The International Journal of Life Cycle Assessment (2019) 24:129–141
https://doi.org/10.1007/s11367-018-1501-5

ROADWAYS AND INFRASTRUCTURE

Screening LCA of torrent control structures in Austria

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Received: 26 September 2017 / Accepted: 4 July 2018 / Published online: 17 July 2018

Abstract

Purpose The purpose of this article is to find a suitable life cycle assessment (LCA) method to quantify the most important environmental burdens caused by construction processes of torrent control structures. To find these environmental burdens, 17 construction projects of the "Austrian Service for Torrent and Avalanche Control" (WLV) were analyzed using the "cradle to gate with options" LCA methodology (CEN, 2013).

Methods This article explains an LCA methodology for the product stage and the construction process of torrent control structures following existing standards. The iterative approach of LCA methodology (ISO, 2006a) was used to record all important processes of the system and to supplement missing information. The LCA methodology has been developed from existing standards of the construction and product sector. Since the production of some construction materials takes place locally, the generic data, for Austria, was adapted. Wood inherent biogenic carbon and primary energy, used as raw material, are treated as materials inherent properties (CEN, 2014). The contribution of the various processes was reproduced by hotspot.

Results and discussion Hotspots of the different stages are related to the construction materials used. The emissions and primary energy inputs in the product stage are clearly dominated by concrete and steel. If these two materials are used sparingly, the focus is on machine application and transportation. Depending on the selected scenarios, the smallest share of emissions, in relation to the total result of product and construction stage emitted by transport, is 3% and the maximum share is 69%. The greatest environmental impacts in the construction stage are caused by excavation work and transportation on-site. With an average of 4% in the construction stage, the transport of workers to the construction site cannot be neglected as is done in the building sector.

Conclusions The conclusion of this study is that existing LCA models can be adapted to protective structures. In contrast to conventional buildings, the construction process and transportation are much more important and cannot be neglected. Shifting the hotspots to these processes requires specific calculation rules for that particular field. There is still a need for research to find a suitable functional unit and to develop a methodology for the use and end of life stage of these structures.

Keywords Civil engineering · Hotspot analysis · Screening LCA · System boundary · Life cycle engineering · Torrent control structures

Responsible editor: Alexander Passer

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11367-018-1501-5) contains supplementary material, which is available to authorized users.

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1 Introduction

In the period from 2010 to 2014, the "Austrian Service for Torrent and Avalanche Control" (WLV) invested an amount of 1262 million € in the sector of torrent control structures (Sinabell et al. 2009). Aimed at an improvement in efficiency, a structural and task-oriented further development of the WLV organization was completed in 2013. In this way, the provision of protective services in sustainable quality—adapted to the natural environment and to the impacts of climate change, socio-political conditions, and socio-economic developments—should be secured for the future.

The presently used assessment methods considering torrent control projects are only referencing monetary and economic data. For the evaluation of projects, only economic feasibility studies are applied. Therefore, two assessment methods are used: cost benefit studies, for project volumes exceeding one million €, and standardized benefit studies, for lower project volumes (ON 1999). The LCA is the missing link to an ecological way of constructing these structures and should be part of resource-friendly management considering natural resource-saving strategies in the planning and decision process. In other building disciplines, such as building construction, methodologies for LCA have been developed recently (CEN 2011, 2013). The standards provide a subdivision of the building life cycle into four modules (Fig. 1): the product stage, the construction stage, the use stage, and the end of life stage. The study represents the product stage, which includes the raw material supply and the manufacturing of the construction materials, the construction process stage including machine use and transport processes, and the end of life stage for representing material inherent properties.

The building sector provides detailed guidelines for the cumulative energy demand (CED) and global warming potential (GWP_{100}) assessments of buildings. These two indicators are considered as the most frequently used environmental indicators for buildings (Bengstsson and Howard 2010), and their calculation methodology is well established, e.g., IPCC 4th assessment report (Solomon et al. 2007; VDI 2012). Both the CED and the GWP_{100} will be considered in this study.

Seventeen construction projects of the WLV served as a basis for the life cycle inventory. These 17 projects come from all Austrian regional headquarters. The sizes of the projects are different and include several construction types. All input data of the projects are recorded as construction reports. Since this article focuses on the representation of the entire construction project and no comparisons are to be made between the projects, the construction types are not dealt with in more detail. Since there are no specific normative regulations for the calculation of their LCA, the existing standards for LCA methodology (ISO 14040, ISO 14044) and the standards of the construction sector are used and if necessary adapted. These adjustments were identified by the screening LCAs and the iterative process of LCA creation.

The purpose of this study is to examine the applicability of the existing LCA methods of the other building disciplines. There are two important standards, which deal with the assessment of environmental performance of buildings. EN 15978 (CEN 2011) defines the calculation method of construction works and EN 15804 (CEN 2013) the calculation method for construction products. This study applies these standards to the field of torrent control structures to answer following questions:

- Which system boundaries are suitable?
- Which cutoff rules should be set?
- Which data are usable to provide a good data quality?
- Where are the hotspots of the processes?

The study is designed to collect data and analyze processes that are important during the product and construction stage (Fig. 2). The aim is to screen the most important as well as negligible processes as well as system boundaries of these structures. The study is intended as basis for the further development of a methodological approach (cradle to grave) of LCA for torrent control structures and to give planners the possibility to decide how to build torrent control structures, not only on a constructive and monetary but also on an ecological level.

2 Methodology

The methodology is designed according to existing standards for LCA methodology (ISO 14040, ISO 14044) and the standards, which are dealing with the assessment of environmental performance of buildings (EN 15978; EN 15804).

According to ISO 14040, LCA is an iterative method. In the course of the collection of data and information, various aspects of the study framework may require a change to achieve the original goal of the study. Through the collection of data and the subsequent screening LCAs, the system was continually developed to make the LCA as accurate as possible. The following steps describe this development.

The first step was the definition of a functional unit and the system boundary. In the initial iteration, the functional unit was set as the construction project to display the full product system and the system boundary was defined by EN 15978 and EN 15804.

Using the iterative approach (Paratscha et al. 2016), the life cycle inventories of the 17 construction projects were created to find out which databases are usable and which data is missing. The creation of the life cycle inventories started in 2015. At the beginning of the study and in the course of the data collection, it has been shown that the ecoinvent 2.2 database (Frischknecht et al. 2005) provides almost all relevant data for the product stage. It was decided to keep this version of the database for this part of the study to maintain the consistency

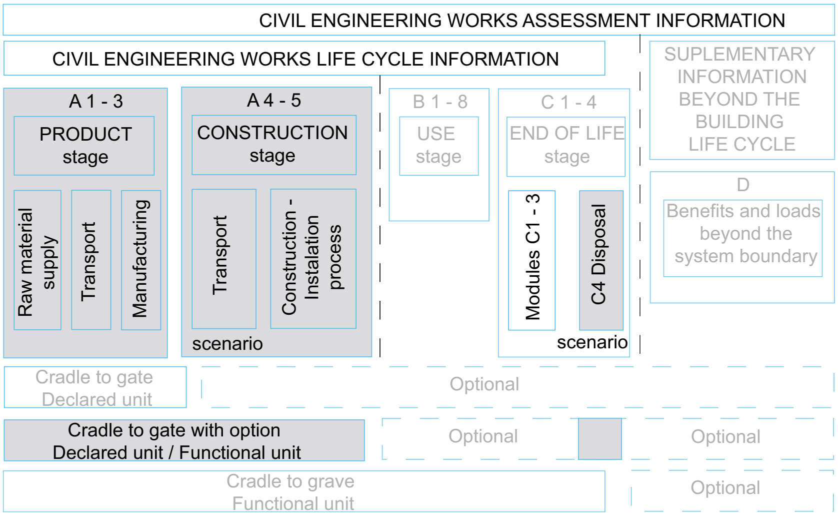


Fig. 1 Description of system boundary according EN 15804 (adapted from CEN (2018b))

of the study. In addition, this database has a very good documentation of the individual processes and flows (Martínez-Rocamora et al. 2016). Some generic data of the various construction machines were missing. In order to solve this problem, the online non-road database tool (FOEN 2017) was used to obtaining the missing data. Fuel consumption and emissions of machines in ecoinvent 2.2 are also calculated on the basis of this data source (Spielmann et al. 2007). In order to adapt to the Austrian context, an Austrian electricity supply mix was used for the production of relevant products. This has been done with products, which, due to their production properties, are forced to be produced in the surroundings (Austria). The construction projects of the WLV are documented with construction reports. These reports only reflect material use, machine use, and on-site processes. The contents of the construction reports are structured according to the Austrian standard ÖNORM B 2061 (ON 1999). Due to this, the information about transportation of materials and machines to the construction site is missing. Therefore, scenarios were developed and evaluated according to EN 15804.

The last step consisted of the life cycle impact assessment which considered the CED and the GWP_{100} for the identification of significant issues. Further impact indicators can be found in Appendix A (Electronic Supplementary Material).

2.1 Functional unit

Each torrent has different characteristics. Accordingly, individual protection measures are required for each project. These protective measures are ensured by different structures made of different materials. This makes it necessary to look at the entire protection system when planning torrent control structures. The complexity of each protection system makes it look different. Due to the individuality and complexity of the protection systems, it is not possible to create a comparative LCA for different protection systems. In the generation of the screening LCAs, the

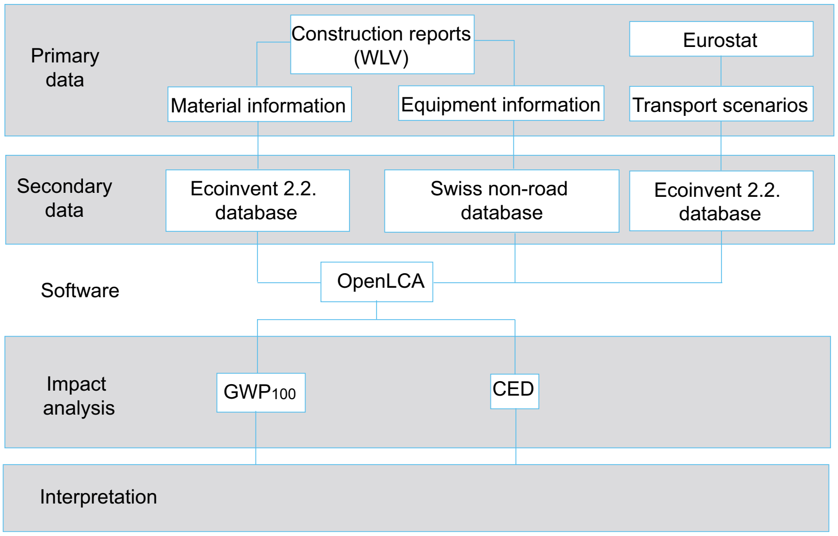


Fig. 2 Data collection framework

entire protection systems were examined with all the structures included. Thus, the functional unit is one protection system.

2.2 System boundary

There are two important standards dealing with the assessment of environmental performance of buildings. EN 15978 (CEN 2011) defines the calculation method of construction works and EN 15804 (CEN 2013) the calculation method for construction products. The framework of this study follows these two standards.

This LCA is to represent the product stage, the construction stage and partially the end of life stage (module A1-A5 + C4) (Fig. 1) of Austrian torrent control structures. This kind of LCA is called "cradle to gate with options" (CEN 2013) in the field of the environmental product declaration (EPD) and is defined in a way that the modules A1–A3 with selected follower modules are included.

2.2.1 The product stage

The modules A1–A3 are made visible in the "cradle to gate" procedure. This procedure is defined in EN 15804. Part of this system is material and energy input as well as manufacturing and transport processes up to the gate. The treatment of waste, resulting from these processes, is also included. The effects and aspects of the production of investment goods (e.g., trucks) are included (CEN 2013).

The data correspond to those of the ecoinvent project (Frischknecht et al. 2005). The ecoinvent project has not set strict quantitative cutoff rules, but environmental knowledge of the people involved in compiling life cycle inventory data is used to judge if data is irrelevant. Estimations and assumptions are defined by ecoinvent, but if data availability is poor, stoichiometric balances are used (Frischknecht et al. 2007a). Most of the used generic data from the ecoinvent database is based on Swiss product systems and processes. Some materials were changed for the application of local conditions. This application should represent the regional system boundary, which is defined for Austria. The modification of the product systems consists in the change of the electricity mix used for the material production. Which materials were changed and a sensitivity analysis can be found in Sect. 4.1.

- Module A1 covers the extraction and processing of raw materials as well as biomass production and processing. The content covers the reuse of products or materials from previous systems. The generation of electricity and heat from primary energy sources, including their extraction, refining, and transport are also included in this module.
- Module A2 includes transport of raw material to the company and internal transport.
- A3 is the module in which the production of the products themselves as well as co-products and the respective packaging is contained. Also included is the production of auxiliaries and supplies or precursors (CEN 2013).

2.2.2 The construction stage

The construction stage (modules A4–A5) covers the processes for the various construction products from the gate of the supplier up to the actual completion of the structure. The effects of the production of investment goods (e.g., trucks, cranes) must be taken into account according to EN 15978 (CEN 2011). *The production of investment goods was excluded in this module since the corresponding data on the various construction machines were not included in the data source used.*

- Module A4 covers the transport of materials and products from the factory to the construction site, including transport, storage, and distribution. The transport of building equipment to the construction site also has to be included (CEN 2013).
- Module A5 contains all construction processes that are carried out on the building site. Examples of this are earthworks, transportation within the building site, installation of the products, and all waste management processes (CEN 2013). According to EN 15978 transportations of persons, to and from the location, do not have to be included in the construction stage. *In this study, they are taken into account in module A5 as they represent a relevant factor in the life cycle assessment.*

2.2.3 The end of life stage

This module was included in the system boundary to correctly display material inherent properties in the product system. In module C4, burdens (e.g., emissions) from waste disposal are considered as part of the product system according to the polluter pays principle. If energy is produced during the waste treatment, such as electricity and heat from waste incineration or from landfill gas, then the potential credits from this usable energy are allocated to module D in the next product system (CEN 2013).

According to EN 15978 (CEN 2011), the end of life of buildings is reached when all components and materials that have to be removed from the site have been removed. The big difference between buildings and torrent control structures is that the torrent control structures have reached their end of life after loss of functionality and then go directly into nature as a landfill. Thus, the material inert CO_2 is returned to the natural cycle and the energy contained in the material is not used any further. This means that the module D (Fig. 2) can be neglected by the missing reuse, and all disposal processes are represented in the system boundary by module C4.

2.3 Data collection

According to ISO 14044, the qualitative and quantitative data that are included in the life cycle inventory must be collected for each process module that is within the system boundary. The data collected either by measurement, calculation, or estimation is used to quantitatively determine the inputs and outputs of a process module. Since the data can originate from different data sources, measures should be taken during data collection to ensure a consistent and conclusive understanding of the product system to be modeled (ISO 2006b).

The basis for the data collection (Fig. 2) consists of the construction reports of the WLV, which provide the primary data for the product systems. In addition to the construction reports, statistical data (Eurostat 2017) was used to define transport distances to the construction site.

The next step was to link the contents of the construction projects with generic data from existing LCA databases. In addition to the ecoinvent database, one more data source had to be used. The data for the construction machinery was generated from the online non-road database (FOEN 2017) for the reference year 2015.

2.3.1 Construction reports

A construction report is a cost calculation for a construction project and is based on calculation rules, which are regulated in the Austrian standard ÖNORM B 2061 (ON 1999). A construction cost calculation is divided into cost groups. These include material costs and equipment costs.

The basis for material costs are the purchase prices either from the delivery point or delivered to construction site, the latter is applied to the analyzed construction reports. Material costs are divided into costs for raw material, auxiliary material, and consumables. The consumables include, e.g., electrical energy, fuels, and lubricants.

The equipment costs are the result of the time required for the supply of the service. In these costs, fuel, lubricants, and transport/removal are already included if they are not stated as material costs.

The total price is obtained by adding up all the item prices. Item prices arise by multiplying the unit price by the quantity of the item. Units of measurement such as m, m^2, m^3, km, to, and h are considered. From this listing, the inventory data for the LCA was filtered out.

2.3.2 Databases

The quality of generic data should be treated in the same way as the other data required for LCAs. In this regard, there is no difference between the use of process-specific data and the use of generic data. In order to select a suitable set of generic data, in the absence of process-specific data, the following aspects should be assessed: representativeness; plausibility, completeness, and consistency and uncertainty (CEN 2010). The following databases have been selected to comply with the requirements of ISO 14044 and CEN/TR 15941.

The ecoinvent database (Frischknecht et al. 2005) was selected for this project because of the documentation quality of the datasets (Martínez-Rocamora et al. 2016). Ecoinvent was developed by the "Swiss Centre for Life Cycle Inventories." Version 2.2 of this database was used. The latest update of the ecoinvent 2.2 database was released in 2010 (Hischier et al. 2010). The ecoinvent 2.2 database includes international industrial life cycle inventory data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services, and transport services. The results of the ecoinvent project are described in several separate reports. These reports describe the methodology and the life cycle inventories and thus contribute to the understanding of all datasets (Frischknecht et al. 2007a).

The online non-road database tool was created by the "Swiss Federal Office for the Environment" (FOEN). The tool provides the necessary data for calculating non-road pollutant emissions and fuel emission in the period from 1980 to 2050, with 2010 as the reference year. The basis of the tool is the non-road database of the FOEN, the structure and methodology of which is documented in the "FOEN Environmental Report No. 1519." The emission calculations for the non-road sector are based on two basic principles. Quantities (stocks and operating hours) and the several emission factors are the basis. The fuel consumption of the non-road sector is calculated according to the same methodology as the pollutant emissions. The consumption factors used for diesel-powered machines are provided by the "Environmental Protection Agency" (EPA 2004; Notter and Schmied 2015).

2.3.3 Adaptation of datasets to compensate differences in local conditions (Switzerland to Austria)

Often, data does not accurately reflect the local conditions. A compensation based on a quantitative empirical basis for local conditions is always the best option. The data should always be documented in the LCA report, and the sensitivity based on these assumptions should be assessed (CEN 2010).

Since the production of some construction materials takes place locally, the dataset, which comes from Switzerland, was adapted for Austria. This application was made by replacing the current electricity supply mix used for the affected processes.

The electricity (medium voltage) used for the production of materials is transported on the high voltage network and transformed to and transported on the medium voltage network. This dataset is used in ecoinvent 2.2 to calculate the electricity supply of industrial processes for example in steel mills, automobile factories, and chemical industries (Frischknecht et al. 2007a).

Table 1 Specification of means of transportation used in the transport scenarios (Spielmann et al. 2007)

Transportation system	Max. weight (KFG) (t)	Average load (t)	Fuel consumption (diesel) (g/km)	
			Full	Empty
Lorry 16 t	18	2.93	200	160
Lorry 28 t	26	5.82	300	200
Lorry 40 t	36	9.68	360	220
Lorry 40 t	40	9.68	360	220
Lorry < 3.5 t	–	0,3	54.9 (diesel) + 32.5 (gasoline)	

For Austria, the operating statistics 2004 (e-control 2005) are used. The used electricity production data is in good agreement with the data from the "International Energy Agency" (IEA) but is 10% higher than that reported in UCTE (Union for the Coordination of the Transmission of Electricity 2005) (Frischknecht et al. 2007b).

For Switzerland, the detailed information of the "Swiss Electricity Statistics" (BFE 2005), the statistics of thermal electricity production (Kaufmann and Gutzwiller 2005), and the statistics of renewable energies (Kaufmann and Rigassi 2005) are used (Frischknecht et al. 2007b).

This information has been applied to the materials produced locally and whose proportion of electricity input is responsible for more than 1% of the GWP_{100}/CED. The percentage of the change in GWP_{100}/CED caused must be at least 1%. These include the products concrete, cement, cement mortar, crushed limestone, crushed gravel, round gravel, sand, mastic asphalt, and grass seed. In order to detect and validate this change, a sensitivity analysis of the 17 case studies was carried out.

2.3.4 Transport scenarios

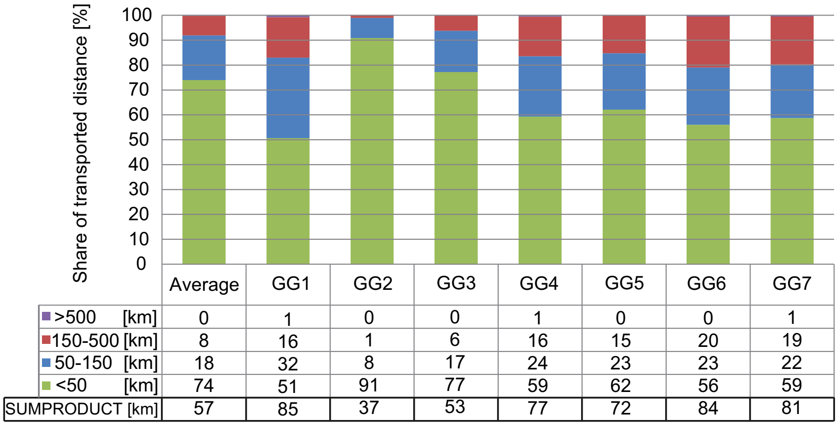
Since the transportations of materials and machines are not specified in the construction reports, four transportation scenarios for all 17 construction projects were developed. In the scenarios, three delivery distances of 30 km, 100 km, and 200 km were assumed. These distances have been used for all materials and machines. In the fourth scenario, the delivery distances were product dependent. The transport scenarios were designed and documented according to EN 15804.

In the development of transport scenarios, five different types of trucks were used (Table 1). If the weight of the cargo was bigger than the average load of the truck, then the next largest truck was used. The information on the trucks and average load comes from the ecoinvent database (Spielmann et al. 2007). In addition, information from the "Austrian Motor Vehicle Act" was collected in order to comply with the local legislation (Motor vehicle law (KFG) BGBl. Nr. 267/1967 §4). The transports were each calculated with an average load and no load.

In scenario 4, statistical data from the "Statistical Office of the European Union" (Eurostat) was used to define realistic distances. The determination of the used transport distances are based on Table D1.1 of the statistics on road transport (Eurostat 2017). Figure 3 shows the proportion of the masses transported annually for different distance classes and groups of goods (GG) for Austria. The groups of goods are derived from the standard goods classification for transport statistics (NST 2007). From the 20 existing product groups, the following were used:

GG 1: Products of agriculture, hunting, and forestry; fish and other fishing products

GG 2: Metal ores and other mining and quarrying products, peat, and uranium and thorium



	Average	GG1	GG2	GG3	GG4	GG5	GG6	GG7
🟪 >500 [km]	0	1	0	0	1	0	0	1
🟥 150-500 [km]	8	16	1	6	16	15	20	19
🟦 50-150 [km]	18	32	8	17	24	23	23	22
🟩 <50 [km]	74	51	91	77	59	62	56	59
SUMPRODUCT [km]	57	85	37	53	77	72	84	81

Fig. 3 Shares of transported weights in relation to the transport distance for each group of goods (GG) (Eurostat 2017) and mean transport distance for each GG in Austria

GG 3: Other non-metallic mineral products
GG 4: Basic metals; fabricated metal products, except machinery and equipment
GG 5: Machinery and equipment
GG 6: Equipment and material utilized in the transport of goods
GG 7: Grouped goods: a mixture of types of goods which are transported together

In order to determine an average transport distance for the groups of goods, the sum product was formed from the data for Austrian domestic transports.

If the weight of the transported materials was not apparent from the construction reports, the densities were taken from the ecoinvent reports (e.g., wood) (Bauer 2007) or assumptions were made (Appendix C, Electronic Supplementary Material).

3 Life cycle impact assessment

3.1 Impact assessment methods and impact categories

The impact assessment methods CED (V.1.0.1) and CML 2001 (Center of Environmental Science of Leiden University) were used in the study. The CED method calculates the total renewable as well as non-renewable primary energy input to represent energy consumption. In this paper, the CED is considered from here on to be an impact category indicator. The indicator is particularly suitable for detecting hotspots and to find potentials for energy savings (VDI 2012). The impact indicator GWP_{100} was selected from the CML 2001 (V.4.4) method. The CML 2001 (V.4.4) is based on the IPCC 2007. The GWP_{100} was selected to show the environmental impact of the emitted greenhouse gas. These two described impact category indicators are most frequently used in the building sector and are therefore part of the evaluation (Bengstsson and Howard 2010).

3.2 Biogenic carbon content and primary energy content

The biogenic carbon content and primary energy content of wood is treated as a material inherent property. The handling of the material inherent properties of wood products is defined in EN 16485 (CEN 2014) and in ISO 21930 (ISO 2017). In the case of wood, the assumption of biogenic carbon neutrality is allowed for wood from countries which have opted to comply with the "Kyoto Protocol" (Art. 3.4) or for wood originating from forests that have the appropriate certification of sustainable forestry (CEN 2014). The biogenic carbon uptake takes place in module A1 as − 1 kg CO_2 and leaves the product system as + 1 kg CO_2 when reaching the end-of-waste status in the module C4. According to ISO 21930, the biogenic carbon flow of 1 kg CO_2 shall be characterized as 1 kg CO_2 eq. in the LCIA. Over the entire life cycle (A1-C4), biogenic carbon flows should result in zero net contribution to the GWP. This was followed in the study.

This concept is also applied to the primary energy content of wood. Solar energy, which is necessary for photosynthesis to grow the tree is included in the calculation in the module A1 and is leaving the product system in the module C4. Thus, the biogenic primary energy content of wood also results in zero net contribution to the CED. The renewable primary energy

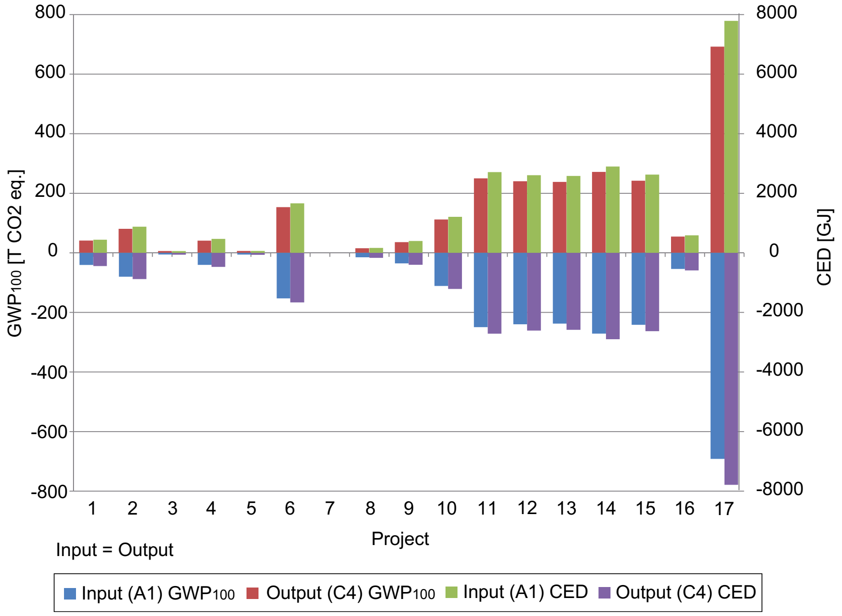
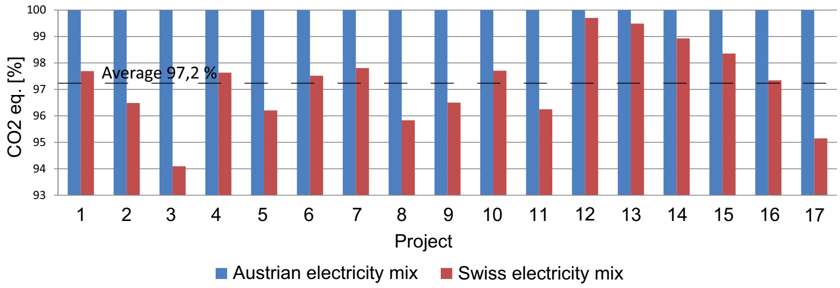


Fig. 4 Material inherent properties of wooden material used in the construction projects (A1 and C4)

Fig. 5 Sensitivity analysis of Austrian and Swiss electricity supply mix used in each project concerning GWP$_{100}$



consumption of wood material was reported separately (CEN 2014; ISO 2017; Rüter and Kreißig 2007).

All processes involved in forestry operations on wood production are part of the product system and are considered accordingly. The absolute results for material inherent properties of used wood material are shown in Fig. 4. The impacts of forestry operations and the material inherent properties can be found in Appendix B (Electronic Supplementary Material).

4 Results

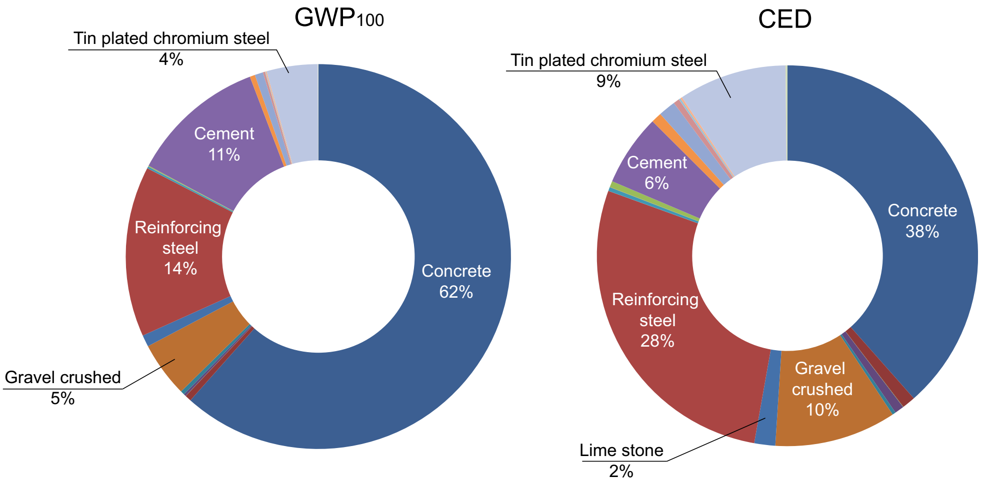
The following results focus on the hotspots of the analyzed projects. For this reason, the relative results are shown and discussed. The absolute results can be found in Appendix A (Electronic Supplementary Material) and the inputs of the projects in Appendix B (Electronic Supplementary Material).

4.1 Application of Austrian electricity supply mix

The electricity supply mix was exchanged as described in Sect. 2.3.3. The sensitivity analysis shows that the GWP$_{100}$ of the 17 projects increases between 5.9% (project 3) and 0.3% (project 12) by application of the Austrian electricity supply mix (Fig. 5). With an average change of 2.8% of the total result, the change appears to be justified (CEN 2013). The different results are obtained by the various proportions of the materials used. The effects of exchange are mainly apparent in the product stage. The difference in the construction stage arises only when electricity consumption is stated on the construction site. Due to the higher proportion of fossil fuels used for energy production, it can be expected that the Austrian electricity mix will emit three times more emissions than the Swiss electricity mix (Frischknecht et al. 2007b). It must be added that the environmental impact of radioactive material, which would show the disadvantages of the Swiss electricity supply mix is not included in this study. Figure 5 shows the change in the results for the GWP$_{100}$ impact category. The impact category GWP$_{100}$ was chosen for the representation since in this category the larger differences are determined.

It can be assumed that the differences have become smaller because ecoinvent 2.2 uses the electricity mix of 2005 and the share of renewable energy in Austrian gross domestic consumption rose from 20.6% (2005) to 30.2% (2014) (BMWFW 2017). As a result, a kWh electricity medium voltage produced in Austria in the year 2014 accounts for 0.0892 kg CO_2 eq. better than the one from 2005 (Treyer, K., electricity, medium voltage, AT, cutoff U, ecoinvent database version 3.4). A sensitivity analysis has shown that the GWP can be reduced by an average of 0.9% by applying the electricity supply mix of 2014.

Fig. 6 Shares (> 1%) of emissions and energy consumption caused by material production in relation to the overall result of the product stage (A1–A3)



4.2 Hotspots in the product stage (A1–A3)

Twenty-five construction materials were used in the 17 construction projects analyzed. The product stage (A1–A3) includes raw material supply, transportation to the company, and production of construction materials. In the overall survey of the product stage (Fig. 6), it was found that construction materials used for concrete structures (concrete, reinforcing steel, cement) represent almost 87% of the GWP_{100}, thus representing the main share of emissions of the product stage. These materials also require the majority (72%) of the required production energy for construction products. The different performance of GWP_{100} and CED of some materials is caused by the use of renewable energy sources with low emissions. This can be caused, e.g., by the direct use of hydropower.

4.3 Transport (A4)

Within the transport module, it is possible to differentiate between material and machine transportation (machines and containers). Depending on the quantity of materials delivered, the share of machine transportation varies. For large construction projects, this share is only small but can account for up to 20% of the transportations for small construction projects.

The composition of the scenarios with respect to transport and transport distances has already been explained in Sect. 2.3.4. Scenario 1 was calculated with an average transport distance of 30 km for all transports to the construction site. In scenario 2, the different average distances of the eurostat statistics were used, and in scenarios 3 and 4, the average distances were 100 and 200 km, respectively.

Figure 7 shows that the variation within the scenario results is very wide because of the different sizes of the analyzed construction projects. The share of the transport module (A4) in relation to the total result (A1–A5) of the various construction sites in scenario 1 can be between 3 and 25%. In contrast, the proportion of the transport module in scenario 4 in relation to the total result of the various construction sites is already between 16 and 69%. Scenario 4 shows the extent of the impact of large transport distances and that transport is an important factor in planning. Scenario 2 provides a way to capture the various delivery distances of the different materials. By using statistical data from eurostat, it is possible to depict the model as realistically as possible.

4.4 Hotspots in the construction process stage (A5)

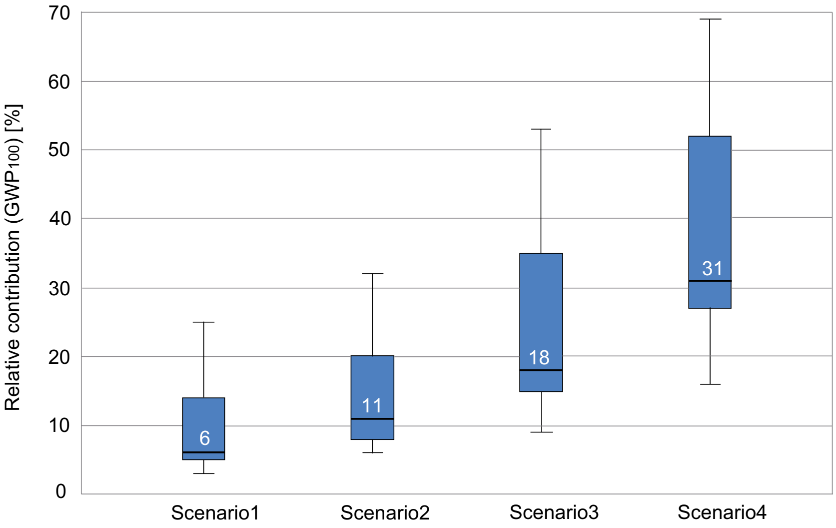
In the construction process stage, 13 construction machines and a variety of means of transport for on-site purposes were modeled. The electricity consumption of the construction site operation is also included.

The hotspots of this module (Fig. 8) are concentrating on excavation work and on-site transportations. The excavation is performed by crawler excavators, spider excavators, wheel roaders, and dumpers and is responsible for almost 42% of GWP_{100} and 39% of the energy consumption in this module. These machines are also used for lifting and transporting heavy loads. By moving huge earth masses, many on-site transports (by lorry 20–28 t) are necessary. These transports account for 19% of the emissions in the construction stage and together with the excavation work account for 60%.

Small appliances such as pumps, compressors, and generators cover the remaining percentage. These machines, which are essential for the construction process, account for a considerable share of 29% (GWP_{100}) and 30% (CED) of this module, respectively. By assuming that these machines are running 8 h a day, the result can be seen as a maximum value.

An interesting result is that the transportation of the workers to the construction site with passenger car or

Fig. 7 Share of the transport module (A4) in relation to the overall GWP_{100} result (A1–A5) of the various construction sites concerning scenarios (median, upper and lower quartiles, maximum and minimum)



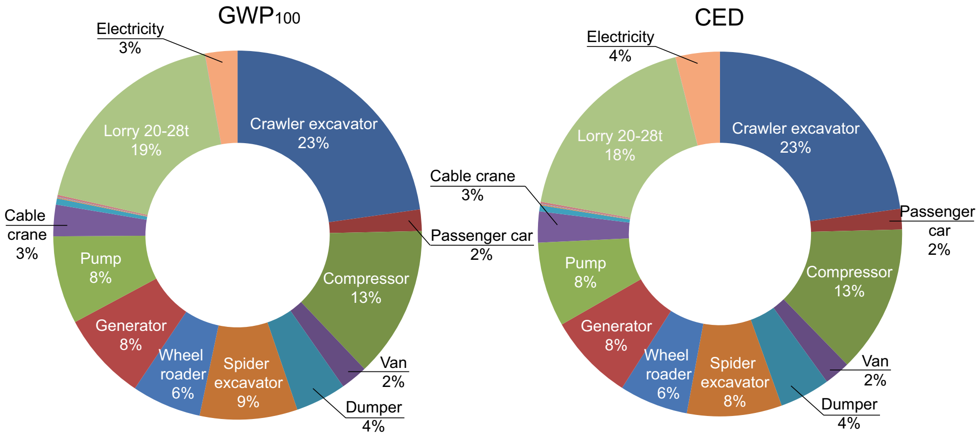


Fig. 8 Shares (> 1%) of emissions and energy consumption caused by construction processes in relation to the overall result of the construction process stage (A5)

van accounts for 4% of GWP_{100} and CED of the construction stage (A4–A5). This finding clarifies that, contrary to the requirements of EN 15978, this transport is not negligible.

Since the construction sites are very different, as already mentioned, the results of the individual construction sites also show great discrepancies (Appendix B, Electronic Supplementary Material). The properties of the construction materials used are the main cause of the discrepancies. The more wood, gravel, or stone is installed, the greater the share of transport and machine use. This correlation can be seen by comparing Fig. 9 with Fig. 10.

4.5 Overall result

Figure 9 shows the contribution of the various modules to the overall results of the projects. Using different construction materials and construction types, the results are quite different and not comparable. Figure 5 shows the material inherent properties of the wooden construction materials. From this figure, the amount of wood that was used in the several projects can be deduced. Because wood requires almost no energy or causes almost no emissions in production, the proportions of the modules shift accordingly. This shift also effects other construction materials, such as lime stone and gravel (compare Fig. 9 with Fig. 10).

Since these materials do not require energy intensive production and thus cause fewer emissions, the influence of the product stage is less pronounced. Due to the high densities of these materials, the transport becomes correspondingly energy intensive in contrast to the production. In the case of materials such as concrete and steel, this effect is reversed and the product stage thus gains in influence.

A further material specific dependency of the transport is to be found in the transport distance. As described in Sect. 2.3.4, different statistic-based delivery distances for the various

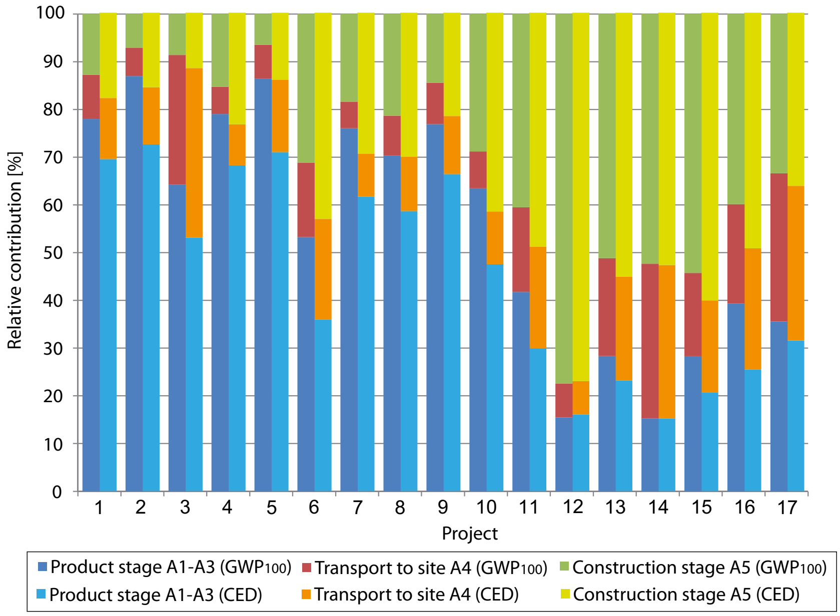


Fig. 9 Shares of product stage (A1–A3), transports to the construction site (A4) and construction process stage (A5) in relation to the overall results of the various projects concerning GWP_{100} and CED (material inherent properties are excluded)

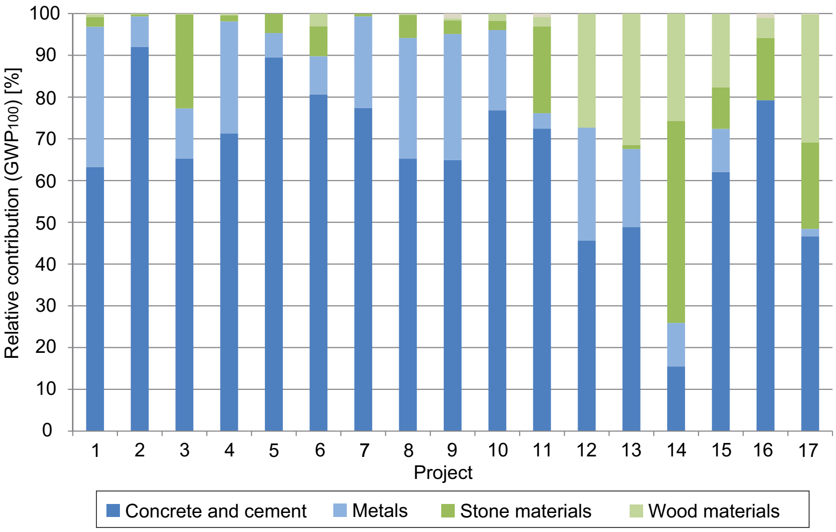


Fig. 10 Shares of emissions caused by material classes in relation to the overall results of the product stage (A1–A3) of the various construction sites

construction materials were determined in module A4. The above described behavior is diminished by the various distances, since stones and gravel are supplied from shorter distances than, e.g., metals.

The different properties of each project make it impossible to compare whole projects. In order to make a project comparable, it will be necessary to concentrate on individual construction types. This in turn means that construction specific functional units are necessary.

5 Discussion

LCA studies in the field of torrent and avalanche control are very rare. For this reason, this screening study was carried out. The study focuses on establishing system boundaries, identifying cutoff criteria and workable data sources as well as process hotspots.

One of the few examples of LCA in the field of torrent and avalanche control provides the study of Noda (Noda et al. 2014). Noda describes in its publication the LCA of three different types of check dam. Since these structures are not identical to those of this study and a different functional unit and database is used, the results are not directly comparable. In addition, transport processes to the construction site were completely neglected. However, what does show parallels is the share of product and construction process stage in relation to the overall emissions. According to Noda, 90% of CO_2 emission of the concrete structure is emitted in the product stage. This statement can be confirmed by this study. In its timber construction, 75% of CO2 emissions are caused by the production of construction materials. In this study, this is much less, because the emission factors of wood are different.

Since the beginning of this study (2015) and the publication, the databases have evolved. Not only the electricity supply mix but also the data basis for construction materials has improved. To illustrate this development, the study-relevant datasets from ecoinvent 2.2 and ecoinvent 3.4 with the "Allocation, cut-off by classification system model (Wernet et al. 2016) were compared in Table S7 (Appendix B, Electronic Supplementary Material). Here are to observe greater differences in the data sets of concrete and reinforcing steel. For concrete, the difference is mainly due to the different compositions. In the 2.2 version, 300 kg cement is contained in a m^3 concrete and in the 3.4 version already 355 kg. From the construction reports, there was no information on the concrete quality so the original dataset from ecoinvent 2.2 was used. The effect of the different composition of ready-mixed concrete was investigated by Passer et al. (2018). In the case of reinforcing steel, ecoinvent 3.4 changed the production location of European steel from Europe to global. By this change, LCA results of steel are much worse though the composition has not changed. Due to the different inventories, a direct comparison is difficult. However, the direct comparison of the electricity mixes as in Sect. 4.1 is easier. The sensitivity analysis shows that the results are improved by a maximum of 1.95% and a minimum of 0.17% by the newer electricity mix.

The study made visible that the transport of materials and machines to the construction site can be an important factor. The change from scenario 2 to scenario 3 already results in an average increase of 16% of the total output of the individual construction sites. It has also been found that this process is one of the biggest uncertainties. In order to reduce or even eliminate this uncertainty, care must be taken in the future preparation of such LCAs that transport distances be well documented.

By transferring the real world in LCA outcomes, there is always a certain amount of uncertainty and variability. Uncertainties in LCA can be in parameter uncertainty, model uncertainty and uncertainty due to choices. Variability covers spatial variability, temporal variability, and variability between objects and sources (Huijbregts 1998). This study should help to identify and minimize these. By knowledge of uncertainty factors and process hotspots, these can be treated in advance in future studies and thus minimized or specified by the methods proposed by Huijbregts.

6 Conclusions

The focus of this article is on the analysis of the potential environmental impacts of the construction of torrent control structures. In the study, a method for calculating the impacts of the product stage and the construction stage are demonstrated. This method was developed on the basis of existing standards and databases. It is shown where the environmental hotspots and thus associated savings in these special structures are.

The emissions and energy inputs in the product stage are clearly dominated by concrete and steel. Saving potentials can be found in the production of these materials or even in their substitution. The application of the Austrian electricity supply mix appears to be meaningful since this has resulted in an average change of 2.8% of the total result and is therefore not insignificant. Further studies should use the version 3.4 of ecoinvent. Version 3.4 provides updated datasets and allows a more precise modeling of the materials concrete and steel by minimizing uncertainties. This screening study has mainly dealt with the impact categories GWP_{100} and CED. In Table 4, other impact categories have been presented, which correspond to the required categories of the current standardization (CEN 2013). This should be done to avoid a one-sided presentation of the results. It has to be mentioned that the EN 15804 is currently being revised and that further impact indicators will have to be evaluated in the future if the standard draft (CEN 2018a) is implemented in the current way. In addition, the separate specification of biogenic GWP would become mandatory.

The uncertainty in the calculation of the transport distances to the construction site is relatively large since no records are available and the assumed distances are based on statistical values or assumptions. Usually, transportations of materials to the construction site is not taken into account in the LCA of conventional buildings (EN ISO 15804). Due to the considerable influence of this service (with scenario 2 12% of all emissions) on the overall result, it must not be neglected. When using materials obtained from stone, special attention is paid to short transport distances. By recording the real transport distances, a more precise evaluation and the resulting optimization measures would be possible.

Concerning the construction stage, it should be noted that excavation work is responsible for most of the emissions. The on-site transports are also responsible for a substantial share of the overall emissions. An interesting detail that is neglected in existing standards and calculations is the transport of the workers to the construction site. As these transports account for an average of 4% of the overall result, they must not be neglected and thus represent an optimization potential.

Due to the differences between conventional buildings and torrent control structures, other processes are becoming more important. The biggest difference is that torrent control structures are hard to compare and do not need any energy for their operation. As a result, the construction stage gains in importance. Due to this difference, the focus of the calculation falls on the construction stage and requires other rules of calculation.

7 Future work

This study should clarify how the product and construction stage have to be treated according to the standards and where the hotspots and uncertainties of this process can be found. The future focus will be on the remaining stages of the life cycle. In order to be able to depict the entire life cycle, use and end of life stages have to be further investigated.

In order to achieve comparability between the construction projects, a consideration of the individual structures and of the specific functions seems to make sense. In future studies, the definition of a functional unit, which makes it possible to compare variants of a protective system, is essential.

The future goal must be to develop a calculation model for protective structures and, subsequently, for the field of civil engineering works. This calculation model is intended to provide an opportunity to quickly and easily visualize the environmental impacts of these structures, enabling decision makers to assess and take into account the environmental impacts of the entire life cycle.

Acknowledgements Open access funding provided by University of Natural Resources and Life Sciences Vienna (BOKU). This study is part of the Austrian Climate Research Program (ACRP) created by the Climate and Energy Fund which made this research project possible. The WLV is also an important partner because of their know-how and the delivery of field data.

References

Bauer C (2007) Holzenergie—final report ecoinvent No. 6-IX. Swiss Centre for Life Cycle Inventories, Dübendorf

Bengstsson J, Howard N (2010) A life cycle impact assessment—part 1: classification and characterisation. Building Products Innovation Council, Sidney

BFE (2005) Schweizerische Elektrizitätsstatistik 2004. Bern

BMWFW (2017) Energiestatus 2016, Bundesministerium für Wissenschaft, Forschung und Wirtschaft edn., Vienna

CEN (2010) CEN/TR 15941:2010—sustainability of construction works—environmental product declarations—methodology for selection and use of generic data. European Committee for Standardisation (CEN), Brussels

CEN (2011) EN 15978: 2011 11—sustainability of construction works—assessment of environmental performance of buildings—calculation method. European Committee for Standardisation (CEN), Brussels

CEN (2013) EN 15804:2012+A1:2013-11—sustainability of construction works - environmental product declarations—core rules for the product category of construction products. European Committee for Standardisation (CEN), Brussels

CEN (2014) EN 16485:2014-03—round and sawn timber—environmental product declarations—product category rules for wood and wood-based products for use in construction. European Committee for Standardisation (CEN), Brussels

CEN (2018a) Draft EN 15804:2012+A1:2013prA2—sustainability of construction works—environmental product declarations—core rules for the product category of construction products. European Committee for Standardisation (CEN), Brussels

CEN (2018b) EN 15643-5:2018 05 01 Sustainability of construction works—sustainability assessment of buildings and civil engineering works. European Committee for Standardisation (CEN), Brussels

e-control (2005) Erzeugung elektrischer Energie in Österreich nach Energieträgern: Gesamte Elektrizitätsversorgung Kalenderjahr 2005. Vienna

EPA (2004) Exhaust and crankcase emission factors for nonroad engine modeling—compression-ignition. Washington, DC

Eurostat (2017) Annual road freight transport, by type of goods and type of transport (1 000 t, Mio Tkm), from 2008 onwards [road_go_ta_tg]. http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=road_go_ta_tg&lang=en. Accessed 20 Feb 2017

FOEN (2017) Non Rooad Database. https://www.bafu.admin.ch/bafu/en/home/topics/air/state/non-road-datenbank.html. Accessed 16 March 2017

Frischknecht R et al (2005) The ecoinvent database: overview and methodological framework. Int J Life Cycle Assess 10:3–9

Frischknecht R et al (2007a) Overview and methodology. Ecoinvent report no. 1., Swiss Centre for Life Cycle Inventories edn., Dübendorf, Switzerland

Frischknecht R, Tuchschmid M, Faist Emmeneger M, Bauer C, Dones R (2007b) Strommix und Stromnetz. In: Dones R (ed) Sachbilanzen von Energiesystemen: Grundlagen für den ökologischen Vergleich von Energiesystemen und den Einbezug von Energiesystemen in Ökobilanzen für die Schweiz. ecoinvent report No. 6, v2.0., Paul Scherrer Institut Villigen, Swiss Centre for Life Cycle Inventories edn., Duebendorf, Switzerland

Hischier R et al (2010) Implementation of life cycle impact assessment methods. Ecoinvent report no. 3, v2.2. Dübendorf, Switzerland

Huijbregts MAJ (1998) Application of uncertainty and variability in LCA. Int J Life Cycle Assess 3:273–280

ISO (2006a) Environmental management—life cycle assessment—principles and framework vol ISO 14040:2006. International Organization for Standardization (ISO), Geneva

ISO (2006b) Environmental management—life cycle assessment—requirements and guidelines vol ISO 14044: 2006. International Organization for Standardization (ISO), Geneva

ISO (2017) Sustainability in buildings and civil engineering works—core rules for environmental product declarations of construction products and services vol ISO 21930:2017. International Organization for Standardization (ISO), Geneva

Kaufmann U, Gutzwiller S (2005) Thermische Stromproduktion inklusive Wärmekraftkopplung (WKK) in der Schweiz 1990 bis 2004. Bern, Switzerland

Kaufmann U, Rigassi R (2005) Schweizerische Statistik der erneuerbaren Energien 2004. Bern

Martínez-Rocamora A, Solís-Guzmán J, Marrero M (2016) LCA databases focused on construction materials: a review. Renew Sustain Energy Rev 58:565–573. https://doi.org/10.1016/j.rser.2015.12.243

Noda R, Kayo C, Sasaki T, Takaoku S (2014) Evaluation of CO2 emissions reductions by timber check dams and their economic effectiveness. J Wood Sci 60:461–472

Notter B, Schmied M (2015) Energieverbrauch und Schadstoffemissionen des Non-road-Sektors. Bern, Switzerland

NST (2007) Classification system for transport statistics (NST 2007). United Nations Economic Commission for Europe, Geneva, Switzerland

ON (1999) ÖNORM B 2061: 1999 09 01—determination of price in building and construction—general principles. Austia Standards Institute, Vienna

Paratscha R, Smutny R, Von der Thannen A, Hörbinger S, Rauch HP, Strauss A (2016) Development of a methodology for environmental life cycle assessment of alpine protective structures. IALCCE, Delft

Passer A, Deutsch R, Scherz M (2018) Beton-LCA-Wie grün ist grau? Paper presented at the Baukongrss 2018, Vienna, Austria

Rüter S, Kreißig J (2007) Grunddatensätze für Holz und Holzwerkstoffe im Netzwerk Lebenszyklusdaten Karlsruhe, Germany

Sinabell F, Fritz O, Puwein W, Streicher G (2009) Eine volkswirtschaftliche Analyse der Wildbach- und Lawinenverbauung. Österreichisches Institut für Wirtschaftsforschung

Solomon S et al (2007) IPCC: climate change 2007: the physical science basis. Cambridge, United Kingdom and New York, NY, USA

Spielmann M, Bauer C, Dones R, Tuchschmid M (2007) Transport Services. ecoinvent report No. 14. Dübendorf, Switzerland

VDI (2012) Cumulative energy demand - terms, definitions, methods of calculation (VDI-Richtlinien 4600). Verein Deutscher Ingenieure, Düsseldorf

Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21:1218–1230