the parameters included, e.g. fuel use to transport construction equipment, workers and off-site fabricated components. To determine the carbon footprint resulting from primary energy use for building assembly activities, it is necessary to know the fuel mix. In the absence of specific data, [13] assumed that half of the construction-related primary energy use was for end-use electricity, and half was diesel fuel.

Biomass residues are generated during silviculture, harvesting, primary processing when logs are sawn into lumber, and in secondary processing for products such as doors, windows and glue-laminated beams. Residues are often used as an energy source in sawmills and wood kiln and as fuels in heat and power plants in Sweden. Residues may also be redirected to non-wood product streams such as pulp and paper, or used as a raw material for particleboard and other composite wood products. Gustavsson et al. [14] describes a methodology to estimate the carbon footprint dynamics of residues from the wood chain. Parameters considered include the mass of different types of residues available from the wood product chain and their heating values, and the energy used to recover the residues.

Bottom-up and top-down approaches are two complementary methods to model production phase carbon footprints. A bottom-up approach, based on process analysis, begins with detailed disaggregated information for a system and then generates aggregate system behaviour to characterize the relationship between the individual components of the system [15]. This approach provides specific information about the individual processes and systems studied, allowing for detailed comparison and optimization. The top-down approach, based on environmental input-output analysis begins, with the aggregate information for a system and then proceeds to disaggregate this to characterize the components. Carbon footprint calculations of bottom-up models may have a high level of accuracy but may suffer from truncation errors, as they may not recognize indirect flows in a studied system (see, e.g. [16]). In top-down models, the problem of truncation error is addressed as indirect flows are taken into account when the aggregate system is considered. However, top-down models suffer from a lack of detail and precision at individual process levels.

Operation phase

Energy-related activities in the operation phase of a building include space heating and cooling, tap water heating, ventilation, and electricity use for lighting and appliances. The space heating demand of a building depends on the interactions of several thermo-physical properties, including the envelope thermal properties of buildings, orientation, glass area, heating and ventilation systems, heat gains from lighting, appliances, human bodies and solar radiation, and operation schedule, indoor temperature, geographical location, and climate besides outdoor temperature. Furthermore, a comprehensive analysis of the carbon footprint of the operation phase of a building may include the thermal mass effect. Effective thermal mass material can absorb and store significant amounts of heat, and this can help to level out temperature variations. Thermal conductivity influences the time lag of absorbing or releasing heat. The effectiveness of thermal mass in buildings depends on the interactions of several parameters, including climatic location, insulation, ventilation, load profile and the occupancy pattern of buildings [17].

Detailed dynamic hour-by-hour models are needed to accurately account for the heating and cooling loads of a building and for one-, two- and three-dimensional heat flow modelling of various building envelope configurations. Commonly used dynamic state models include ESP-r, Energyplus, TRNSYS and VIP+ [18].

The various processes along the energy supply chain, from the extraction of raw material to refining, transport, conversion to heat and electricity, and distribution to the user can be performed with different energy efficiencies and with varying emissions. All the energy inputs for these processes need to be included for a full description of a particular energy system. A comprehensive analysis of the carbon footprint of the operation phase of a building needs to include the entire energy chain, from natural resource extraction to final energy supply, taking into account the fuel inputs at each stage in the energy system chain and the energy efficiency of each process. The heat demand of a building can be provided by different end-use heating systems and energy supply technologies, which can result in significantly different carbon footprints [19], [20]. Maintenance and retrofitting phase

Maintenance and retrofitting tasks include periodic component replacements and aesthetic and energy renovations. Maintenance and material replacement activities can have a significant effect on life cycle impacts and can vary substantially as a function of material; hence, they are generally included in a carbon footprint analysis. The building structure can be assumed to have the same life span as the building and basically no maintenance need, regardless of structural system used. However, different exterior surface materials and some other building materials may have significantly different service lives or maintenance requirements.

Depending on the energy efficiency standard to which buildings are originally built, there may be significant CO_2 benefits of retrofitting buildings to a higher energy efficiency standard [21]. Evaluation of the overall effectiveness of energy efficiency retrofitting measures requires a system-wide perspective that considers the complete building life cycle phases and heat supply systems.

End-of-life phase

End-of-life management options for building material may include reuse, recycling, energy recovery and landfilling with or without the capture of landfill gas. The end-of-life management of building materials is inherently uncertain, as this life cycle phase will occur in the future. Still, a carbon footprint analysis of a building must consider the fate of the building material at the end of their service life, as the ISO draft standards [22] require that “all the GHG emissions and removals arising from the end-of-life stage of a product shall be included in a [carbon footprint] study”. End-of-life management of wood products is the single most significant variable for the full life cycle energy and carbon profiles of wood products [23]. The energy used directly for demolition of buildings is generally small (1-3%) in relation to the energy used for material production and building assembly [24]. The percentage of demolition materials that is recoverable is variable and depends on the practical limitations linked to the building design and whether material recovery is facilitated. Methods of accounting for the climate effects of recycling materials are still at an early stage of development, particularly in the context of potential policy instruments for climate change mitigation. End-of-life materials are increasingly recovered, as efficient management of post-use building materials is a priority in many European countries [25].

Re-use or reprocessing of materials at the end of the building life cycle can have significant effects on the net carbon emission[26]. Optimization of end-of-life product recovery and recycling systems may become increasingly important in the future for wood, concrete and steel. The climate performance of non-wood materials can also be significantly affected by post-use management. Production of steel products from recycled steel scrap requires less primary energy, and emits less CO_2, than production of steel from ore. However, the analytical methodology used (e.g. closed-loop, value-adjusted substitution, cut-off) will affect the calculated benefits. Post-use management of concrete can also lead to reduced net CO_2 emissions by promoting increased carbonation by, e.g., crushing the concrete and leaving it exposed to air. Nevertheless, wood material has relatively more opportunity to improve its climatic performance, due to its dual role of both material and fuel [27].

Recovery of energy by burning the wood is a resource-efficient post-use option where material reuse of recovered wood is not practical. The use of recovered demolition wood for biofuel directly affects the life cycle carbon balance of the material. The use of the biofuel to replace fossil fuels, thus avoiding fossil carbon emissions, also affects the carbon balance.

Carbon dynamics in landfills are quite variable and uncertain and can have a significant impact on the carbon footprint of wood-based systems. Landfilling of wood should be avoided as is not allowed in the EU; thus this option is not expected to be significant in European analyses.

Temporal aspects of wood-based products and forest

Consideration of system boundaries related to time is an essential part of the analysis of carbon balances of wood products [28]. Important temporal aspects of the wood life cycle include dynamics of forest management, the duration of carbon storage in wood product, and the time dynamics of carbonation cement process reactions. Consideration of forest dynamics at both stand level and landscape level is an essential part of an analysis of the carbon footprint of wood-based building [29].

As part of a dynamic biogeochemical cycle, carbon storage in wood products is an inherently transient phenomenon, though some long-lived wood products may store carbon for centuries. Over the life cycle of a building, there is no change in carbon stock in the building itself. Before the building is built, it contains no carbon stock; and it contains no carbon stock after it is demolished. Combustion of wood-based demolition material ensures that 100% of the carbon stock is oxidised and re-enters the atmosphere as CO_2. If the demolition material is used as biofuel to replace coal, the fossil carbon emissions that are avoided are roughly equivalent to the carbon stored in the wood material during the building lifespan [30]. On a larger scale, a carbon sequestration effect occurs if the total stock of wood products is increasing. This could occur as a result of general economic growth, whereby more products of all kinds are produced and possessed, or through a societal transition from non-wood to wood-based products. If the total stock of carbon in wood products is increasing, carbon storage in products contributes to reducing atmospheric CO_2 concentration. The carbon stock in wood products would increase if a change were made from non-wood to wood-based construction. This would occur if non-wood buildings, representing the baseline, are replaced by wood-framed ones, which after demolition are always replaced by new wood-framed buildings with a similar carbon stock. This would result in a step change in carbon stock compared to the baseline, at the point in time when the non-wood material is replaced by wood. The permanence of the carbon stock in buildings depends on the difference between the amount of wood added to new construction and the amount of wood removed from demolished buildings [31]. The stock of wood products will stabilise if the rate of wood entering the wood products reservoir is equal to the rate at which used wood is oxidised and releases its stored carbon to the atmosphere. At this point, the storage of carbon in wood products has no net effect on the atmospheric CO_2 concentration.

Spatial aspects of wood product systems

Wooden buildings require greater amounts of biomass, and thus a larger forest area, than non-wooden buildings. Gustavsson et al. [32] described three different land-use modelling approaches to address the issue. The first assumes that the incremental wood material is produced through more intensive management of forest land, or from land that was not previously used for wood production. The second assumes that an equal area of land is available to both the wood-frame and concrete-frame buildings, and analyses the carbon balance impacts of biological carbon sequestration on the "surplus forest," or the part of the land not used for building material production. The last approach assumes that the difference in wood quantity between the wood and concrete buildings is used for energy instead of for construction.

Energy supply systems

The use of fossil fuels produces CO_2 emissions in quantities that depend on the carbon intensity and fuel-cycle characteristics of the fuel. Specific CO_2 emission values are applied to end-use quantities of fossil fuels to give total emissions. To ensure accurate reporting, specific emission values must include emissions occurring over the entire fuel cycle, including the end-use combustion of the fuels as well as from fuel extraction, conversion and distribution [33]. Uncertainties arise in accounting for fossil fuel emissions, due to methodological differences, heterogeneity of fuels, and imprecision in measuring [34]. The marginal effects of changes in fossil fuel use, rather than average effects, should be considered.

There are different electricity production systems, and these are characterized by significant variation in their primary energy use and CO_2 emission. Two different approaches to accounting for primary energy use and CO_2 emission from electricity supply and use are the average and marginal methods. There is much discussion in literature about which method should be employed in an analysis (e.g., [35]). In principle, the method employed should reflect the purpose and relevance of a study. The marginal accounting method may be used because it captures the consequences of changes due to variation in system parameters. The average accounting method is not suitable because changes do not readily reflect

F.4.5-3 Tree hotel, Harads, Sweden

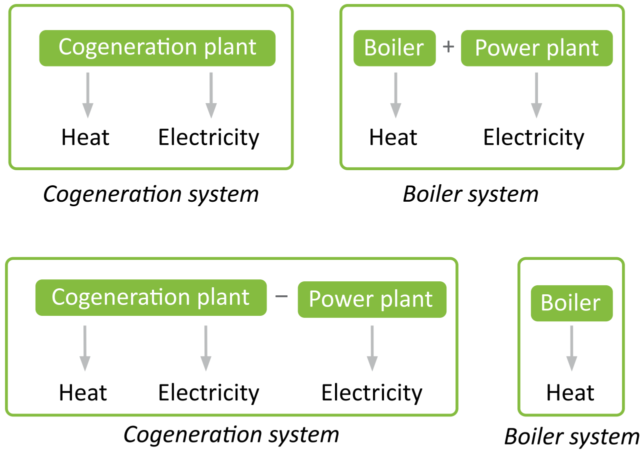
the average level [36]. In addition, this approach does not reflect the technologies and inputs affected by a variation in a system.

The electricity production in the EU in 2006 originated mainly from conventional, thermal plants (54%) and nuclear plants (30%). Hydro (11%) and other renewables (5%) accounted for the remainder (Eurelectric, 2008). Only some 11% of the EU's electricity is produced in combined heat and power (CHP) plants (Eurostat, 2009). The marginal electricity in northern Europe is typically coal-based (STEM, 2002). Fossil gas plants have dominated investments during the past decade, but a number of coal and lignite plants are also under construction and more are planned [37]. Future development will depend on several factors, such as concerns regarding the security of the energy supply and emission restrictions. The supply of fossil gas is considered less secure than the supply of coal. Because the electricity production system may not be known with certainty, it is worthwhile to conduct the analysis with more than one reference electricity production system to determine the significance of this uncertainty.

Allocation in co-products systems

The allocation approach used may have a significant effect on the results of a carbon footprint analysis for co-product systems[38]. Cogeneration systems, or combined heat and power (CHP) systems, produce both heat and electricity. Sawmills can use wood processing residues to cogenerate both process heat for kiln drying, for example, and electricity for use within the mill and for export. Different methods can be used to compare cogeneration and separate heat and electricity production. It is preferable to use a method that avoids allocation because of the subjective nature of allocation ([39], [40]).

Allocation can be avoided if the systems being compared all use the same functional unit. The functional unit is defined based on the products produced by the systems. Therefore, to compare cogeneration systems producing both heat and electricity with systems producing heat or electricity only, both the energy carriers should be considered in the functional unit [41], [42]. (Figure 2). This can be done by expanding the systems by adding an alternative means of producing heat or electricity to systems that produce only one of the energy carriers, thereby making the systems multi-functional. In a multi-functional method, the functional unit is expanded to include all products produced. When heat and electricity are co-produced, they are both part of the functional unit and either one of them can be considered the main product. Subtracting either heat or electricity production from cogeneration is another way of comparing such systems [43], [44]. In this case, the functional unit will be only electricity or heat. The subtraction is typically based on the avoidance of an assumed electricity or heat production in stand-alone plants using comparable fuels and technologies. The transparency is poorer when using the subtraction method than when using the multi-functional method [45]. In some cases, however, it may be preferable to use this method, for example when analysing the heat at end user, to whom the cogenerated electricity is of no interest [46].The choice of system expansion method does not affect the primary energy ranking of the heating systems [47].



F.4.5-4 An example of system expansion (top) with multi-functional products in the functional unit, and system subtraction (bottom) where cogenerated electricity is subtracted so the functional unit is heat ([48], [49])

- Holistic analysis of carbon footprint of wood versus nonwood based building systems is a complex issue.
- Full lifecycle and energy chains should be considered to optimize the carbon footprint of buildings.
- System boundaries should be broad enough to include all significant impacts.
- Allocation should be avoided if possible, e.g. by system expansion.

4.5.3 Simple system boundary for practical implementation

A. Hafner, A. Takano, S. Winter, S. Ott

This section focuses on the basic methodologies for the simplified system, from wider aspects described in Section 4.4.2. The points related to the system buildings: all inputs and outputs related to the system, system boundaries, allocations and cut-of-criteria, are described concisely. This approach aims at describing environmental profile of a building in its life cycle. As a building process is a complex issue, system boundaries get limited. Due to the interactions of different issues, borders are drawn with the awareness that some issues are being left outside the system.

Scope and goal

The scope of calculation is the system building. Due to complex interactions of different issues in the building context (energy standard, fire regulation, sound protection, building services, material choice, detailing, and national building regulations and standards), reasonable borders are recommendable as a starting point.

The whole life cycle process should be considered, and all direct influences from the system building should be included. EN 15978 defines the following life cycle stages:

- Product stage (module A1-3)
- Construction stage (module A4-5)
- Use stage (module B)
- End-of-Life stage (module C)

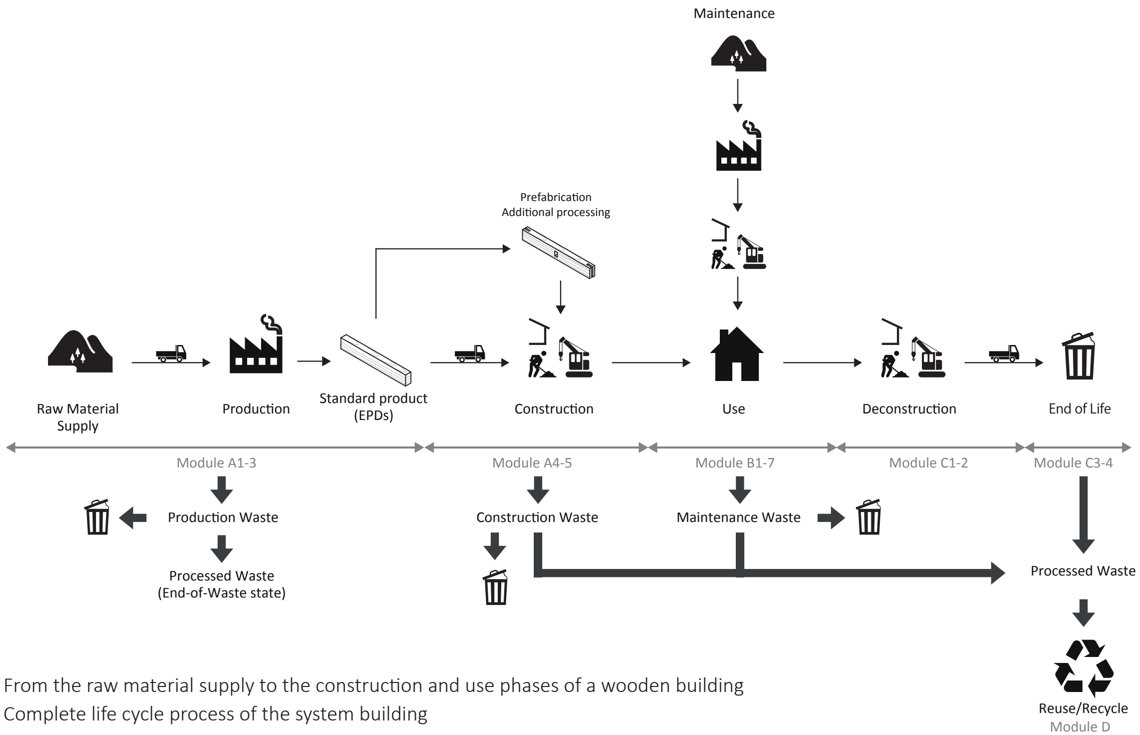
In addition to that, the environmental burden and benefit over each life cycle phase can be described in module D for the studied system. Figure F.4.5-6 shows the complete life cycle of the system building, from material extraction to end-of-life of a building.

System boundaries

A clear statement is needed in order to specify which building elements and building life cycle stages are included in the studied

F.4.5-5

F.4.5-6



F.4.5-5 From the raw material supply to the construction and use phases of a wooden building

F.4.5-6 Complete life cycle process of the system building system. Figure F.4.5-7 is an example of a clear indication of the system boundary. Chapter 8 – Case studies also provides an example of such an indication. As shown in figure 4.4-8, visualization can help clarify the system boundary regarding building parts.

Service life

The service life affects the use phase of the studied building. Operation energy and maintenance frequency varies depending on the defined service life. Fifty years would be relevant as the service life of a studied system building for practical LCA. This is used for the examples calculated in Chapter 6. For maintenance and replacement of building parts, appropriate RSL needs to be defined..

Functional unit

"Functional unit provides a reference to which the input and output data are normalized." [50]. For buildings, the reasonable functional units are the following: entire building, per m² of gross floor area/ net floor area / living floor area, and m² of the building element according to the purpose of the study. A clear definition of different floor area calculations is important. Figure 4.4-6 shows the definition used in this book. Gross floor area is an area of the house along the outside of a wall; exterior space (e.g. a balcony) is not included. Net floor area is an area along the inside of the walls. Living floor area is an area along the inside of the walls excluding technical space and maintenance space (e.g. machine room and storage space). Living floor area is used in the case studies of this book in order to compare different reference buildings on the same basis.

Cut-off criteria

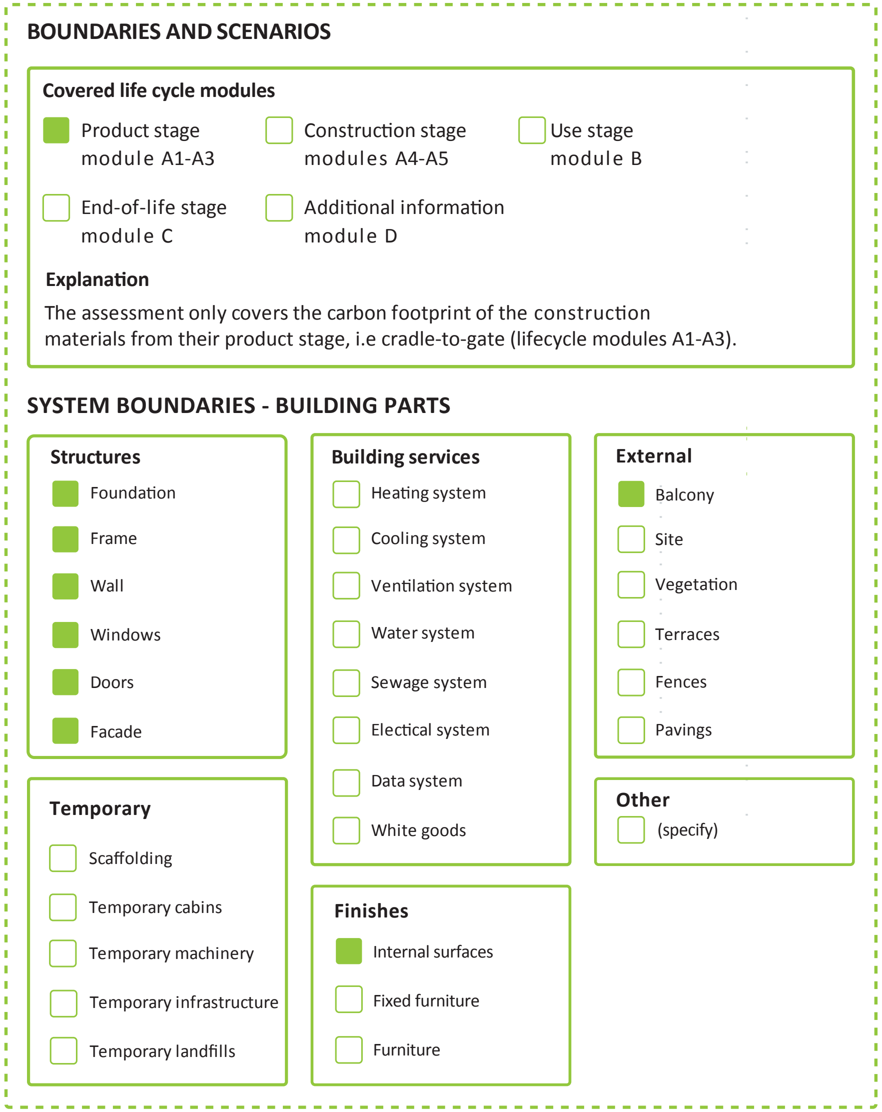
Not all inputs have relevant influence on calculation results. To make calculation easier, cut-off criteria can be defined. They have to be described clearly in the reports. According to EN15804, in principle all input and output shall be included in the calculation. But it also states that "In case of insufficient input data or data gaps for a unit process, the cut-off criteria shall be 1% of renewable and non-renewable primary energy usage and 1% of the total mass input of that unit process."

The total of neglected input flows per module, e.g. per module A1-A3, A4-A5, B1-B5, B6-B7, C1-C4 and module D (see Figure 1), shall be a maximum of 5% of energy usage and mass. Conservative assumptions in combination with plausibility considerations and expert judgement can be used to demonstrate compliance with these criteria.

LCA data source

There are several LCA data types: generic data, average data, and product specific data. Type and quality of data, such as age of data source, calculation method and allocations, related standards, etc., need to be shown clearly. There are various data sources available in Europe. They vary significantly due to different purposes, methodologies, data collection methods, etc. New calculations done according to standard EN 15804 cannot be easily compared to old data without close inspection of the content.

At the beginning of the design stage, generic/ average data is recommendable to get an overall picture. For calculations in later stages of the building process, specific data from producers


BOUNDARIES AND SCENARIOS

Covered life cycle modules

- [x] Product stage module A1-A3
- [ ] Construction stage modules A4-A5
- [ ] Use stage module B
- [ ] End-of-life stage module C
- [ ] Additional information module D

Explanation

The assessment only covers the carbon footprint of the construction materials from their product stage, i.e cradle-to-gate (lifecycle modules A1-A3).

SYSTEM BOUNDARIES - BUILDING PARTS

Structures
- [x] Foundation
- [x] Frame
- [x] Wall
- [x] Windows
- [x] Doors
- [x] Facade

Temporary
- [ ] Scaffolding
- [ ] Temporary cabins
- [ ] Temporary machinery
- [ ] Temporary infrastructure
- [ ] Temporary landfills

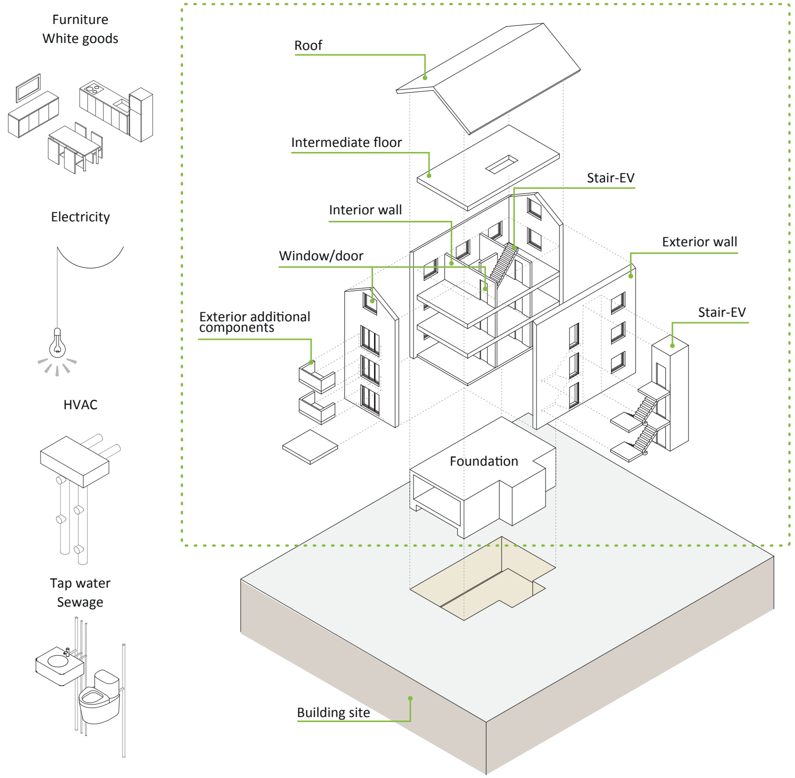
Building services
- [ ] Heating system
- [ ] Cooling system
- [ ] Ventilation system
- [ ] Water system
- [ ] Sewage system
- [ ] Electical system
- [ ] Data system
- [ ] White goods

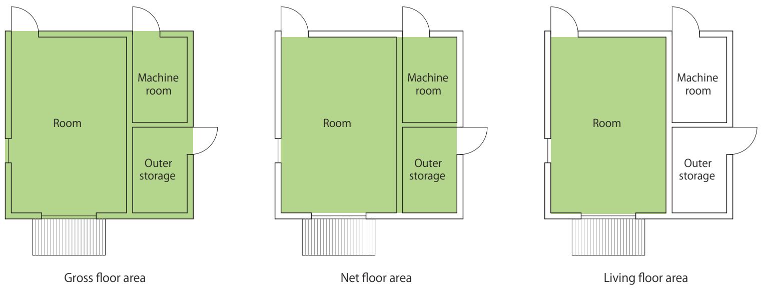
Finishes
- [x] Internal surfaces
- [ ] Fixed furniture
- [ ] Furniture

External
- [x] Balcony
- [ ] Site
- [ ] Vegetation
- [ ] Terraces
- [ ] Fences
- [ ] Pavings

Other
- [ ] (specify)

F.4.5-7 Example of a list to describe life cycle stages and building parts included in an LCA study.





F.4.5-8 Example for visualization of included building elements
F.4.5-9 Different types of floor areas

are relevant to show the status as-built. An Environmental Product Declaration (EPD) is the most relevant data as specific data for the calculation.

Allocation

Allocation should be done according to physical flows where it cannot be avoided. The allocation issue regarding the production stage of building materials is described in Section 4.3. After the production stage, allocation of consumed energy during the construction stage (A5) needs to be taken into consideration. In many cases, several construction works are running at the same time in both the prefabrication factory and the construction site. In order to allocate consumed energy to each production line or construction work, the physical amount could be used.

Basically it is difficult to collect the data from the construction stage due to the lack of resources and time. Therefore, a simple method is required without missing certain reliability. For instance, the allocation of space heating energy for a building in a prefabrication factory could be done based on the floor area of all buildings in the factory as considering the setting of temperature. Electricity consumption for the operation of prefabrication or on-site construction could be allocated based on the production volume of a factory or the duration of each work from the monthly electricity consumption. Although available information would be case by case, the use of some physical basis is recommended.

Interpretation of results

The interpretation is closely linked to the scope of the life cycle analysis. For instance, the outcome shall show:

- environmental impact and benefit according to the life cycle phases (module A to C and D);
- environmental impact and benefit according to the building elements in order to understand the influence of specific parts;

- variations/scenarios on the same building with different construction systems, building service systems, etc., in decision-making; and

- material and mass distribution.

Reporting of the result is required to be as clear, understandable, and transparent as possible. All related carbon flow in the system needs to be described. In order to avoid misreading, the contents of the impacts and benefits shall be documented separately according to the scope and purpose of the study. For instance, GHG emission from fossil fuel and biogenic fuel or carbon and energy storage capacity in the building components should be displayed individually. A basic conclusion and recommendation shall be shown based on the findings and objectives of the study.

4.6 Conclusions

This chapter introduces the international normative standards related to carbon footprints and gives information regarding the tools and databases for calculating the carbon footprint an entire building. In addition, methodological issues, specifically those for assessing wood products and buildings, are discussed in detail.

To assess the carbon footprint of a building, the following information is required: the quantities and qualities of the building materials, the environmental impacts of products, the energy demand of the building and the energy supply systems and their environmental impact. In addition, the service life of building components and elements need to be taken into account based on the particular situation. Nowadays, many databases and tools are available for such calculations. Relevant data should be used in the calculations as much as possible. In principle, the use of specific LCA data is recommended, but generic (average) data is relevant in the early assessment phases. There are significant variations in different databases. The variations may be caused by actual differences in the production processes, energy supply solutions and the applied methodology, such as the system boundaries. The system boundaries and principles used in the calculation could significantly influence the assessment results for wood products. In particular, the consideration of sequestered carbon and biogenic CO_2 has a major effect on the results. Therefore, a clear description of the assessment assumptions and results is a fundamental requirement.

In principle, scope and goal of the assessment is dependent on the purpose. Thus, the most relevant methodology is applied on a case-by-case basis, and it would be impossible to strictly standardize the methodology. However, it makes it so that results of the assessment cannot be compared, which is a significant issue when it comes to the practical implementation of carbon footprint calculations. Allocating the environmental impact in a multi-output process has been one of the main issues when assessing wood products. The manufacturing process for wood products generates several co-products. In principle, the allocation method is selected on a case-dependent basis. Allocation is a subjective procedure and the ISO 14044 indicates that it should be avoided whenever possible. In case allocation cannot be avoided, physical mass allocation is recommended for the assessment of wood products as a default methodology. The environmental impact, which is a physical phenomenon, should not be affected by a fluctuating social and economic situation.

The carbon footprint analysis of buildings is more complex than that of many other products. A wood-based system in particular is rather complicated. The analysis should take into account all the inputs and outputs over time across every stage of processing, from forest regeneration and management to harvesting, product processing, product use, maintenance and the final disposal of the wood in order to understand the full carbon flow connected to a building. The entire life cycle and energy chain should be considered with broad enough system boundaries to include all significant impacts. On the other hand, a practical simplification of the system may be required, for instance when the purpose is to assess the building system itself. We propose that a simplified system boundary should only include the direct environmental effect of a building. A simple and accurate system is a good starting point for a practical implementation of the carbon footprint analysis.

F.4.5-10 Installation of a TES-element, Finland

- For a description of environmental properties of a building in practical use, a simplified system boundary is applicable, shown as a red line in Figure F.4.5-1.

- A transparent description of system boundaries, cut-off criteria, service life, data sources and allocation is needed.

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