ETSI

BRIDGE LIFE CYCLE OPTIMISATION

ETSI Stage 3

Task group 4:
Life Cycle Assessment of Bridges

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Preface

This is the final report from the work by Task Group 4 in the ETSI-III (Bridge Life Cycle Optimization – Stage 3) project, where the focus has been the examination of environmental effects of bridges, with development of the *BridgeLCA* tool for life cycle assessment (LCA) of road bridges.

The work in ETSI-III builds upon earlier work in ETSI-II (Stage 2). In this earlier work, the aim was to develop a package of web-based versions of tools for calculations of life cycle costing (LCC), life cycle assessment (LCA) and life cycle aesthetics of road bridges, i.e. analysing the economic, environmental and aesthetic performance of road bridge designs. The LCC and LCA tools where in Stage 2 written in Matlab codes, and the intention was to refine these tools in Stage 3, towards an integrated web-based solution. However, as it turned out that the server and Matlab code system for such a solution was very unstable, and it would require resources far beyond what was available in the ETSI Stage 3 funding, it was during the work process decided to develop EXCEL-based standalone and independent tools for all three parts of the project.

On these premises our current deliverable to the project, *BridgeLCA*, is an EXCEL-based standalone tool for life cycle assessment of road bridges. The tool is developed according to state-of-the-art LCA methodology, where there has actually been significant progress in proposing international standardized methods during the last few years (after ETSI Stage 2 ended). The tool also refers to the standard road bridge definition, which was agreed upon among the ETSI partners, and which is outlined in Section 3.2 of the LCC chapter in this report.

Professor Helge Brattebø at the Norwegian University of Science and Technology has coordinated the work in Task Group 4, and the work has been carried out as a close collaboration with research assistant Marte Reenaas and PhD student Johanne Hammervold, both at NTNU, and in dialogue and with inputs from environmental specialist Linda Høibye at COWI Denmark.

From September 2011 NTNU has subcontracted Rambøll Norge for assistance on developing the final version and documentation of the *BridgeLCA* tool, since Marte Reenaas during 2011 started to work as a consultant engineer at Rambøll Norge, in Trondheim. During the course of the project we have had several inputs and a fruitful discussions also with the other partners in the ETSI project, in particular with Otto Kleppe and Marianne Hvaal Larsen at the Norwegian National Road Administration. I hereby express my deep gratitude to everybody who contributed to this work, in particular to Marte Reenaas who has done a large share of the work during the course of this project, and to Johanne Hammervold who was instrumental in the early phase of the work, including developing good links to the national road administration.

This report gives an overview of the LCA methodology, a brief reference to LCA studies of bridges in literature, and an introduction to the structure and application of *BridgeLCA* as a tool for environmental assessment of road bridges.

Trondheim, 2nd May 2012

H. Brattebø

Professor Helge Brattebø

Acronyms and notations

Acronyms[1]

AP	Acidification potential
BridgeLCA	Name of the LCA tool for environmental life cycle assessment of road bridges
EOL	End of life
EP	Eutrophication potential
ET	Ecotoxicity potential
ETSI	Bridge Life Optimisation project
FD	Fossil depletion potential
GWP	Global warming potential
HTC	Human toxicity potential – cancer
HTNC	Human toxicity potential – non cancer
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCC	Life cycle costing
LCP	Life cycle plan
ODP	Ozone depletion potential
OM&R	Operation, Maintenance & Repair
TG1, TG2, TG3,…	The ETSI project is performed within different sub-projects, and different task-groups are responsible. TG3 is responsible for the LCC subproject and TG4 for the LCA project.

Upper case roman letters[1] (quantities)

ADT	Average daily traffic/(vehicle/day)

Lower case roman letters[1] (quantities)

e_{ij}	Amount of substance or stressor *j* (e.g. CH_4, in kg) caused by the total consumption of input resource *i* (e.g. concrete)
x_i	Consumption of resource *i* (concrete, in kg)
f_{ij}	Emission of substance *j* per unit of resource *i* (e.g. kg CH_4 per kg concrete)
d_k	Total potential impact in environmental category *k*
c_{jk}	Characterization factor for substance *j* with respect to impact category *k*
m_k	Per capita normalized potential impact of environmental category *k*
n_k	Normalization factor for category *k*
w_k	Weighting factor of environmental impact category *k*
v	Weighted single score LCA result

[1] Acronyms should according to ISO be written in Romans style (upright). Quantities, always including a unit, should be written in italic (sloping style).

1 What is Bridge Life Cycle Assessment

1.1 General

The environmental effects of road projects, including the location and design of road elements such as bridges, have played an important role in road planning in many decades, however, this focus has more or less exclusively covered local environmental impacts, as part of Environmental Impact Assessment (EIA) documentation in the early-phase planning of road projects. Due to the increasing focus on life cycle environmental impacts (including global environmental problems such as climate change, ozone depletion or scarce resources, and regional problems such as acidification, eutrophication and toxicity), this (traditional) scope on local environmental impacts of road and bridge projects had to be extended by a more systems-based philosophy and life cycle assessment (LCA) calculation approach.

A bridge life cycle assessment is, as indicated above, a calculation methodology and a life cycle thinking concept, where all potential environmental impacts of a given bridge project are quantitatively determined, regardless of where they occur, and which also includes the whole service life of the bridge and the life cycle of bridge materials and energy inputs. The aim of a bridge LCA is to try to quantify, as good as possible, likely impacts of a given bridge design, taking into account a large number of environmental impact categories (types of problems), according to an internationally standardized methodology. We will come back to this in more detail later. After such a quantification it should be possible to understand better what are the important elements of a bridge system that contribute to critical environmental impacts, which one of course would like to reduce as much as possible, and which can (only) be influenced by an environmentally-motivated better bridge design or location. In reality, however, it is important to note that such environmental qualities of a bridge design will have to be evaluated in parallel to the life cycle costing qualities and the life cycle aesthetic qualities of the bridge. Hence, there is of course a trade-off between such bridge qualities.

This report on LCA is a part of the ETSI project. ETSI is interpreted as bridge life cycle optimisation. This term is of course very general, but within the project it has been decided that only the situation when a new bridge is to be built, is studied. The tools developed are thus only suitable at this stage, where costs, environmental, aesthetical and cultural values are compared and the "best" bridge is to be sorted out at the early design stage.

1.2 Life Cycle Assessment and BMS

Life cycle assessment, LCA, is a technique that enables comparative environmental assessments to be made over a specified period of time, taking into account a predefined selection of environmental factors. The methodology takes into account all phases of a bridge life cycle system; including i) production of bridge materials and components, ii) transportation to the bridge site and construction of the bridge, iii) operation, maintenance and repair (OM&R) during the bridge's service life, and iv) end-of-life (EOL) demolition and waste disposal and materials recycling.

LCA can be one important tool in a bridge management system (BMS), and although this is not at all common practice today we believe that LCA will gain much interest in future. Such LCA methods may differ in scope and depth; depending upon what planning phase it is used in and for what purpose. LCA methods are required in order to quantify the whole life cycle energy consumption and the carbon footprint, for which there is already today a practical demand. Moreover, LCA is also needed in order to verify other environmental impacts of a bridge.

As outlined earlier in this report, in the life cycle costing (LCC) chapter, a bridge management system (BMS) is usually divided into the country or county level, the road network level, and the project level (which usually is interpreted as a BMS for individual bridges). Similar to what is needed for LCC calculations, there has to be a close interaction between bridge LCA and BMS, because much of the information needed is the same. This would include information related to: i) the definition of the bridge, its parts, elements, details and equipment with measures and quantities, ii) planned operations, maintenance and repair (OM&R) measures for the bridge parts and elements, iii) planned information on the use of the bridge like the amount and type of traffic flow, and iv) a planned demolition scheme.

As for LCC, such information could be collected in a 'Life cycle plan' (LCP), and this plan is then the basis for how to calculate the inputs of physical resources (materials and energy carriers) that become a direct consequence of activities during the service life of a bridge.

1.3 LCA tools

There are numerous LCA tools available internationally, and they are used for a large number of applications and purposes, in various sectors (industrial and governmental) and in research. A common observation is that current LCA tools are not at all specifically developed for road infrastructure; hence, one has to rely on the use and adaptation of generic, commercially available and very often complex LCA software packages. An LCA is traditionally therefore work for LCA experts only. In the ETSI project, the Norwegian University of Science and Technology (NTNU) has developed an EXCEL-based LCA tool – *BridgeLCA* – which a bridge design team with some environmental competence included should be able to use without a long learning transition phase on LCA theory or methodology. The tool will be described later, but first it is necessary to give an introduction to the LCA methodology and the literature on LCA of bridges.

2 Methodology for LCA calculation

2.1 General principles and structure of LCA

According to ISO 14040:2006, *LCA* is defined as 'compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle'. The *life cycle* is defined as 'consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal' and a *product* is defined as any goods or service. For the ETSI purpose of a road bridge design, the bridge at a given location, serving a given traffic over a given service life, is the obvious product to study.

LCA considers the entire life cycle of a product, from raw material extraction through energy and material production and manufacturing, to use of the product and end-of-life treatment and final disposal. Through such a systematic overview and perspective, the shifting of a potential environmental burden between life cycle stages or individual processes can be identified and possibly avoided.

LCA addresses the environmental aspects and impacts of a product system, see Figure 2.1. This product system could be a given bridge system in a life cycle perspective.

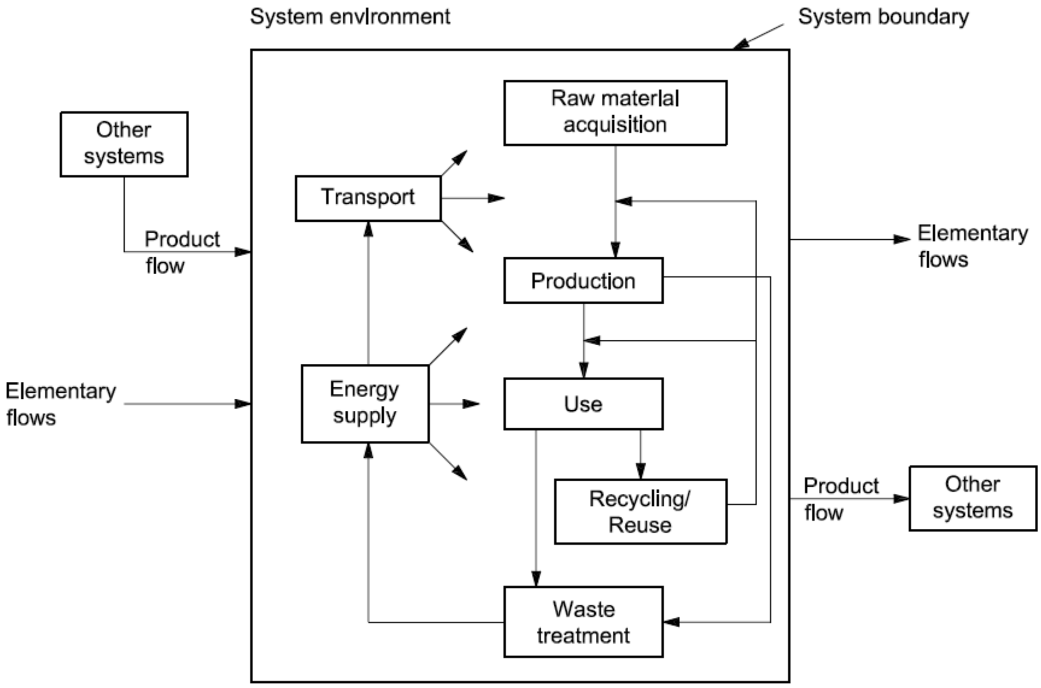

Figure 2.1: Illustration of a product system in LCA (Source: ISO 2006a)

As shown in Figure 2.1, the *system boundary* of the product system includes all phases of the product's life cycle (raw material acquisition, production, use, recycling/reuse and waste treatment), as well as the transport and energy supply needed to support all the other activities. This means that all processing and transport of materials and energy for the given product system can be included in the LCA. There may be product flow inputs from and outputs to other product systems, and there are elementary flows entering and leaving the system. *Elementary flows* are defined as 'material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation' (European Commission 2006a). Hence, the elementary flows are resource inflows taken from nature and waste and emission outflows deposited back to nature. It is these flows we are interested in determining and quantifying in an LCA, as well as their potential environmental impacts.

The structure of LCA shows that it has four phases; see Figure 2.2, namely; 1) Goal and scope definition, 2) Inventory analysis, 3) Impact assessment, and 4) Interpretation. The goal and scope definition is where the purpose of the assessment is decided, the system is defined and what to include and not is decided. The inventory analysis is also called LCI (life cycle inventory), and it is the phase involving the compilation and quantification of elementary flow inputs and outputs for a given product throughout its life cycle. The impact assessment is also called LCIA (life cycle impact assessment), and it is the phase aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for the product system throughout its life cycle. The life cycle interpretation is a systematic procedure in order to identify, qualify, check, evaluate and present the conclusions from the study, and it is iterative with other phases of the LCA. In the following sections each of these phases will be briefly explained.

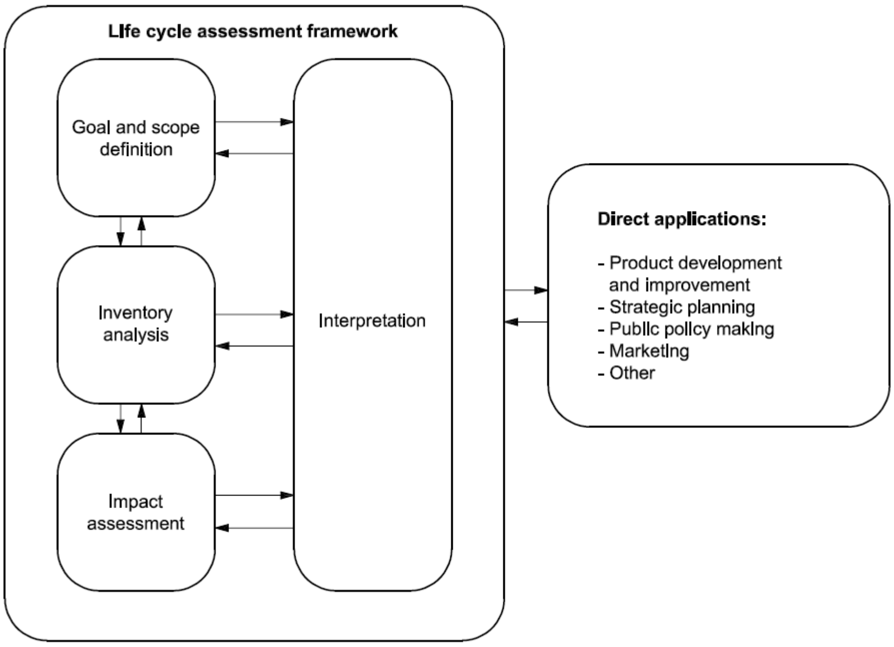

Figure 2.2: The four phases of LCA (Source: ISO 2006a)

2.2 Goal and scope definition

LCA starts with defining the problem formulation and system definition, which is part of defining the goal and scope of LCA. The assessment can be used for a variety of objectives, but common ones are to document potential environmental impacts as a basis for focusing possible improvements, comparing alternative designs, identify waste management solutions, and develop environmental documentation for use in external communication (such as in environmental product declarations, EPD).

The goal of an LCA should clarify the intended application and why the study is carried out. It should also identify the intended audience, and whether the results are to be used for comparative purposes and communicated to the public. With reference to the ETSI project, the goal of an LCA would be to examine the environmental effects of a bridge design, so that one could choose the best alternative among different design options, for given bridge location(s) and traffic.

The goal of an LCA, and the way the analysis is to be carried out (particularly in the inventory analysis) is closely linked to the *decision context* of the study. Figure 2.3 is taken from the ILCD Handbook (European Commission 2010b) detailed guide on how to carry out LCA, and it presents three different situations – A, B and C – or decision contexts, depending on whether or not the LCA is actually used to support decisions regarding future policies, and if so, whether or not one expect large-scale process-changes in the background system or other systems, as a consequence of possible changes to be implemented in the (foreground) product system.

<table>
<tr><td rowspan="5">Decision support?</td><td rowspan="3">Yes</td><td colspan="2">Kind of process-changes in background system / other systems</td></tr>
<tr><td>None or small-scale</td><td>Large-scale</td></tr>
<tr><td>Situation A
"Micro-level decision support"</td><td>Situation B
"Meso/macro-level decision support"</td></tr>
<tr><td rowspan="2">No</td><td colspan="2" rowspan="2">Situation C
"Accounting"
(with C1: including interactions with other systems, C2: excluding interactions with other systems)</td></tr>
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Figure 2.3: The decision context of LCA (Source: European Commission 2010b)

If the LCA results are to be used for decision support, the decision context is either Situation A or B. Hence, if we want to carry out an LCA of alternative road bridge designs, in order to choose the best design or location of a bridge, we do use the LCA results for active decision support. We are then in Situation A or B, not Situation C where one only accounts the environmental impacts of an existing product system.

In such cases (A and B) one sometimes has to consider the possibility that there will be potential large-scale and structural consequences of the decisions taken on the basis of the LCA. This could for instance occur if the market has a limited production capacity for materials X and Y, or energy carrier Z, and decisions in our product system will lead to consumption of such beyond what the market can supply without mobilizing the extra production capacity from plants using marginal technologies. This might even mean that new production facilities, employing distinct technologies need to be built.

In Situation A we have cases with none or only small-scale, non-structural consequences in the background system and potentially on other systems of the economy. These cases imply that only the extent is changed to which already installed equipment e.g. of a production facility is used (e.g. the existing technologies that produce material X). In the LCI model, the additional demand from our system would then be modelled with the processes of the existing equipment (technologies). Very often, LCI modelling in Situation A is based on the assumption of average technologies, for instance the average electricity mix (relative composition of electricity-generating technologies in the electricity market) within a given region (e.g. the Nordic or European electricity market).

In Situation B we deal with cases that may have large-scale structural effects. These cases imply that the decision may result in large-scale market changes; such as additionally installed or decommissioned production capacity. If so, we may have installation of new production plants and technologies for material X, or we may have some existing ones taken out of operation, as a direct market change consequence of the given decision. The result is that at least parts of the technologies in background or other systems in the economy, outside our foreground product system, change as consequence of actions taken according to the analyzed decision. Often only a few processes actually have these large-scale effects and only those processes need the respective modelling; most of the background system will only have small-scale effects. However, for those processes affected, the difference between the ‘large-scale’ and ‘small-scale’ cases can be substantial, as newly installed technologies may differ fundamentally from the currently installed technologies that are modelled in case of small-scale consequences. A typical example of LCI modelling in Situation B would be the assumption of marginal electricity technologies, including their respective specific greenhouse gas emissions, in a market where excess power generation capacity is needed.

It is important to stress that the above refers to changes in the background or other systems that are *caused via market-mechanisms,* i.e. market changes in response to changed demand and supply resulting from the decision within our product (foreground) system. Direct changes in the foreground system, such as the installation of a new technology that is to be installed at the producer's site as part of the analyzed product system, are to be modelled as explicit scenarios in both cases.

The *scope analysis* in LCA is about what to analyze and how. The scope of LCA should be so that the breadth, depth and detail of the study are sufficient to address the stated goal. The scope includes the product system, the functions of the product system (or the functional unit), the system boundary, allocation procedures, selected impact categories and the methodology of impact assessment. It also addresses data and data quality requirements, assumptions and limitations.

The *functional unit* is a key feature of LCA, and it is important to define the functional unit in the best possible way. A system may fulfil different functions, and the ones selected for a given LCA study depend on its goal and scope. According to ISO 14040:2006 (ISO 2006a):

> *'The functional unit defines the quantification of the identified functions (performance characteristics) of the product. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. This reference is necessary to ensure comparability of LCA results. Comparability of LCA results is particularly critical when different systems are being assessed, to ensure that such comparisons are made on a common basis. It is important to determine the reference flow in each product system, in order to fulfill the intended function, i.e. the amount of products needed to fulfill the function'.*

The functional unit shall be identified and specified in detail, including the following aspects:

- Function provided (what)
- In which quantity (how much)
- For what duration (how long)
- To what quality (in what way and how well is the function provided)
- Changes in the functional performance over time (e.g. due to ageing of the product) shall be explicitly considered and quantified, as far as possible

The system boundary has to be selected so that it is consistent with the goal of the study. The deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study. When the functional unit and boundary of a system is defined, one can determine the corresponding *reference flow*, which by definition is the 'measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit', i.e. the amount of products needed to fulfil the function.

With reference to the ETSI project we assume that the location and traffic capacity of a given bridge is know, hence also its length, width and effective area. Therefore, the functional unit of the bridge LCA can be simply defined as: 'Given bridge (name) over its service life of 100 years'. With this functional unit one can easily carry out an LCA for a number of different design options, and compare the designs in order to choose the best.

2.3 Life cycle inventory analysis (LCI)

The LCI involves data collection and calculations to quantify relevant inputs and outputs of a product system, and it is an iterative process that may lead to the need for better data and revisions of the goal or scope of the study. Figure 2.4 illustrates this for a simple example of three unit processes within a product system.

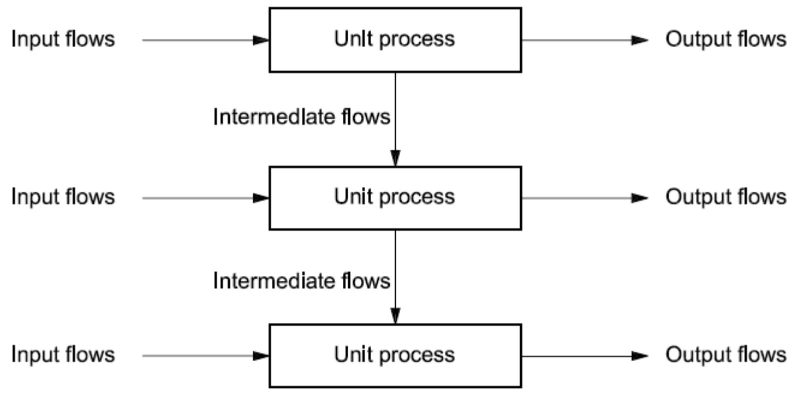

Figure 2.4: Example with a set of unit processes within a product system (Source: European Commission (2010b)

Data have to be collected for each unit process within the systems boundary, which can be a resource-intensive process. However, the use of commercial LCA software and databases (such as the SimaPro LCA software and the Ecoinvent v2 database) help reducing time and work for such data collection, but these represent average data for technologies that often are not sufficiently specific for the given product system that is studied.

The calculation of energy flows are of particular importance in LCA, and one needs to account for the use of different fuels and electricity sources, energy conversion and distribution efficiencies, and the inputs and outputs related to the generation and use of different energy flows.

According to the decision context illustrated in Figure 2.3, the choice of situation A and situation B lead us to two different principles of LCI modelling; called '*attributional LCI modelling*' and '*consequential LCI modelling*'. Attributional modelling is a modelling frame that inventories the input and output flows of all processes of a system as they occur. Hence, in this modelling one normally use project specific or average technology foreground LCI data and one assumes average technology LCI data for the background system. Consequential modelling is a principle that identifies and models all processes in the background system of a system in consequence of decisions made in the foreground system. Hence, in this modelling one normally have to use *marginal* technology LCI data, for selected parts of the background or other systems in the economy, i.e. those systems that are likely to be large-scale influenced by decisions in our product system.

In the context of the ETSI project, we are convinced that when doing an LCA in order to decide what is environmentally the best design of a new road bridge, we are normally in a situation of type A – the given bridge is not a project of sufficient size to influence market technologies. Only in extreme cases, such as for the very long Öresund bridge, one *may* come in a situation of type B, where this given project can cause a demand for bridge materials beyond the current production capacity in the market, and thereby mobilizing marginal production technologies. It is important to take note of the fact that this issue is important, since there is lot of confusion on how to carry out an LCA with respect to the choice of technology assumptions, and the choice of average or marginal technologies of a given material or energy carrier can influence the LCA results a lot, since emissions from various technologies are sometimes very different in type and magnitude.

Another comment of importance is that one should, of course, and if available, use as exact and project-specific assumptions as possible, including emission data from production processes that supply major materials consumed in the bridge system. This implies that one should use emission data from Environmental Product Declarations (EPD) of defined material suppliers to the bridge, if the suppliers are known or can be assumed with a high degree of certainty. And further, if such project-specific data are not know, or cannot be assumed, one should use average technology assumptions of the given country (if available) rather than average technology assumptions for a region (like Western Europe) or for the world in total.

Industrial processes often give more than one product output, e.g. products and co-products, and they may recycle intermediate or discarded products as raw materials. In such situations we have what is called *multifunctional process*, i.e. a process that provides more than one function, see Figure 2.5.

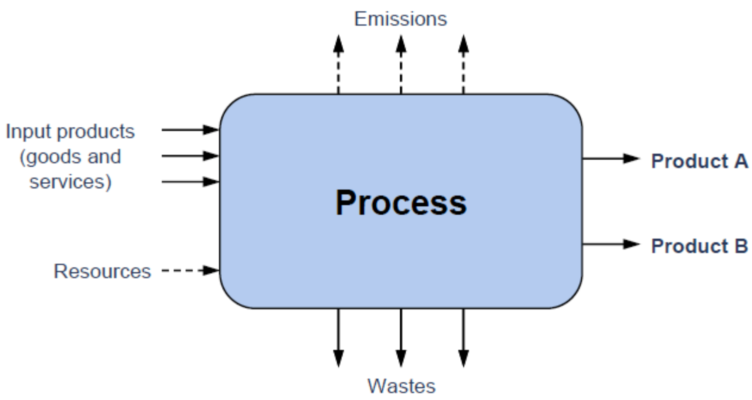

Figure 2.5: Example of a multifunctional process, with several inputs, emissions and wastes, and providing two co-products A and B (Source: European Commission 2010b)

In order to cope with such issues, the use of allocation procedures is needed. According to the ISO 14040:2006 standard, *allocation* is defined as 'partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems'. The simple meaning of this is, that if a product (incl. co-product, reused product or recycled materials from a product) has a value (benefit) for another product system, part of the environmental impacts from the processing of this should be accounted for in that other system. The study shall identify the processes shared with other product systems and deal with them in the following way:

- Wherever possible, allocation should be avoided by 1) *dividing* the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or 2) *expanding* the product system to include the additional functions related to the co-products.

- Where allocation cannot be avoided, the inputs and outputs should be partitioned between its different products or functions in a way that reflects the underlying *physical* relationships between them.
- Where physical relationship alone cannot be established or used as the basis for allocation, other relationships can be used, such as the *economic* value of each of the co-products.
- The inventory is based on *mass balances* between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics.

Since loop closing (open and closed loop recycling) is such an important issue, it is particularly important to use the correct allocation procedure when carrying out an LCA for product systems where recycling is involved. Reuse and recycling may imply that the inputs and outputs associated with unit processes for extraction and processing of raw materials and final disposal of products are to be shared by more than one product system, and reuse and recycling may change the inherent properties of materials in subsequent use. Hence, care should be taken when defining system boundary with regard to recycling and recovery processes.

With reference to the ETSI project, we believe it is very important to decide upon a principle for how to deal with recycling and recovery that is also in agreement with the state-of-the-art rules for Environmental Product Declarations (EPD) and Product Category Rules (PCR). PCR is a predefined and internationally standardized set of rules, specifying how one should develop EPDs within different categories of goods and services. The International EPD®System (2010) provides a "PCR Basic Module" for Constructions, which covers EPDs for buildings and for civil engineering works including i) Highways, streets, roads, railways and airfield runways, ii) bridges, elevated highways and tunnels, iii) harbours, waterways, dams, irrigation and other waterworks, etc. The International EPD®System (2009) also provides a more detailed PCR document for railways, however, they have yet not developed PCR documents for bridges. These rules should also be used for EPDs, and LCA studies as part of EPDs, for bridges.

Figure 2.6 shows the general presentation of Core Module (core processes), upstream and downstream processes of constructions, according to the PCR Basic Module for Constructions (International EPD®System 2010). All relevant upstream, core and downstream processes should be included.

The upstream processes include the following inflow of raw materials and energy needed for the production of the construction product:

- Extraction and production of raw materials for all main parts and components
- If relevant, recycling process of recycled material used in the product
- Transportation of raw material

The core processes include:

- Manufacturing process for main parts and components
- Assembly of the final product

- Treatment of waste generated from the manufacturing of main parts and assembly of the product
- The core process include external transportation of materials to the factory and internal transportation within the factory

The downstream processes include:

- Transportation from final manufacturing to customer
- Lifetime operation of the product including power losses and emissions
- Maintenance, replacements of parts, during life time
- Recycling of material after end of life

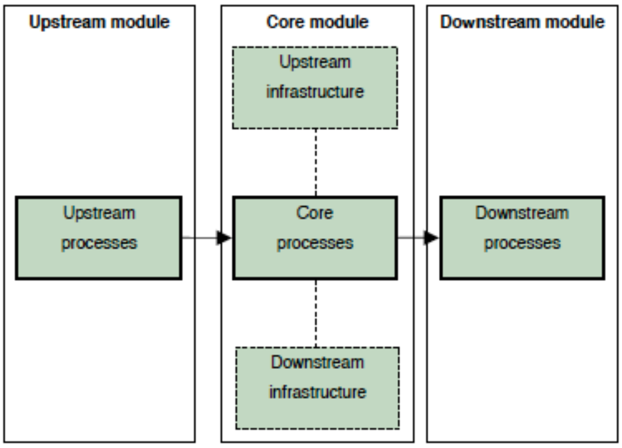

Figure 2.6: General system boundaries of construction project with upstream and downstream processes (Source: International EPD®System 2010)

The PCR Basic Module for Constructions document (International EPD®System 2010) states that allocation between different products and co-products shall be based on physical relationships, if possible. The document also states that EPDs for constructions should use an allocation cut-off criterion of 99 per cent, which means that LCI data for a minimum of 99 per cent of total inflows to the core module shall be included.

The document does not refer in detail how to allocate when recycling materials after end of life, but states that the PCR shall specify which allocation rules should be used. Therefore, as there is today no PCR for bridges available, we use the PCR for railways, which clarifies in detail how allocation is to be done when recycling materials after end of life (International EPD®System 2009):

> *'For resource inputs that come from recycling processes and waste outputs that go to recycling processes, no allocation should be made. That means that inputs of recycled materials or energy to a product system shall be included in the data set without adding their environmental impact caused in "earlier" life cycles. However, potential environmental impact from recycling processes (e.g. collection, treatment etc.) shall be included in the system under study. Consequently, outputs of products subject to recycling shall be regarded as inputs to the "next" life cycle. That means that they will not carry any environmental impact to the next life cycle and the environmental impact from recycling processes shall be included in the next life cycle. If it is difficult to decide whether*

recycling processes should be included in the previous or the next life cycle, the delineation between the product systems shall be drawn where the waste has its lowest market value.'

There are some important implications of this for the ETSI project:

- When the construction of a given bridge is consuming components or materials that are recycled from scrap from earlier life cycles, i.e. using secondary materials (such as reinforcement steel from arch furnace technologies, based on scrap steel), the LCA of the bridge shall include the emissions and environmental impacts from collection, transport and processing of these secondary materials. This will give an advantage to the bridge system, compared to the alternative of using virgin steel. Hence, in ETSI, when using secondary (recycled) materials in a bridge, one should use the emission data for those given secondary materials, such as from the EPD of a secondary materials supplier, if available.
- When a bridge is demolished, and materials are separated from the demolition waste for materials recycling or for energy recovery in another (later) life cycle, the emissions and environmental impacts from collection, transport and processing of these waste materials shall be allocated to the next life cycle system, not the bridge system. This also means that the advantage of recycling and energy recovery, compared to the use of virgin materials, is credited the next life cycle, not the bridge. Hence, in ETSI, one should not include the fate of recycled materials or recovered energy in another product system, after the bridge end of life.
- If bridge materials after end of life demolition are not recycled, but disposed of in landfills or given any other end treatment (such as incineration without energy recovery), one has to include the emissions and impacts from such disposal or end treatment. Hence, in ETSI, one should include such emissions in the LCA of the bridge system.
- Likewise, the demolition activity itself has to be included in the LCA of the bridge system.

The final outcomes from LCI is a quantified list of all elementary inflows from nature and outflows back to nature, as shown in Figure 2.1, allocated to the given product system, and as a consequence of the overall life cycle activity in the system in order to fulfil its function as defined by the functional unit. This quantification is in physical units only, without any assessment of the corresponding potential environmental impact.

2.4 Life cycle impact assessment (LCIA)

The next phase of LCA, life cycle impact assessment (LCIA), serves the purpose of determining the potential environmental impacts that may be caused by the inputs and outputs from LCI. There are numerous and different kinds of environmental effects, and all effects that may be a problem, due to the product system we analyze, have to be included in the impact assessment.

LCIA methods exist for *midpoint* and for *endpoint* level, and for both levels in integrated LCIA methodologies (see Figure 2.7). Both levels have advantages and disadvantages. In general, on midpoint level a higher number of impact categories is differentiated (typically around 10) and the results are more accurate and precise compared to the three areas of protection at endpoint level that are commonly used for endpoint assessments.

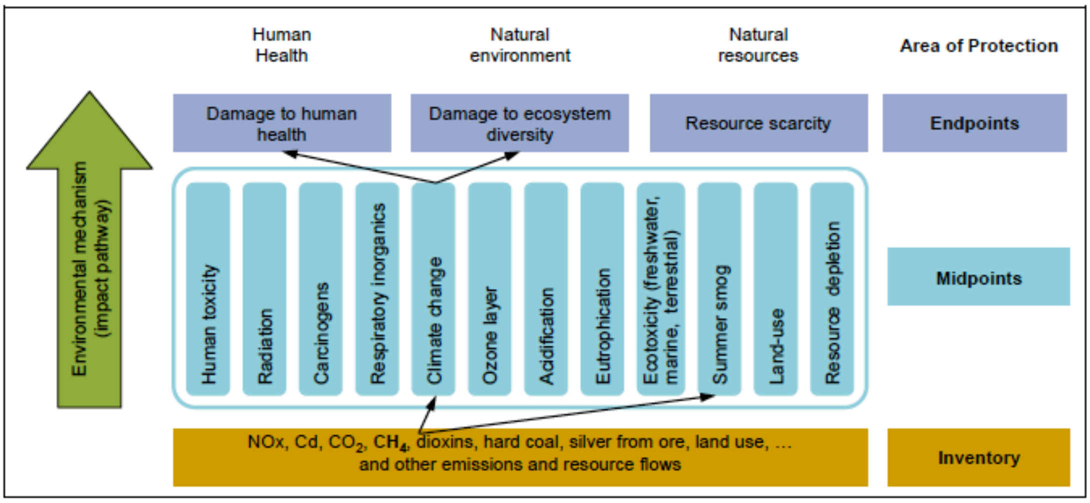

Figure 2.7: Life cycle impact assessment (LCIA) on the basis if inventory data (Source: European Commission 2010b)

The following environmental impact categories are to be included in an EPD for constructions (International EPD®System 2010), and accordingly, they should also be included in an LCA for constructions, when the LCA is a basis for an EPD:

- Emissions of greenhouse gases (expressed in global warming potential, GWP, kg CO_2-equivalents, in 100 year perspective)
- Emission of ozone-depleting gases (expressed as the sum of ozone-depleting potential, OPD, in kg CFC 11-equivalents, in 20 years perspective)
- Emission of acidification gases (expressed as the sum of acidification potential, AP, in kg SO_2-equivalents)
- Emission of gases that contribute to the creation of ground level ozone (expressed as the sum of ozone-creating potential, POCP, in kg ethene-equivalents)
- Emission of substances to water contributing to oxygen depletion (expressed as eutrophication potential, EP, in kg PO_4^{3-}-equivalents)

Many other environmental impact categories than those listed above are part of a comprehensive LCIA. For instance, Figure 2.7 shows 12 midpoint indicators, each indicator representing a different environmental impact category. In practice, the choice of how many, and which, indicators to include in an LCA should be decided as part of the goal and scope definition, and refer to the purpose of the analysis.

It is common to say that the LCIA methodology has four steps; see Figure 2.8. The first two are *classification* and *characterization*, and transform LCI results (amounts of input and output elementary flows, such as NH_3, NO_x, SO_2, P, etc.) to midpoint level equivalent values (such as acidification potential AP, eutrophication potential EP, global warming potential GWP, etc.). One environmental *stressor*, i.e. substance from LCI, may contribute to several midpoint indicators, such as NO_x (contributing both to AP and EP), and several stressors can of course contribute to the same midpoint indicator, such as different greenhouse gases (CO_2 and CH_4, contributing to GWP).

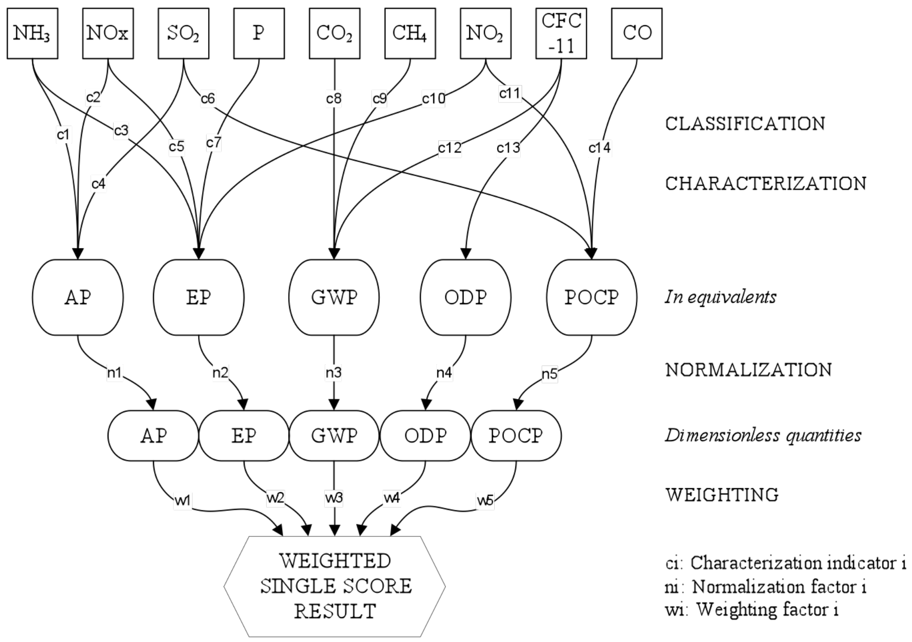

Figure 2.8: Steps in the life cycle impact assessment (LCIA) methodology

In classification, it is decided which of the stressors are contributing to which of the midpoint environmental impact categories. In characterization, their relative importance with respect to that impact potential is decided, in *equivalent units*. For instance, methane CH_4 has a global warming potential GWP_{100} of 25 CO_2-equivalents (over a 100 years time horizon), which means that methane is 25 times stronger than carbon dioxide with respect to global warming potential, and therefore has a characterization factor (*c*) of 25.

Classification and characterization is needed in order to categorize all the numerous LCI results into a limited number of known environmental impacts, and therefore, these two steps have to be included in any LCIA methodology. However, there are several different *LCIA methods* on how to calculate the midpoint indicator values on the basis of a given LCI dataset. These include LCIA methods such as the IPCC baseline model of 100 years for GWP, the USEtox model for human toxicity and ecotoxicity, and the CML2002 method for several indicators. Similarly, there are different methods available for transforming midpoint indicators to endpoint level results. The ILCD Handbook project has developing recommendations on which methods to use (as the preferred ones) for each midpoint and endpoint indicator (European Commission 2011b), and it is expected that commercial LCA software systems will adapt to this in the near future.

As shown in Figure 2.8, midpoint level results (in equivalents) may be further processed, through the steps of normalization and weighting, in order to obtain one weighted single score result. In the normalization, midpoint equivalent results (such as for GWP) are multiplied by a normalization factor (*n*) equal to the inverse value of the per capita equivalent of the same indicator (GWP) for a given region (such as the global or European per capita level GWP contributions). In the weighting, normalized values are multiplied by a weighting factor (*w*), which reflect the stakeholder or political priority of relative importance of the different environmental impact categories. These two steps are not compulsory parts of LCIA, and in fact, if LCA results are to be disclosed to the public, normalization and weighting is not to be carried out. The reason is that these two steps are much less objective, and therefore without a scientific basis, but subjective and strongly related to stakeholder priorities and policy preferences. On the other hand, however, many stakeholders do not (of course) understand much of the details of

LCA, and therefore they also prefer a limited number of dependent variables (results) to take into account in their decision-making process.

2.5 Mathematical description of LCA

The mathematical description of the LCI and LCIA methodology is as follows. First, we have to calculate, as part of LCI, the amount of each input and output (i.e. the stressors with respect to environmental impact, see the bottom layer in Figure 2.7 or the top layer in Figure 2.8):

$$e_{ij} = x_i \cdot f_{ij} \tag{2.1}$$

where; e_{ij} is the amount of substance or stressor j (e.g. CH_4, in kg) caused by the total consumption of resource i (e.g. concrete), x_i is the consumption of resource i (concrete, in kg), and f_{ij} is the emission of substance j per unit of resource i (e.g. kg CH_4 per kg concrete).

Next follows classification and characterization, by use of Equation 2.2:

$$d_k = \sum_{i=1,j=1}^{i=o,j=p} (e_{ij} \cdot c_{jk}) \tag{2.2}$$

where; d_k is the total potential impact in environmental category k, and c_{jk} is the characterization factor for substance j with respect to impact category k.

Normalization is carried out by using Equation 2.3:

$$m_k = d_k \cdot n_k \tag{2.3}$$

where; m_k is the per capita normalized potential impact of environmental category k, and n_k is the normalization factor for category k. The normalization factor is the inverse value of the per capita sum of emissions (contributions) to the given impact category, e.g. GWP in kg CO_2-eq per capita per year.

Finally, weighting is calculated as follows:

$$v = \sum_{k=1}^{k=q} (m_k \cdot w_k) \tag{2.4}$$

where; w_k is the weighting factor of environmental impact category k, and v is the weighted single score result, see also Figure 2.8 above.

The first two steps, using Equations 2.1 and 2.2, are required parts of any LCIA method, in order to come to midpoint indicators. On the other hand, the last two steps, using Equations 2.3 and 2.4, are voluntary options that can be skipped, and must be skipped of the LCA results are to be used for external communication and competition (such as in a product EPD). The advantage of including these last steps is that LCA results are aggregated into one indicator only, which is easier to relate to by a non-environment expert. However, this then requires that a set of normalization factors n_k and weighting factors w_k are agreed upon. Common normalization factors in LCA are the ones developed for Western Europe or for the World in total, which then represent the inverse of per-capita annual emissions of the given impact category indicator (such as CO_2-equivalents) in Western Europe or the World. The LCA Handbook (European Commission 2010b) states that if normalization is applied, one also has to show which weighting factors are applied. These can relate to an equal weighting (1:1:1:etc) of all environmental midpoint indicators, or one can define a project specific or sector specific set of weighting factors that reflects the policies within that given project or sector type. Hence, weighting factors are clearly subjective choices.

2.6 Interpretation

The Interpretation phase in LCA has two main purposes (European Commission 2010b):

- During the iterative steps of the LCA and for all kinds of deliverables, the interpretation phase serves to steer the work towards improving the LCI model to meet the needs derived from the study goal
- If the iterative steps of the LCA have resulted in the final LCI model and results, and especially for comparative LCA studies, the interpretation phase serves to derive robust conclusions and - often - recommendations.

The interpretation phase is where the results of the other phases are considered collectively and analyzed in the light of the achieved accuracy, completeness and precision of the applied data, and the assumptions, which have been made throughout the study. In parallel to doing the LCI work this serves to improve the LCI model. The final outcome of the interpretation should be conclusions or recommendations, which are to respect the intentions and restrictions of the goal and scope definition of the study. The interpretation should present the results of the LCA in an understandable way and help the user of the study appraise the robustness of the conclusions and understand any potential limitations.

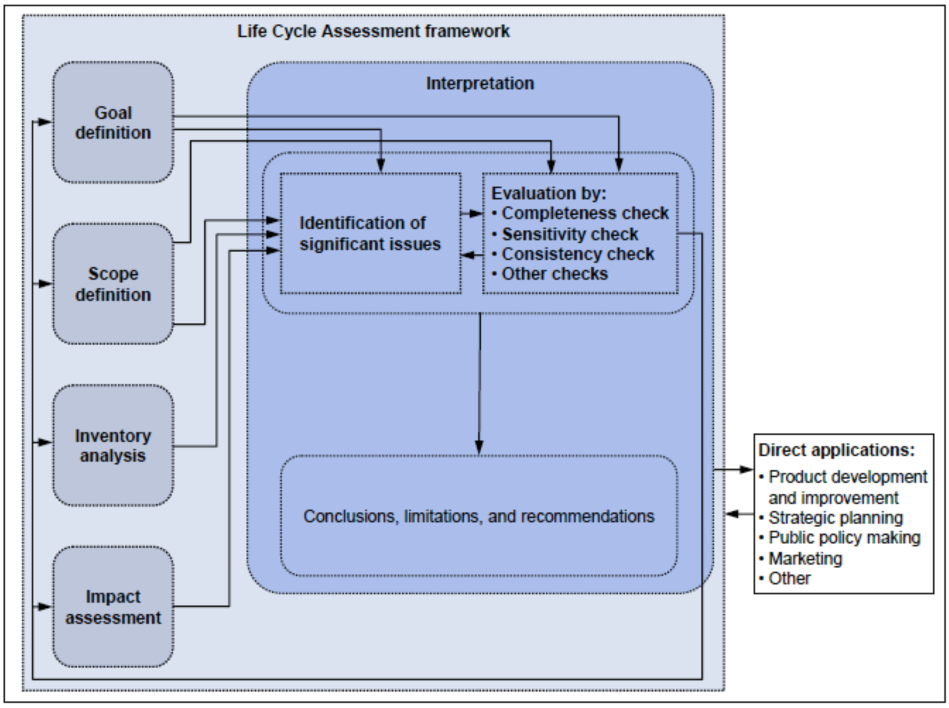

Figure 2.9: Activities in the interpretation phase of LCA

The interpretation phase include three activities as shown in Figure 2.9:

- First, the significant issues (key processes, parameters, assumptions and elementary flows) are identified.

- Then these issues are evaluated with regard to their sensitivity or influence on the overall results of the LCA. This includes an evaluation of the completeness and consistency with which the significant issues have been handled in the LCI/LCA study.
- Finally, the results of the evaluation are used in the formulation of conclusions and recommendations from the LCA study.

It is important to understand that an LCA, despite the fact that it is an internationally standardized and recognized methodology, several assumptions and value choices are taken, and there are often large uncertainties in data. This will of course influence the reliability, accuracy and robustness of the LCI and LCIA results, and therefore also the conclusions and recommendations from the LCA study. Hence, it is very important to carry out the completeness check, the sensitivity check and the consistency check in the evaluation step of LCA interpretation.

3 Literature review on LCA of road bridges

A thorough examination of the international literature on LCA for bridge studies was carried out in ETSI Stage 2. The results from this examination were given in the final report of that stage of the project (Hammervold et al. 2009). The main findings from literature are presented also in a more recently published paper by Hammervold et al. (2012), in addition to a comparative study of three case bridges, using an earlier version of the *BridgeLCA* model. The three case bridges we analysed are already built and in use in Western Norway; one steel box girder bridge, one concrete box girder bridge and one wooden arch bridge. This means that one could also get hold of detailed facts about the various kinds of resource consumption in the production and construction phase of the bridges. Main literature findings as reported in Hammervold et al. (2012) are referred to below.

3.1 Comparison of different bridge alternatives

Gervásio and da Silva (2008) compared a prestressed concrete box girder bridge and a steel-concrete composite I-girder bridge. The emissions considered are CO_2, SO_2, NO_X, VOC, CO, CH_4 and particulates, classified into 6 categories of environmental impact: global warming, acidification, eutrophication, criteria air pollutants, smog formation and water intake. These categories are normalised using US emissions per capita and year. The LCA results shows that the composite bridge has the best overall environmental performance, but for the categories global warming, water intake and eutrophication the concrete bridge is the best alternative.

Collings (2006) did an environmental comparison of bridge forms, presenting two studies; one (the initial study) is on three alternative bridges designed for the same site (a major creek crossing in the Middle East), the second (the primary study) is on three alternative bridge forms crossing a river in the UK (river width approximate 120 m). The initial study comprises a concrete cantilever bridge, a concrete cable stay bridge and a steel arch bridge. The results show that relative to the concrete cantilever bridge, the concrete cable stay bridge represents 1.3 times as much environmental burden and the steel arch bridge represents 1.9 times as much. The study also concludes that paint, waterproofing and plastics have relatively high values per ton of embodied energy and CO_2. The primary study considers three basic forms with three material choices for each alternative. This gives 9 alternatives in total; girder, arch and cable stayed bridges of steel, concrete or steel-concrete composite. It is found that concrete bridges have the lowest embodied energy and CO_2 values for all bridge forms. For shorter-span structures though, the difference between concrete and steel-concrete is found insignificant. Emissions throughout the use phase are approximately the same for the three material choices, and most of the emissions in this phase are related to resurfacing of the bridge.

Horvath and Hendrickson (1998) present an environmental assessment on two bridge alternatives; steel versus steel-reinforced concrete bridges. Three groups of environmental impact are quantified in this study; TRI chemical emissions, hazardous waste generation and conventional air pollutant emissions. The concrete design has lower overall environmental effects (10 – 60 % of environmental effects for the steel bridge in the various impacts calculated). Environmental effects through the lifetime of the bridge can be highly important, as SO_2, NO_X, CH_4 and VOC emissions are significantly higher for paint manufacturing than for the production of all girders for the example bridge.

Itoh and Kitagawa (2003) used a modified life cycle methodology to evaluate and compare two types of steel bridges; a conventional and a minimised girder bridge. The bridges are compared regarding CO_2 emissions and costs. The minimised girder bridge gives both lower CO_2 emissions and costs in total, and also when looking at maintenance only.

3.2 Comparison of different bridge component alternatives

Two types of deck systems are compared in Keoleian et al. (2005); a steel-reinforced concrete deck with conventional steel expansion joints and a steel-reinforced concrete deck with a link slab design using a concrete alternative; engineered cementitious composites (ECC). Various pollutants to air (CO_2, CH_4, CO, PM_{10}, NMHC, NO_X, SO_X) and water (BOD, NH_3, PO_4^{3-}, oils, suspended matter and dissolved matter) are considered. The analysis shows that the ECC deck yields significantly lower environmental impacts, for all pollutants.

Steele et al. (2003) presents a methodology applicable to all kinds of bridges. The paper concludes that material use reduction is important, but one should not compromise durability and longevity of the structure. Steel and concrete constitutes the majority in new bridges. Manufacture of these materials is the single biggest contributor to environmental impact over the life cycle of the structure. Joints, bearings and parapets often made of other materials have much less impact, even when allowing for service life renewal. It is stated that it is unlikely that either steel or concrete is inherently better from the environmental point of view. Good maintenance prevents deterioration and extends structural life. Mostly, refurbishment and strengthening represents a lower environmental impact than structure replacement. At structure closures, traffic disruption can represent higher environmental impact than the maintenance activity, and in some case, higher than the actual construction of the bridge. Foreseeing future needs, for instance the need for extra deck or abutment width, homogenous load capacity or use of loose-fit components gives allowance for increase in capacity. Findings indicate that this raises initial impacts, but will reduce impact in the long run. It is, however, remarked that this must be balanced with over-design.

In Martin (2004) environmental issues regarding concrete bridges are described and two earlier studies comparing different alternatives for bridge decks (including girders) are presented. The first study presented is on two bridge deck designs, including girders; one steel-reinforced concrete deck on steel girders and one steel-reinforced concrete deck on concrete girders. The decks are compared regarding energy use and GHG emissions. The results shows that for virgin materials the concrete deck alternative consumes 39 % less energy and yields 17 % less CO_2

than the steel alternative. Considering recycling, it is more gain here for steel, partly because it is easier to separate in end-of-life. The second study presented compares three concrete type alternatives for the same deck; lightweight, normal density and high-strength concrete. It is concluded that there is no significant difference in energy consumption. However, the high-strength concrete has supposedly longer durability, and might thus be the environmentally preferred alternative.

In a study by Bouhaya et al. (2009) an innovative bridge structure made of wood and ultra-high performance concrete is studied using LCA methodology. The study includes energy use and greenhouse gas. For wood, CO_2 uptake during growth is included, and three scenarios for end-of-life treatment is assessed; Scenario 1) burying in landfills, assuming that only 15 % deteriorates and emits CO_2 and CH_4, the remaining 85 % constitutes a stock of carbon, Scenario 2) Incineration, compared to burning of natural gas and Scenario 3) Recycling (zero emissions). The total results for the three scenarios shows that the inclusion of CO_2 captured during tree growth offsets the emissions stemming from other parts of the system. For scenarios 1 and 3 the uptake of CO_2 during tree growth is actually higher than the emissions in the remaining of the bridge life cycle, and hence the total life cycle GHG emissions for the bridge are negative. Other findings are that the transportation and the construction phase contribute small amounts to the total energy use and GHG emissions (savings), while it is the production phase that contributes most both in energy use and in GHG emission savings.

As a conclusion from the literature referred to above, we may agree that there are several (yet surprisingly not very many) LCA studies carried out on bridges, providing helpful information to designers. On the other hand, it may be difficult to extract a set of a few generic recommendations for environmentally benign bridge design, due to the fact that the studies are carried out under very different assumptions. One important observation is that no study yet documented the environmental life cycle performance of bridges, comparing different designs by using a standardised bridge design classification, where consumption of materials and energy carriers in a more systematic way is related to the various bridge parts (components).

The work of Hammervold et al. (2012) also examined three case bridges, as shown in Table 3.1, and the main results of the LCA studies are given in Figure 3.1 and Figure 3.2 below.

Table 3.1. Basic data for three Norwegian case bridges

	Klenevaagen	**Fretheim**	**Hillersvika**
Type	Steel box girder	Wooden arch	Concrete box girder
Bridge span	42.8 m	37.9 m	39.3 m
Effective width	7.5 m	6.1 m	10.6 m
Traffic lanes	2	1	2
Pavement	0	1	1
Bridge deck area	321 m^2	229 m^2	417 m^2

Hillersvika is the largest bridge, with a deck area of 417 m^2. This bridge has two traffic lanes and one pavement, while Klenevaagen has two traffic lanes and no pavement and Fretheim has one traffic lane and one pavement. Klenevaagen has a surface area of 321 m^2 and Fretheim has a surface area of 229 m^2. These three bridges are chosen as they represent bridges of three material choices; steel, concrete and wood. In this way, important parameters affecting environmental performance for these types of bridges can be identified. The production of the bridges consume different amount of inputs (materials and energy), and different OR&M schedules were also assumed. More detailed information is available in the published paper (Hammervold et al. 2012) and in the previous ETSI Stage 2 report (Hammervold et al. 2009).

Total weighted results per functional unit for all the bridges are shown in Figure 3.1, relative to Klenevaagen Bridge. After normalisation and weighting, the impact categories Global Warming Potential, Abiotic Depletion Potential and to some extent Acidification Potential turns out the most important. There are some impacts to Eutrophication Potential and Photochemical Oxidation Potential, but insignificant impacts to Ozone Depletion Potential. Hillersvika (concrete bridge) performs best compared to the other two bridges. Figure 3.2 shows the total weighted impacts split up in input parameters for each bridge.

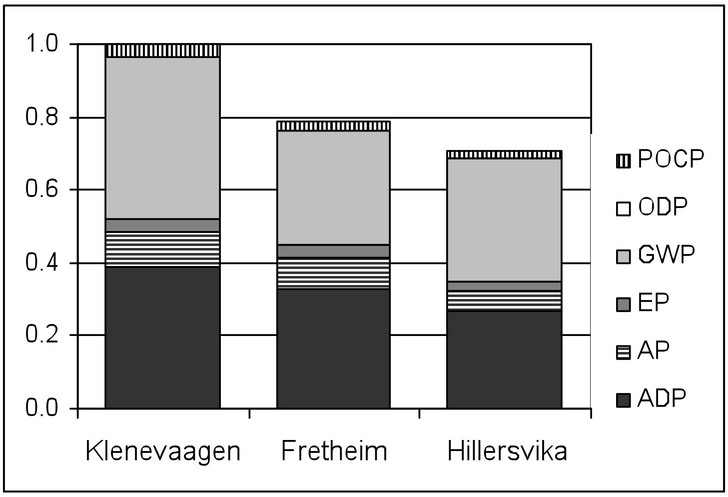

Figure 3.1: Total weighted impacts, relative to results for Klenevaagen Bridge (calculated on a per m^2 effective bridge area basis).

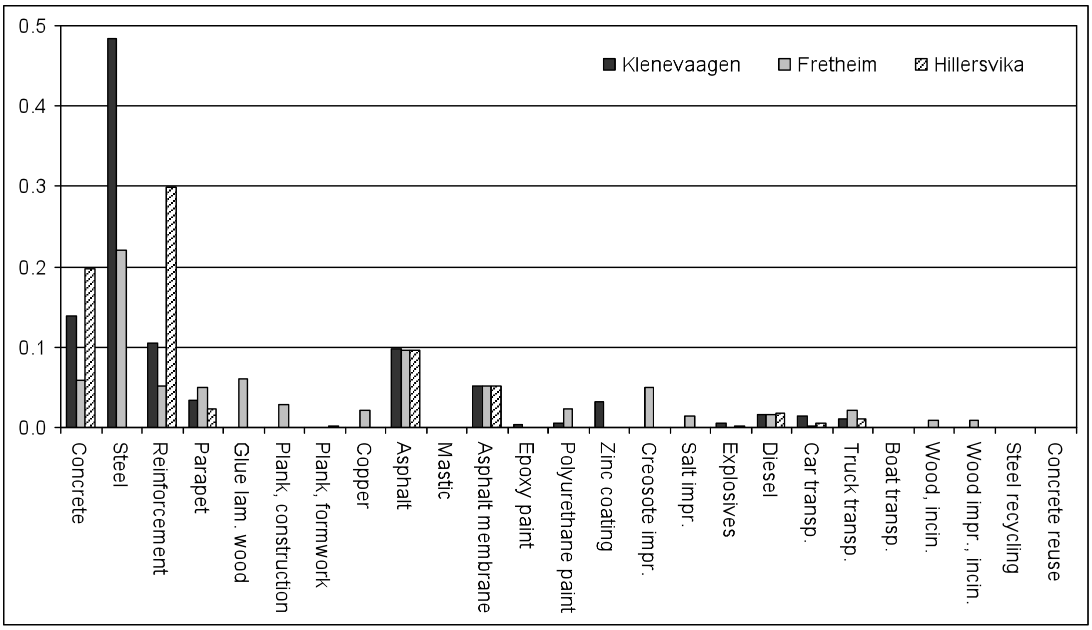

Figure 3.2: Total weighted impacts per functional unit, split up for input parameters

The main materials concrete, steel, wood and asphalt are contributing the major share of the emissions. But also some of the materials used in smaller quantities are contributing somewhat, like asphalt membrane, copper, creosote, zinc coating, and diesel and transportation by truck and car. This is examined more in-depth for each of the bridges. This analysis shows that Hillersvika concrete box girder bridge is the environmentally preferred alternative of the three bridges studied, however, Hammervold et al. (2012) state that one cannot draw general conclusions on this for other bridges not studied.

From literature we can conclude that the most important materials regarding bridges' environmental performance are the materials in the main load bearing structures (construction steel, concrete, reinforcement, glue laminated wood, copper), followed by the concrete and reinforcement in the abutments, and finally the parapets and the surfacing materials asphalt and asphalt membrane. Impregnation treatment and/or painting of the wood and the surface treatment of steel (at least zinc coating) are also of relevance. Use of building equipment and transport of materials and personnel in all life cycle phases (construction, use and end-of-life) of the bridges are of minor importance. This is also the case for use of formwork, mastic, blasting and the incineration of wood at end-of-life. Especially is it worth paying attention to the diesel consumption in the construction phase, as this is a parameter that varies quite much for different bridge designs and construction site conditions.

4 Definitions and measures used in the ETSI *BridgeLCA* tool

4.1 Background

In the same way as for a bridge LCC analysis, one has to define and explain the parameters that are used in a bridge LCA. Some of these parameters are already included and explained earlier in this ETSI final report, in Section 3 of the LCC chapter. A supplementary explanation is given below.

The bridge LCA tool that is developed in ETSI is given the name *BridgeLCA*, and this is what is often referred to below.

4.2 Definition of bridge parts and their measures

The definition of bridge parts and their measures are the same as for LCC, and this is already presented in Section 3.2 of the LCC chapter.

BridgeLCA is structured with use of an 'Input sheet', where the user can manually input the actual amounts of materials and energy carriers that are consumed in the production of the bridge parts that are listed in Table 3.1 in the LCC chapter of this report. This is essential so that the analyst or bridge designer can spot back on exactly which bridge parts that contribute how much to the total environmental impact or a given midpoint indicator impact of a bridge, after having run *BridgeLCA* for a given bridge design.

In addition to the production phase of bridge parts, the bridge system also includes the construction phase, the operation, repair and maintenance (OR&M) phase, and the end of life (EOL) phase, where there will also be consumption of material and energy inputs.

Moreover, all masses in the system will have to be transported, either by ship, lorry or train. Emissions from transportation within the production phase are normally included in the emission data from production of a given material, therefore such transportation will not have to be specified explicitly in *BridgeLCA*. However, one must define the transportation mode and distance for: i) materials from production (factory) gate to site in the construction phase, ii) replacement materials during the OR&M phase, and iii) waste materials to disposal during the EOL phase.

4.3 Definition of bridge materials

Bridge materials are defined and listed in Table 3.2 in the LCC chapter of this report. Some of them are common for both LCC and LCA, and some are used only for LCA.

BridgeLCA distinguishes between:

- Materials with major LCA impact (i.e. concrete, construction steel, reinforcement steel, prestressing steel, timber and asphalt)
- Materials with minor LCA impact (i.e. asphalt membrane, epoxy, rubberized bitumen lotion, asphalt mastic, polyurethane, zinc coating, paint, glass, creosote impregnation, salt impregnation, acryl, polycarbonate and plastic)
- Other input factors (i.e. energy – electricity or diesel, and blasting and transportation)

The materials with major LCA impacts are selected on the basis of what was learned in ETSI Stage 2, using the philosophy that one would want to keep the LCA fairly simple and only specify country specific or project specific emission data for a limited number of materials. This should of course be the materials that are likely to contribute to the largest share of environmental impact for a bridge system, regardless the specific design of the bridge. Hence, it was decided to select concrete and construction steel, both with the option of specifying different qualities, as well as reinforcement steel, prestressing steel, timber and asphalt.

The materials with minor LCA impacts are selected due to the fact that these materials may also be consumed in quantities such that they give a significant added contribution to the environmental impact of a bridge. Hence, in a detailed LCA of a bridge, the analyst may choose to input also good estimates of such materials. However, unlike for the materials with major LCA impact, materials with minor LCA impact do not need the use of country specific or project specific emission data. For these one may rely on emission data from commercial LCA databases.

Other input factors like electricity and diesel, blasting explosives and transportation are important to include, because they may give substantial contributions to environmental impact from the construction phase, the OR&M phase or the bridge demolition in the EOL phase.

4.4 Definition of actions

Actions after the bridge is built are fairly much the same as for LCC calculation, as defined in Section 3.4 in the LCC chapter of this report. However, when doing an LCA not all these actions are of main importance, as it is the consumption of materials and energy that are the direct reasons for environmental impacts in an LCA perspective.

BridgeLCA has defined the following actions:

- Operation, repair and maintenance (OR&M), with all actions in this phase lumped together in one phase regardless of when during the service life they occur

- The end of life (EOL) phase is defined with four actions: i) input to demolition, ii) materials to landfill, iii) materials to material recycling, and iv) materials to energy recovery

The estimated consumption of inputs (materials and energy) related to the actions in the OR&M phase of a bridge should be taken from the Life Cycle Plan (LCP) of the given bridge, according to the LCP structure developed in Task 2 of the ETSI project.

According to what is decided in the ETSI project, the default service life of a road bridge is set to 100 years, and the LCP should reflect this when calculating how many times certain bridge parts (like bearings and parapets) or layers (like asphalt and surface coating) have to be repaired or replaced.

The consumption of inputs to the demolition of the bridge will have to be estimated by experience best assumption methods, if such information is not included in the LCP of the given bridge.

4.5 Extra traffic caused by repair and maintenance actions

In situations when the bridge is subject to repair and maintenance actions it is a common situation that extra traffic is generated. This could be due to partly or full closure of the bridge, in one or in both driving directions. When this occurs, extra traffic is generated, due to slowing down the average speed of traffic, with congested driving patterns or one or more full stops. In such situations part of the traffic may choose alternative routes, i.e. detours that will give a longer driving distance. The extreme situation is a full closure of a bridge, in both directions, and all traffic has to travel a detour of significant length, and maybe also passing urban areas with other traffic that is also affected and slowed down due to local road capacity limits.

An LCA of a bridge has to be able to account for such situations. If the emissions and environmental impacts from extra traffic caused by planned repair and maintenance actions for one given bridge design are much higher than for another bridge design, the LCA should clearly be able to calculate the difference between the two design. Hence, one may try to optimise a bridge design also regarding environmental impacts due to planned OR&M actions, as specified in the life cycle plan (LCP) of the bridge. This would be particularly important when a bridge is located where there is heavy traffic, and different bridge designs would cause different OR&M actions, which again would lead to different emissions from extra traffic generation.

BridgeLCA offers the possibility of input of information in order to calculate vehicle fuel consumption due to extra traffic generated by planned OR&M activities. The analyst would need to input the number of days with planned OR&M action in the whole bridge service life that lead to partly or full bridge closure. In addition the analyst need to input assumptions on the traffic pattern during such days, and the following information:

- Assumed mix of vehicle fleet (% share of passenger petrol cars, passenger diesel cars, buses and lorries)
- Assumed extra driving distance, average driving speed, average daily traffic (*ADT*), and assumed traffic load driving pattern (free flowing traffic, average flowing traffic, congested traffic).

On this basis the fuel consumption from extra traffic generated by planned OR&M actions are calculated based on *ADT*, the mix of the vehicle fleet, distance, average speed and assumed traffic load driving pattern. This fuel consumption (petrol or diesel) is then used to calculate emissions and environmental impacts caused by the extra traffic due to planned OR&M actions.

4.6 Environmental impact categories and LCIA method

BridgeLCA includes a selection of 8 different environmental impact categories; see Table 4.1. The first five categories are all calculated by use of the ReCiPe life cycle impact assessment (LCIA) method, while the last three categories are calculated by use of the USEtox method.

Table 4.1: Environmental impact categories and corresponding LCIA characterization method

Environmental impact category	LCIA method
Climate change	ReCiPe, kg CO2 eq
Ozone depletion	ReCiPe, kg CFC-11 eq
Terrestrial acidification	ReCiPe, kg SO2 eq
Freshwater eutrophication	ReCiPe, kg P eq
Fossil depletion	ReCiPe, kg oil eq
Human toxicity, cancer	USEtox, CTUh
Human toxicity, non-cancer	USEtox, CTUh
Ecotoxicity	USEtox, CTUe

The chosen impact categories are selected partly due to what was proposed in the PCR Basic Module for Constructions (International EPD®System 2010), as referred in Section 2.4, and partly due to what has earlier been decided by the ETSI project:

- *BridgeLCA* should include environmental impact categories that are commonly important to construction projects, without using too many categories. This points in the direction of what is proposed by the above-mentioned PCR.
- According to results from ETSI Stage 2 one found that Climate change, Acidification and Abiotic resource depletion were the most important impact categories for road bridges. Europhication was found to be less important, and the creation of ground level ozone was found to be not important.
- In addition, one wished to include in particular energy consumption and toxicity impacts. Hence, *BridgeLCA* includes the impact categories Fossil depletion, Human toxicity (cancer and non-cancer) and Ecotoxicity. These impact categories were not included in the LCA model developed in ETSI Stage 2, and are now added in Stage 3.

As methods for life cycle impact assessment (LCIA) calculation, *BridgeLCA* uses methods that are recommended for best-practice LCA in the LCA Handbook (ILCD 2010b). According to this ReCiPe is used for the calculation of midpoint indicator values for the first five impact categories, and USEtox is used for the calculation of the three toxicity midpoint indicators. Both methods are available in the SimaPro LCA software, and the Ecoinvent v2 database is used for calculating the LCI stressors of inputs to the bridge system.

Midpoint indicator impact values in *BridgeLCA* are specified for each input (material or energy) to the bridge system. There are three alternatives for use of such values, as shown in Table 4.2. The default values are taken from the Ecoinvent v2 Database. For this the user of *BridgeLCA* needs a licence from Ecoinvent. These default values are always used for input materials of minor LCA impact, however, for materials of major LCA impact (see Section 4.3) *BridgeLCA* also offers the possibility of using country specific average impact values (if available) or project specific impact values (if available). Country specific average impact values for major materials are developed by Task 2 in the ETSI project, and can be inserted in *BridgeLCA* as soon as they are finally reported. Project specific impact values could be inserted on the basis of local more precise information, such as EPD data for a given materials. The calculations are coded in a way so that project specific data will always be preferred and used if they are present. If not, the code asks for country specific values, in the given country of the bridge. If also these are not present, the code automatically tells to use Ecoinvent values in the calculations.

Table 4.2: Options for use of midpoint indicator impact values in BridgeLCA

Input type	Ecoinvent	Country specific	Project specific
Materials of major LCA impact	X	X	X
Materials of minor LCA impact	X		
Energy	X	X	X
Blasting	X	X	X
Transportation	X	X	X

BridgeLCA midpoint indicator values for the first five environmental impact categories listed in Table 4.1 are also calculated further by normalization and weighting, according to Equations 2.3 and 2.4. Normalization is calculated by using latest ReCiPe normalization factors on a per capita emission basis in EU 25+3 for year 2000. Default weighting in *BridgeLCA* is equal weighting among all impact categories, but the analyst can change this according to future policy priorities defined by the national road administrations. See Table 4.3 for the values of normalization and default weighting factors used in the LCA model.

Table 4.3: Normalization and weighting factors used in BridgeLCA

Environmental impact category	Normalization factors	Weighting factor
Climate change (GWP)	8,92E-05 kg CO2 eq	1 (default value)
Ozone depletion (ODP)	4,55E+01 kg CFC-11 eq	1 (default value)
Terrestrial acidification (AP)	2,91E-02 kg SO2 eq	1 (default value)
Freshwater eutrophication (EP)	2,41E+00 kg P eq	1 (default value)
Fossil depletion (FD)	6,01E-04 kg oil eq	1 (default value)
Human toxicity, cancer (HTC)	Not included	Not included
Human toxicity, non-cancer (HTNC)	Not included	Not included
Ecotoxicity (ET)	Not included	Not included

Toxicity impact values are not subject to normalization and weighting, and are therefore not included in the calculation towards a single-score aggregated impact result. The reason for this is that toxicity impacts are still (today) subject to much higher uncertainties.

4.7 Energy consumption

In ETSI Stage 3 one decided to include more explicitly the calculation of energy consumption. This is done by calculating:

- Non-renewable energy consumption: i) fossil energy, ii) nuclear energy, and iii) non-renewable biomass energy
- Renewable energy consumption: i) renewable biomass energy, ii) wind, solar and geothermic energy, and iii) hydropower

The share of these different energy sources is calculated in absolute values (MJ) and in per cent of the total. It is also shown how much each bridge part, or activity in the service life, contributes to the energy consumption.

5 *BridgeLCA* program description

The LCA tool developed in the ETSI Stage 3 project is given the name *BridgeLCA*, and it is an EXCEL tool for calculating the life cycle environmental impacts of a bridge system, according to the specifications given earlier in Section 2 and 4. In this section we present only some basic features of the tool.

However, first, let us revisit some of the key issues when running BridgeLCA in order to examine a given bridge. These are:

- The goal is intended to get information on how the design of a new bridge will influence the environmental life cycle quality of the bridge, so that one can improve the bridge design.
- The scope covers all life cycle phases: production, construction, OR&M, and EOL.
- Environmental impacts will occur as a result of consumption of inputs to the bridge system, and inputs are grouped in: i) materials of major LCA impact, ii) materials of minor LCA impact, and iii) other input factors (energy, blasting and transportation).
- For materials of major LCA impact one should use project specific emission data if available, if not, national average emission data, and if not such is available, default values from the Ecoinvent LCA Database. For materials of minor LCA impact, only Ecoinvent default data are used. For other input factors one can use project specific or national specific emission data, if available.
- Five selected environmental impact categories are included, in light of what is recommended used in Environmental Product Declarations (EPD) for construction materials, and according to what is found to be the most important impact categories in literature and own tests. In addition we also include three toxicity impact categories.
- System boundaries and allocation is drawn is such a way that benefits from using secondary (scrap) materials in a bridge are credited the LCA of the bridge, however, benefits from materials recycling and energy recovery to other product systems, after the end of life of the bridge, are credited the other systems, not the LCA of the bridge.
- The tool calculates midpoint impact indicator values, so that one can identify their causes in the bridge system.
- The tool can also calculate a normalized and weighted single-score indicator, however, this result will be far more subjective and will rely upon a consensus on weighting factors among key bridge stakeholders. In order to reduce uncertainty, toxicity impact categories are not part of such single-score calculations.

The tool has 18 worksheets, linked into a complete model. Below is given a synopsis of what is included in each worksheet. More detailed information is given in the User Manual.

- Worksheet No. 1 is just a welcome information, and links also to the User Manual
- Worksheets No. 2 and 3 are where the bridge input data are inserted. Consumption of input materials, energy, blasting and transportation amounts, related to each phase of the bridge life cycle are inserted in worksheet No. 2, while data on the generation of extra traffic due to bridge closures in the OR&M phase are inserted in worksheet No. 3.
- Worksheets No. 4 and 5 give the calculated results. Worksheet No. 4 presents LCA results (in figures and tables), as a single-score normalized and weighted value, and as parallel midpoint values for each environmental midpoint indicator. Worksheet No. 5 gives results for consumption of various types of energy carriers (renewable and non-renewable sources).
- The following worksheets are for background information and calculation basis mainly. Worksheet No. 6 gives the actual impact matrix that is used in a given LCA calculation, and lists all midpoint indicator values for all inputs to the bridge system, according to what information is provided regarding product specific emission data, national specific emission data, and Ecoinvent data. Worksheets No. 7 to 14 provide the opportunity to give such data for each midpoint indicator (GWP, ODP, AP, EP, FD, HTC, HTCN and ET), and this then feed automatically into Worksheet No. 6.
- Worksheet No. 15 collects an overview of all Ecoinvent data that are used in the model.
- Worksheet No. 16 collects an overview of all energy consumption results that are related to each input to the bridge system.
- Worksheet No. 17 contains a menu-set for macros used in the model.
- Worksheet No. 18 contains codes for calculating fuel combustion on the basis of composition of a car-fleet used as the basis for calculating how extra traffic due to bridge closure in OR&M actions influence fuel consumption.

Screen-print of some of the Worksheets in *BridgeLCA* are shown in the following figures. The contents of the figures are hardly readable, due to small fonts, but this is not important. The aim of showing the figures is merely to give an illustration of how these worksheets function.

Figure 5.1 and Figure 5.2 show the left-hand and the right-hand parts of a large table, where the user is to insert (in the white cells) quantities of inputs to the bridge system, as well as transportation (one-way) distances by each transportation mode (ship, lorry, train), and distinguish between the different phases of the bridge life cycle (material production, construction, OR&M and EOL). This table is where most of the input data from the user is to be inserted, and the user can decide to carry out a rough (simplified) LCA with little information only, or a detailed LCA with lots of information inserted.

Figure 5.3 shows a screen-print of the Input traffic worksheet, where the user is expected to manually insert data related to the assumptions on bridge closure duration due to OR&M actions, and traffic disturbances caused by such closures. This represents a simple traffic calculator with 4 waypoints and 4 different paths for traffic. The user is to insert also assumptions on detour driving distance, speed of traffic, the daily average traffic (*ADT*), the type of traffic load (congested traffic, average flowing traffic or free flowing traffic), as well as the assumed mix of the vehicle fleet.

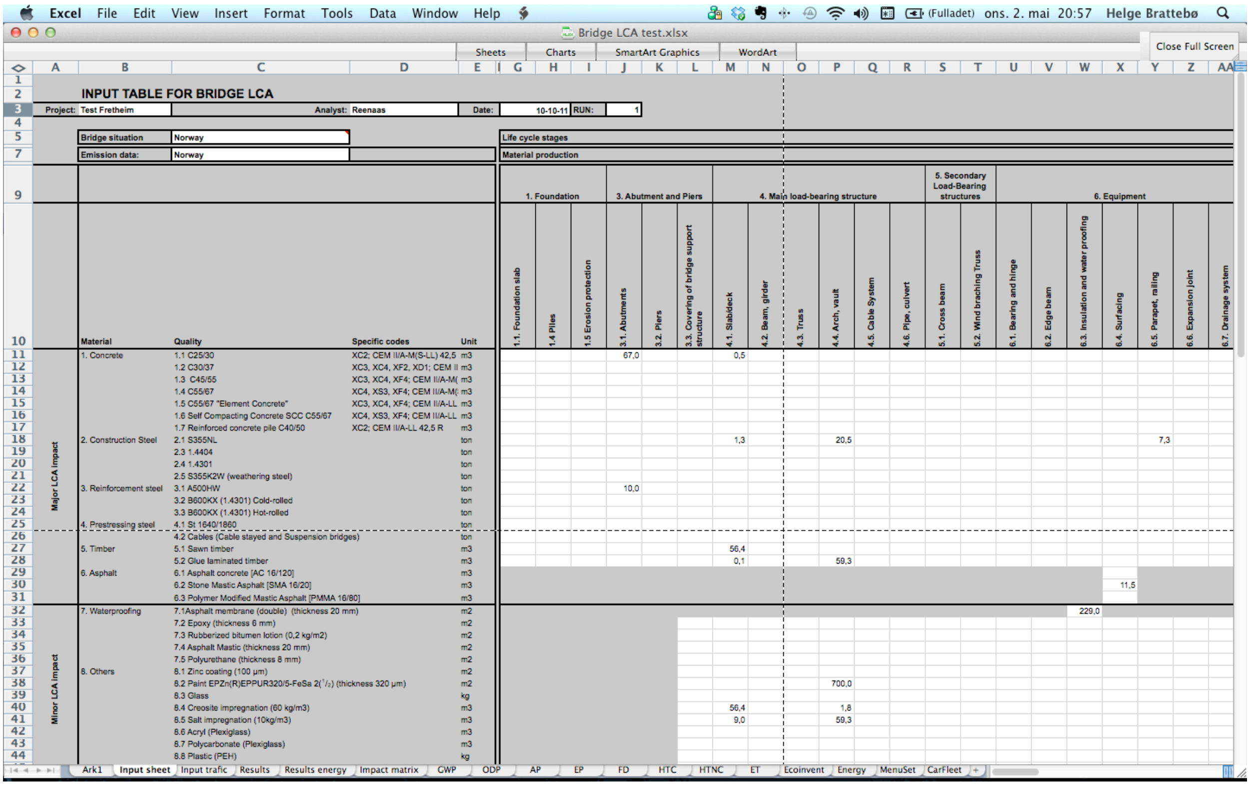

Figure 5.1: The left-hand side of the Input worksheet, for the user to manually insert data

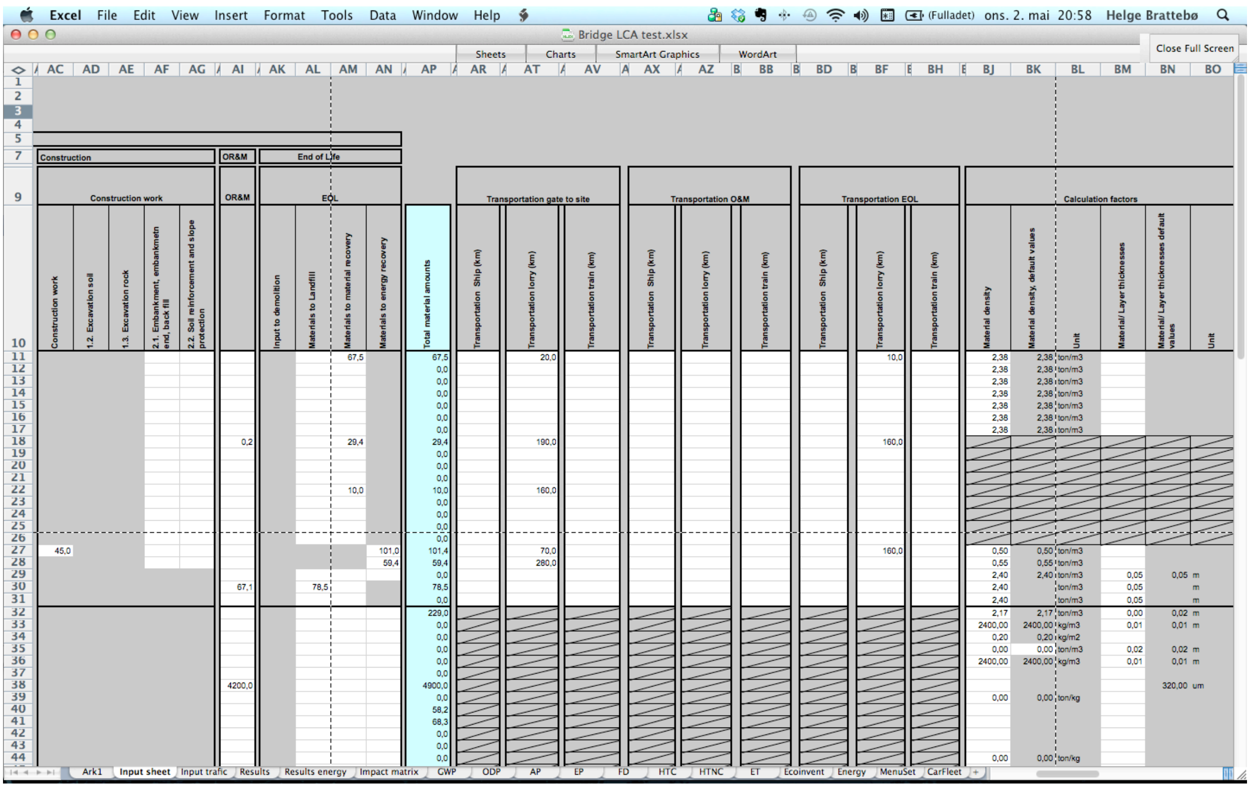

Figure 5.2: The right-hand side of the Input worksheet, for the user to manually insert data

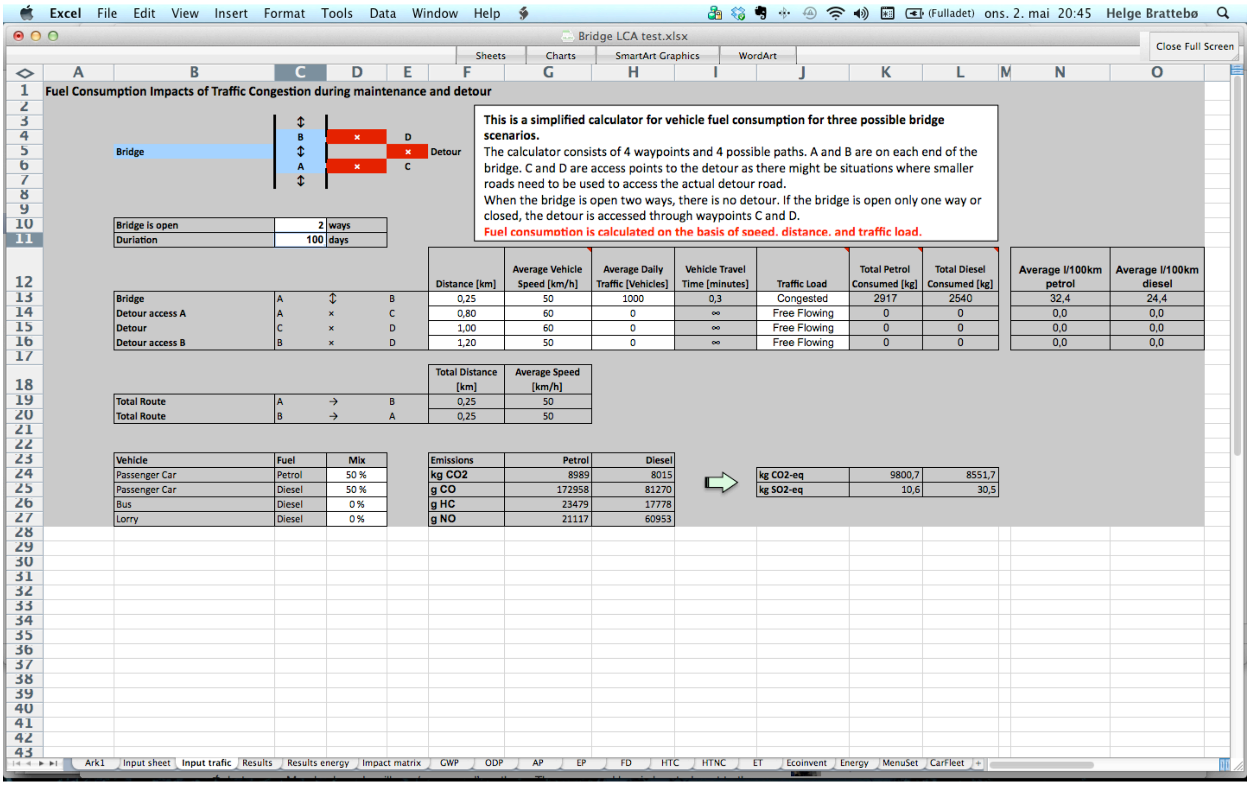

Figure 5.3: Screen-print of the Input traffic worksheet, for the user to manually insert data

In the example shown in the figure above, the bridge is never assumed to be fully closed, either driving direction, but there is OR&M actions during the service life for 100 days, and this causes a congested traffic load pattern for 1000 *ADT* vehicles (50% passenger petrol cars and 50% passenger diesel cars), for a distance of 250 meters at a speed of 50 km/hour. As seen, this simple (hypothetic) example will cause a total petrol consumption of 2917 kg and a total diesel consumption of 2540 kg.

The user is free to assume any combination of traffic disturbances, within the framework of this calculator method (4 waypoints and 4 possible paths). The calculator can be used to examine likely consequences of different bridge OR&M actions during the service life of a bridge. Hence, one may estimate the corresponding impacts of different life cycle plans for a given bridge, which will of course depend on where the bridge is located in relation to traffic loads, disturbances and extra driving distances.

Figure 5.4 and Figure 5.5 shows a screen-print of the Results worksheet, with the upper part (aggregated LCA results) and the lower part (detailed LCA results) of the worksheet, respectively. The aggregated results represent values after normalization and weighting. As seen in Figure 5.4 (see the two bar graphs to the left) there is no difference between normalized LCIA results and weighted LCIA results in this example, since one has used equal weighting factors (1:1:1:etc) for all midpoint impact categories. If a non-equal weighting were used, there would be a difference between the two graphs. This example shows that the aggregated impact is mainly due to fossil depletion (FD) and global warming (GWP). The upper graph to the right shows 'Relative midpoint LCIA results', where each environmental impact indicator is presented on a relative basis, in order to illustrate which phases of the bridge system are the most important. We can see that the material production phase of bridge components (lower blue part) dominate for all impact indicators, but there is also a significant contribution from the OR&M phase (next to upper green part) for some indicators.

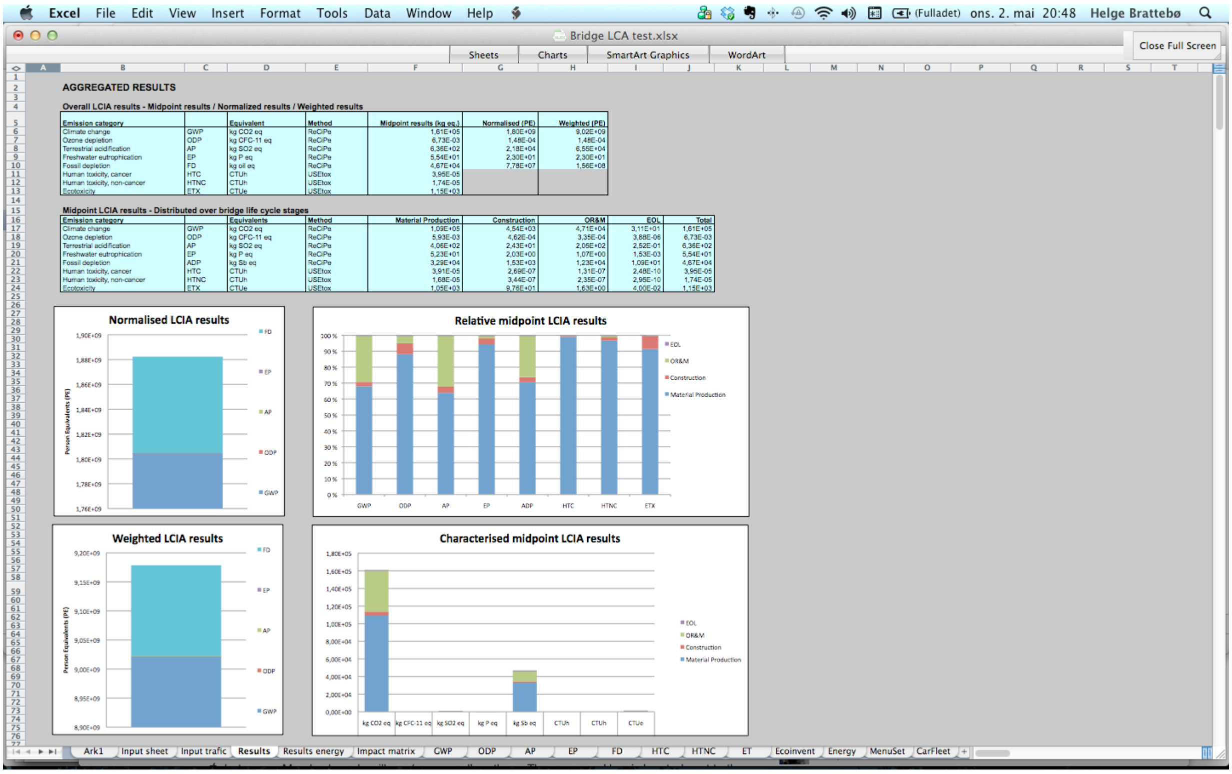

Figure 5.4: Screen-print of upper part of the Results worksheet, with aggregated LCA results

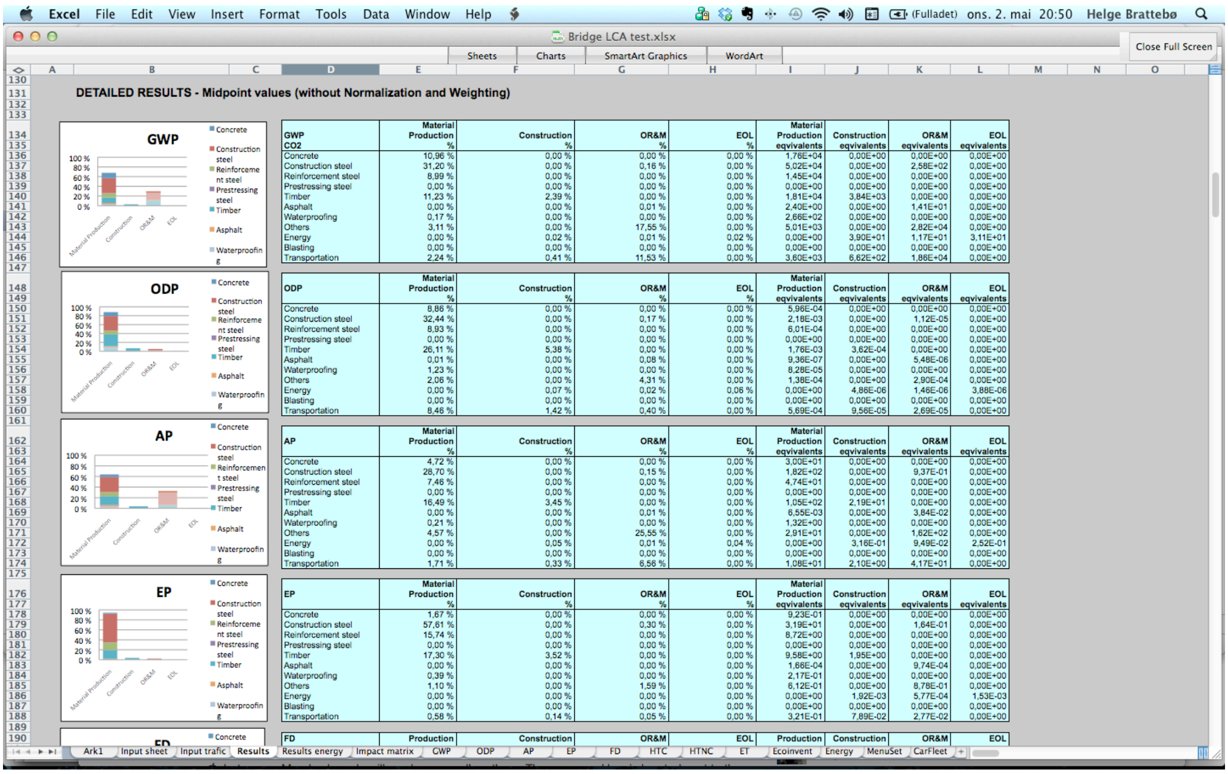

Figure 5.5: Screen-print of lower part of the Results worksheet, with detailed LCA results

In Figure 5.5 we can see more detailed results, i.e. how selected inputs to the bridge system, in each phase of the life cycle, contribute to each of the impact indicators. Such results provide an excellent basis for locating what are the most important causes to each of the environmental impacts. Hence, this may also serve as a basis for simulations during planning, and learning how best to change the design of a bridge in order to minimise life cycle environmental impacts.

Figure 5.6 shows results for life cycle energy consumption within the bridge system, i.e. what are the amounts of energy consumed (MJ and %) for different energy sources (renewable and non-renewable), and which inputs the energy consumption is caused by. The example shows that fossil energy is the main source, then biomass energy, and that many types of inputs contribute to energy consumption, but with timber, asphalt and construction steel as the three largest ones.

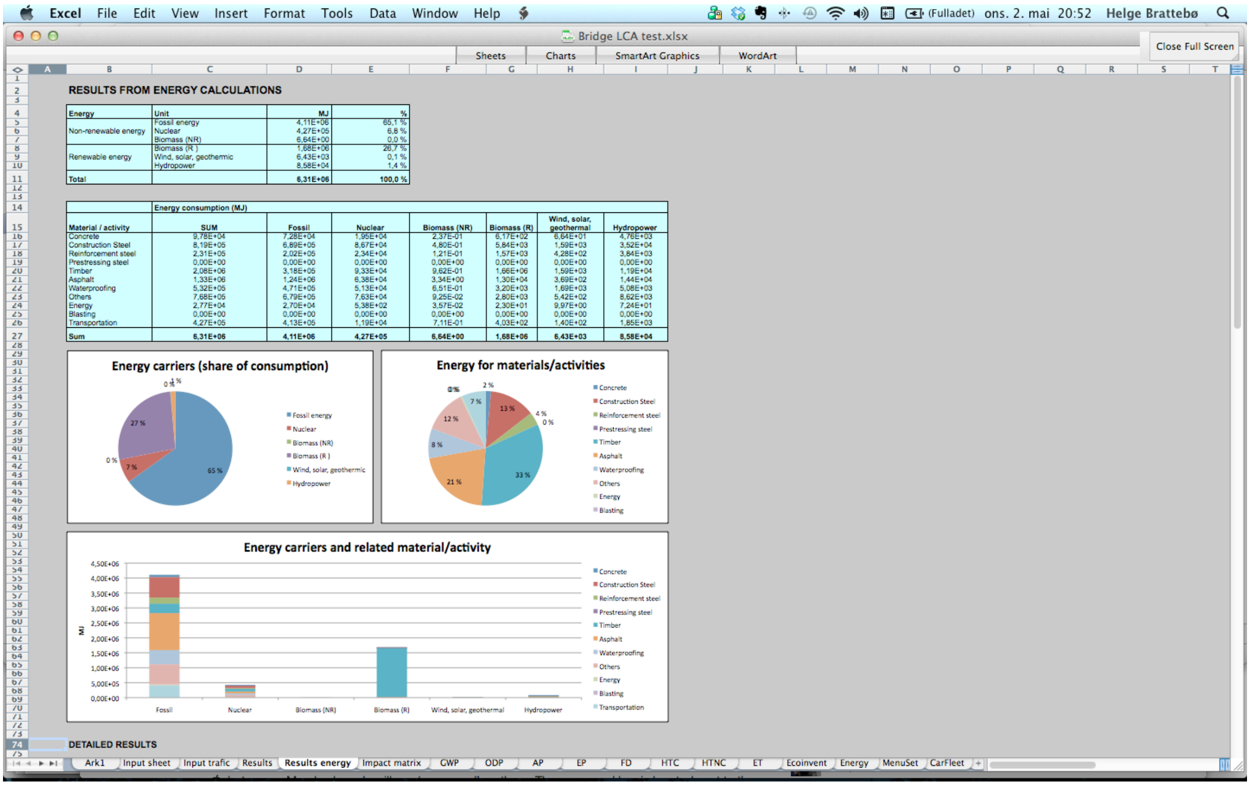

Figure 5.6: Screen-print of Results energy worksheet, showing energy consumption results

BridgeLCA will of course give different results if a bridge is designed in different ways. For comparative purposes, the tool should be used for one given bridge, serving a defined traffic (and thereby a defined function) over a given service life. One may then test alternative design options, each with its own life cycle plan (LCP) and OR&M actions. One could also test alternative locations of a given bridge, if this might imply that the bridge would need to have different lengths and/or heights, and thereby consume different amounts of inputs. One may also test alternative bridges, using different designs and locations, on a per m^2 effective bridge area basis.

The examples given in this section are not at all exhaustive. There are several possible ways to use the *BridgeLCA* tool in order to support decisions in the planning and design phase. This could be for early-stage planning, when actually little exact information about the bridge is known. Then, many assumptions and best estimates would have to be taken. Or, the analysis could be made in the detailed-planning phase, or even after a bridge is built, when accurate data on all inputs to the bridge system are available.

In order to speed up the process of applying LCA for road bridges, it is highly recommended that *BridgeLCA* is tested for a large number of case studies in all Scandinavian countries. This would provide a good basis for understanding better the following critical questions for the future design and analysis of road bridges:

- What types of environmental impacts do road bridges cause?
- Where in the bridge life cycle are the main contributions to environmental impacts?
- Which bridge parts and which materials are the most important ones?
- How are different design options effective in reducing environmental impacts?
- What are the strengths and the weaknesses of *BridgeLCA* for a robust analysis?
- Which elements of the bridge system do we really need better data for?
- What should be the priorities for building and updating bridge LCA databases?
- How can bridge designers most actively take the methodology and the *BridgeLCA* tool into use, and what is the needed support from LCA experts and from the national road administrations?

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