BenchValue – Benchmarking the Sustainability Performances of Value Chains

BenchValue Method

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Preface

European Forest Institute (EFI) is coordinating the research project - Benchmarking the Sustainability Performances of Value Chains - BenchValue. The project is funded under the framework of transnational ERA-NET network by the national funding bodies (Austria, Finland, France, Ireland, Lithuania and Sweden). The project aims to provide a tool for comparison between the sustainability performances of forest biomass-based vs. fossil/mineral-based value chains.

BenchValue describes value chains in a process-based approach aimed at decision making by assessing environmental, social and economic impacts of alternative chains using ToSIA (Tool for Sustainability Impact Assessment). BenchValue focuses on wooden buildings and develops generic indicators covering economic and socio-environmental aspects to be used in a benchmarking method that compares forest biomass-based materials against others.

This publication is a part of the BenchValue project.

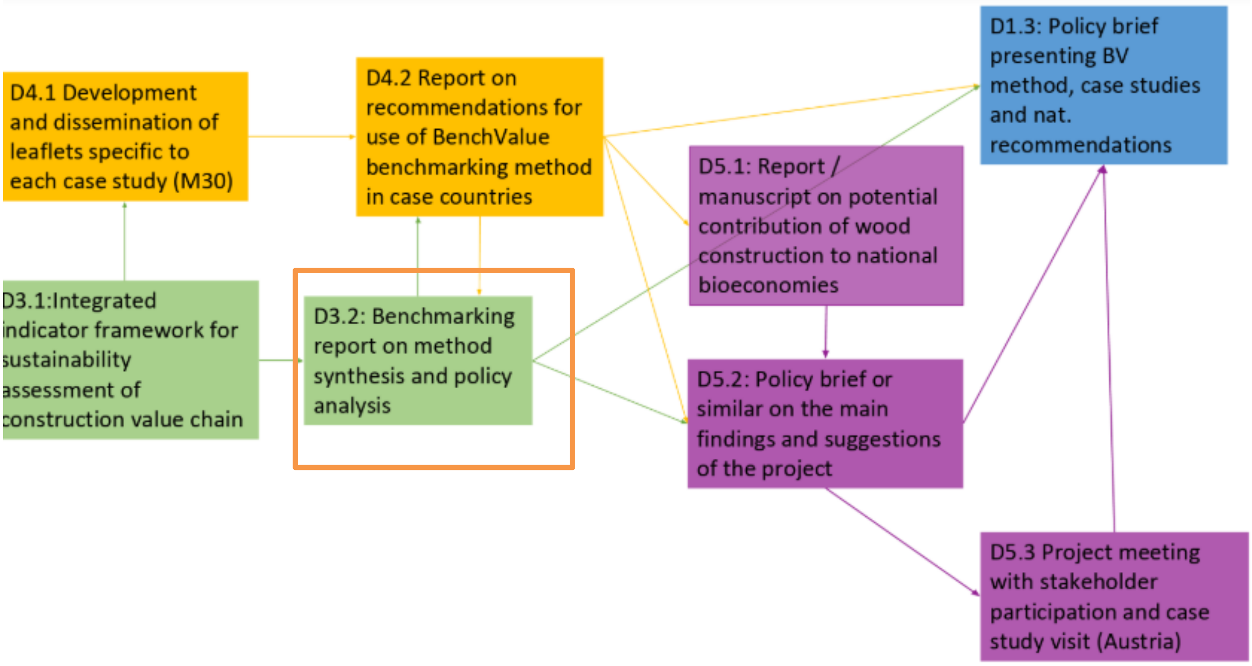


Figure 1 How Deliverables Fit Together

This report summarizes the developments related to the BenchValue benchmarking method and integrates the findings from WP 2 (and in particular Deliverable 2.2 “Gap analysis of ToSia with respect to sustainability analysis) and discussed methodological options as well as decisions taken by the consortium to streamline the methodological options into a decision support system operated by the ToSIA application. It reflects the results from the method-oriented work conducted during the course of the BenchValue project and describes the agreed and tested BenchValue method.

The sole responsibility for the content of this report lies with the authors.

1 Timber-steel-concrete chains: how can we compare between them and integrate or replace different materials

In order to compare different construction materials and to assess their sustainability performance in a value chain perspective, integrating life cycle thinking and striving for comparability of indicator results, as BenchValue proposes, it is a prerequisite to understanding the supply of raw materials and to identifying existing value chains for a generic assessment. BenchValue investigates three different materials: i) wood, ii) cement, and iii) steel. It compares them with regard to contemporary construction. In the following chapters, the background information on the BenchValue method is provided to understand the methodological foundation and to learn about generic value chains for selected raw materials. It integrates current assessment approaches as discussed and applied in Sustainability Science (in particular Life Cycle Assessment (LCA) and Sustainability Impact Assessment) and is embedded in the ToSIA software (Tool for Sustainability Impact Assessment).

Further on, the document describes a benchmarking approach as a way to understand the differences among investigated materials. In these regards, substitution of raw materials and displacement factors play a key role for the comparison.

The BenchValue method, based on generic chains for wood/cement/steel, shall provide the knowledge base for a sustainability assessment of contemporary construction projects. This document is meant to serve as a "toolkit" for decision makers, and stakeholders interested in the assessment of construction materials in general, and shall safeguard a proper application of the method for users who are striving to apply, respectively set up, a case study in ToSIA.

1.1 Common and basic elements in and across value chains

For the cement and steel chain, we have chosen tons of mass, as the base unit, and for wood we use elemental organic carbon (C). The reason here is that cement (which is further processed to form concrete) is a very heterogeneous product, also regarding the basic elements it is composed of. This choice was made to assist in understanding how the material flows behave, to be able to account for all material flows along the value chain and to help in managing conversion factors (i.e. when a raw material is processed and converted to a product). Conversion factors are inter alia required to calculate indicator results for selected materials, the main output of the ToSIA application.

For indicator results (which are the main parameters of a ToSIA analysis), the choice of the base unit, or process unit is irrelevant. The final output of the assessment is provided as a) CO^2 equivalents of emissions, b) person years of employment or c) Euros of production cost for instance, depending on the selected indicator and its underlying definition. If someone finally wishes to allocate the results to a unit of a given product, such as one single concrete house frame with a certain foundation, this does not depend on the choice of the base unit nor the selected process units of inherent processes.

Another relevant consideration is the perspective applied to build the value chains, i.e. should the chains be initialized from pools of resources or should they be initialized from the production of e.g. one house frame? This design choice will reflect on the definition and values that need to be collected (see Figure 2).

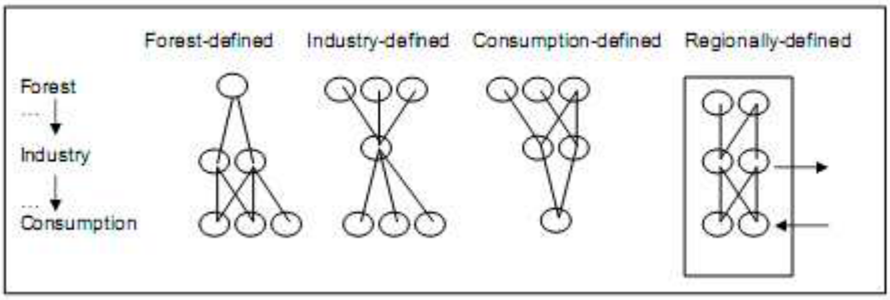


Figure 2 Value chain design options from Forest to Industry and Consumption

Building the value chain from a resource perspective, as indicated in "Forest defined" traces the raw material flow from the resource pool (i.e. the forest). Initializing production from natural regeneration of forest stands, as an example, and applying specific forest management throughout the lifetime of single trees that are harvested at a certain time and further processed as roundwood that is transported from the forest to a mill where it will be further processed to provide certain wood products, would integrate the various processes that have to be considered in a value chain perspective. The same holds true for other design examples and vice versa for other raw materials (e.g. cement, steel). Common characteristics between all value chains regardless of material are the need for:

- a common base unit
  - functional unit (t) as in substitution factors and LCA; this would be tons (dry) for all materials
- Individual base units for specific chains
  - Timber: tons of Carbon (t of C)
  - Steel: tons of mass
  - Cement: tons of mass
- Modules and stages:

  Following the European standard for LCA-based Environmental Product Declarations (EPDs) of building products (EN 15978:2011, see Figure 3)[1]

[1] NSAI, "I.S EN 15978:2011 Sustainability of construction works-Assessment of environmental performance of buildings-Calculation method," National Standards Authority of Ireland, 2011.

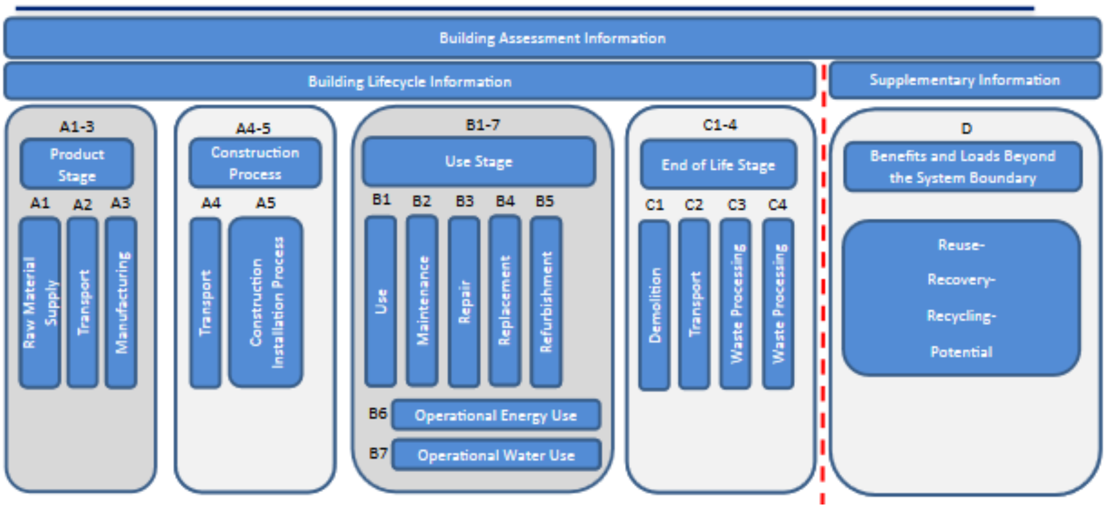


Figure 3 Stages for Life Cycle Assessment (EN 15978:2011)

- System boundaries
  - Similar for all value chains: Covering the main and most energy intensive production processes, with a particular focus on sourcing of main raw materials
- Separate value chains
  - One chain per material

1.2 Replacing one material for another: substitution factors and conversion factors between materials

Forests have an important role in climate change mitigation in the form of carbon sinks and storing carbon in biomass and soil. In addition, when forests are harvested, part of the carbon is stored in wood-based products and substituting carbon intensive materials and products (Figure 4) such as concrete or steel in construction.

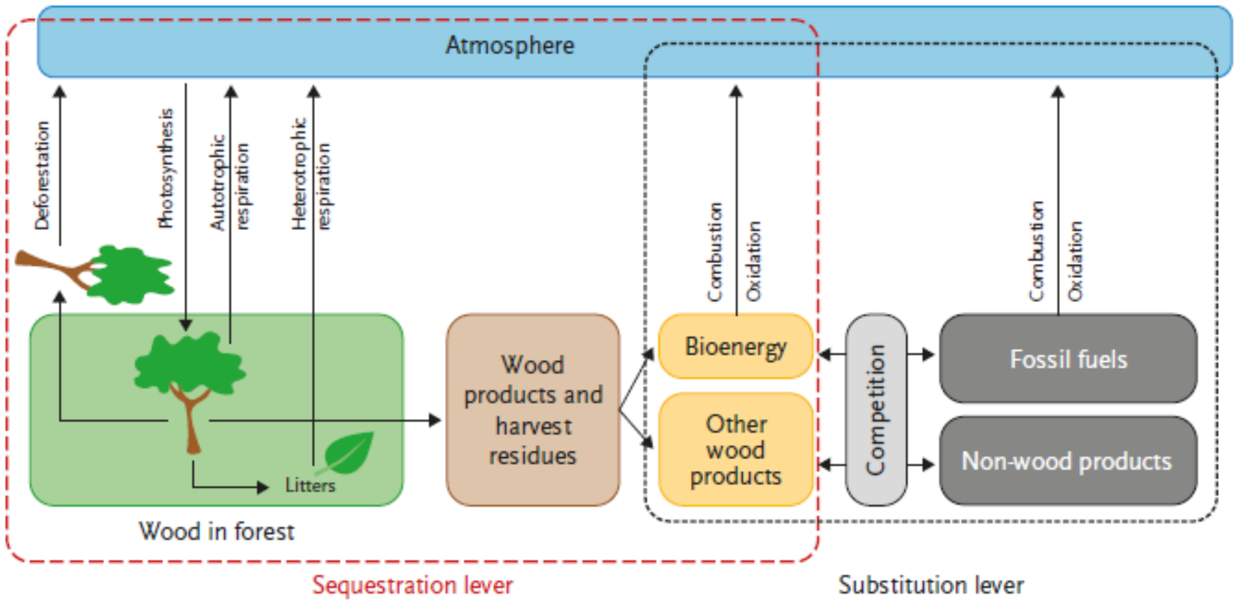


Figure 4 Carbon stocks and flows between atmosphere, biosphere and fossil reservoir (source: Gert-Jan Nabuurs, Philippe Delacote, David Ellison, Marc Hanewinkel, Marcus Lindner, Martin Nesbit, Markku Ollikainen and Annalisa Savaresi. 2015. A new role for forests and the forest sector in the EU post-2020 climate targets. From Science to Policy 2. European Forest Institute).

1.2.1 Substitution

By definition, substitution factor, or **displacement factor (DF)** is a technical term that **measures how much greenhouse gas emissions are avoided if using a wood-based product instead of a reference product that provides the same function**. Wood construction as replacing concrete and steel is one example of potential substitution benefit. According to Sathre & O'Connor (2010), the DF can be calculated as:

$$DF = (GHG(non\text{-}wood) - GHG(wood))/(WU(wood) - WU(non\text{-}wood)),$$

Where GHG(non-wood) and GHG(wood) are the GHG emissions resulting from the use of the non-wood and the wood alternatives expressed in mass units of carbon (C) corresponding to the CO_2 equivalent of the emissions, and WU(wood) and WU(non-wood) are the amounts of wood used in the wood and non-wood-alternatives expressed in the mass units of C contained in the wood.

Sathre & O'Connor (2010) conducted a literature review to estimate the value of DF related to buildings and construction elements such as apartment buildings, office buildings, wood doors, roof beams, flooring etc. against concrete and steel alternatives with the same functionality. The review was based on published data from 21 different studies. Based on the review, the displacement factors ranged from a low of -2.3 to a high of 15, and the average DF was 2.1 meaning that for each tC in wood products substituted in place of non-wood products, there was an average GHG emission reduction of approximately 2.1 tC (Sathre & O'Connor 2010). This estimate corresponds about 3.9 t CO2 eq emission reduction per ton of dry wood used (Sathre & O'Connor 2010).

According to a literature review by Leskinen et al (2018) substitution factors vary heavily according to products with the following average substitution factors. Based on a literature review by Leskinen et al 2018 which analyzed 51 studies, which provided information on 433 separate substitution factors. The large majority of studies indicate that the use of wood and wood-based products are associated with lower fossil and process-based emissions when compared to non-wood products. Overall, the 51 reviewed studies suggest an average substitution effect of 1.2 kg C / kg C, which means that for each kilogram of C in wood products that substitute non-wood products, there occurs an average emission reduction of approximately 1.2 kg C.

Table 1 Substitution

Product categories	Average substitution effect kg C / kg C wood product	Average substitution effect kg CO2 eq. / kg wood product
Structural construction	1.3	2.4
Non-structural construction	1.6	2.9
Textiles	2.8	5.1
Other product categories	1 – 1.5	1.8 – 2.7
Average across all product categories	1.2	**2.2***

These reviews (Leskinen et al. 2018) highlight the highest impact during the production phase, and in the consequence, during deconstruction and end-of-life.

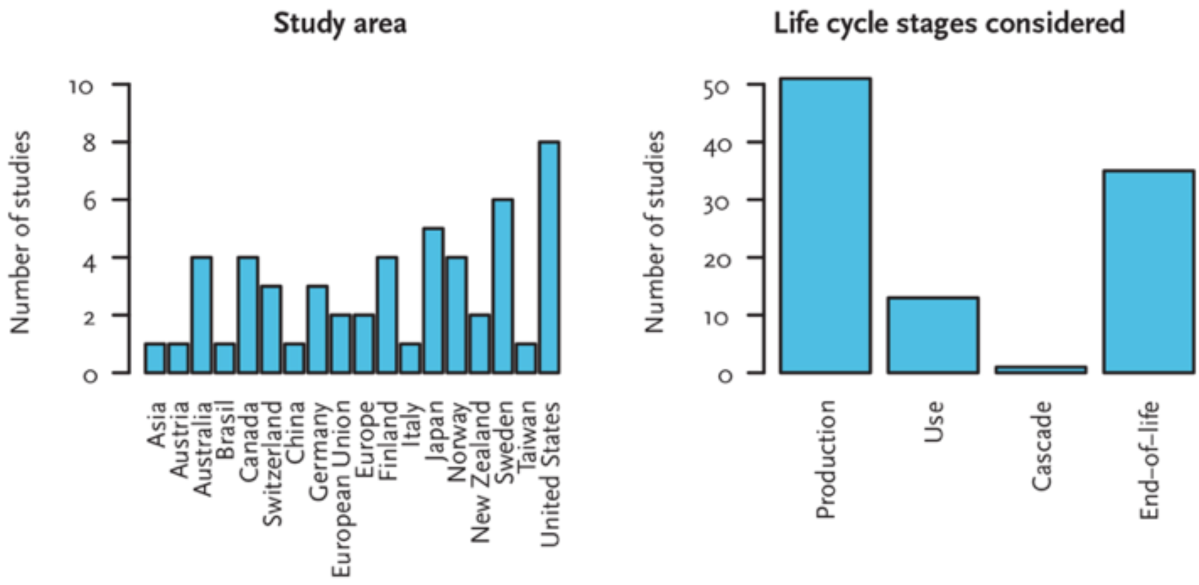


Figure 5 Study area and Life Cycle Stages

As can be seen from the range of variation of DF above (Figure 5), there are also considerable uncertainties and/or variability in DF values. It must be also remembered that DF is only one component of climate mitigation (see Fig 4). In addition, the overall substitution potential of wood construction, for example, depends on the market volumes, i.e. the upscaling of product level assessment to the level of markets. DFs can also change over time e.g. due to changes in emissions levels of alternative products.

1.2.2 Comparability and Substitution in house construction (BV method)

The aim within BenchValue is to compare a single entity, i.e. one building (e.g. 1 m^2 of house after stage A5 Construction), where the (main) materials used to build the house may vary, i.e. timber-frame house vs steel-frame house vs cement-frame house, but the house itself fulfills the same function (i.e. it is designed to meet a specific purpose) regardless of the material used.

Usually, when the impact assessment is performed in building level the comparison is a unit of a living area (1 m^2) per year or lifetime (50 years) (Peuportier 2001). As engineers base their choice on the material/ product in accordance with material properties (e.g. modulus of elasticity, density, strengths etc.) and cost, besides various other factors that play an important role in the design of a structure (e.g. energy efficiency, HVAC, architecture, etc.), BenchValue simplifies the construction project for the assessment.

The focus is only on carrying elements (e.g. structural system), and frame of the structure. Elements that can be in either house such as windows, foundations, etc. are disregarded at first sight as they are assumed to be the same for all investigated house types.

Recent projects dealt with similar approaches and analyzed construction projects/elements to compare different construction materials, resulting in equivalence ratios that express how much material is needed if a frame structure for an industrial hall is mainly built of a) wood, b) concrete, or c) steel (FORMIT project). Table 2 gives an overview on these ratios and propose a reference for cross checking the final results of the BenchValue method tests (i.e. case studies).

Table 2 Primary construction: Equivalence rations for wood frame for industrial hall (FORMIT)

	Ratio use of steel in competing structure/ use of wood in wood structure (kg/kg)				**Ratio use of concrete in competing structure/ use of wood in wood structure (kg/kg)**				**Ratio use of reinforcing steel in competing structure/ use of wood in wood structure (kg/kg)**			
	Name of Variables in model	**Average**	**Min**	**Max**	**Name of Variables in model**	**Average**	**Min**	**Max**	**Name of Variables in model**	**Average**	**Min**	**Max**
Steel structure	_struct_glulam_equivalence_Steel_steel	1.35	0.78	1.91	_struct_glulam_equivalence_Steel_concr	-1.02	-4.09	0.00	_struct_glulam_equivalence_Steel_s_concr	-0.05	-0.22	0.00
Concrete structure	Non applicable	0.00	0.00	0.00	_struct_glulam_equivalence_concr_concr	6.04	3.42	8.47	_struct_glulam_equivalence_concr_s_concr	0.21	0.02	0.37

The negative number in Table 2 means that if the wood structure needs less of one material, it may need more of another. For instance, one kg of wooden structure saves 1.35 kg of steel in steel structure but requires 1.02 extra kg of concrete.

3 Generic chains

To set up a framework for the BenchValue method and investigate the differences of selected materials (i.e. wood, concrete, steel), generic chains are constructed. For each construction material the entire processes that form the (value) chain need to be modelled. For ToSIA flow modelling, i.e. modelling the (raw) material flow from resource to consumer or beyond (cf. recycling), it thus is a prerequisite to study the raw materials from supply to on-site construction - as the main emphasis of the system analysis within BenchValue lies on stages A1-A5 (see Chapters 1.1 and 5 for further details).

To come to grips with generic data applicable for a generic value chain of a certain construction material, various sources have been researched to allow a generalization of a distinct chain that aims to be applicable at various spatial levels. Data was collected from national (e.g. EPD databases) and from pan-European (association based) levels.

3.1 EU level

3.1.1 Wood

The European Union (EU) accounts for approximately 5% of the world's forests, and contrary to what is happening in many other parts of the world, the forested area of the EU is slowly increasing.

For commercial timber production strict guidelines, certification and legislation exists to ensure sustainable and legal forest management, while maintaining diverse ecosystem service and natural capital functions (CICES).

Forests are one of the major natural resources in Europe, covering about 42% of the land area. With an active forest industry, most forests in the EU are managed according to principles of sustainability (Forest Europe 2015). Felling rates are at 66% of the increment and forest areas are increasing by 44000 km^2 per year (Forest Europe 2015). 44% of EU territory is under Natura 2000 protection (EEA 2016), more than 60% of forests are certified. Forests and wood products – both from virgin and recycled uses – feature heavily in the circular Bioeconomy strategy (2018). To be sustainable, this demands resilient management of the European forests,, while increasing material supply. The potential to increase wood supply is given according to calculations by Verkerk et al. 2019: forests in 39 European countries could currently provide 401 million tonnes dry matter yr-1 of biomass. The total potential availability of woody biomass for all uses from forest resources in the 28 EU member states is estimated at 335 million tonnes dry matter yr-1 overbark in 2020 and 319 million tonnes dry matter yr-1 overbark in 2050. By 2050, this potential could increase to 321 and 406 million tonnes dry matter yr-1 overbark for the Enhanced production and Improved supply scenarios, respectively. The minimum basis for these scenario calculations stipulates that the felling levels never exceed the annual increment and excludes environmentally fragile areas.

In the EU each national state has its own legislation concerning forest management, maximum clearcut or felling volumes, and conditions to ensure regeneration and resilient forests. In addition, at EU level, separate legislation ensures the legality and traceability of homegrown and of imported timber: the EU Timber Regulation (2013) aims to reduce illegal logging by ensuring that no illegal timber or timber products can be sold in the EU. It was created as part of the EU's FLEGT Action Plan (Forest Law Enforcement, Governance and Trade). The EU Timber Regulation prohibits operators in Europe from placing illegally harvested timber and products derived from illegal timber on the EU market. ‘Legal' timber is defined as timber produced in compliance with the laws of the country where it is harvested.

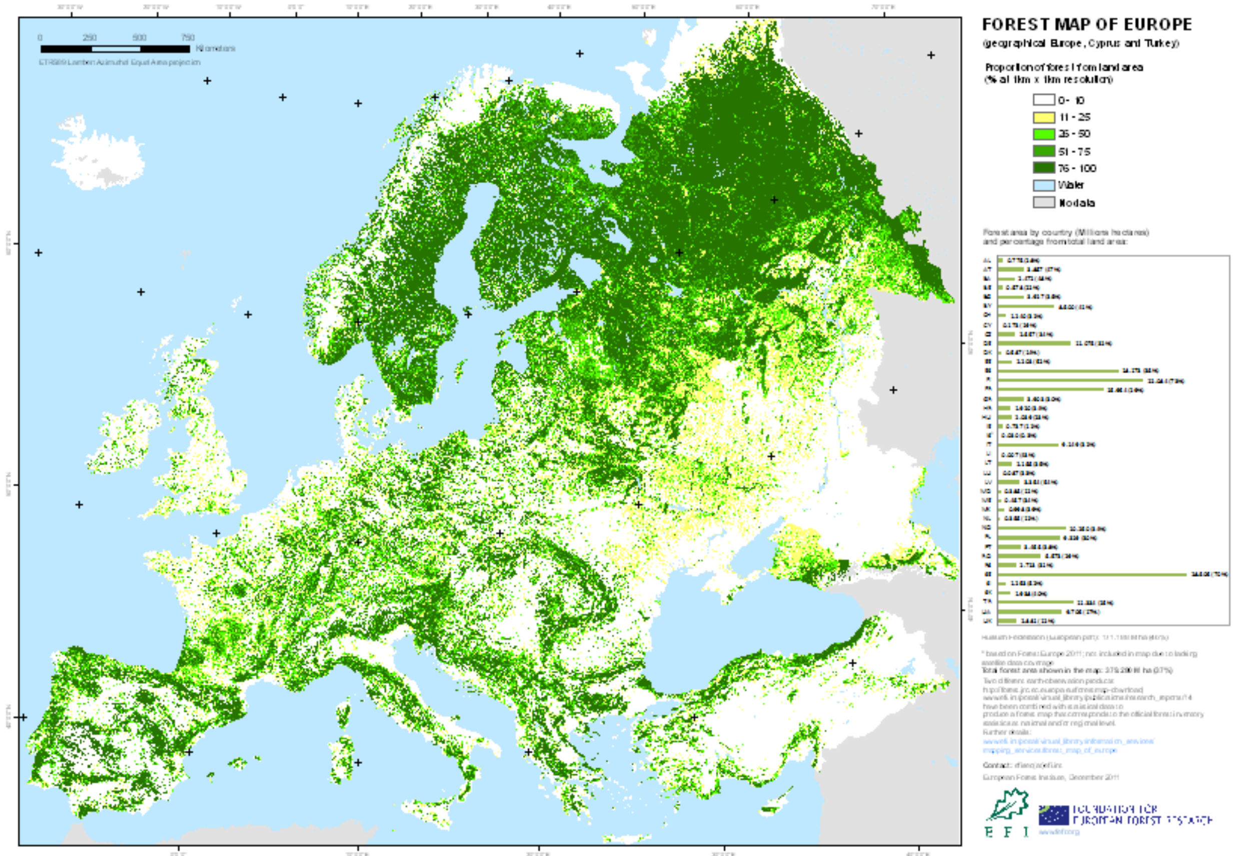


Figure 4: Forest map of Europe (EFI, 2011)

Apart from the forests' ecological value and impact on the EU landscape, the forest sector is also an economic resource. The overall level of EU-28 roundwood production reached an estimated 458 million m^3 in 2016. Among the EU Member States, Sweden produced the most roundwood (81 million m^3) in 2016, followed by Finland, Germany and France (each producing between 51 and 61 million m^3). Slightly more than one fifth (21.6%) of the EU-28’s roundwood production in 2016 was used as fuelwood, while the remainder was industrial roundwood used for sawnwood and veneers, or for pulp and paper production. The total output of sawnwood across the EU-28 was approximately 100 (106 in 2016) million m^3 per year from 2010 to 2016.

The EU’s wood-based industries cover a range of downstream activities, including woodworking industries, large parts of the furniture industry, pulp and paper manufacturing and converting industries, and the printing industry. Together, some 420 000 enterprises were active in wood-based industries across the EU-28; they represented one in five (20 %) manufacturing enterprises across the EU-28, highlighting that - with the exception of pulp and paper manufacturing that is characterised by economies of scale - many wood-based industries had a relatively high number of small or medium-sized enterprises.

The economic weight of the wood-based industries in the EU-28 as measured by gross value added was equivalent to EUR 139 billion or 7.3 % of the manufacturing total in 2015. Within the EU-28's wood-based industries, the highest share was recorded for pulp, paper and paper products manufacturing (32.9 % or EUR 46 billion), while the other three sectors had nearly equal shares - printing and service activities related to printing and the manufacture of furniture each amounted to 21-22 % of the gross value added of wood based industries, while the manufacturing of wood and wood products made up 24 %. The wood-based industries employed 3.3 million persons across the EU-28 in 2015 or 11 % of the manufacturing total. There were 2 million persons employed within both the manufacture of wood and wood products and the manufacture of furniture, 644 000 persons were recorded for the activity of pulp, paper and paper products manufacturing, the lowest employment of the four activities (EUROSTAT, 2018).

Timber is suitable for cascade use. The follow-up applications are determined by the treatments (untreated, painted, bonding, preservation, other treatments), dimension and form (solid, chipped, particle board, pulp derivatives) of its previous use. The wood flow analysis (Mantau U, 2012) describes the major flows of sourcing timber from virgin, trade, semi-fabricated and prefabricated sources.

For construction, sourcing of virgin material (wood harvest; top of graphic, before split into material and energy utilization) and material uses such as solid and sawn wood products (LVL, sawn wood, glulam, CLT) and panels (OSB, plywood) are of interest.

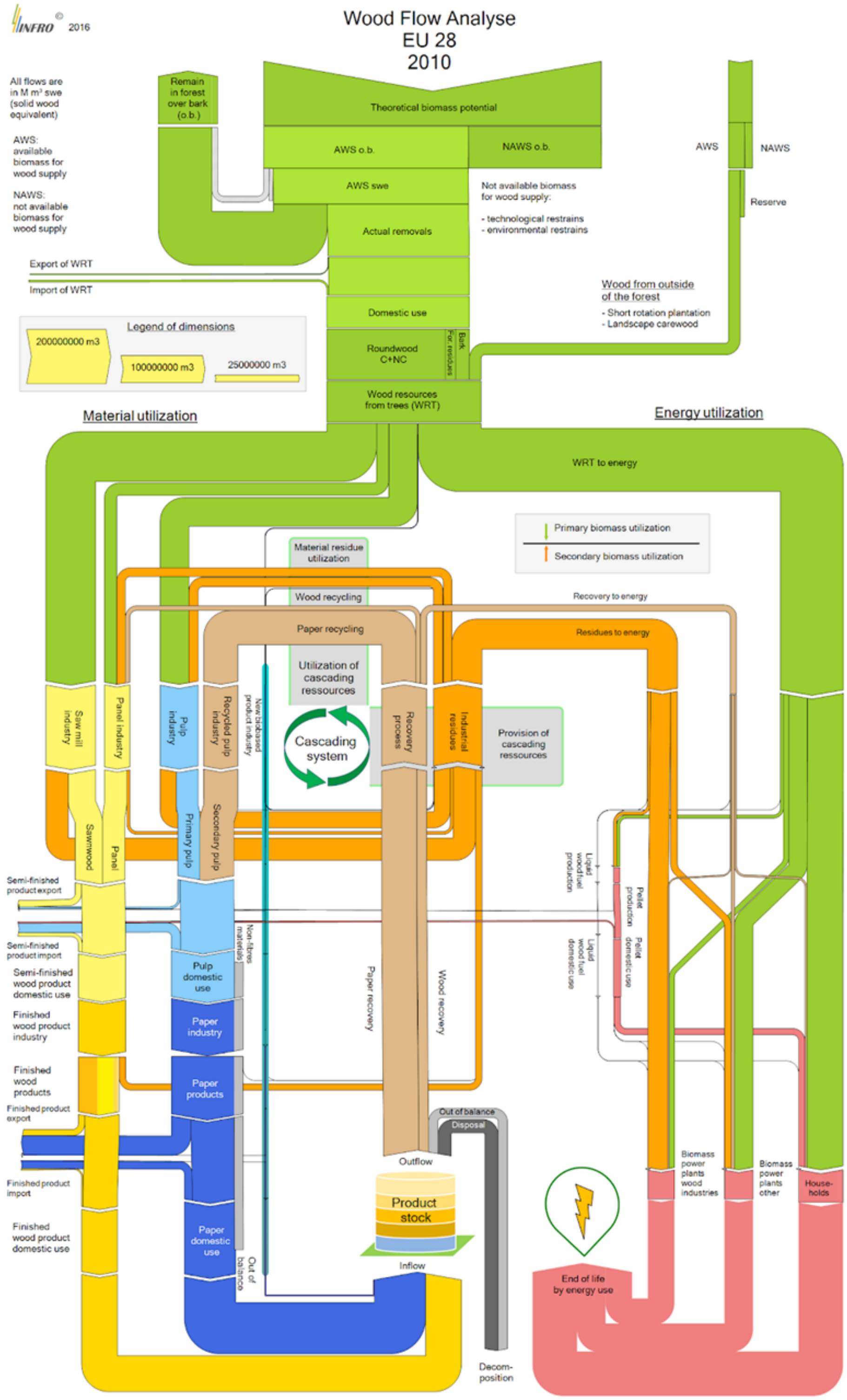


Figure 6 Major wood flows

Main harvesting systems and sources

Tree harvesting systems are either motor-manual, often with tree-length method, or fully mechanised, with cut-to-length method. In Europe these are the most common systems:

1) ***Harvester + forwarder in cut-to-length method:*** This is the most common and efficient method, working best on coniferous trees in rather flat terrain (i.e. slopes up to 30%). Deciduous trees (like beech, birch, eucalypt, other mass assortments) are also felled and processed by harvester in the forest stand and forwarded by Forwarder to the forest road side.

2) ***Winch-assisted harvester + forwarder in cut-to-length method*****:** Same as above, but for more steep terrain with slopes up to 60%. This requires suitable and strong enough anchor trees upslope to provide sufficient security for the machine using it as an anchor. It is important to highlight that the anchoring is serves as decreasing slip and rut of the machine, not to haul the machine uphill.

3) ***Chainsaw + skidder in tree length method*****:** tree-length, also full-tree method with chainsaw and skidder is the more traditional method which has been continuously replaced by mechanized approached due to higher efficiency, lower costs and increased safety for the operators. The method is still in use in less mechanized countries, particularly Eastern Europe, in difficult terrain with poor accessibility or fragile soils, and in high value tree stands such as selected deciduous trees (oak, cherry, etc) or large-dimensioned, long timber to be cut in the sawmill. The same system is also used in poor, badly formed stands, where harvester cutting would have too much loss, as the harvester is designed for relatively straight, single-stem logs with small-dimensioned side branches.

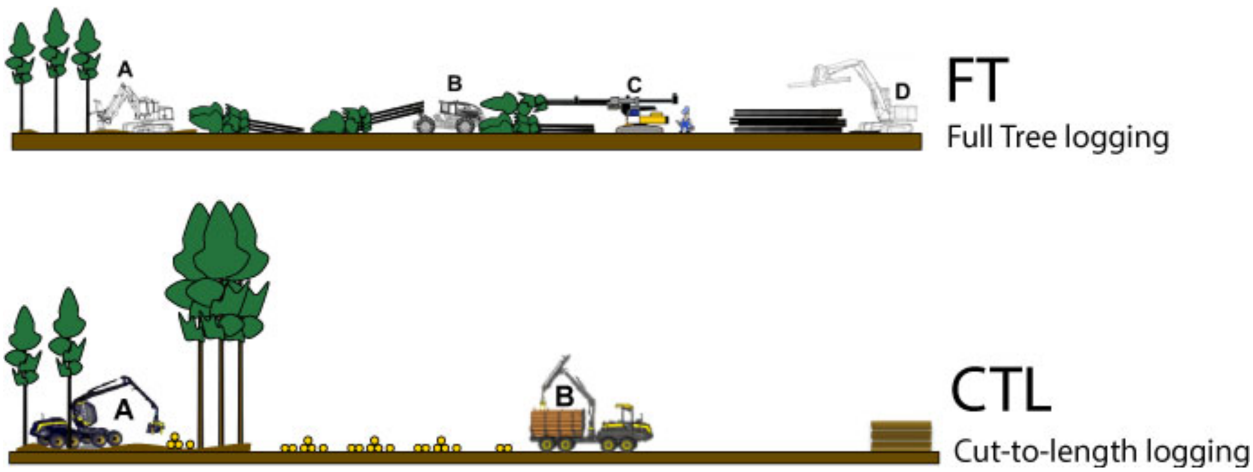


Figure 7: Cut-to-length versus tree length / full tree method (Source: PNG Biomass)

4) ***Chainsaw + cable yarder*****:** In steep terrain with long hauling distances, trees are felled by chainsaw either as whole trees or cut-to-length, and then hauled up or down-hill by cable yarder. This system is not very common in most of Europe as it was developed for mountainous regions with poor stand accessibility.

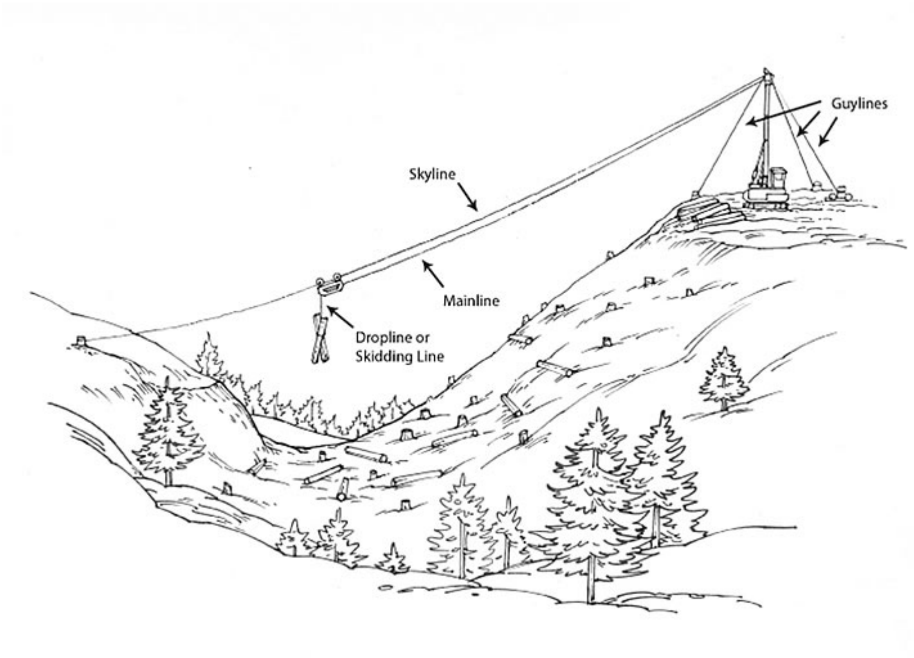


Figure 8: Cableyarding in steep terrain (Source: FED US)

In work carried out in the EU projects INFRES, S2BIOM and TECH4EFFECT the following distribution of forest operation systems has been obtained, which can be used as a reference to building European-level supply chains or national supply chains for timber (Tuomasjukka et al 2018):

Country	^EFISCEN [2010] [1000m3]	^roundwood [2010] [1000m3]	^harvest residues [2010] [1000m3]	^precom thin tree [2010] [1000m3]	^stumps [2010] [1000m3]	*motorsaw CTL [%]	*motorsaw WTS [%]	*harvester CTL [%]	*harvester WTS [%]	#forwarder CTL [%]	#skidding WTS [%]	#cableyarding [%]	~Transport distance to incineration [km]
Austria	28 850	27 065	1 785		0	26	56	18	0	33	45	22	60
Bulgaria	6 925	6 405	521		0	0	100	0	0	0	100	0	20
Czech Republic	19 967	18 728	1 238		0	9	60	31	0	31	68	1	25
Denmark	3 042	2 778	264		0	0	10	90	0	95	5	0	150
Estonia	8 902	8 729	173		0	0	5	95	0	100	0	0	100
Finland	72 054	67 464	3 281		1 309	0	0	100	0	100	0	0	
Germany	78 245	72 255	5 990		0	0	53	47	0	47	50	3	
Ireland	2 330	2 289	42		0	0	5	95	0	95	5	0	58
Italy	10 194	9 770	425		0	85	0	15	0	40	45	15	100
Latvia	8 566	8 057	510		0	0	25	75	0	100	0	0	
Lithuania	15 520	14 864	656		0	71	0	29	0	100	0	0	
Netherla nds	1 397	1 361	35		0	0	20	80	0	80	20		
Poland	47 456	44 686	2 771		0	0	95	5	0	15	85	0	250
Portugal	9 262	8 689	573		0	90	0	10	0	80	20	0	25
Romania	20 666	19 855	811		0	0	98	2	0		99	1	30
Slovakia	10 083	9 369	714		0	100	0	0	0	0	100	0	0
Slovenia	4 304	4 159	145		0	88	0	12	0	12	68	20	100
Spain	21 235	19 923	1 312		0	0	65	35	0	30	60	10	60
Sweden	96 933	89 335	5 246		2 352	5	0	95	0	100	0	0	93
United Kingdom	10 735	10 277	343		114	0	0	100	0	100	0	0	
EU 2010 Removal Total	**476 667**	**94**	**6**	**0**	**1**	**10**	**31**	**54**	**0**	**62**	**35**	**3**	**95**
CEU	111 533	93	7	0	0	7	52	41	0	45	47	8	69
SEU	47 617	94	6	0	0	15	19	9	0	38	55	8	56
EEU	102 476	94	6	0	0	15	75	9	0	13	85	1	145
NEU	215 041	93	5	0	2	7	1	91	0	100	0	0	93

Figure 9 Most common harvesting systems and removal volumes for 2010 (Tuomasjukka et a. 2018)

Ramage et al. (2017) gives a very good overview over the different uses of timber for wood constructions, the wood properties and ways of production.

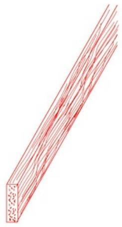
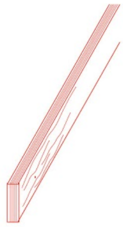
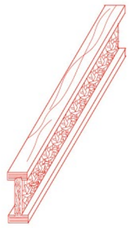
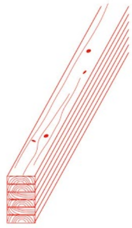
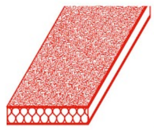
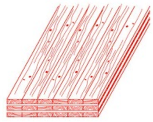
Engineered Timber Product	Parallel Strand Lumber (PSL)	Laminated Veneer Lumber (LVL)	I-Joist	Glulam	Structural Insulating Panel (SIP)	Cross Laminated Timber (CLT)	Brettstappel
Typical Detail							
Application	• Beams • Columns	• Beam • Columns • Cord	• Joist • Beam	• Beam (Long span) • High Loading	• Roof • Wall • Floor	• Roof • Wall • Floor	• Roof • Wall • Floor
Usage	Interior	Interior	Interior	Interior / Exterior	Interior	Interior/ Exterior	Interior/ Exterior

Figure 10 Common structural engineered timber products in Europe according to Ramage et al. 2017

In terms of production processes, three different types of conversion of round wood to to wood products exist:

- ***Sawmilling***: In the sawmill processes roundwood is graded, cut and dried. Further conversion may include gluing in different set-ups and / or chemical treatment for improved weather-, moisture-, fungi- fire-resistance. Sawmills have increased in their efficiency due to advanced scanning, grading and sawing technology to obtain 70% of products out of the incoming materials. the remaining cutter shavings and sawdust are used for other products (like particle boards) or for energy generations often within the mill (heating of the kilns). Output products are sawn timber products like Clue-laminated timber (Glulam), Cross-laminated timber (CLT).
- ***Peeling or veneering***: Peeling produces mainly plywood or veneer products. In this production roundwood is debarked and then peeled into a thin veneer sheet while rotating the log around its own axis. These plates are then cut, pressed, dried, glued and further formed in different products like plywood panels or laminated-veneer panels and lumber (LVL).
- ***Stranding***: Stranding covered processes where low-grade timber or side stream products (like cutter shavings, reclaimed timber, sawdust) are stranded or chipped into predefined particle sized, optionally oriented, glued, pressed, cut and formed into different types of boards or elements. Resulting products are oriented strand board (OSB), LVLs and I-Joists, fibreboard.

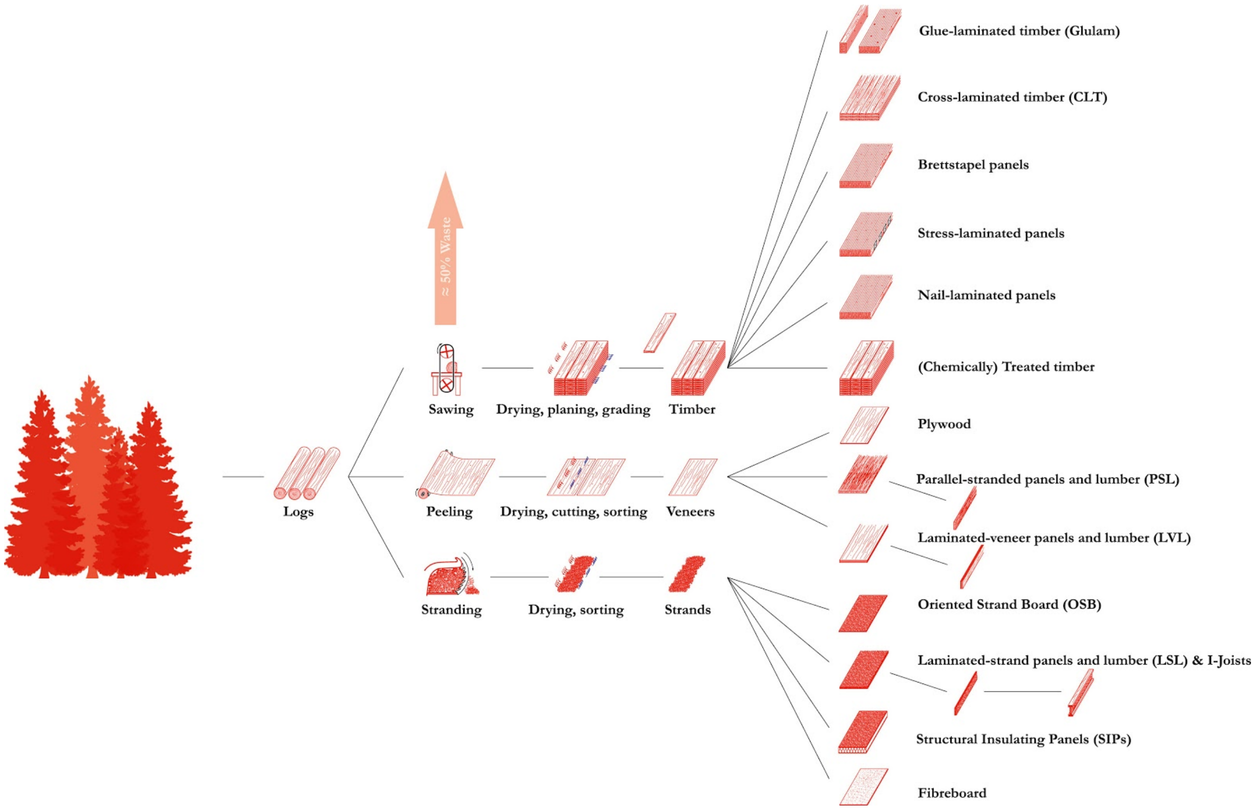


Figure 11 The main processing chains for timber products used in construction by Fleming (Ramage et al 2017)

More information on solid wood products:

European Organisation of the Sawmill Industry (https://www.eos-oes.eu/; webpage currently down. Check your national equivalent like the Finnish Sawmill Association; https://sahateollisuus.com/?lang=en)

More information on panel: European Association for Panels and Profiles: https://www.ppa-europe.eu/home.html

Further potential data sources:

EUROSTAT: https://ec.europa.eu/eurostat/data/database

FAOSTAT (forestry database): http://www.fao.org/faostat/en/#data/FO

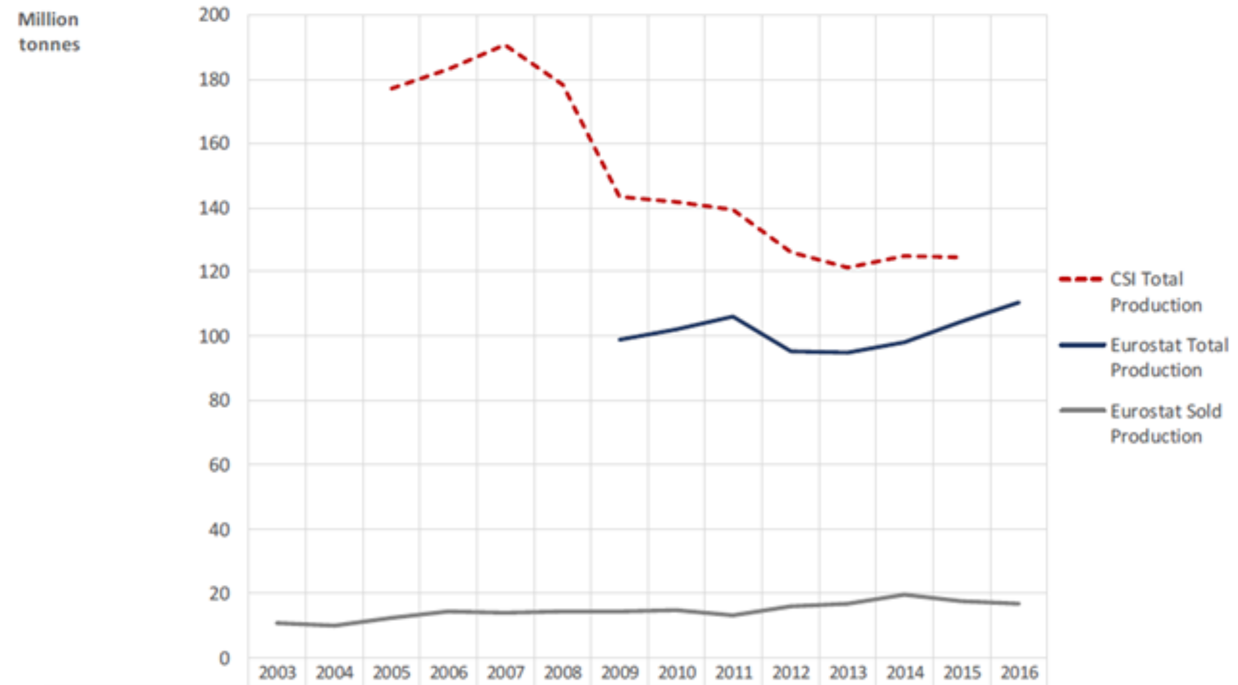
Directly from major companies:

e.g. https://www.upm.com/responsibility/, https://www.storaenso.com/en/products/wood-products/massive-wood-construction

For the generic chains we focus on massive wood products (sawn wood products) with loadbearing functions. This category includes cross-laminated timber (CLT), laminated veneer lumber (LVL), solid wood products (beams, stripwood, planed and unplaned), glulam.

3.1.2 **Cement**

According to Eurostat the EU cement clinker production in 2015 was more than 100 million tonnes, with 85% of it going directly into production of cement. The largest cement industries in Europe are in Italy, Spain, Germany, France and Poland. In 2007 cement products amounted to 268 million tonnes, while in 2016 the total production was 163 million tons. The 2008 financial crisis has severely influenced the sector: from 2008 to 2015, sales decreased by 37%, added value by 49%, jobs by 25% and the amount of companies by 20%. Cement production reduced for two main reasons; firstly, as European countries dealt with economic crisis construction industry was seriously affected, and secondly because of the exogenous factor of climate change.



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
CSI Total Production			177.3	183.3	190.8	178.3	143.5	141.8	139.6	126.3	121.5	125.1	124.8	
Eurostat Total Production							99.0	102.2	106.1	95.3	94.8	98.3	104.5	110.8
Eurostat Sold Production	10.8	10.1	12.4	14.2	14.0	14.5	14.5	14.9	13.0	15.9	16.7	19.6	17.5	16.6

Figure 12 EU28 Cement Clinker production 2003 – 2016 (European Comission, 2017)

The cement manufacturing industry in the EU represented an estimated € 15.2 billion in turnover and € 4.8 billion in value added in 2015, the most recent year of comparative data available from Eurostat. Almost 71% of EU revenue, 70% for EU enterprises and 68% for EU wages in the cement industry were in Germany, France, Italy, Spain, Poland and Belgium. In 2015, 47 thousand people in the EU, split over approximately 350 companies, received jobs from the industry. EU28 cement manufacturing accounted for 4% of worldwide manufacturing in 2015, putting the EU behind China (51%) and India (6%) as the third biggest producer (European Commission, 2017).

Product

Concrete consists of two main elements; paste and aggregates. Paste is a mix of cement and water, while it binds with sand, crushed stone or gravel. Cement is made through a firmly controlled chemical blending of calcium, silicon, aluminum, iron and other materials. Regular materials used to produce cement incorporate limestone, shells, and chalk or marl joined with shale, clay, slate, blast furnace slag, silica sand, and iron ore. These raw materials, when warmed at high temperatures structure a stone like substance that is ground (1 - 25 mm or more in diameter) into the fine powder that we usually consider as cement. Typically, a cement clinker mix consists of approximately 80% limestone and 20% clay. (Portland Cement Association, 2018)

Main types	Notation of the 27 products (types of common cement)		Composition (percentage by mass [a])										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana		Fly ash		Burnt shale	Limestone		
						natural	natural calcined	siliceous	calca-reous				
			K	S	D [b]	P	Q	V	W	T	L	LL	
CEM I	Portland cement	CEM I	95-100	–	–	–	–	–	–	–	–	–	0-5
CEM II	Portland-slag cement	CEM II/A-S	80-94	6-20	–	–	–	–	–	–	–	–	0-5
		CEM II/B-S	65-79	21-35	–	–	–	–	–	–	–	–	0-5
	Portland-silica fume cement	CEM II/A-D	90-94	–	6-10	–	–	–	–	–	–	–	0-5
	Portland-pozzolana cement	CEM II/A-P	80-94	–	–	6-20	–	–	–	–	–	–	0-5
		CEM II/B-P	65-79	–	–	21-35	–	–	–	–	–	–	0-5
		CEM II/A-Q	80-94	–	–	–	6-20	–	–	–	–	–	0-5
		CEM II/B-Q	65-79	–	–	–	21-35	–	–	–	–	–	0-5
	Portland-fly ash cement	CEM II/A-V	80-94	–	–	–	–	6-20	–	–	–	–	0-5
		CEM II/B-V	65-79	–	–	–	–	21-35	–	–	–	–	0-5
		CEM II/A-W	80-94	–	–	–	–	–	6-20	–	–	–	0-5
		CEM II/B-W	65-79	–	–	–	–	–	21-35	–	–	–	0-5
	Portland-burnt shale cement	CEM II/A-T	80-94	–	–	–	–	–	–	6-20	–	–	0-5
		CEM II/B-T	65-79	–	–	–	–	–	–	21-35	–	–	0-5
	Portland-limestone cement	CEM II/A-L	80-94	–	–	–	–	–	–	–	6-20	–	0-5
		CEM II/B-L	65-79	–	–	–	–	–	–	–	21-35	–	0-5
		CEM II/A-LL	80-94	–	–	–	–	–	–	–	–	6-20	0-5
		CEM II/B-LL	65-79	–	–	–	–	–	–	–	–	21-35	0-5
	Portland-composite cement [c]	CEM II/A-M	80-94	<------------------------ 6-20 ------------------------>									0-5
		CEM II/B-M	65-79	<------------------------ 21-35 ------------------------>									0-5
CEM III	Blastfurnace cement	CEM III/A	35-64	36-65	–	–	–	–	–	–	–	–	0-5
		CEM III/B	20-34	66-80	–	–	–	–	–	–	–	–	0-5
		CEM III/C	5-19	81-95	–	–	–	–	–	–	–	–	0-5
CEM IV	Pozzolanic cement [c]	CEM IV/A	65-89	–	<---------- 11-35 ---------->					–	–	–	0-5
		CEM IV/B	45-64	–	<---------- 36-55 ---------->					–	–	–	0-5
CEM V	Composite cement [c]	CEM V/A	40-64	18-30	–	<----- 18-30 ----->			–	–	–	–	0-5
		CEM V/B	20-38	31-50	–	<----- 31-50 ----->			–	–	–	–	0-5

a The values in the table refer to the sum of the main and minor additional constituents.
b The proportion of silica fume is limited to 10 %.
c In Portland-composite cements CEM II/A-M and CEM II/B-M, in pozzolanic cements CEM IV/A and CEM IV/B and in composite cements CEM V/A and CEM V/B the main constituents other than clinker shall be declared by designation of the cement (for example see clause 8).

. Figure 13 Cement composition as stipulated in EN 197-1:2011

3.1.2.1 Standardization

The main European cement standard is the EN 197-1 Cement – Part 1: "Composition, specifications and conformity criteria for common cements" in which 27 cement products with their main constituents and proportions are grouped in five categories. (see Portland cement).

3.1.2.2 Portland Cement

Portland cement is considered the "typically made cement or most common type of cement", it is made by calcareous and argillaceous materials. To produce cement raw materials are grounded, blended, pre-calcined, and burned. In that way, the creation of cement includes quarrying; crushing, and pounding of raw materials (principally limestone and clay); calcining the materials in a rotating furnace; cooling the subsequent clinker; mixing the clinker with gypsum; and milling, storing, and bagging the final product. During the manufacturing process chemical analyses are taking place for all the ingredients to provide uniformly high-quality cement (Hyderaba, 2009).

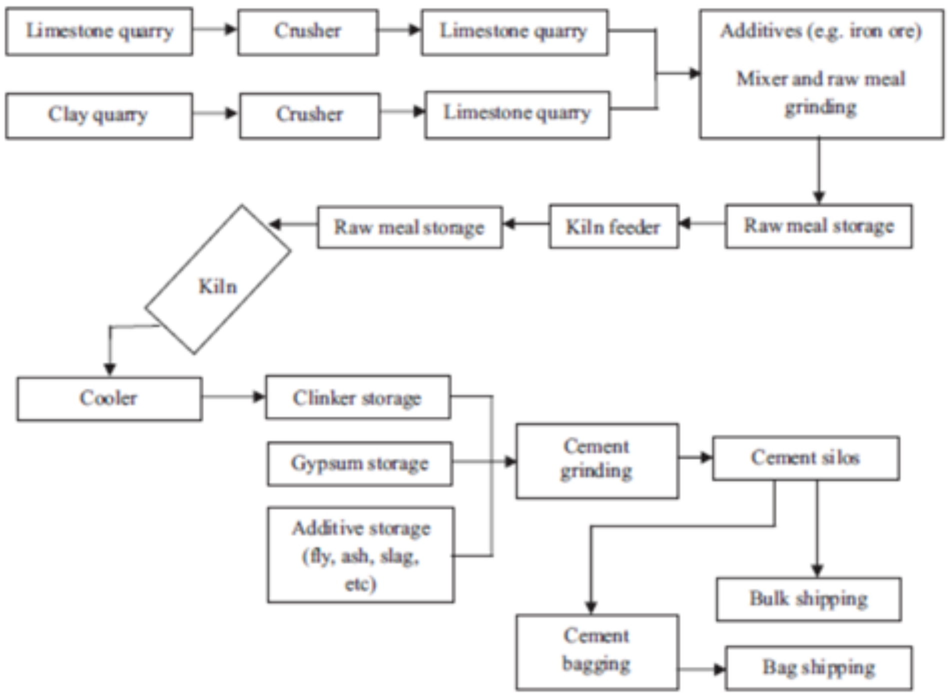


Figure 14 Manufacturing process - simplified (dry SP/PC Kiln) (Hyderaba, 2009; Madlool, Saidur, Rahim, & Kamalisarvestani, 2013)

<u>Characteristics</u>

Portland cement is normally grey, but also it can be found in white. It is characterized as calcium silicate hydraulic cement. As reference the European cement standard EN 197-1 the table 3 and figure 13 display the classification of common cements based on Portland cement clinker with other additives. They are grouped into five main categories, and 27 fundamental common cement products.

Table 3 Five main cement types as stipulated in SR EN 197-1:2011

Main Types	Composition
CEM I	Portland cement (>95% clinker)
CEM II	Portland-composite cement (65-94% clinker, and 6-35% other constituents
CEM III	Blast-furnace cement (5-64% clinker, and 36-95% blast-furnace slag)
CEM IV	Pozzolanic cement (45-89% clinker, and 11-55% of silica fume or, pozzolana or fly ash or a combination thereof)
CEM V	Composite cement (20-64% clinker, and 18-50% blast-furnace slag, and 18-50% pozzolana or siliceous fly ash or a combination thereof)

3.1.2.3 Manufacturing Process

Cement production involves multiple stages and actions from the quarry to the final product. As illustrated on the report by European Commission (2018) which discussed the completeness of cement and limestone industry; the production process can be grouped into four basic steps:

- **Extraction** (Quarrying of raw materials): First step is the quarrying of raw materials; the main ingredients are clay and limestone. Other ingredients that may added are sand, iron ore and bauxite. Usually the quarries are located close to the manufacturing area to save time and costs.
- **Crushing and grinding of raw materials** (processing): On this step the "raw meal" is prepared, raw materials are ground to powder and blended.
- **Calcination** (Pyroprocessing) / **Sintering the calcinated part into clinker**: This step is the main step to form cement clinker. It includes the chemical reaction (calcination) of limestone (CaCO3) to lime (CaO), and the release of carbon dioxide following the reaction of other ingredients. In European level, the most widely used method is the "dry" production, while there are also the "wet", "semi-dry", and "semi-wet" technologies. Here the "dry" technology is illustrated in the subsequent steps.
    - Preheating: raw meal is preheated to decrease the energy needed for the next step
    - Pre-calcination:
    - Clinker Production (rotary kiln): the raw meal, now pre-calcined meal is entering the rotating kiln and it burns up to 1450°C (sintering into clinker), coal oil, gas or other fuels are used directly to the kiln to reach that temperature.
    - Cooling: Then the cement clinker is passing to cooling down to 100-200°C.

- **Grinding and Blending:** Together with gypsum is conveyed to grinding mills to form Ordinary Portland Cement. Small amount of gypsum is added to regulate the setting time of cement, and to improve shrinkage and strength development properties. For other types of cement, other additives are added.

3.1.2.4 Supply chain

Below is a simplified representation of the supply chain of cement. Beginning with the upstream processes, the quarrying activities, through the manufacturing of cement, the illustration of multiple downstream cement related activities, and finally with the final product in the construction sector.

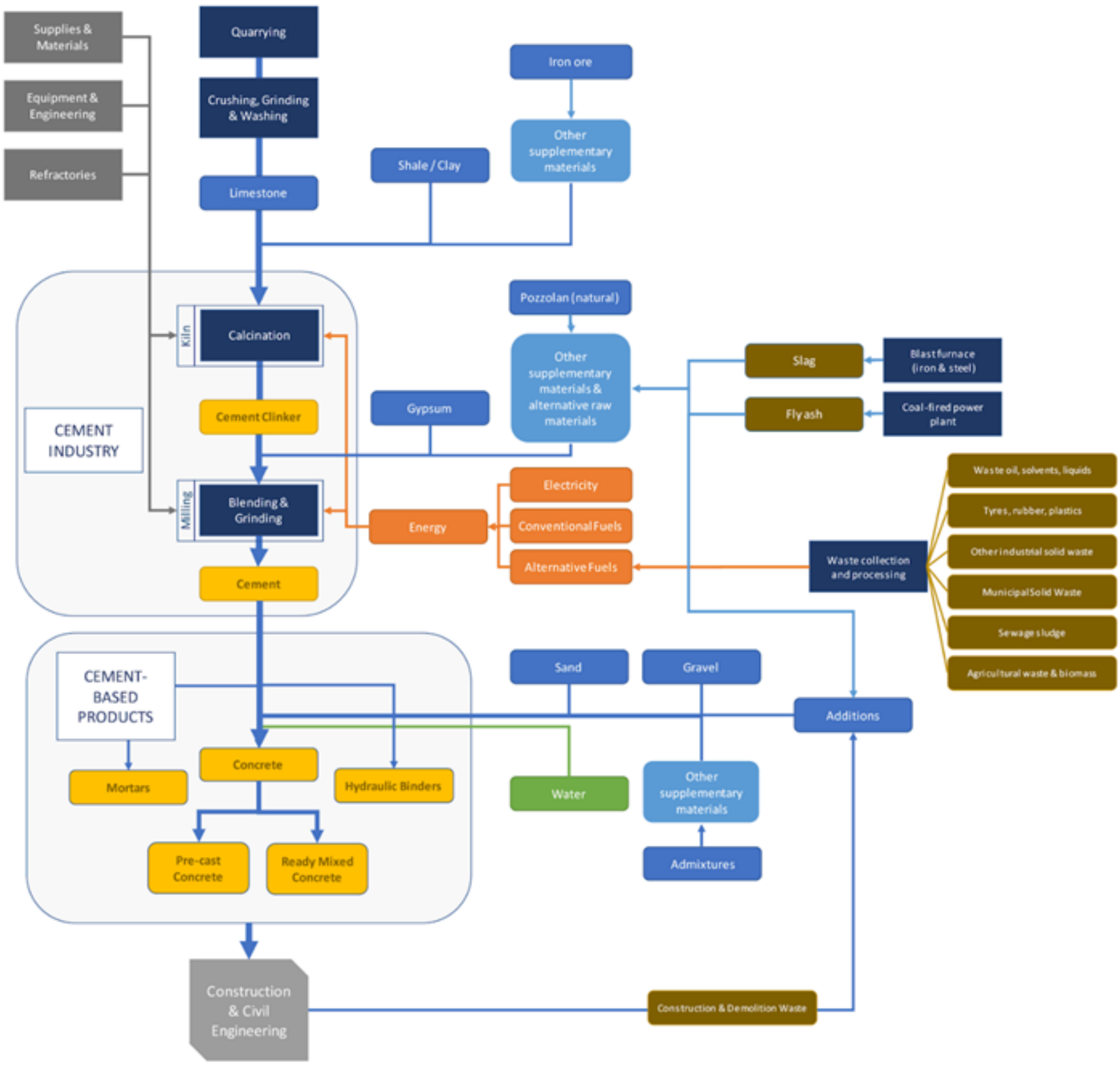


Figure 15 Simplified cement supply chain (European Commission, 2018)

3.1.2.5 Equipment

To produce cement, inter alia, there are multiple pieces of equipment like: grindings millis, kiln, cooling systems, fans, furnaces, electrical motors, crushers, conveyors, storage silos (Gao, Shen, Shen, Liu, & Chen, 2016).

3.1.2.6 Raw Materials

Clinker is primary made of lime (calcium oxide, CaO) mixed with silica (silicon dioxide, SiO2) and alumina (aluminum oxide, Al2O3). After the quarrying, the materials are transferred to the manufacturing area where the cement production takes place. There are various cement types, and for its of them the percentage of its ingredients is different; in most of the cases when cement is mentioned it means that it is Portland cement. An average percentage range of cement́s raw materials is given in table 4.

● Limestone, CaO: Calcium oxide is usually made by the thermal decomposition of materials, such as limestone or seashells, that contain calcium carbonate in a lime kiln.

● Sand/Quartz, SiO2: Silicon dioxide (silica) is an oxide of silicon and is known by its hardness. It helps on the workability, consistency, and strength of cement. Usually it can be found on extend up to 30% on cement. It is considered as the most common and abundant mineral in the Earth's lithosphere.

● Clay, Al2O3: Aluminum hydroxide minerals are the main component of bauxite, the principal ore of aluminum. Alumina regulates the setting time of concrete and improves its mechanical strength. Excessive amount of alumina in cement, can be negative as its presence lowers the temperature on clinkering and weakens the cement.

● Iron ore, Fe2O3: Iron ore has two main functions; to give color to the cement, and to liquidize the material to easily pass from kiln. It also provides hardness to cement.

Table 4 Proportioning of raw materials for cement manufacturing (M.T. Shah, 2007)

Raw materials	Percentage
CaO	60-67%
SiO2	17-25%
Al2O3	3-8%
Fe2O3	0.5-6%

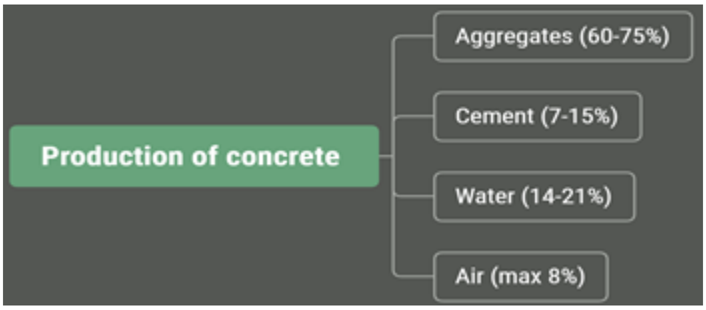


Figure 16 Average proportions of raw materials in concrete mix

While many industrial byproducts are likely to be used as raw materials for cement manufacture; table 5 shows the main raw material sources.

Table 5 Main sources of Raw Materials in Manufacture of Portland Cement (Kosmatka, Steven H.; Kerkhoff, Beatrix; and Panarese, 2011)

Calcium	Iron	Silica	Alumina	Sulfate

Aragonite	Clay	Clay	Clay	Gypsum
Limestone	Iron Ore	Marl	Fly ash	Calcium sulfate
Calcite		Sand	Shale	
Marl		Argillaceous rock	Bauxite	
Shale		Quartz	Aluminium Ore refuse	
Seashells				

3.1.2.7 Concrete

Concrete is essentially a two-component mixture: aggregates and paste. The paste, consisting of Portland cement and water, binds the aggregates (usually sand and gravel or crushed stone) into a rocky mass as the paste hardens due to cement and water's chemical reaction. Usually, additional cementitious materials and chemical admixtures are added in the paste. The most common EU concrete standard is EN 206-1 Concrete – Part 1: "Specification, performance, production and conformity" which covers cast in situ structures, precast structures, and precast products for buildings and civil engineering construction.

Aggregates that account for 60-75% of the total amount of concrete should consist of clean, hard, strong particles free of absorbed chemical products or of clay coatings and other fine materials as that may result in the decay of concrete. Generally, aggregates are divided into two groups: fine and coarse. Fine aggregates incorporate natural or processed sand on sizes of up to 5 mm. The coarse aggregate usually has a size between 9.5 mm and 37.5 mm. Sometimes an intermediate aggregate, approximately 9.5 mm, is added to enhance the general gradation of the aggregate.

Table 6 Class of Aggregates ("Scientific Principles of Concrete," University of Illinois[2].)

Class	**Most common raw materials**	**Application**
Ultra-lightweight	vermiculite ceramic spheres perlite	lightweight concrete which can be sawed or nailed, also for its insulating properties
Lightweight	expanded clay shale or slate crushed brick	used primarily for making lightweight concrete for structures, also used for its insulating properties.

[2] http://matse1.matse.illinois.edu/concrete/prin.html

Normal weight	crushed limestone sand river gravel crushed recycled concrete	used for normal concrete projects
Heavyweight	steel or iron shot steel or iron pellets	used for making high density concrete for shielding against nuclear radiation

Aggregates are taking up to 75% of the total amount of concrete, thus its careful selection will give high quality concrete. Aggregates are having continuous gradation, as it helps to bond with the paste. For a high-quality concrete; aggregates are completely covered with the paste, and there is no gap between the particles.

The paste consists of cement, water, and trapped air or intentionally trapped air. Paste is made by combining cementitious material with water which allows the chemical reaction of hydration, and for the final concrete product to develop its properties. The paste represents approximately 25-40% of the overall concrete quantity. The absolute cement quantity is generally between 7-15% and the water between 14% and 21%. In many cases, entrained air adds another 4-8%.

For the concrete mix the main equipment is the concrete batching plant (ready-mix concrete plant), in which the aggregates, water, cement and other additives are proportioning, weighting, mixing, and packing/transported. For the transport of ready-mixed concrete to the site there are pump trucks which transfer liquid concrete by pumping. During the pouring of the concrete it is important to use vibrators, as it is certain that air is trapped, and it can cause concrete degradation. All the raw materials are getting through laboratory processes to ensure high quality. Also, lab tests are taken place once the final product is ready to observe the properties associated with the strength of hardened concrete, chemical reactions between cement, and water of concrete.

Table 7 Standards related to cement and concrete raw materials

Cement	EN 197-1, ASTM – C150
Aggregates	EN 12620, ASTM – C33
Admixtures	EN 934-2. ASTM C494
Concrete	EN 206-1, ASTM – C94
Concrete mix design (Absolute volume method)	ACI 211.1

Aggregates are saved on site, and cement is coming from its production site (or it is produced on the same site as concrete plant) and it is stored in silos. Based on the specification of each project the quantity of each ingredient is determined and weighted. Then, a uniform mixture is made with the aggregates, cement, water, and additives.

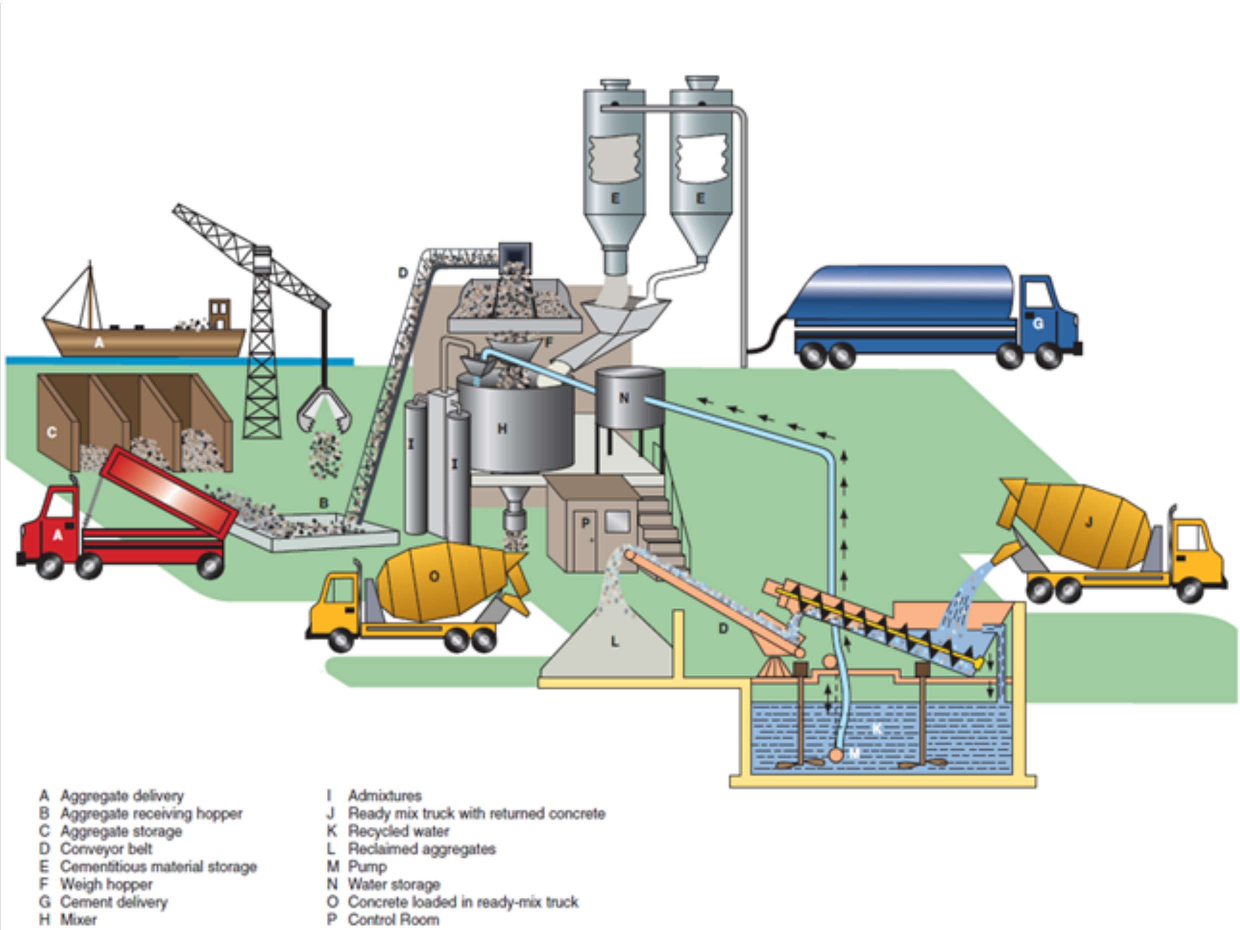


Figure 17 Concrete production process flow (Kosmatka, Steven H.; Kerkhoff, Beatrix; and Panarese, 2011)

Strength of concrete

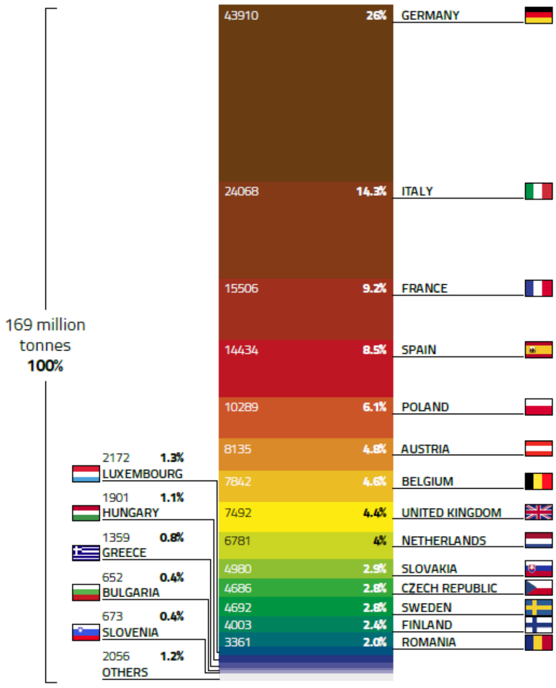
Principally, the engineering properties of concrete that routinely specified, and provide the basis for other tests is the 28- days characteristic compressive strength *(f_{ck})* (Phil Bamforth, Derek Chrisholm, John Gibbs, 2008). It is determined by the characteristic cylinder strength, and the characteristic cube strength on laboratory tests. Besides compression there are other strengths that are examined; tensions, shear, flexure, and torsion. For all of them, there are specified test methods that are taking place. The standard which explains in detail the requirements for the concrete structures is; Eurocode 2: Design of concrete structures EN1992-1-1. Figure 16 shows the classes of strength of cement as they presented on EC2, these mix ratios are decided based on type of construction and mix designs. For example, C25/30 has a 28 – day cylinder strength of 25 N/mm² and a corresponding cube strength of 30 N/mm².

	Strength classes for concrete													
f_{ck} (MPa)	12	16	20	25	30	35	40	45	50	55	60	70	80	90
$f_{ck,cube}$ (MPa)	15	20	25	30	37	45	50	55	60	67	75	85	95	105
f_{cm} (MPa)	20	24	28	33	38	43	48	53	58	63	68	78	88	98
f_{ctm} (MPa)	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1	4,2	4,4	4,6	4,8	5,0
$f_{ctk,0,05}$ (MPa)	1 1	1,3	1,5	1,8	2,0	2,2	2,5	2,7	2,9	3,0	3,1	3,2	3,4	3,5
$f_{ctk,0,95}$ (MPa)	2,0	2,5	2,9	3,3	3,8	4,2	4,6	4,9	5,3	5,5	5,7	6,0	6,3	6,6
E_{cm} (Gpa)	27	29	30	31	32	34	35	36	37	38	39	41	42	44
ε_{c1} (‰)	1,8	1,9	2,0	2,1	2,2	2,25	2,3	2,4	2,45	2,5	2,6	2,7	2,8	2,8
ε_{cu1} (‰)	3,5									3,2	3,0	2,8	2,8	2,8
ε_{c2} (‰)	2,0									2,2	2,3	2,4	2,5	2,6
ε_{cu2} (‰)	3,5									3,1	2,9	2,7	2,6	2,6
n	2,0									1,75	1,6	1,45	1,4	1,4
ε_{c3} (‰)	1,75									1,8	1,9	2,0	2,2	2,3
ε_{cu3} (‰)	3,5									3,1	2,9	2,7	2,6	2,6

Figure 18 Strength classes of Concrete as stipulated in EN 1992-1-1:2004 (Bsi, 2004)

3.1.3 Steel

Steel is a versatile material that can be found everywhere in the world. According to Eurofer, the steel sector produces 170 million tonnes of steel per year and directly employs 320 thousand people. The production is shared across the 24 EU member states with 500 steel production areas, while it influences and supports indirectly around 2.2 million more jobs. Germany followed by Italy, France, and Spain are the leaders in European Steel Production (Eurofer 2018).



Country	2013	2014	2015	2016	2017	% share 2017
Austria	7953	7876	7687	7438	8135	4.8%
Belgium	7093	7331	7257	7687	7842	4.6%
Bulgaria	523	612	543	527	652	0.4%
Croatia	135	167	122	0	0	0%
Czech Republic	5152	5360	5262	5305	4686	2.8%
Finland	3517	3807	3988	4101	4003	2.4%
France	15685	16143	14984	14413	15506	9.2%
Germany	42645	42943	42676	42080	43910	26%
Greece	1030	1022	910	1158	1359	0.8%
Hungary	883	1131	1674	1279	1901	1.1%
Italy	24093	23714	22018	23373	24068	14.3%
Luxembourg	2089	2193	2127	2175	2172	1.3%
Netherlands	6713	6964	6995	6917	6781	4%
Poland	7950	8541	9198	8940	10289	6.1%
Romania	2985	3158	3352	3276	3361	2%
Slovakia	4511	4705	4562	4808	4980	2.9%
Slovenia	654	641	625	644	673	0.4%
Spain	14130	14187	14846	13631	14434	8.5%
Sweden	4372	4514	4348	4595	4692	2.8%
United Kingdom	11874	12061	10853	7635	7492	4.4%
Others	2206	2053	2015	1998	2056	1.2%
EU 28	**166191**	**169126**	**166042**	**161982**	**168992**	**100%**

Figure 19 Source EUROFER Production share per EU member state country and Crude Steel Production Output Production per Country.

The EU steel industry is the second largest in the world with a total Gross Value Added of € 148 billion. The steel demand increased by 3.3% in 2018, as EU`s economy grew. Steel is a basic engineering material, it is often used in the construction sector, and it is 100% recyclable. In 2018, the construction sector was the leader on steel consumption of finished steel products with 35%, followed by the automotive sector with 19%, and the mechanical engineering sector with 15%. The total world crude steel production was estimated to 1.8 billion tonnes in 2018 (WSA 2019) .

A publication that discusses the future of EU Steel Industry (Rosseti, 2017), reports that the sector together with other heavy industries is influenced by China´s increased capacity the last decade, the new technologies and technical advances, and finally by the drive to achieve carbon neutrality

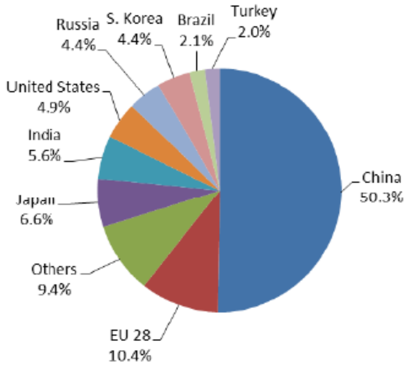
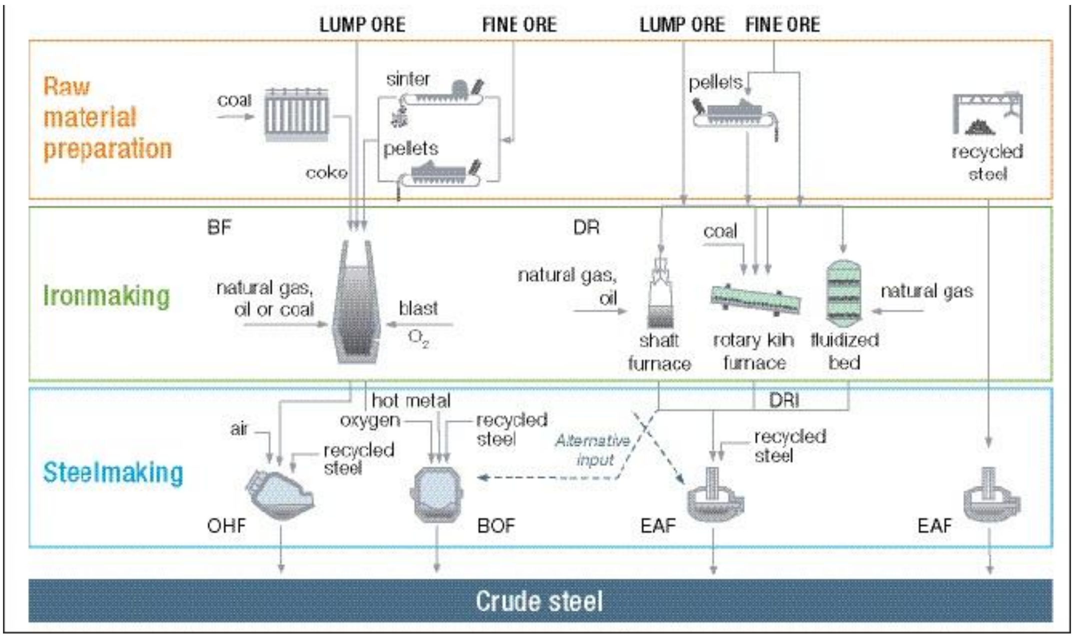


Figure 20 Global Share of Steel Production (European Commission, 2018[3])

<u>Product</u>

Steel has great tensile strength and comparative low cost. Those characteristics make steel a major material for civil and mechanical engineering works, automobile industry, and others. Key raw materials needed in steelmaking include iron ore, coal, limestone and recycled steel. There are two main production routes, the Basic Oxygen Furnace (BOF) and the Electric Arc Furnace (EAF). In Europe around 60% of the plants use the BOF production route. Key processes in steel making include the coke making, sintering, Iron Making, Steel Making. The primary inputs to produce 1 ton (or 1000 kg) of crude steel are (roughly): 1.4 tonnes of iron ore, 0.8 tonnes of coal, 0.3 tonnes of limestone, and 0.12 tonnes of recycled steel (World Steel Association 2019). Approximately, 3 out of 4 plants in the world using are using the integrated method (Blast Furnace) to produce Crude Steel.



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[3] Steel Statistical Yearbook, 2016. World Steel Association

Figure 21 Steel production routes (World Steel, 2018)

3.1.3.1 Iron and Steel Production

Stainless steel always includes other metals than iron. In superalloys, the other metals can be half of the mass in the metals. The integrated steel and iron works consist of several separately trackable processes, which are carried out as sequential operations on a single site, to modify iron ores and other raw materials into semi-finished steel products. The steel is processed in order to meet the requirements of material characteristics in the final product, for example with the addition of alloys (Johansson and Ljungstedt 2009).

The main processes are identified as follows:

- **Coke making**: Coking coal is a key ingredient in steel making, it is produced by destructive distillation of coal in coke making unit. It is either 'cooked' or heated in an oxygen-free atmosphere until all of the volatile elements of coal evaporate (EPA 2011).
- **Sinter Production** (Ore preparation and agglomeration): Main inputs on sintering process is iron ore, coke breeze, and limestone to form agglomerated product on a suitable size. The output product is sent to blast furnaces.
- **Iron production**: From the top, the blast furnace is charged with iron ore pellets, coke and limestone (flux); from the bottom, hot air, often enriched with oxygen, is blown in; and the carbon monoxide produced by the coke transforms the iron ore into carbon-containing pig iron.
- **Steel making**: The liquid iron then is transported to a converter, which reduces its carbon level by less than 2% and alters the iron into steel. This is achieved by blowing oxygen under high pressure on the molten metal surface. Limestone with other oxides from the burned iron form slag as by-product.
- **Casting:** The liquid steel is poured into continue casting machines to form semi-finished products such as slab, bloom or billet, and a variety of finished products, including plate, sections, bars, rod, hot and cold rolled sheet and coil, together with various types of coated flat products ((UK) Environment Agency 1999).

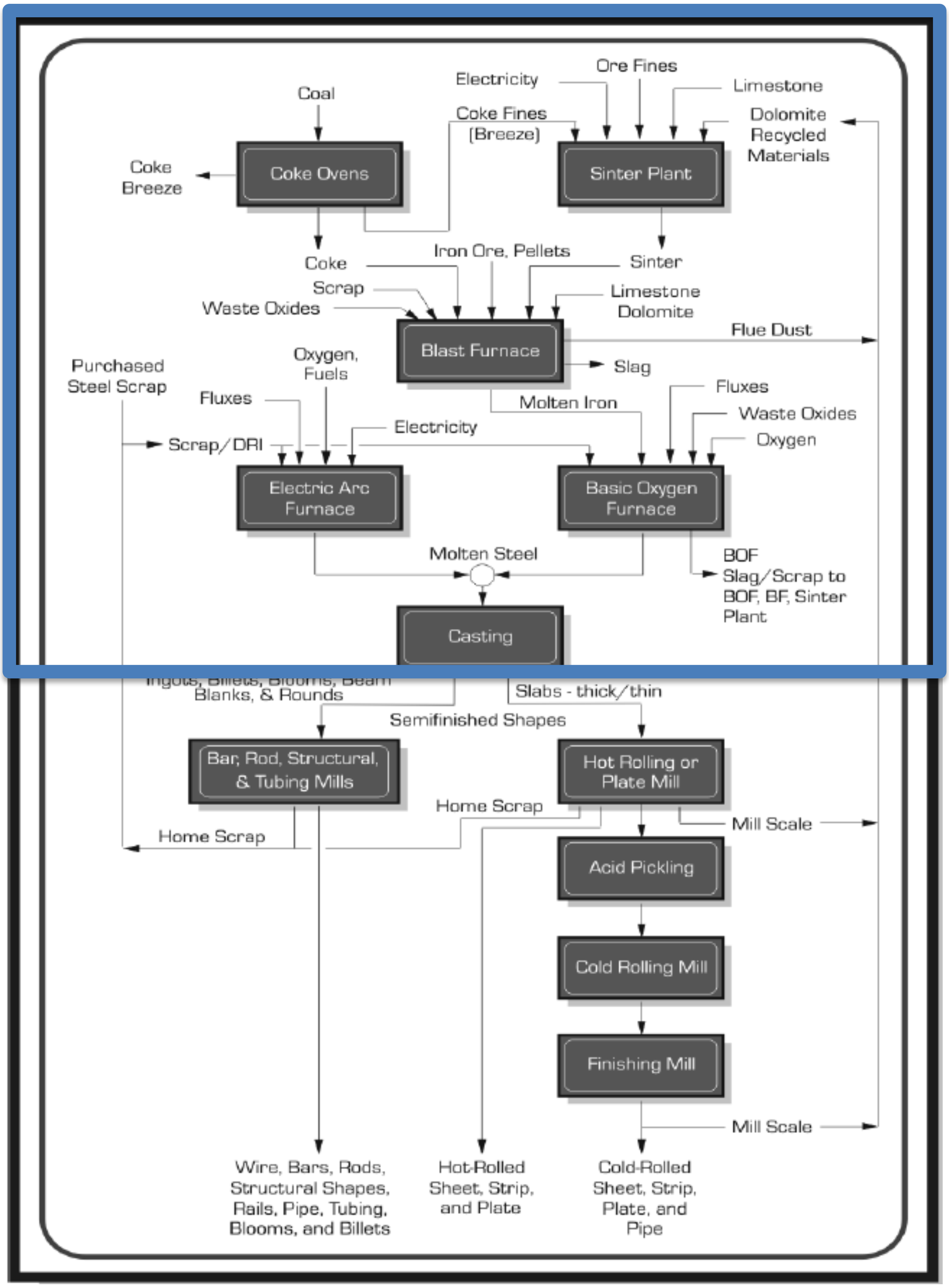


Figure 22 Process flow for steel making (Adapted by ITP Steel: Steel Industry Technology Roadmap, 2001[4])

[4] https://www.energy.gov/sites/prod/files/2013/11/f4/roadmap_chap2.pdf

Equipment

In steel making, the main equipment that is needed is the blast furnace, the BOF, coke oven, sintering equipment, converter for steel manufacturing, and continuous casting machines.

Supply chain

Below is the simplified steel industry supply chain, the upstream processes include the main raw materials, following by the manufacturing processes of iron and steel, and finally with the steel as upstream product.

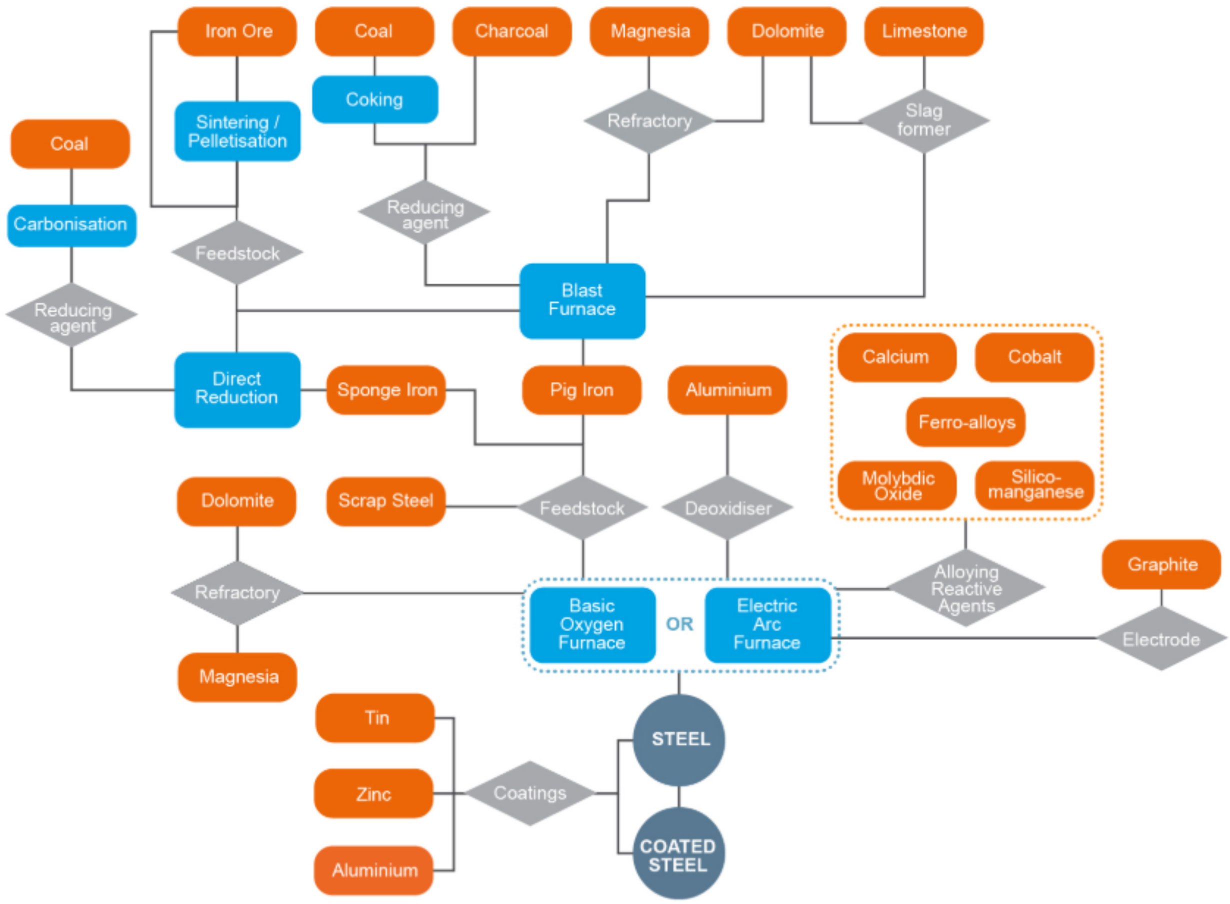


Figure 23 Simplified steel industry supply chain (World Steel Association, 2019)

Steel Construction Products

Steel is a strong material that is highly resistant to forming at normal temperatures, but this resistance is significantly reduced at higher temperatures. Thus, the semi-finished materials from the steel making process form the basic products at carefully controlled elevated temperatures. The temperatures reach in average 1.280 °C in a reheat furnace and then the steel is rolled etc. to shape it. Semi-finished products (billets, blooms or slabs) can be transported to the manufacturing industry or transformed into finished products such are bars, beams, sheets by the mean of hot rolling.

Finished steel products are falling under two basic categories: **flat and long products**. Long products include blooms, billets, rods, bars, wire, reinforcing, nails, and others. Flat steel products are made from steel slabs and include plate, strip, hollow sections, large diameter welded pipe and structural beams (Environment Agency 1999; The New Zealand Ecolabelling Trust 2015).

Table 8 Overview of finished steel products

Finished Products	
Flat	**Long**
Plate	Rods
Strip	Billets
Slabs	Sections
Hollow section	Wire
Structural Beams	Bars/Coils
Large diameter welded pipe	

4 Generic Chains – ToSIA Application

To test the BanchValue method for usability, validity and applicability a generic case shall provide a reference against the individual BenchValue case studies of the partner countries (i.e. Austria, France, Ireland, Lithuania). Several studies examined a comparison of materials in construction projects, most often wood vs concrete (Sathre and O'Connor, 2010). In BenchValue it was the aim to identify a case that suits the needs of a comparison of all three materials (wood, concrete, steel). However, there are no existing studies that provide data on such a case nor was there an opportunity to get a hypothetical case designed within the lifetime of the project. The idea was to set up a building that is designed to meet a distinct purpose and fulfills the same function in order to compare the sustainability impacts of a certain material:

- 1 m² living area single-family house
- Only load bearing structures (house frame -> structural system)
- 50 years service life

For the generic chains the raw material supply (routes) for the most common construction processes are modelled:

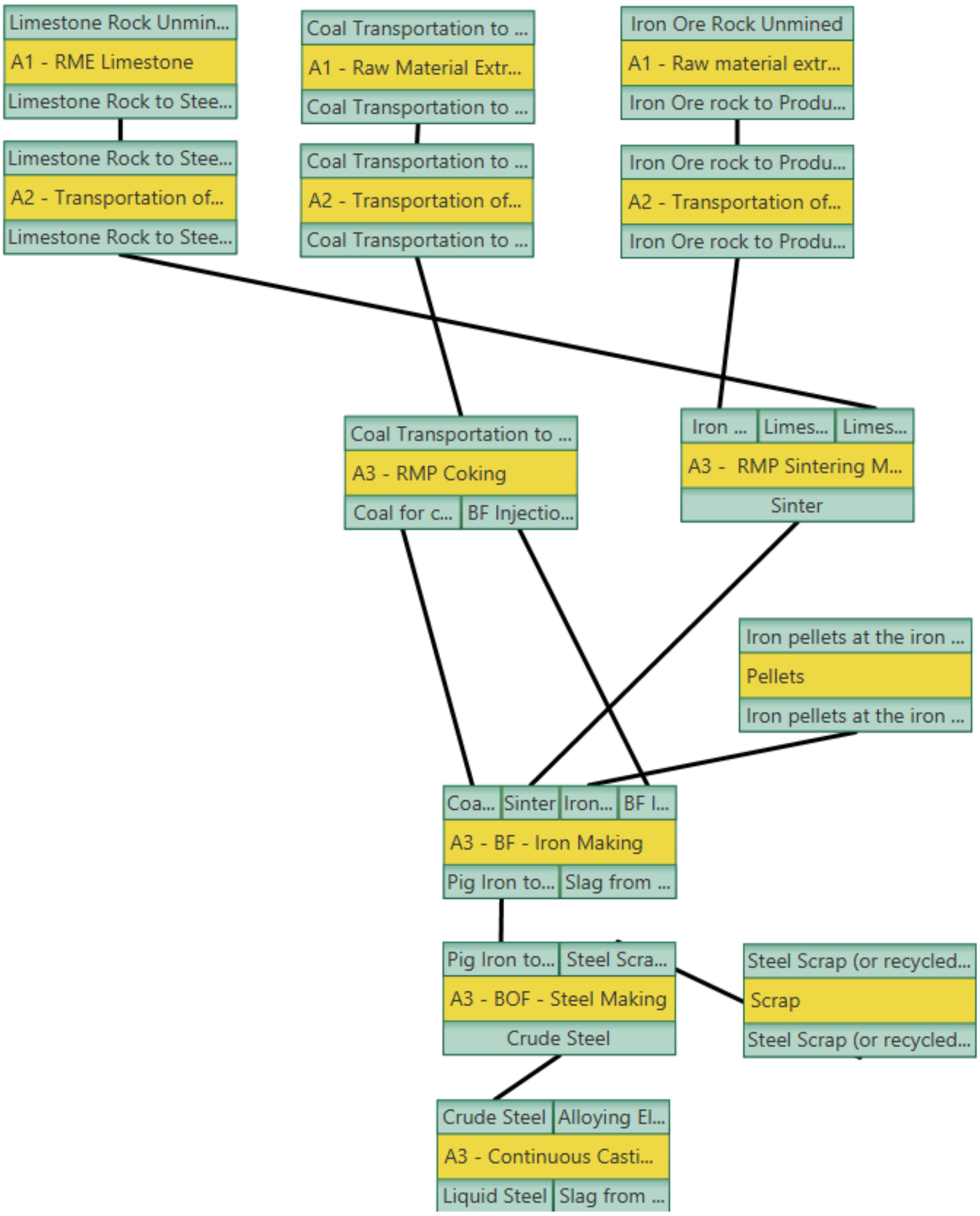
- Steel production
- CEM I cement, and 25/30 concrete mix
- Roundwood (to be used for various wood products, according to tree species composition)
- Sawn wood in first conversion

The goal of the generic chain after the end of the BenchValue project is to aid new studies in covering the raw material sourcing processes with consistent system boundaries for consistent comparisons. It helps with describing the main process and materials flows to allow for each adjustment to case-specific realities. Further suitable sources for specific or updated data are given.

4.1 Generic steel chain

4.1.1 Flow Calculation

Steel is an alloy of iron and carbon and other elements, with carbon contributing up to 2.14% of its weight in typical steel alloys (with variations between 0.002-2.14 %). For steel production the recommended process unit is 1 tonne of crude steel. An alternatively suitable unit would be tonnes of atomic iron (t of Fe), which is almost the same as tonnes of product unit due to the purity of the product. There were multiple indicating averages of raw materials for steel production, the final decision for the steel generic value chains is based on the information available in Word Steel Association, papers and literature that are focusing on LCA of steel production with the Integrated Steel plant method. The other sources gathered their inventory directly from steel plants, databases and publicly available LCI information for the World Steel Association and International Iron and Steel Institute. The value chain illustrates the main processes occurred to produce crude steel. The amount of materials used, consider any losses to produce crude steel. It is expected that steelmaking process have the highest environmental impact as it requires a massive amount of energy.



Process name	Stage	Process unit
Raw material Extraction - Limestone	A1 Raw Material Supply	tonnes
Raw material Extraction - Coal	A1 Raw Material Supply	tonnes
Raw material Extraction – Iron Ore	A1 Raw Material Supply	tonnes
Transportation – Limestones	A2 Transport	tonnes
Transportation – Coal	A2 Transport	tonnes

Transportation – Iron Ore	A2 Transport	tonnes
Coking Coal	A3 Manufacturing	tonnes
Sintering	A3 Manufacturing	tonnes
Iron Making	A3 Manufacturing	tonnes
Steel Making	A3 Manufacturing	tonnes

Quantities of material for 1 tonne Crude Steel

Raw materials

- Iron ore: 1.321 tonnes
- Coal: 0.584 tonnes
- Limestone: 0.040 tonnes
- Steel scrap: 0.127 tonnes
- Pellets: 139 tonnes

Sintering

- Iron ore: 1.321 tonnes
- Limestone: 0.040 tonnes

Output

- Sinter: 1.421 tonnes

Coking

- Coal: 0.584 tonnes

Output

- Coking coal: 0.117 tonnes

Iron Making

- Sinter: 1.421 tonnes
- Pellets: 0.139 tonnes
- Coal: 0.117 tonnes
- BF Injection coal (gas): 0.467

Output

Liquid Iron: 1.029 tonnes

Steel Making

Liquid Iron: 1.029 tonnes

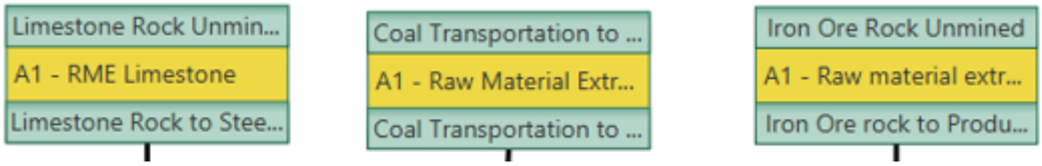
Steel scrap: 0.127 tonnes

Output

Crude steel: 1.086 tonnes

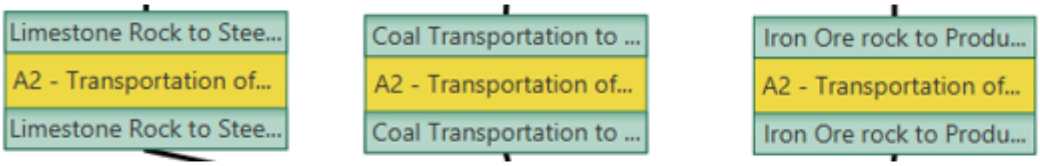
4.1.2 **Value Chain Topology**

A1 Raw Material Supply



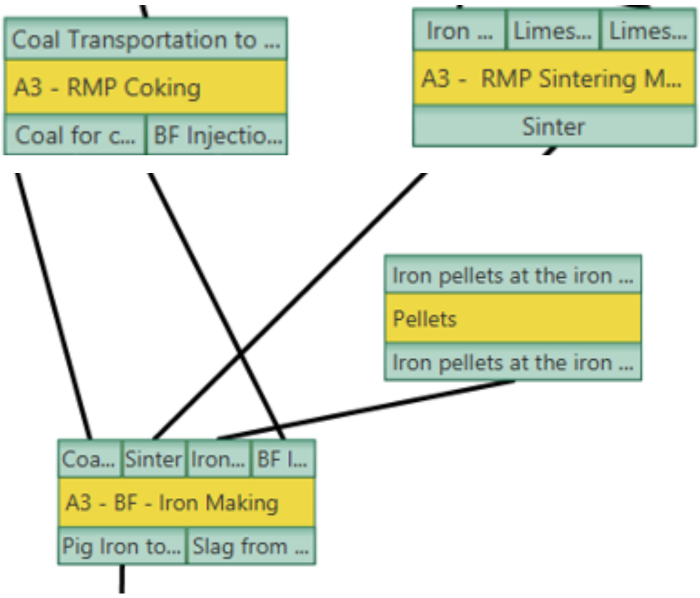
Starting with the Extraction of iron ore and baking of iron pellets (stage: A1 Raw Material Supply). Rock material with a high iron ore content is extracted from the ground by exploding rocks and mechanized digging. The crude rocks are transported on site by trucks or conveyor belts for processing, grinding and crushing for magnetic separation of iron ore (20-60%) and rock (80-40%). The default values are 50:50 and are recommended to be adjusted to reflect the conditions of the used iron source. The resulting iron ore is crushed to powder (=slurry), and baked with water and clay into pellets.

A2 Transportation



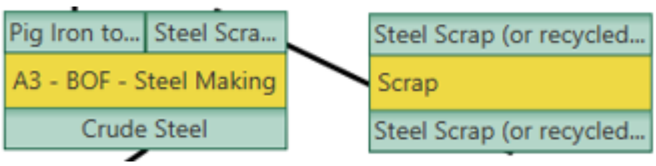
Depending on the local conditions a (potential) transport process (stage: A1 Raw Material Supply) may take place is iron and steel production is in happening at the same site. This process may be excluded.

Iron Making (stage: A3 Manufacturing)



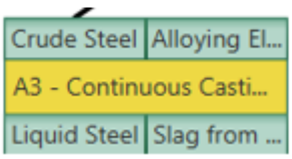
Iron pellets are usually transported with deep loaders or conveyor belts to the blast furnace (iron production): iron ore, coke, and limestone are fed into the furnace and burned in gradual steps from 200 to 1500 C (a variety of processes and temperature steps take place in the blast furnace while oxygen removed from iron oxides to form CO2. The hot waste gases are collected, cleansed and used to power the furnace to reach the high temperatures). The two main output products are molten iron (collected and transported in iron ladles for later use) and slag/waste used for building the roads.

Steel Making (stage: A3 Manufacturing)



Molten steel is transported from the blast furnace to the steel furnace, sometimes called a "converter". In the steel furnace steel scraps are added to the molten iron, while a high-pressure stream of oxygen and powdered lime is blown through the mixture to remove some of the carbon from the iron. The amount of carbon removed, determines quality of the molten steel. Slag is produced as a side product.

Casting (stage: A3 Manufacturing)



Steel (pre-)fabrication: Hammering and rolling of raw steel to pre-fabricated slabs or rolled thin into roles of steel sheets. Sometimes surface treatments are included.

4.2 Generic timber chain

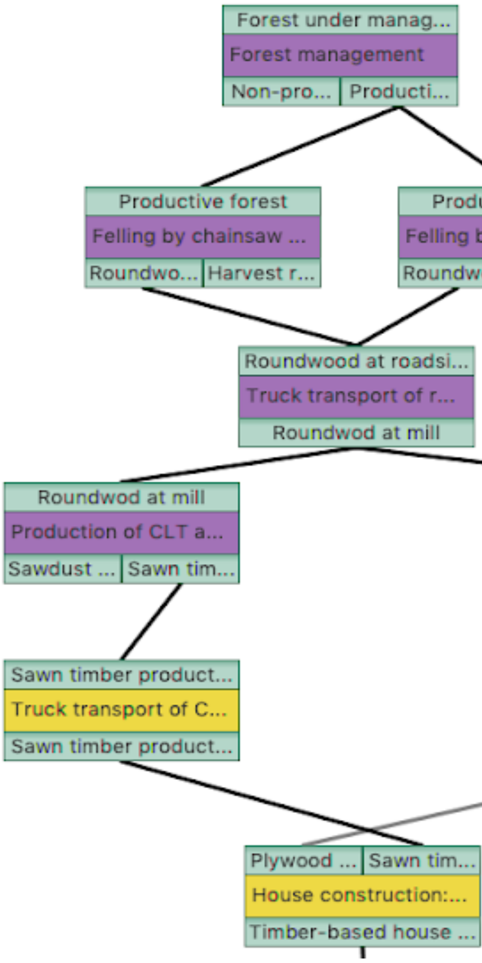
4.2.1 Flow Calculation

Timber is a natural, renewable product grown from trees in natural unmanaged or managed landscapes. Timber is produced as a result of photosynthesis:

$$6\ CO_2 + 12\ H_2O + \text{photons} \rightarrow C_6H_{12}O_6 + 6\ O_2 + 6\ H_2O$$

(carbon dioxide + water + light energy ➔ glucose + oxygen + water)

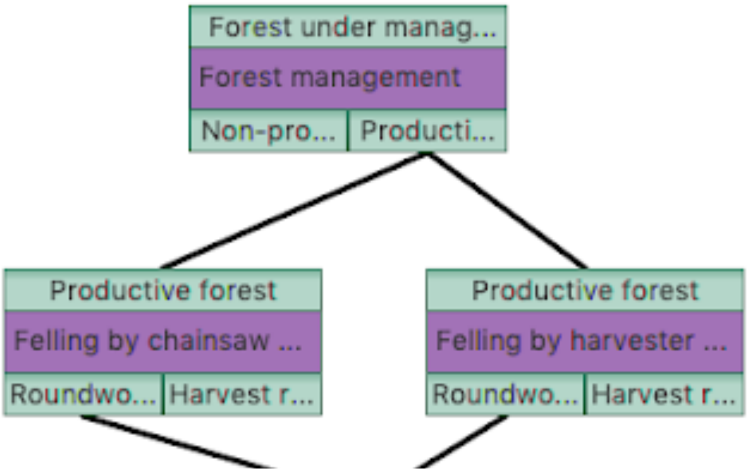
During photosynthesis CO2 is absorbed from the atmosphere and stored as wood. The chemical composition of wood varies from species to species, but is approximately 50% carbon, 42% oxygen, 6% hydrogen, 1% nitrogen, and 1% other elements (mainly calcium, potassium, sodium, magnesium, iron, and manganese) by weight. Wood also contains sulfur, chlorine, silicon, phosphorus, and other elements in small quantity. As a living organism, wood also transports and holds considerable amounts of water. For this reason, wood can be expressed as "fresh weight" or "dry weight". Directly after filling the water starts evaporating from the vessels. Drying further reduces the water content. In the generic chain we will refer to dry-weight and use 50% carbon content based on the species-specific dry weight. A comprehensive list of most tree species can be found here: www.wagnermeters.com/specific-gravity/ or from national data. The most common tree species are spruce (Picea abies) with 0.43 t/m^3 and 0.125 t of C/m^3, Scots pine (Pinus sylvestris) with 0.45 t/m^3 and 0.275 t of C/m^3, and beech (Fagus sylvatica) with 0.67 t/m^3 and 0.315 t of C/m^3. For national average the volume weighted densities based on the national timber fellings per tree species need to be used.


Forest under manag...
Forest management
Non-pro...
Producti...
Productive forest
Felling by chainsaw ...
Roundwo...
Harvest r...
Productive forest
Felling by harvester ...
Roundwo...
Harvest r...
Roundwood at roadsi...
Truck transport of r...
Roundwod at mill
Roundwod at mill
Production of CLT a...
Sawdust ...
Sawn tim...
Roundwod at mill
Production of plywo...
Plywood ...
Sawdust ...
Sawn timber product...
Truck transport of C...
Sawn timber product...
Plywood elements at ...
Truck transport of P...
Plywood elements at ...
Plywood ...
Sawn tim...
House construction:...
Timber-based house ...

Process name	Stage	Process unit
Forest management	A1 Raw Material Supply	ha
Felling by chainsaw and hauling by forwarder	A1 Raw Material Supply	m^3
Felling by harvester and hauling by forwarder	A1 Raw Material Supply	m^3
Truck transport of roundwood to sawmill / CLT / Glulam mill	A2 Transport	tonnes
Production of CLT and GluLam elements at sawmill	A3 Manufacturing	m^3
Production of plywood panels	A3 Manufacturing	m^3
Truck transport of CLT elements to construction site	A4 Transport	tonnes
Truck transport of Plywood panels to construction site	A4 Transport	tonnes
House construction: Assembly of wooden elements on site	A5 Construction Installation Process	tonnes

Described stages are A1-A3: Product Stage, A4-A5 Construction stage.

A1 Raw Material Supply

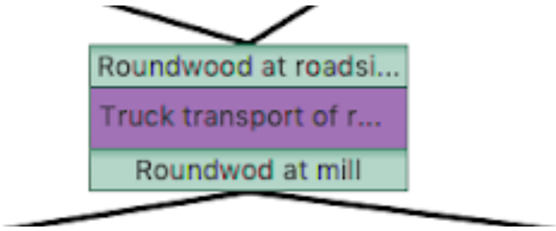


Forest management	A1 Raw Material Supply	ha
Felling by chainsaw and hauling by forwarder	A1 Raw Material Supply	m^3
Felling by harvester and hauling by forwarder	A1 Raw Material Supply	m^3

The generic value chain starts with forest management, focusing on the commercially harvested timber. This process may also be neglected, and instead started with the raw material sourcing, i.e. forest operations. Forest operations are aggregated by combining the felling and hauling process. It includes the felling of the standing tree, delimbing and debranching, as well as cutting into assortments (saw logs, pulplogs, industry wood, harvesting residues). The log assortments (ca 75%) are hauled out of the forest to the roadside, where they are stacked. The harvest residues (ca 25%) remain in the forest.

Depending on the region, fellings are done motor-manually (chainsaw plus skidder) or fully mechanized (harvester plus forwarder).

A2: Transport



Truck transport of roundwood to sawmill / CLT / Glulam mill	A2 Transport	tonnes

The roundwood is transported to the sawmill. In this chain sawmilling for Glulam product and for CLT products are combined. Transport for logs usually requires a truck with a crane. In the EU the general maximum truck weight is 40t, in France 44t, in Finland and Sweden 60t. In exceptions, for timber transport higher loads are permitted for designated trucks. In Sweden 74t and 90t trucks were developed and tested.

A3: Manufacturing

Production of CLT and Glulam elements at sawmill	A3 Manufacturing	m^3
Production of plywood panels	A3 Manufacturing	m^3

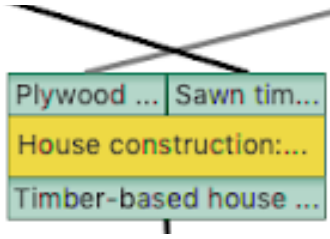
Efficiencies of sawmills vary with the used technology for sawing and grading, and of course with the quality of the input material. 70% efficiency in modern sawmills is normal, 60% for older ones. For plywood mills efficiency is at about 50%. Cut-offs are used for other products and sawdust for energetic purposes. In this study plywood production is excluded, as we focus on structural, load-bearing elements.

A4: Transport

Truck transport of CLT elements to construction site	A4 Transport	tonnes
Truck transport of Plywood panels to construction site	A4 Transport	tonnes

Transport from the mill to the construction site is by truck, with the national limitations for truck transport (40t, 44t or 60t). Depending on the type of transported material, sometimes overlong trucks need to be used. For instance, for glulam roof elements for sportshalls, churches, etc.

A5: Construction Installation Process



House construction: Assembly of wooden elements on site	A5 Construction Installation Process	tonnes

Assembly of the materials on site. If prefabricated house elements are used the construction time and loss of materials is considerably reduced. If timber frame or log-based methods are used, the construction is also rather fast. Timber does not constitute leave hazardous rest materials or require drying time.

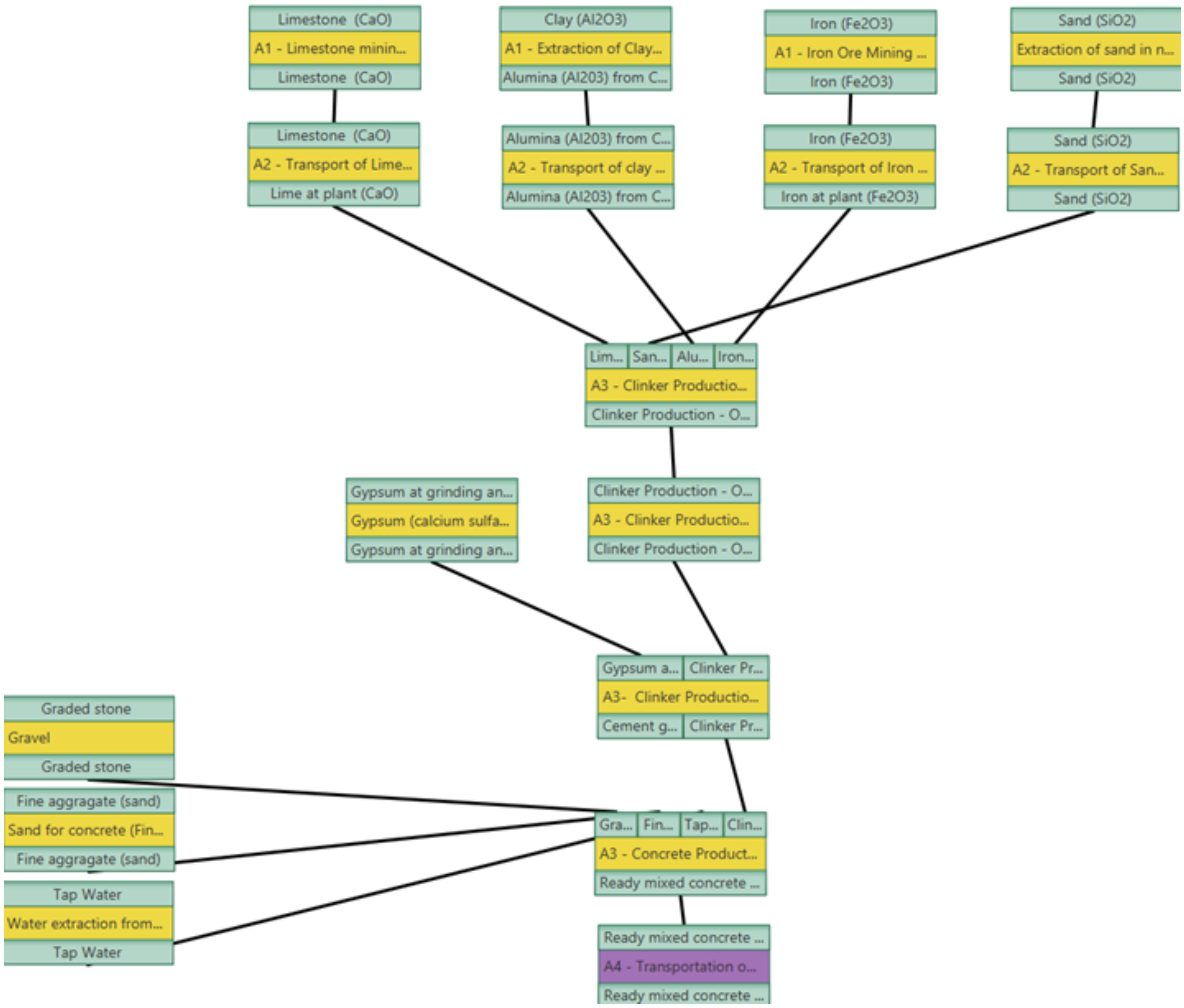
House use (50 years)	B1 Use	tonnes

4.3 Generic cement chain

4.3.1 **Flow Calculation**

For the generic chains we have chosen to illustrate manufacturing of Ordinary Portland Cement, and further C25/30 concrete type. The proportions of raw materials for cement production are for 1 ton of Portland cement, following with 1 m^3 (~ 2400 kg/m^3) of concrete. The proportions have taken from reports, papers, and other credible sources all focusing on the production of Portland cement. The choice of base and process unit was made to assist in understanding how the flows behave, and to be able to account for all the material flows and to help in managing conversion factors. For the eventual indicator results (which are the main point of a ToSIA analysis), the choice of base unit, or process unit is irrelevant, as the output is in any case CO_2 equivalents of emissions, person years of employment or euros of production cost for instance.

As there is no specific study to be followed, the flow calculation followed the value chain of cast in situ concrete. The amount of materials used in ToSIA; consider loss of ignition to produce cement, and any other losses associated with the raw materials.



Process name	Stage	Process unit
Limestone mining (CaO)	A1 Raw Material Supply	tonnes
Extraction of Clay (Al2O3)	A1 Raw Material Supply	tonnes
Iron Ore Mining (Fe2O3)	A1 Raw Material Supply	tonnes
Extraction of sand in nature	A1 Raw Material Supply	tonnes
Transport of Limestone	A2 Transport	tonnes
Transport of Clay	A2 Transport	tonnes
Transport of Iron Ore	A2 Transport	tonnes
Transport of Sand	A2 Transport	tonnes

Clinker Production (Processing/Blendid mix)	A3 Manufacturing	tonnes
Clinker Production (Calcination/Pyroprocessing)	A3 Manufacturing	tonnes
Clinker Production (Finish Grinding and Blending)	A3 Manufacturing	tonnes
Gypsum (calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$))	A3 Manufacturing	tonnes
Gravel for concrete	A3 Manufacturing	tonnes
Sand for concrete (Fine aggregate)	A3 Manufacturing	tonnes
Water	A3 Manufacturing	tonnes
Concrete Production	A3 Manufacturing	tonnes
Transportation on Site	A4 Transportation	tonnes

Quantities of material for 1 ton Ordinary Portland Cement (Huntzinger & Eatmon, 2009)

Raw materials

- Lime (CaO): 1.41 tonnes
- Alumina (Al_2O_3): 0.139 tonnes
- Silica (SiO_2): 0.034 tonnes
- Ferric oxide (Fe_2O_3): 0.015 tonnes

Crushing, Grinding and Blending

- Blended mix: 1.598 tonnes

Calcination

- Clinker: 0.95 tonnes

Finish Grinding and Mixing

- Gypsum ($CaSO_4$): 0.05 tonnes

Output Final Product

- Portland Cement: 1 tonne

Quantities of material for 1 m^3 (~ 2400 kg/m^3) concrete C25/30

- Portland Cement: 0.366 tonnes
- Sand: 0.700 tonnes
- Coarse aggregate: 1.2 tonnes

- Water: 150 l = 0.128 tonnes

In flow calculation, below are two main chemical reactions during the manufacturing process:

1. Calcination, which happens in a kiln at high temperature, where ground material containing calcium carbonate (CaCO3) is converted to calcium oxide (CaO), in a reaction that produces significant CO_2 emissions - and thus also a concrete and significant loss of mass, according to the formula: $CaCO_3 \rightarrow CaO + CO_2$
   A detailed description, broken down into the sub processes:
   a. Broken into 10cm pieces in primary/secondary crushers,
   b. The raw materials are mixed and milled together to produce ‘raw meal’.
   c. Preheating: Hot exhaust gases coming from the kiln preheat the powdered raw meal before it enters the kiln.
   d. Precalcining: Calcination is the transformation of limestone into lime. Part of the high temperature reaction in modern installations takes place in a ‘precalciner’, a combustion chamber at the bottom of the preheater above the kiln, and partly in the kiln. Here, the chemical decomposition of limestone, generating typically 60% of total CO_2 emissions of the cement manufacturing process occurs. Fuel combustion generates the rest of the CO_2.
   e. Clinker production in the rotary kiln: Precalcinated meal enters the kiln at temperatures of around 1000°C. Fuel (such as coal, petroleum coke, gas, oil and alternative fuels) is fired directly into the rotary kiln at up to 2000°C to ensure that the raw materials reach material temperatures of up to 1,450°C. Decomposition occurs from the loss of bound water and carbon dioxide.
   f. Cooling and storing: From the kiln, the hot clinker is cooled using large quantities of air, part of which can serve as combustion air. Coolers are essential for the creation of the clinker minerals which define the performance of the cement. In this process, the combustion air is preheated, thereby minimizing overall energy loss from the system. Clinker is usually used on site but can be transported by truck, train or ship to other grinding plants.
2. Hydration of CaO into $Ca(OH)_2$, according to formula: $CaO + H_2O \rightarrow Ca(OH)_2$, which takes place through the addition of water to the cement, and then the consequent chemical binding of water into the concrete as it dries and hardens. Part of the water is bound, and another part evaporates in the drying of concrete. Concrete is also sometimes submerged in water to allow for adequate hydration (water doesn’t dry off too fast) and to ensure even drying to prevent e.g. cracking of concrete due to fast or uneven drying.

4.3.2 **Value Chain Topology**

A1 - Cement Raw Materials

For making cement and concrete, several raw materials are required, the most important of which is calcium carbonate ($CaCO_3$), which is derived from naturally occurring materials like limestone, marl or chalk, which are extracted from quarries. The main processes where products are converted (also chemically), are the cement and concrete making.

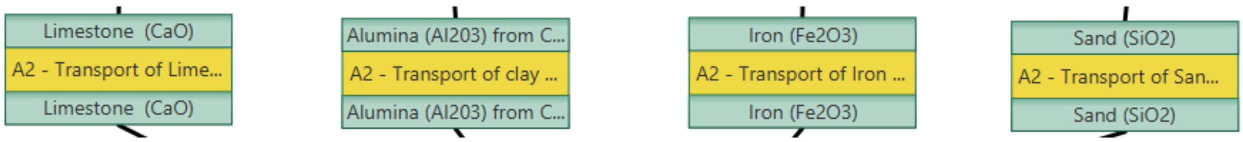
In addition to the main materials listed below, in clinker production, small quantities of iron oxide (Fe_2O_3), alumina (Al_2O_3) might be added for desired mineral properties, and Gypsum ($CaSO_4$ 2 H_2O) is added in grinding of clinker. Ordinary Portland Cement (OPC) is often mixed with fillers such as slag, fly ash, limestone or other materials. These fillers affect the properties of cement. Various admixtures are applied in small quantities specifically to change the properties of the cement. Finally, in making concrete, cement (blended or not) is mixed with sand and aggregate, such as gravel, recycled and crushed concrete, or other suitable materials.

Limestone mining (CaO)	A1 Raw Material Supply	tonnes
Extraction of Clay (Al_2O_3)	A1 Raw Material Supply	tonnes
Iron Ore Mining (Fe_2O_3)	A1 Raw Material Supply	tonnes
Extraction of sand in nature	A1 Raw Material Supply	tonnes

The four main raw materials that we extract from nature, are also transported to factories. Also cement factories are often co-located with mines, so in fact the transport might only be by conveyor belts.

As it is mentioned above, cement is mainly made from limestone and clay while there are other minor ingredients. Depending on the type and needs of each structure that are different categories of cement. It is evident that Portland cement is the most commonly used cement worldwide. In Europe, cement has been standardized as a product, so guidelines and instructions are easy to be found.

A2 – Transportation

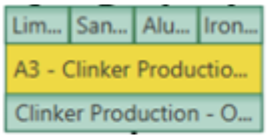


Transport of Limestone	A2 Transport	tonnes
Transport of Clay	A2 Transport	tonnes
Transport of Iron Ore	A2 Transport	tonnes
Transport of Sand	A2 Transport	tonnes

It is typical that raw material quarries will be located vary close to cement plants, in any case the transportation to plant is usually preferred to not be for a distant location. Most of the times, the transportation mean is a truck.

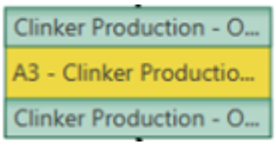
A3 – Clinker Production (Processing)

Clinker production is split into 3 main processes; firstly, the raw materials are crushing, grinding and processing, then the calcination is occurring, and finally the grinding and mixing where gypsum is added.



Clinker Production (Processing/Blended mix)	A3 Manufacturing	tonnes

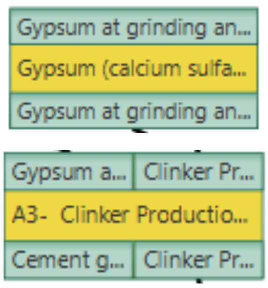
A3 – Clinker Production (Calcination)



Clinker Production (Calcination/Pyroprocessing)	A3 Manufacturing	tonnes

A3 – Clinker Production (Finish Grinding and Blending)

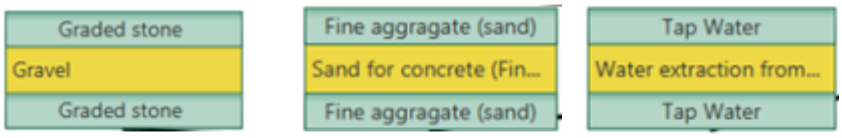
When the clinker is cooled, a small quantity of gypsum is added during as final processing phase. Gypsum is added to control the "setting time" of cement, it slows down the hydration process of cement once it is mixed with water.



Clinker Production (Finish Grinding and Blending)	A3 Manufacturing	tonnes
Gypsum (calcium sulfate dihydrate ($CaSO_4 \cdot 2\ H_2O$))	A3 Manufacturing	tonnes

A3 – Concrete mix

It is considered that the concrete is produced in the site, so the paste with the aggregates are mixed in that phase, to come up on the final product which is concrete C25/30 cast-in-situ. Reinforcement is not considered in this value chain, as its value is examined on the generic chain of steel.



Gravel for concrete	A3 Manufacturing	tonnes
Sand for concrete (Fine aggregate)	A3 Manufacturing	tonnes
Water	A3 Manufacturing	tonnes
Concrete Production	A3 Manufacturing	tonnes

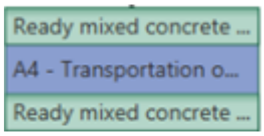
The modern and most common way of producing cement is the dry process, which is the one that is explained in previous chapters. Cement, between other reasons is considered impactful material due to the energy intensive processes that are taking place during the calcination. The final product is a grey powder which is used to produce concrete. Depending on the type of application, there are multiple types of concrete, which are mainly defined by their strength in compression, and accordingly have different proportions of raw materials and additives.

The selection of the precise concrete type suited for each purpose plays a role for analyzing the value chains, as the different varieties of concrete imply different aggregates, admixtures - different impacts. The below graphic illustrates the exposure classes related to environmental actions but these recommendations for selection vary country by country - due to different climatic conditions. The classification for exposure classes is described in Eurocodes and more specific in EN206-1 “Concrete - Part 1: Specification, performance, production and conformity”. For example, in Finland you will need a concrete that can handle being thoroughly frozen and thawing and freezing again for many months of the year, while in southern France this might be less relevant. In coastal zones, resistance to the corrosive effect of sea water is important.

Also, concrete can be found with different techniques; precast and cast-in-situ. Precast is mainly manufactured on the production area and transported to the building site. In this instance, concrete is formed into molds or formworks, cured to take the strength and then it is ready to be placed on the building. In-situ, which is the most common method is poured to a specific formwork with reinforcement on the side and cured to get the designed strength.

In reinforced concrete frame structures, members are fixed to each other with the so called “moment connections”. The reinforced concrete structure should be resistant to dead loads, live loads, wind loads, dynamic load and earthquake loads. Concrete is a mix of cement, water, aggregates and sand. Concrete is strong under compression, but weak tension resistance. To overcome this, reinforcing steel (rebar) is added. Steel for reinforcement is designed in different diameters, and length sizes to meet the requirements of different designs. Typically, is a long-ribbed bar. To reach the final product concrete is poured into molds in which the reinforcement steel is already placed according to the requirements, this can be done either in situ or in the production area.

A4 – Transportation to building site



5 How to use generic chains in a specific setting

The generic chains always need to be adjusted to the local realities. While they can be consulted for inspiration, they always have to be adopted. Similar as the wood-based chains, that comes along with questions such as:

- Where are the raw materials produced?
- How far are they transported?
- How are they further treated (pre-assembly)?
- How much of cement or steel is used instead of timber beams or pillars?
- Which type of beams or pillars are used? Steel I-beams or H-beams?, cement : XF1 CEM I – for beams?, foundation?:e.g., XC1 in France as foundation, XC2 in Finland and Ireland as foundation – what is it in your country?
- Which type (chemical composition) of cement is used in your country and where/how is it produced?
- Construction and use of elements / building in your country: construction time, constraints, product life expectancy, comfort of living, etc.

The following alternative approaches for using the generic chains exist (demonstrated at the example of Lithuania):

a) Copy the existing timber chain twice in ToSIA and save it as two new chains under the names “[country] multistory cement” and “[country] multistory steel”. Then adjust them to reflect the selected building and national realities. In this case, the building data will reflect the type of the building (but needs to be adjusted, of course, to reflect the different material).

b) Copy the generic cement and generic steel chain in ToSIA and save it as two new chains under the names “[country] multistory cement” and “[country] multistory steel”. Then adjust them to reflect the building and national realities. With that the general processes are obtained, but keep in mind that these chains may still change quite a bit as work continues. They need adjustment to reflect the selected building type in any case.

c) Build the specific cement and steel chains from scratch. In this case the user may not get confused with semi-finished chains, but they might spend much time to learn about cement or steel value chains. In this case, the generic chains can be used as checkpoints and reference.

6 Comparing one material-based value chain with another

A functional unit is a measure of the required properties of the studied system, providing a reference to which input, and output flows can be related (EN 15978). Defining a functional unit allows the comparative analysis of different buildings or building materials. Energy use or GHG emissions per unit of mass or volume of material is inadequate as a functional unit because equal masses or volumes of different materials do not fulfil the same function. Standard EN 15978 gives rules for the functional equivalent for buildings. According to the standard, the functional equivalent of a building (or an assembled system) shall include the following aspects: building type, relevant functional and technical requirements, pattern of use, structural system/element, and we focus on stage A so maintenance etc. is not included. However, we assumed components that last as the building´s lifetime which meant in Europe minimum 50 years, country specific 50-100 years. Different structural and material options can be compared for different building components such as wall structures and roof structures. Performance can be compared based on the services provided by the building rather than the building itself. For example, if the primary service provided by a building is protection against climatic elements, a comparison can be made on the basis of m2 or m3 of climate-controlled floor area or interior space (ECO 2 book).

7 Quantification: Indicators and Criteria

In order to quantify impacts on the sustainability dimensions of value chains with ToSIA indicators are used. An indicator shows something or points to something and can thus be defined as: “A parameter, or a value derived from parameters, which points to / provides information about / describes the state of a phenomenon / environment / area with a significance extending beyond that directly associated with a parameter value (OECD 1992).” Various indicator frameworks for the built environment exist and are applied in context of environmental assessments of sustainable buildings. As ToSIA originally has been designed for the analysis of wood value chains (or Forestry-Wood-Chains, cf. Green et al 2015), to integrate several life cycle aspects for different raw materials for the benchmarking approach within BenchValue, a limited indicator cohort shall secure the validity, reliability and robustness of the method expansion (cf. BenchValue Deliverable “D3.1”). Existing indicator sets (see below 6.1) and stakeholder perceptions as regards the relevance of indicators needed to holistically assess the sustainability of buildings in Europe form the basis of the BenchValue indicator cohort.

7.1 Indicators from other frameworks

Bridging methods (i.e LCA and SIA approaches) and assessing the sustainability dimensions of construction projects in a holistic way, as BenchValue is aiming at, requests for contemporary knowledge on the state of the art in assessment methods, as addressed within Sustainability Science. The following subchapters give insights to the frameworks that have been considered for setting up the BenchValue method and its underlying indicators.

7.1.1 LCA

Life Cycle Assessment (LCA) quantifies and assesses the emissions, resources consumed, and pressures on health and the environment attributed to different products over their entire life cycle (EC 2012). The new EU guidelines for LCA, or Product Environmental Footprints, stipulates a list of 16 impact categories (EU 2013). LCA takes inventory data and converts it to indicators for each impact category, which typically include:

Global warming potential (GWP100)	Ozone depletion potential (ODP)
Photochemical ozone creation potential (POCP)	Acidification potential (AP)
Eutrophication potential (EP)	Non-renewable primary energy (PE-NR)
Total primary energy demand (PE)	Share of renewable primary energy (%PE-R)

Although LCAs rarely include all of these, they may include the following impact categories in addition (EU 2013):

Ecotoxicity for aquatic fresh water	Human Toxicity - cancer effects
Human Toxicity - non-cancer effects	Particulate Matter/Respiratory Inorganics
Ionising Radiation - human health effects	Resource Depletion - water
Resource Depletion - mineral, fossil	Land Transformation

7.1.2 Level/s

In 2015 the European Commission initiated a study to develop an EU framework of core indicators for the environmental performance of buildings (LEVELs) and identified six macro-objectives that establish the strategic focus and scope for the framework of indicators. These priorities are: i) greenhouse gas emissions throughout the buildings life cycle, ii) resource efficient and circular material life cycles, iii) efficient use of water resources, iv) healthy and comfortable spaces, v) adaptation and resilience to climate change, and vi) life cycle cost and value (EU 2017). Following the macro-objectives and building upon stakeholder consultation a suite of indicators was identified, with the following ones suggested as core indicators within the framework (Dodd et al 2016):

Operational energy consumption • Total primary energy consumption • Final energy consumption	Operational and embodied Global Warming Potential
Service life of bill materials	Construction and demolition waste
Construction and demolition waste	Mains drinking water consumption
Airborne pollutant levels • Quantitative airborne pollutant levels • Qualitative airborne pollutant levels	Indoor air class (ventilation, CO2 and relative humidity)
Occupant thermal comfort	Additional energy required
Life Cycle cost • Utility costs • Acquisition and maintenance costs	Value and risk factors

Level(s) yet represents a voluntary reporting framework to improve the sustainability of buildings and provides a common EU approach to environmental performance in the built environment.

7.1.3 ToSIA indicators

In ToSIA, indicator values per material flow are taken from a database client, where the set of indicators are introduced (based on existing case studies and indicators that have been used for recent SIA studies). In ToSIA, the calculated process indicator values are determined based on the material flow through the process and the indicator values per material flow from the database. Calculated module and FWC indicator values are then determined by aggregating the calculated process indicator values along the chain taking into account the system boundaries selected by the user. In the following table 9 a brief, but not at all complete, list of indicators available in the database client is shown.

Table 9 Indicator list per sustainability pillar available in ToSIA (exzerpt from ToSIA database client

Economic	**Social**	**Environmental**
Gross value added	Employment	Energy generation and use
Production cost	Wages and salaries	Greenhouse gas emissions and carbon stock
Trade Balance	Occupational safety and health	Transport
Resource use, incl. recycled material	Education and training	Water Use

Forest sector enterprise structure	Corporate social responsibility	Forest Resources
Investment and research & development	Quality of employment	Soil condition
Total Production	Provision of public forest services	Water and Air Pollution
Productivity	Cultural heritage & Sense of Place	Forest biodiversity
Innovation	Traditional Knowledge and Stories	Generation of waste

First try-out of adding LCA perspectives into ToSIA by defining separate indicators for direct and indirect energy use and Greenhouse gas emission, as well as an Emission Saving Criteria calculating the sum of direct plus indirect emissions for a renewable value chain and comparing it against a fixed Fossil Fuel Comparator (FFC) to express Emission savings of renewable versus fossil value chains was described in detail in Tuomasjukka et al (2017).

7.1.4 **SDGs**

One of the most recent indicator frameworks came into force in 2016 and mark the 2030 Agenda for Sustainable Development (UN 2018). The Sustainable Development Goals (SDGs) provide a tool to monitor and track progress towards a more sustainable global future. Among the key challenges to be addressed include poverty, inequality and injustice as well as climate change. Table XX gives an overview of the 17 goals that have been formulated and agreed by world leaders at the UN Sustainable Development Summit in New York in 2015 (UN, 2018).

Table 10 Sustainable Development Goals (SDGs) as agreed by world leaders at the UN Sustainable Development Summit in New York (UN, 2018)

Goal 1. End poverty in all its forms everywhere	Goal 10. Reduce inequality within and among countries
Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable	Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable
Goal 3. Ensure healthy lives and promote well-being for all at all ages	Goal 12. Ensure sustainable consumption and production patterns
Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all	Goal 13. Take urgent action to combat climate change and its impacts

Goal 5. Achieve gender equality and empower all women and girls	Goal 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development
Goal 6. Ensure availability and sustainable management of water and sanitation for all	Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
Goal 7 Ensure access to affordable, reliable, sustainable and modern energy for all	Goal 16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
Goal 8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	Goal 17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development
Goal 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	

7.2 Indicator for temporary carbon storage

The most important component currently driving human-induced climate change is CO_2 emissions caused by human activities (IPCC 2014). This gas is also important in a comparison between buildings and building components produced from different construction materials such as steel, concrete and wood. Production of steel is associated with large emissions of fossil CO_2. Most steel is produced from iron ore that include iron oxides. The oxygen in the ore reacts with carbon from coal-based coke in a blast furnace, forming CO_2 and CO. The latter also forms CO_2 when the blast furnace gas is combusted. If the blast furnace gas is instead released into the atmosphere, the CO eventually reacts with oxygen in the air to form CO_2. A significant share of the steel is produced from scrap in electric furnaces. This is associated with less; however, the production of electricity used in steel recycling is to varying degrees associated with combustion of fossil fuel in power plants.

Concrete is a mixture of cement and coarse aggregates. The cement is typically produced from limestone (essentially calcium carbonate, $CaCO_3$), which is calcinated to lime (calcium oxide, CaO) at a high temperature in a cement kiln. The production of cement is associated with large quantities of CO_2 emissions, partly from the combustion of fuel in the kiln and partly released from the carbonate itself. Part of the latter is eventually recaptured by the concrete, when calcium hydroxide Ca(OH)2 is combined to atmospheric CO2 (Andersson et al. 2013). This phenomenon, called carbonation, occurs in a very slow process. As the carbonation induces a drop in pH, the depassivation of reinforcing steels is reached, the corrosion develops, causing a deterioration of the concrete elements periphery. Carbonation is a pathology of concrete structures. However, also the recaptured CO_2 contributes to climate change for the time period when it is in the atmosphere.

The CO_2 associated with wood products is mainly biogenic and part of a circular flow between the forest and the atmosphere. However, forestry operations affect the sequestration and stock of carbon in the forest and, hence, the current and future quantities of CO_2 in the atmosphere. Carbon is also stored in wood products. After forest harvest, a significant amount of biogenic carbon is removed from forest and could be stored for decades in harvested wood products (Anderson et al. 2013). This carbon is kept from the atmosphere for a shorter or longer period of time, depending on the service life of the product and on the waste management process at the end of the service life. The service life varies between products and can also depend on economic cycles or fashion trends, which very likely vary from one country to another (Chang et al. 2014). The service life for wooden houses is defined at 50 years in Eurocodes but can be 100 years or more (Skog & Nicholson 1998), which means the carbon is stored in the building for over a century. Such temporal storage of carbon contributes to reducing the climate impacts during the time of the storage.

Kirschbaum (2006) observes that global warming has three types of effects: instantaneous effects related to a higher temperature (e.g., health impacts of heat waves), effects that relate to the rate of temperature change (on ecosystems and technological systems that require time to adapt), and effects that relate to the long-term average temperature (e.g., sea level rise). He argues that all three types of impacts are important, but that temporal carbon storage only reduces the last type of effects. He concludes that temporal storage is not important enough to warrant policy incentives. Other researchers (e.g., Helin et al. 2013) argue that the time of carbon capture and release should be taken into account in climate assessments.

Temporal release of CO_2 and temporal carbon storage are not taken into account in calculations of Global Warming Potential (GWP), the traditional indicator for climate change as calculated using the LCA methodology as defined in the ISO-14040 and ISO-14044 standards. This indicator accounts for radiative forcing from the time of the emission and a fixed number of years after that (often 100 years), independent of when the emission occurs. This means it does not distinguish between emissions at different points of time and, hence, does not account for any delay in the emission.

For estimating temporal carbon storage (carbon stocks changes) in the pool of wood products, IPCC good practice guidelines propose to apply the first-order decay function which is a flux data method that takes into account carbon sinks and emissions during the certain period of time (IPCC 2014).

Other methods have been suggested to account for delays in emissions and for temporal storage and release of carbon. The simplest methods propose to model the climate impact of CO_2 with a linear reduction of 0.76% (Clift & Brandao 2008) or 1% (European Commission 2010) per year of delay in the emission. More accurate methods take into account that CO_2 and other greenhouse gases are removed from the atmosphere or decay in a non-linear rate. Instead of integrating radiative forcing from the time of the emission until a fixed number of years afterwards, Levasseur et al. (2010) integrate the radiative forcing from the time of the emission until a fixed time horizon in the future. If the emission is delayed until a point in time closer to this time horizon, the results of the integration will be reduced.

Brandao et al. (2013) discuss these and other approaches to climate assessment. They conclude that the results do not diverge very much between linear and non-linear methods, indicating that linear approximations to the non-linear methods can at least in some cases be sufficient. They also observe that storage of carbon for a given number of years will be more important if the time horizon of the assessment is short.

8 System boundaries and allocation

8.1 Boundaries towards nature

The life cycle has a system boundary towards nature. In LCA, the life cycle should ideally be modelled in such a way that the flows across this boundary are elementary flows. This means that the life cycle should include all human transformation of the flows. However, processes that do not significantly affect the conclusions of the study need not be included in the model.

As stated by, for example, Finnveden et al. (2009), it is often not known in advance which activities are insignificant and can be excluded from the model. Finnveden et al. indicate that the significance of excluded activities could be estimated through the use of input-output analysis and/or through accumulated experience of, for example, the importance of capital equipment. Activities of unknown significance can be included in the model but based on rough, easily accessible data. This gives an initial estimate of the importance of the data. The model can then be refined through the collection of better data to the extent it is possible and necessary for the purpose of the study.

The boundary towards nature can be difficult to define when the life cycle includes activities that integrate technology and nature, such as agricultural activities and forestry. Soimakallio et al. (2015 and 2016) argue that an ALCA should model land-use as the difference between the actual land-use and a baseline that represents nature. They discuss several different options for baseline. They argue that the most coherent baseline is natural generation, because natural generation is what happens if no further forest or agricultural products are produced. This suggests that ACLCA should model forestry as the difference between the actual, managed forest and a forest that is abandoned to develop on its own. Using natural generation as baseline means that any extraction of biogenic carbon will be accounted for as a reduction in the stock of carbon in the forest. If the wood is used in buildings, most of the carbon will be stored there instead. However, extraction of wood for production of short-lived products, such as packaging or newsprint, will result in a net total reduction in carbon stock and an associated impact on the climate, if the baseline is natural generation. On the other hand, such an ALCA should also account for any increase in the carbon stock that results from continued forestry processes.

Brander (2015 and 2016) agrees that an ALCA needs a baseline and that this baseline should represent nature. However, he questions the arguments and conclusions of Soimakallio et al. Brander emphasises the parallel between ALCA and other accounting systems, for example national carbon accounting, and argues that natural generation cannot be used as baseline in such a system. He claims that a baseline that represents nature should instead be the more or less stable sequestration of carbon that would occur in a natural ecosystem if no forestry or agricultural processes ever took place there. An ALCA of a wood product would then account for the difference in carbon sequestration between the managed forest and a natural forest. This would result in a lower net climate impact of wood products.

The issue has not yet been scientifically resolved. In practice, the baseline in ALCA often does not represent nature. Erlandsson & Zetterberg (2017), for example, use the carbon stock of current forest management as the baseline. If no change in forest management occurs, no change in the average carbon stock occurs. The ALCA of a wood product will not account for any change in carbon storage in the forest. It will, of course, include carbon emissions from machines used in the forestry. On the other hand, Erlandsson & Zetterberg account for temporal storage of carbon in the wood products and an associated reduction in climate impacts.

In BenchValue, we use the defined processes as system boundaries, as described in the chapter on “generic chains”. Hereby upstream processes (material sourcing and pre-manufacturing) are included as far as they are described as such. The extend of modeled processes has to be the same for value chains that are compared to each other (e.g. cement and wood).

8.2 Boundaries between life cycles - allocation

The life cycle also has a system boundary towards other life cycles. Products can flow across this boundary. A life cycle study that includes a flow of products, material or energy from one product system to another, encounters an allocation problem: what part of the environmental impacts of the production of this product, material or energy should be assigned to the product system investigated? An allocation problem can be managed in various ways – individually or in combination (Heimersson et al. 2017):

- by subdivision: reduces the magnitude of the allocation problem by identifying parts or aspects of the system that clearly belong to only one of the functions,
- by system expansion: avoids the problem by expanding the study to include all functions of the system,
- by substitution (often also called system expansion): avoids the problem by expanding the study to include the processes displaced by the other functional output(s) of the system. What to replace depends on what is considered as foreseeable consequences of the studied change within the studied time frame, or
- by partitioning: solves the problem by dividing the potential environmental impacts of the joint processes between the functions of these processes.

ISO 14044 (§4.3.4.2) states that allocation problems should be reduced or avoided when possible. Allocations that cannot be avoided should be solved through partitioning, preferably in a way that reflects how the inputs and outputs of the unit process are changed by a change in the products or functions provided by the system.

The allocation problem might occur because a material is recycled from one product system into another. If the recycling does not affect the inherent properties of the recycled material, ISO 14044 (§4.3.4.3.3) allows for avoiding such allocation problems by modelling the recycling as a closed loop within the investigated product system.

In CLCA, allocation problems are often avoided through substitution (Finnveden et al. 2009), because a CLCA should include the activities that are affected by the production and use of the product, regardless of whether these activities are within or beyond the boundaries of the life cycle. An ALCA, in contrast, includes only activities inside the life cycle. This excludes substitution as way to avoid allocation. Instead, allocation problems are typically solved through subdivision and/or partitioning.

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Appendix I…

Input into discussion document on generic data chains and EPDs

J Goggins, NUI Galway 11 May 2018

Table 1: National EPD organisations

Country	**Organisation**	**Website**
Norway	The Norwegian EPD Foundation (epd-norge)	epd-norge.no
Germany	Intitut Bauen und Umwelt	ibu-epd.com
Netherlands	The Dutch Institute for Building Biology and Ecology (NIBE)	www.nibe.org
Ireland	Irish Green Building Council	www.igbc.ie
UK	BRE	https://www.bre.co.uk/page.jsp?id=3312
France	inies	http://www.inies.fr/le-programme-de-verification/
Sweden	EPD International AB	https://www.environdec.com/

Table 2: Sustainability Indicators used by International Organisations (part 1)

	Environmental indicators					Social Indicators				Economic Indicators		Boundaries
Organisation	**GHG emissions**	**Energy Intensity**	**Material Efficiency**	**EMS**	**WC**	**Injury Frequency rate**	**Employee training**	**New Employee**	**Community involvem**	**R & D**	**Economic value distribut**	
World Steel	X	X	X	X		X	X			X	X	**Cradle - Gate**
(Units)	Tonnes CO_2/ Tonnes of Steel	GJ/ Tonnes of steel	% of raw material used	% registered production		injuries / MHW	training days / employee			% of revenue	% of revenue	
CSI	X	X				X			X			**Cradle - Gate**
(Units)	Tonnes CO_2	MJ/ ton of clinker				LTI / MHW			% of sites with community			
BRMCA	X	X	X	X	X	X	X		X			**Cradle - Gate**
(Units)	kg CO_2/ Tonne of concrete	kWh / tonne of concrete	kg waste to landfill / tonne of concrete	% of production sites covered by a 'UKAS'	litres of water / tonne of	LTI / MHW	% of employees covered by 'UKAS' certified training and evaluation		% of relevant sites that have community liaison activities.			

EMS: Environmental Management System; R&D: Research and Development; LTI: Lost Time Injuries; MHW: Million Hours Worked; WC: Water Consumption; 1 ton = 0.907 tonne

Table 2:Sustainability Indicators used by International Organisations (part 2)

	Environmental indicators					Social Indicators				Economic Indicators		Boundaries
Organisation	**GHG emissions**	**Energy Intensity**	**Material Efficiency**	**EMS**	**WC**	**Injury Frequency rate**	**Employee training**	**New Employees**	**Community involvement**	**R & D**	**Economic value distributed**	
Knauf Insulation	X	X	X		X	X		X		X		**Cradle - Gate**
(Units)	CO_2 Tons / m^3 of	mWh / m^3 of	Tons waste / m^3 of insulation		m^3 water / m^3	LTA / MHW		No. of Employee		€€€€		
UK CARES	X		X	X	X		X		X			**Cradle - Gate**
(Units)	Tonnes CO_2/ Tonnes of Steel		Kg waste (landfill/ incinerated/recycled)/ tonne steel	% employees employed at ISO14001 certificated	m^3 water / tonne of steel		Training hours / employee		Producers who engage with community stakeholders (%)			
EURIMA	X	X			X							**Cradle - Grave**
(Units)	kg CO_2 / m^2 insulation	MJ / m^2 insulation			kg water / m^2 insulation							
EUROGYPSUM	X	X			X							**Cradle - Gate**

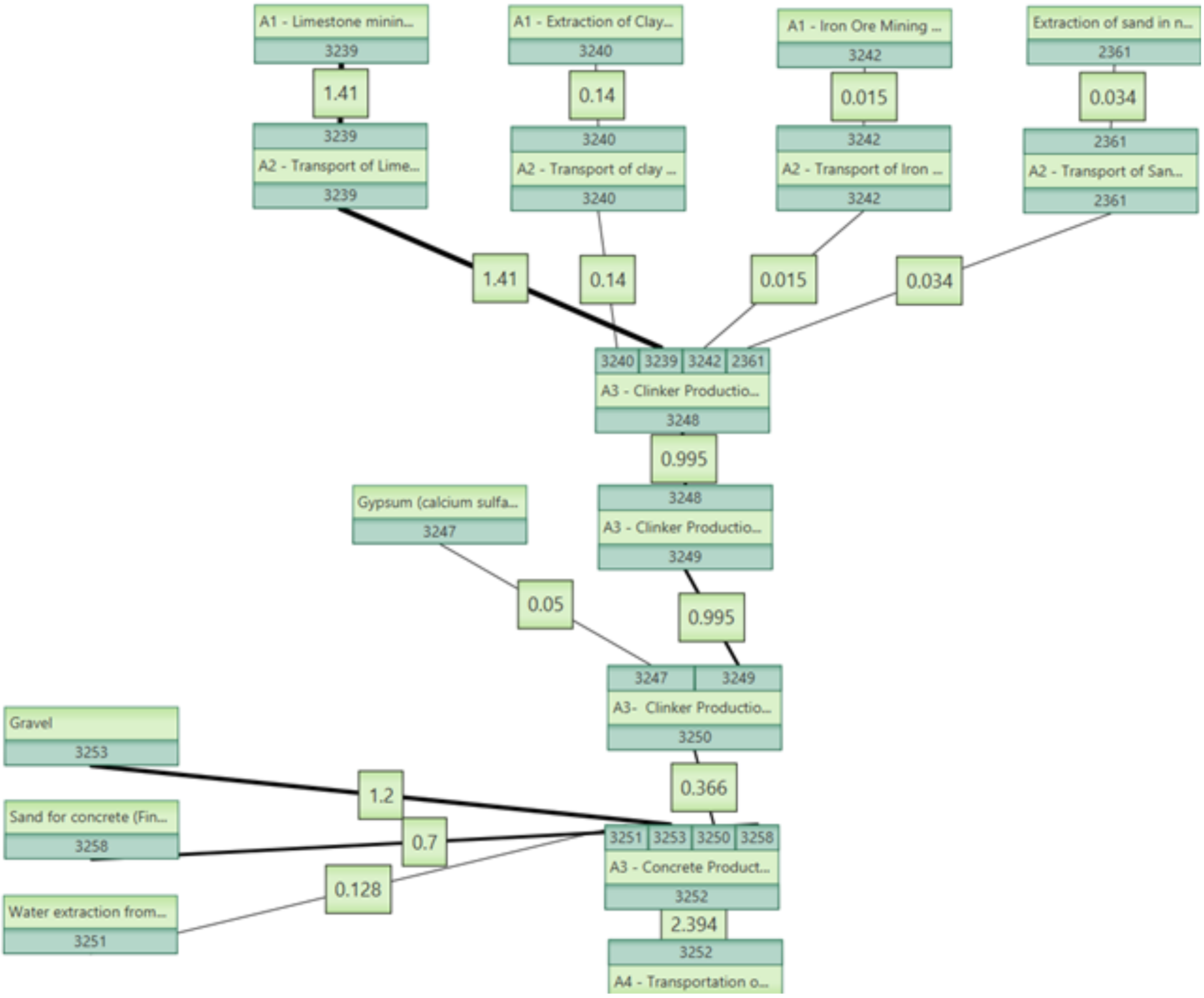
(Units)	kg CO_2 / m^2 plasterboard	MJ / m^2 plasterboard			kg water / m^2							

EMS: Environmental Management System; R&D: Research and Development; LTA: Lost Time Accidents; MHW: Million Hours Worked; WC: Water Consumption;
1 ton = 0.907 tonne

Table 2: Sustainability Indicators used by International Organisations (part 3)

	Environmental indicators					Social Indicators				Economic Indicators		Boundaries
Organisation	**GHG**	**Energy Intensity**	**Material Efficiency**	**EMS**	**WC**	**Injury Frequency**	**Employee training**	**New Employees**	**Community involvement**	**R & D**	**Economic value distributed**	
British Precast	X	X	X	X	X	X	X		X			**Cradle - Gate**
(Units)	kg CO_2 / tonne precast	kWh /tonne precast	kg waste to landfill / tonne of precast	% of produce covered by a	litres water / tonne precast	LTA / MHW	Training hours / employee		% of sites operating local liaison schemes			
Wood for Good	X	X	X		X							**Cradle - Grave**
(Units)	kg CO_2 / m^3 wood	MJ / m^3 wood	kg waste to landfill / m^3 wood		m^3 water / m^3 wood							
Stora Enso	X	X	X		X	X			X			**Cradle - Gate**
(Units)	kg CO_2 / tonne wood	mWh / tonne wood	tonnes of waste to landfill		m^3 water / tonne of wood	LTA / MHW			Community Investment			

EMS: Environmental Management System; R&D: Research and Development; LTA: Lost Time Accidents; MHW: Million Hours Worked; WC: Water Consumption;
1 ton = 0.907 tonne



A1 - Limestone minin...
3239
1.41
3239
A2 - Transport of Lime...
3239
A1 - Extraction of Clay...
3240
0.14
3240
A2 - Transport of clay ...
3240
A1 - Iron Ore Mining ...
3242
0.015
3242
A2 - Transport of Iron ...
3242
Extraction of sand in n...
2361
0.034
2361
A2 - Transport of San...
2361
1.41
0.14
0.015
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3240
3239
3242
2361
A3 - Clinker Productio...
3248
0.995
3248
A3 - Clinker Productio...
3249
Gypsum (calcium sulfa...
3247
0.05
0.995
3247
3249
A3- Clinker Productio...
3250
Gravel
3253
1.2
0.366
Sand for concrete (Fin...
3258
0.7
3251
3253
3250
3258
A3 - Concrete Product...
3252
Water extraction from...
3251
0.128
2.394
3252
A4 - Transportation o...

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