KUNGLIGA TEKNISKA HÖGSKOLAN

Citybanan

Life Cycle Assessment

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Abstract

Citybanan is a project of building a 6 km tunnel running North to South of Stockholm. This infrastructure will have some impacts on the environment that should be evaluated. This report presents a short Life Cycle Analysis of the tunnel part, the tracks and the power supply. Modeling with SimaPro shows that steel in the construction phase presents the main impact by far. Efforts for improving the whole life cycle of the Citybanan should be put on the manufacturing of steel.

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Introduction

Environmental impacts of transportation systems are often discussed in the society today. The discussion is mostly focused on emissions related to vehicle operation, but studies have shown that construction, maintenance and operation of infrastructure also have a significant contribution to the environmental load of the infrastructure system (Stripple and Uppenberg, 2010). Rail transportation is often pointed out as the most environmentally sustainable alternative. This is mainly due to the fact that the trains are driven by electricity. However, to give a complete description of transport related environmental problems it is necessary to analyse the whole transportation system in a holistic way and apply a life-cycle approach (Stripple and Uppenberg, 2010). This does not only include analyses of the operation of vehicles, but also the entire infrastructure needed for operating the vehicle.

Citybanan in Stockholm is a new tunnel for commuter trains. When the construction is complete, the commuter train traffic in the city will be improved and other train traffic to and from Stockholm can increase. According to Trafikverket (The Swedish transport administration) (2010a) this is described as a positive feature of the tunnel as the greenhouse gas emissions will decrease, due to a decrease in the use of cars. However, this statement is only based on operation of the trains and impacts from construction, operation and maintenance of the tunnel itself has not been analysed. The Environmental Impact Assessment (EIA) (Banverket, 2007a) concludes that impacts will be highest during construction; however this is related to local impacts such as changed hydrology and health impacts. Impacts from material and fuel use are not discussed.

Furthermore the EIA is written with a time perspective from start of construction (2006) until 2030 (Banverket, 2007a). As tunnels and railways have a long lifetime, big parts of the life-cycle are excluded, such as maintenance which could cause significant impacts in terms of material use and machine related activities. By widen the analysis and also consider extraction of raw materials; production of components such as cables and rails; energy use during construction of the tunnel; material need for maintenance; possibilities for recycling of used components etc. it is possible to determine what parts of the lifecycle have the most significant impacts and where it is most important to make changes so that the environmental load can be decreased.

This report describes how a Life Cycle Analysis (LCA) of Citybanan has been performed. In a first part, the frame and context are described. Then the methods for performing the modelling with SimaPro are explained. Results of the modelling are then described in the third section, and then analysed. Recommendation and discussion about the performed LCA are presented at the end of the report.

1. Goal and scope

In the goal and scope definition, the aim of the study is determined and based on this, the scope and the requirements for modelling are determined (Bauman and Tillman, 2004).

1.1. Aim

The aim of the study is to assess the environmental impacts of a railway tunnel using LCA-methodology and thereby identify the materials and processes that have the most significant contributions to the environmental load. The case of Citybanan in Stockholm is chosen as a basis for the analysis.

1.2. Methodology

There are different types of quantitative LCA studies with differences in methodology and applications (Bauman and Tillman, 2004). This study was performed as a stand-alone, accounting LCA. Accounting LCA allows identification of the environmental impacts associated with a product or service. Stand-alone LCA implies that only a single product or service is studied (Bauman and Tillman, 2004). Choice of data depends on type of LCA used. For accounting LCA-studies average data is used (Bauman and Tillman, 2004), as it is the case in this analysis. As far as possible site specific data has been used. When this has been lacking, data has firstly been taken from other railways in Sweden or Trafikverkets minimum standards for construction of tunnels. Detailed explanation of the data used is found in section 2.2. and table 15 in appendix.

Suggestions for how to construct the model have been taken from the product category rules (PCR) for Rail Transport and Railway Infrastructure, in the PCR 2012 and from the environmental product declarations prepared for Botniabanan (Stripple and Uppenberg, 2010). The guidelines could however not be applied directly due to lack of data for Citybanan. This is explained further in section 1.6.

The software tool SimaPro 7 (PRéConsultants, 2008) was used for modelling.

1.3. Impact categories and impact assessment methods

There are a number of different impact assessment methods available in SimaPro. In this study, the method ReCiPe Midpoint (Hierarchist) has been used. This means that impact categories are studied at the midpoint level (e.g. acidification) as opposed to the endpoint level (e.g. damage to human health). The characterisation models are a source of uncertainty and in ReCiPe the sources of uncertainty are grouped into three different perspectives (Individualist, Hierarchist and Egalitarian). The Hierarchist perspective is based on the most common policy principles with regards to different issues, e.g. the time-frame. The time frame is different for different impact categories. Climate change and terrestrial acidification have a time frame of 100 years; ionising radiation 100 000 years; human-, terrestrial-, freshwater- and marine ecotoxicity infinite time-frame. No time-frame is given for the other impact categories. The Hierarchist perspective coincides with the view that impacts can be avoided with proper management (Ministry of housing, spatial planning and the environment – Netherlands, 2009).

The impact categories considered in the model are:

1. climate change
2. ozone depletion
3. terrestrial acidification
4. freshwater eutrophication
5. marine eutrophication
6. human toxicity
7. photochemical oxidant formation
8. particulate matter formation
9. terrestrial ecotoxicity
10. freshwater ecotoxicity
11. marine ecotoxicity
12. ionising radiation
13. agricultural land occupation
14. urban land occupation
15. natural land transformation
16. water depletion
17. mineral resource depletion
18. fossil fuel depletion

Normalisation can be performed in order to relate the impacts of a studied product to the total environmental impact in a region. In that way, the relative contribution of the product can be determined. While normalisation can facilitate comparison, it also hides the real numbers (Bauman and Tillman, 2004). To avoid a false sense of reality, normalisation is not performed in this study, except for the sensitivity analysis of the steel since no comparison between impacts is made (use of the methodology ReCiPe Midpoint (H) V1.05 / Europe ReCiPe H available in SimaPro).

1.4. Intended application and audience

The LCA could be used by authorities to lessen the impacts on the environment of future tunnel projects. The performed LCA needs to be developed more (e.g. more exact data or more complete processes) but the results could be used as a start for a more complete LCA. Intended audience would be authorities, the Swedish Transport Administration (Trafikverket) and other interested parties such as planners and scientists.

1.5. Functional unit

The main function of the tunnel Citybanan is to make it possible for passenger trains to cross Stockholm rapidly, and stop at three different stations. For the sake of the study, the functional unit chosen is the tunnel itself. Each quantity is therefore given for the entire tunnel, within the defined system boundary. The tunnel is 5600 meters long and mostly constructed as a tunnel for double tracks with a width of 12m, with exceptions at stations where the tunnels are for single tracks with a width of 7m. A more detailed description of Citybanan is found in section 1.7.

1.6. System boundaries

60 years has been chosen as time-frame as recommended in EPD (Stripple and Uppenberg, 2010). Some could say that a LCA which does not consider the end-of-life is a biased LCA, but as there are so many uncertainties regarding the end-of-life of the tunnel, it is still worth performing the LCA without the end-of-life.
The chosen system therefore includes all steps of the life cycle of the tunnel, except the end-of-life, since the study is performed over a life-frame of 60 years. This means that the performed LCA takes into consideration all steps from the extraction of raw materials to the operation and maintenance of the tunnel.

The tunnel itself is chosen as functional unit, but this does not include the stations, as well as the trains circulating in the tunnel, telecommunication and signalling systems and other installations such as pipes for water supply or cables for bringing the electricity from the power plant. Only the tunnel part between stations has been considered, including the tracks and the power supply system for train. This is a difference from the guidelines in the PCR and EPD, where these excluded installations should all be included in the system. The reason for excluding them in this LCA has been lack of time and data to do a LCA for the whole tunnel as described in the PCR. Furthermore, the PCR states that only resources that are contributing to more than 1% of the different resource use categories should be listed. In the performed LCA, this rule has not been applied.

Table 1 shows how the problem has been approached in the LCA performed.

Table 1 Assemblies and sub-assemblies in the LCA for Citybanan

Track	Tunnel	Power supply
Rails	Explosives	Cables
Sleepers	Rock bolts	Contact line
Ballast	Concrete and shotcrete	Contact rail
Sound protection mat	Construction steel	
Geotextile	Other construction material	
Rail laying train	Construction machines and ventilation	
	Tunnel equipment	

Many resources used originate from mining, such as the iron used for the steel or the rocks used for the ballast. Some other materials are produced from oil, such as the neoprene pads used in the sleepers, or plastic parts of other components. Impacts due to the extraction of the raw materials are taken into consideration and have been indirectly modelled in SimaPro. “Intermediate” manufactured products have been chosen, making it possible to include also the impacts due to extraction, and simplifying the model. For instance, “hot rolled steel” has been directly chosen in SimaPro as input for the rails, and the impacts of extracting materials for this “hot rolled steel” as well as the production impacts were already taken into account in SimaPro.

The project of Citybanan is relevant to be considered in the region of Stockholm, since the real use and most of the impacts of Citybanan concern this area. This project needs however to be in some cases thought at a larger scale when performing the LCA. Some products used for Citybanan are in fact produced out of Sweden, such as the steel for rail produced in Austria. Details of the transportation terms needed for most of the products are available in Table 13 in the appendix.

As mentioned before, stations are not included in the LCA. This is mainly due to a lack of data, and a relative uncertainty concerning the bill of quantity of those stations since they have not been finished yet. The main drawback by omitting the stations is that some important factors leading to main impacts for Citybanan could be omitted, such as the impacts due to the large quantity of concrete used for building the stations. Trains are also not considered, since they constitute by themselves an entire LCA, and require much information from the manufacturer of the train. Linked to the trains, telecommunication and signalling systems are not included. Telecommunication system used for Citybanan might therefore be partly embedded with others public transportation infrastructures. Computer used for guiding the trains might for instance already exist and being used for another purpose in a telecommunication centre for public transportation in Stockholm region.

Allocation problems are arising when several products/functions are sharing the same processes and the environmental load is to be expressed in relation to only one of the products/functions (Bauman and Tillman, 2004). In the LCA performed this occurs during manufacturing of all the infrastructure components when other products than those used in Citybanan are manufactured in the same place (multi-output allocation). This can be solved by increasing the level of details, however no such efforts have been made as there are so many different types of components manufactured and limits have had to be drawn. Allocation problems are also occurring during transportation of the components as it can be assumed that other products are transported at the same time. This has also not been considered. Allocation problems occurring due to waste treatment are described in section 2.2.4. – Waste management.

1.7. Description of Citybanan

Citybanan is a 6 km long railway tunnel crossing Stockholm from Stockholm Södra in the southern part of the city, to Tomteboda in norther Stockholm, see Figure 1. There are three stations: Odenplan, City and Stockholm Södra. The main idea of the project Citybanan is to improve the traffic of trains crossing Stockholm. Nowadays, commuter trains as well as national and regional trains use the same two tracks to access Stockholms Central. This constitutes a bottle neck for the train traffic in the whole Stockholm region, and is limiting the development of the train traffic. All commuter trains should use the Citybanan tunnel after the end of its construction in 2017, letting the other tracks free for national and regional trains. The project has been proposed by the Swedish State Railway in 1988 and has been seriously considered from 2002. The construction started in 2007. The total cost of this infrastructure is estimated in 2007 to be 16.8 billion Swedish crowns (Trafikverket, 2012a).

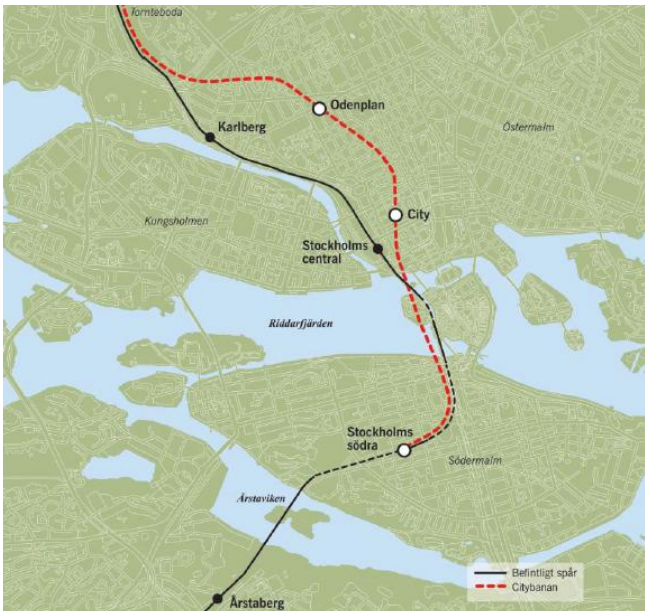

Figure 1 Map of the route of the Citybanan (Source: Banverket, 2007a)

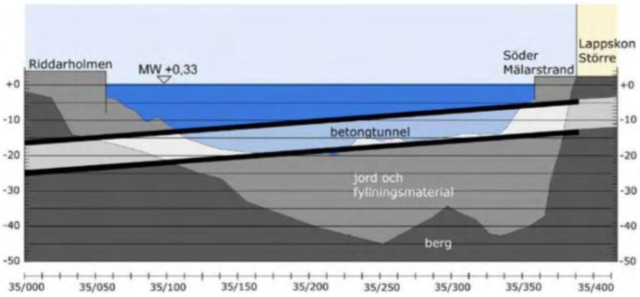

Figure 2 Cross-section of the Citybanan between Riddarholmen and Södermalm (Source: Banverket, 2007b)

Citybanan is mainly constructed as a rock tunnel. Two major sections of the tunnel are constructed in concrete, more precisely the first 150 meters of the tunnel at Tomteboda as well as the tunnel under Söderström, between Riddarholmen and Söder Mälarstrand, see Figure 2. The tunnel section under Söderström has required special engineering solutions and is an immersed tunnel resting on steel poles attached to the seabed. Parallell to the tunnel there is service- and rescue tunnel running along the whole length of the main tunnel (Trafikverket, 2011a)

Table 2 Specific tunnel related data for Citybanan

Length of the tunnel	5600 meters
Length of the service- and rescue tunnel	5600 meters
Total length of concrete tunnels	510 meters
Width of concrete tunnel under Söderström	21 meters
Width of tunnel (one track)	7.5 meters
Width of tunnel (double track)	12 meters
Area of tunnels (one track)	65 m^2
Area of tunnels (double track)	110 m^2
Area of service- and rescue tunnel	40 m^2
Height of tunnel	6.5 meters

1.8. Assumptions and limitations

Following assumptions and limitations applies to all parts of the model. Assumptions and limitations related directly to a specific material or component are described in section 2.

1. Material quantities needed for construction are as far as possible site specific data gathered from environmental reports for Citybanan and information from Trafikverket. It is assumed that these data include materials both for the main tunnel and the service and rescue tunnel.

2. For all materials needed it is assumed that there is a waste factor of 5%, except for concrete and shotcrete where the waste factor is 30% (Miliutenko, et al., 2012). To avoid double counting, the waste factor is not added in the production of materials (as this is included in SimaPro), but it is assumed that the construction companies need to buy more material than they will actually use in the tunnel.

3. Transportation is only specified between production of infrastructure components (e.g. rails) and construction of the tunnel. Transportation of raw materials and of waste to waste treatment does not need to be specified because included in SimaPro.

4. Since many maintenance activities consist of replacement of components of Citybanan, material inputs and transportation linked to these maintenance activities are assumed to be the same as during construction.

2. Life cycle inventory and analyses

2.1. Process flowchart

The following flowchart (Figure 3) shows the main processes included in the LCA. The raw material processes concern the import, transport, mining and exploration processes for the energy carrier supply chain. Then these raw materials are transported to a first manufactory where they are transformed into a manufactured product, such as iron ore is transformed into rails. This step can group several sub-processes. This new material is then transported to the construction site. On site, materials are re-cut, re-shaped or just applied for their use in the tunnel. After this construction phase come the operation and maintenance phases, when the tunnel is fully operational, and trains are circulating in the tunnel. At each stage, waste is produced and there are some emissions of pollutants. Also, natural resources and energy are needed.

As explained earlier in the report, the end-of-life is not taken into consideration, since the study is performed on a life-frame of 60 years. This is mainly due to the fact that we do not have much information about the end-of-life of the tunnel. Also all processes of construction and transportation of the machines used have been excluded as well as impacts related to construction workers on site

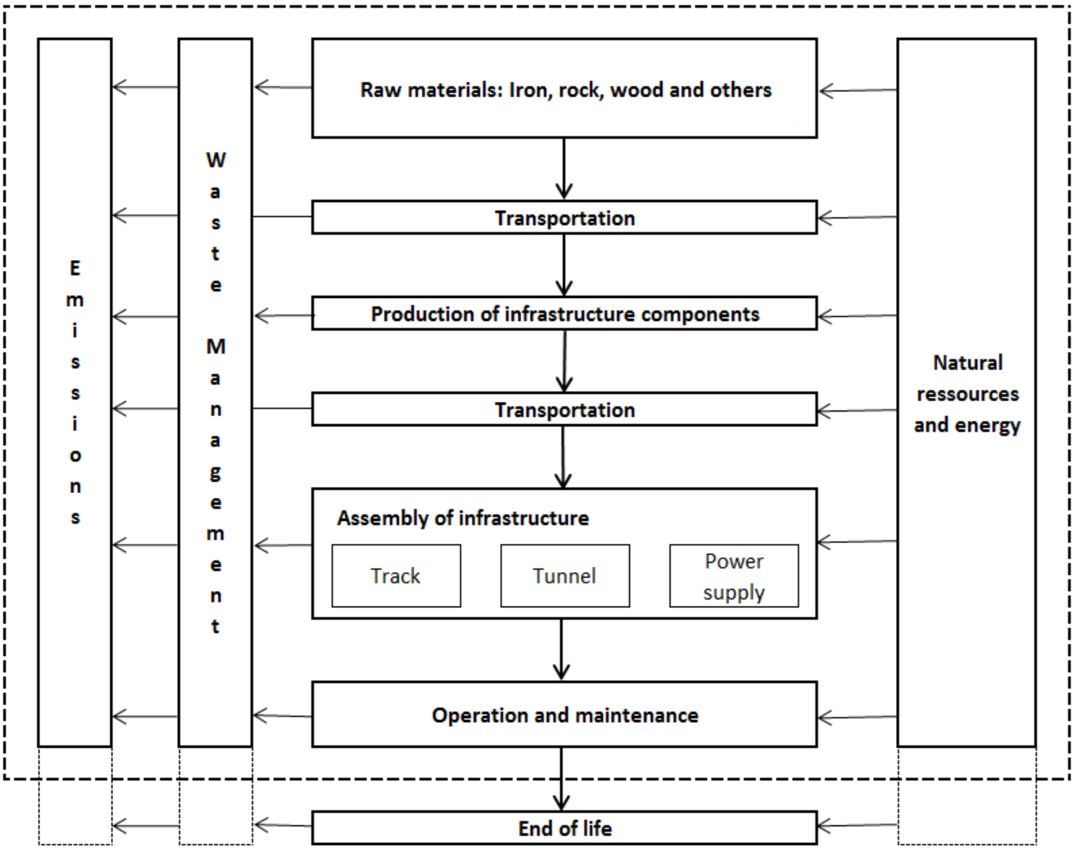

Figure 3 Flowchart of the Citybanan LCA

2.2. Data

In this section, materials and processes considered for construction, maintenance, operation and waste management of tracks, tunnel and power supply are described.

2.2.1. Construction

Tracks

The tracks consist of rails lying on concrete sleepers, over macadam ballast. Under the ballast there is a special sound protection mat made of rock wool to reduce structure born sound (Banverket, 2007b). The mat is covered by a geotextile (Trafikverket, 2012b). The concrete sleepers are assumed to include the same materials as the sleepers in Botniabanan, i.e. steel reinforced concrete, steel blocks and e-clips for attachment, neoprene pads and nylon isolator. The track construction is carried out by a diesel driven automated train that handles both sleepers and rails and filling of the track with ballast (Stripple and Uppenberg, 2010).

Table 3 shows material consumption for the construction of the tracks. For detailed assumptions and basis for calculations, see Table 8 in appendix.

Table 3 Materials and fuels needed for construction of tracks

Materials and fuels	Quantity	Use
Steel	878.33 tons	Rails
Concrete	1920 tons	Concrete in sleepers
Rubber	2.13 tons	Neoprene pads in sleepers
Nylon	1.41 tons	Nylon isolator in sleepers
Macadam	200000 tons	Ballast
Rock wool	1087.2 tons	Sound protection mat
Polypropylene	13.62 tons	Geotextile
Diesel	1497600 MJ	For rail lying train

Tunnel structure

Construction of the tunnel structure includes the following processes: blasting, removal of rock, rock reinforcement with bolts and application of shotcrete on the roofs and the walls of the tunnel (Trafikverket, 2010a). Some tunnel sections are also covered in concrete as explained in section 1.7. In addition to explosives, rock-bolts, shotcrete and concrete, there is also an input of steel, wood, asphalt and natural gravel during the tunnel construction (Banverket, 2009b; Trafikverket, 2010b; Trafikverket, 2011b; Trafikverket, 2012c).

Once the tunnel is excavated, it is equipped with doors, lights and other components. Included in this model are emergency exit signs and fire doors. The fire doors are considered to be steel doors with gypsum filling and the emergency exit signs to be made of polycarbonate with LED-diodes inside. Construction activities that are considered are electricity for pumping water and also electricity needed for drilling and ventilation during blasting.

Table 4 shows material and electricity consumption during construction of the tunnel structure. For detailed assumptions and basis for calculations, see Table 9 in appendix.

Table 4 Materials and electricity needed for construction of the tunnel structure

Materials and electricity	Quantity	Use
Explosives	2000 tons	Blasting
Steel	518680.49 tons	Used for concrete reinforcement, tunnel structures, rock-bolts and fire doors.
Concrete and shotcrete	350000 tons	To cover walls and roofs of the tunnel
Wood	394.45 tons	Tunnel construction
Asphalt	2189 tons	Tunnel construction
Natural gravel	33676.1 tons	Tunnel construction
Gypsum	0.89 tons	Filling in fire doors
Polycarbonate	0.45 tons	Emergency exit signs
LED-diodes	0,0007 tons	Lights in emergency exit signs
Electricity	31.21TWh	For drilling, ventilation and pumping water

Power supply

The power supply assembly consists of an overhead copper-wire in a contact rail attached to the roof. In addition there are also copper cables in the ground (Banverket, 2007b). It is assumed that the contact rail is made in aluminium and that it is similar to the one mentioned in Balfour Beatty Rail (n.d.). No site specific construction activities are considered.

Table 5 Materials needed for construction of the power supply

Material	Quantity (ton)	Use
Copper	24.14	Copper wires and copper cables
Aluminium	78.08	Contact rail

2.2.2. Operation

Only operation of the tunnel structure itself is included in the model and activities considered are pumping of water and electricity for emergency exit signs. Ventilation equipment is installed during construction for ventilation in case of fire and for good air quality at the stations (Trafikverket, 2010b). However, stations are not included in this study and ventilation is therefore not a part of the operation activities. In general for tunnels, one relies on the trains themselves to push the air out (Vägverket, 2004). The emergency exit signs on the other hand are assumed to always be lit.

Table 6 Electricity needed for the operation phase

Electricity	Quantity (for 60 years in total)
Pumping water	695121.9 kWh
LED-lamps	153159.5 kWh

2.2.3. Maintenance

Maintenance activities are modelled for tracks and the tunnel structure. There are no particular maintenance activities for the power supply (unless extreme events) and the contact wire and cables have a lifetime of up to 60 years (Swärd, 2006). It is therefore assumed that they are not replaced within the operation time considered in this study (see also Table 11 in appendix).

Tracks

Maintenance of the tracks consists of milling and exchange of rails, exchange of concrete sleepers and cleaning and exchange of ballast. Other maintenance activities are not considered.

Rails are milled every second year in order to reduce the maintenance frequency (Stripple and Uppenberg, 2010). It is here assumed that data from Botniabanan is directly applicable for Citybanan. However, the frequency of milling could depend on the yearly track load. The milling is performed with a diesel driven service train with a diesel consumption of 4.188 MJ diesel/meter railway (Stripple and Uppenberg, 2010). The diesel need is calculated for a total amount of 60 years. The lifetime of the rails is assumed to be around 50 years. Rails can be reused on other tracks with lower demand for high quality rails, such as in railway yards. However, they must then be removed from the original track while still in good condition (Swärd, 2006). In this specific study the rails are considered to be used for 50 years and then exchanged completely.

Sleepers also have a lifetime of around 50 years if they are of good quality and not exposed to frost and other degrading factors (Swärd, 2006). Eventual replacement of individual sleepers or components during that time is not considered in the analyses.

Ballast aggregates are worn out with time and have to be replaced. However it is rare that all of the ballast is changed. Instead the ballast goes through a cleaning process where the ballast is screened and stones that have become too small are replaced with new ballast material. Cleaning frequency depends on speed of trains and the track load and is estimated to be between 20 and 50 years (Swärd, 2006). Calculations are here made for cleaning after 30 years. The exchange of ballast is about 20% per cleaning time (Swärd, 2006).

Tunnel

Maintenance of the tunnel calls for change of tunnel lining and change of LED-diodes in the emergency exit signs.

The shotcrete is changed two times and the concrete once in 100 years (Miliutenko, et al., 2012). In this study it has not been possible to separate between shotcrete and concrete and it is therefore assumed that the tunnel lining is changed once during the time-frame of analyses. 50mm of tunnel lining is changed each time (Miliutenko, et al., 2012).

LED-diodes are assumed to have a lifetime of 10 years, hence they are exchanged six times within the time-frame of the study.

2.2.4. Waste management

Waste management is considered for all types of materials that are put in to the modelling. During construction there will be a waste stream of excess construction material. For sake of simplicity it is assumed that it all goes to waste treatment and that a certain fraction does not go to reuse. There will also be a huge amount of excavated rock and soil from construction of the tunnel structure. According to Banverket (2009a), a total of 4.57 Mtons rock and 191 000 tons soil are excavated from the tunnel, crushed and transported for storage outside Stockholm. Due to the high quality demands on ballast material, the removed rock cannot be reused in construction of Citybanan. Instead it will be reused as ballast in other construction projects in the Stockholm area (Banverket, 2009a). It is also assumed that the soil will be reused.

Steel is assumed to go back to a steel production plant for recasting and concrete to be crushed and reused as ballast material in for example asphalt. Macadam can also be reused as ballast elsewhere than for Citybanan. Other material types are either put on landfill, incinerated or recycled depending on type of material. Allocation problems in waste management was solved by system expansion including avoided burdens for steel, concrete and crushed rock as recycling of these materials prevents production of new materials. For other materials recycled, allocation has not been solved by system expansion, rather the whole burden is put at the tunnel. Allocation problems are also arising from waste incineration as heat can be used as a by-product but no credits have been assigned to the tunnel for this heat. This would require assumptions about type of fuel saved in the district heating plant and has been considered a too large uncertainty. Table 12 in appendix shows amount of waste for each material, type of waste treatment and how it was modelled in SimaPro. Modelling was not performed for small amount of wastes in case of missing data in SimaPro.

3. Life Cycle Interpretation

3.1. Results

3.1.1. General results

A network of the SimaPro model is found in Appendix A. Pictured in Figure 4 is a comparison between construction, operation and maintenance phases of Citybanan. It is clearly seen that the construction phase have the highest contribution to the environmental load. This is likely due to the large material input as only few construction activities are considered in the analysis. The maintenance phase have impacts related to material input as well linked to the fact that less material is used, while the impacts from operation of the tunnel structure only are related to electricity use for pumping water and lighting emergency exit signs. It is interesting to compare this result with for example a road tunnel, where lighting and ventilation are important aspects of the operation phase and operation of the tunnel structure has the highest impacts in the life-cycle (see for example comparison with the greenhouse gases emissions in Miliutenko, et al., 2012). It should also be noted that the operation phase here does not include operation of the trains, which also would significantly change the results. Table 7 shows the exact contributions of the three phases to the impact categories.

To determine what materials and processes have the highest contribution to impacts in the construction phase, the assemblies tunnel structure, power supply and tracks are compared as in Figure 5. Results show that construction of the tunnel structure has the highest impacts for all impact categories. The impacts from construction of tracks are very small in comparison and the impacts from construction of the power supply are not even visible in the graphs. This is due to the quantities of materials that are used in construction of the tunnel structure as compared to the other phases. For example, the tunnel structure contains 560 times more steel and 180 times more concrete than the track assembly. The other rail components such as neoprene pads and nylon isolator are included only in very small amounts compared to the amount of concrete and steel. The power supply modelled only included smaller amounts of copper and aluminium from cables and contact rails. Figure 6 shows the impact contributions from the different materials used in construction of the tunnel structure. Due to the large quantities used, steel has the highest impacts of the materials. As construction steel contributes so much to the overall environmental load, it is interesting to analyse why this is so in order to suggest improvements (see section 3.1.2.). A sensitivity analysis for the steel is found in section 3.3.

Table 7 Characterisation results for the construction, maintenance and operation phases of Citybanan

Sel	Impact category	Unit	Construction	Maintenance	Operation
☑	Climate change	kg CO2 eq	1.02E9	5.35E7	8.61E4
☑	Ozone depletion	kg CFC-11 eq	49.5	2.22	0.0119
☑	Human toxicity	kg 1,4-DB eq	7.43E8	5.07E6	1.2E5
☑	Photochemical oxidant formation	kg NMVOC	4.38E6	1.23E5	273
☑	Particulate matter formation	kg PM10 eq	3.59E6	4.38E4	240
☑	Ionising radiation	kg U235 eq	2.2E8	6.34E6	5.52E5
☑	Terrestrial acidification	kg SO2 eq	4.28E6	1.07E5	368
☑	Freshwater eutrophication	kg P eq	5.79E5	3.65E3	64
☑	Marine eutrophication	kg N eq	1.28E6	4.03E4	99.1
☑	Terrestrial ecotoxicity	kg 1,4-DB eq	1.4E5	1.61E3	165
☑	Freshwater ecotoxicity	kg 1,4-DB eq	2.59E7	8.09E4	1.29E3
☑	Marine ecotoxicity	kg 1,4-DB eq	2.68E7	8.55E4	1.45E3
☑	Agricultural land occupation	m2a	3.27E7	3.79E5	1.51E4
☑	Urban land occupation	m2a	1.08E7	3.03E5	680
☑	Natural land transformation	m2	1.48E5	5.68E3	18.4
☑	Water depletion	m3	1.13E7	7.2E5	3.72E3
☑	Metal depletion	kg Fe eq	1.6E9	1.83E6	2.24E4
☑	Fossil depletion	kg oil eq	3.16E8	6.34E6	2.08E4

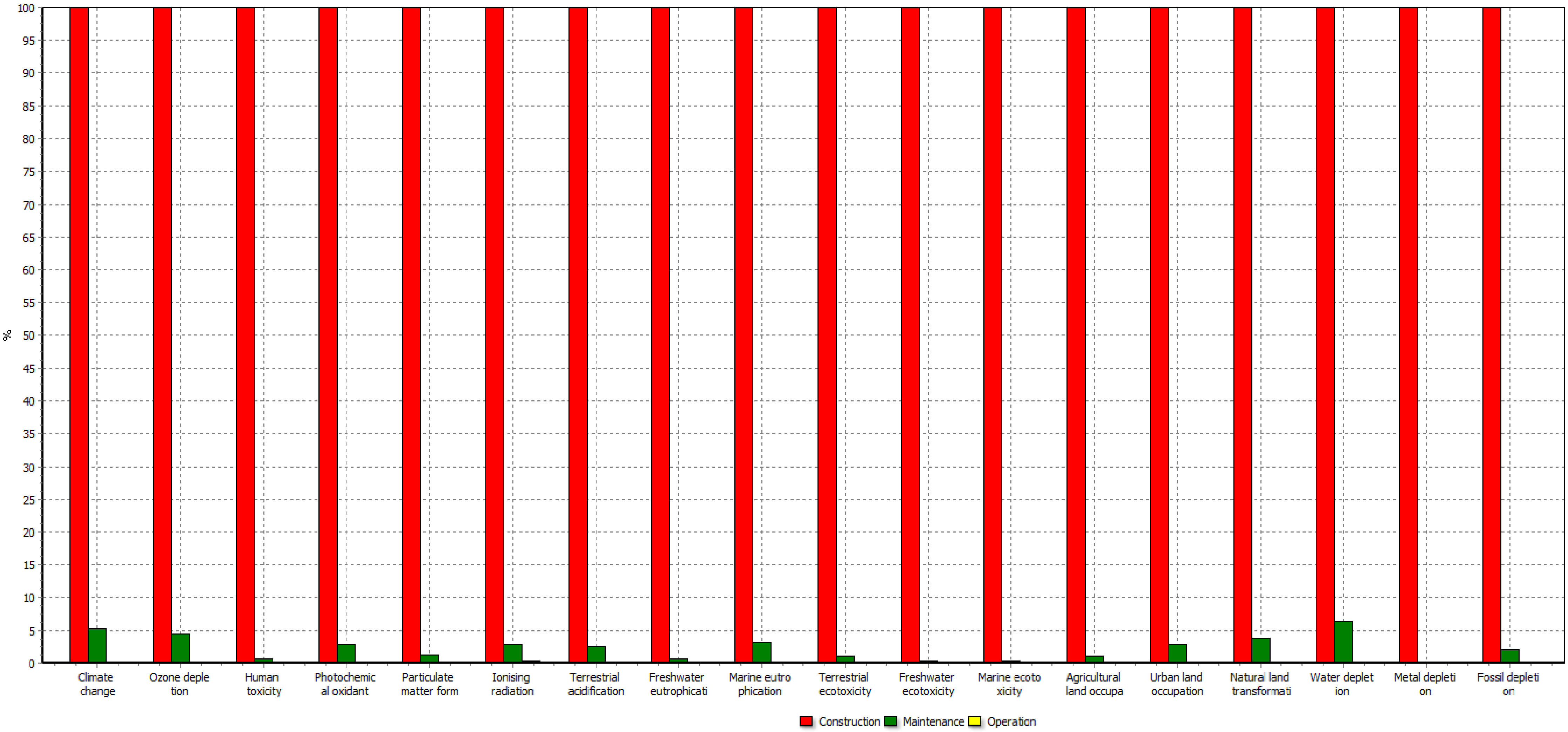

Figure 4 Characterization results for the construction (red), maintenance (green) and operation (yellow) phases of Citybanan

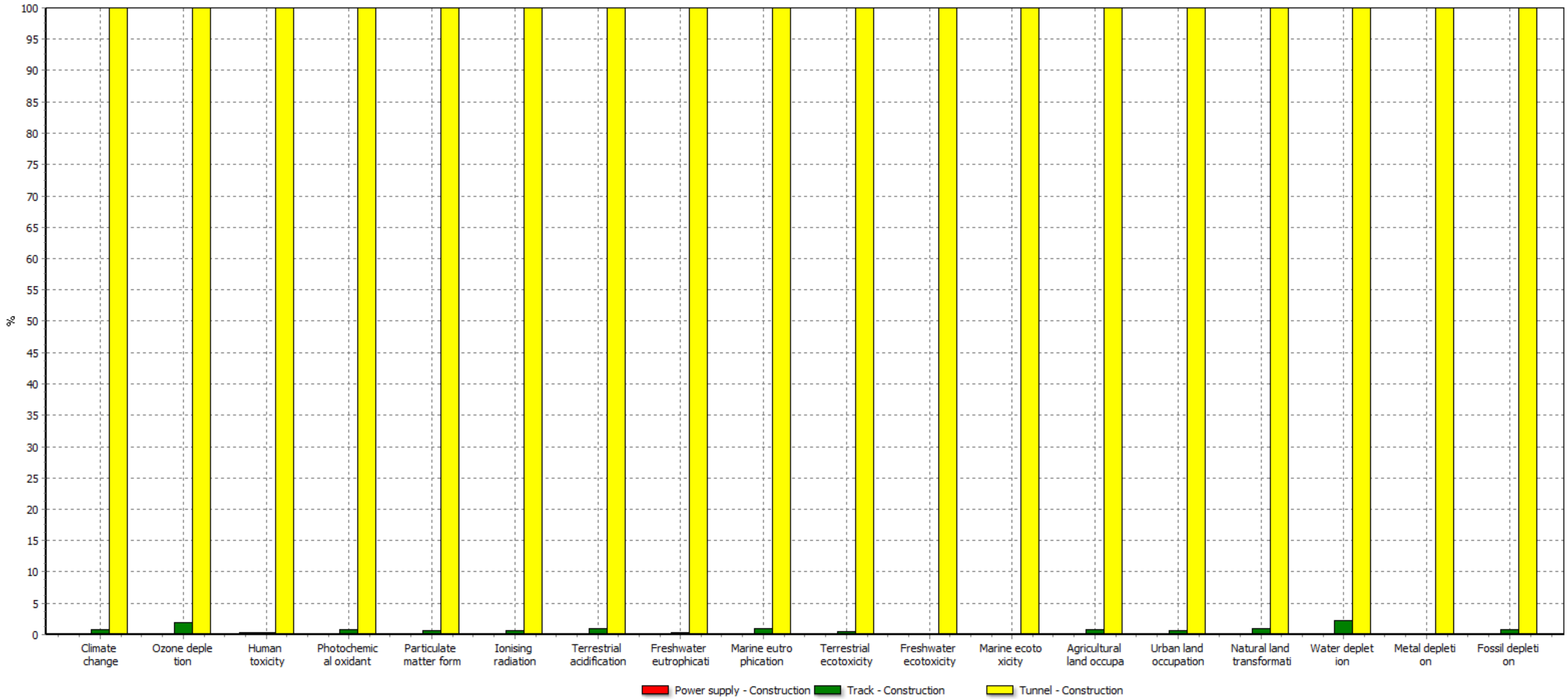

Figure 5 Characterization results for the construction phase of Citybanan

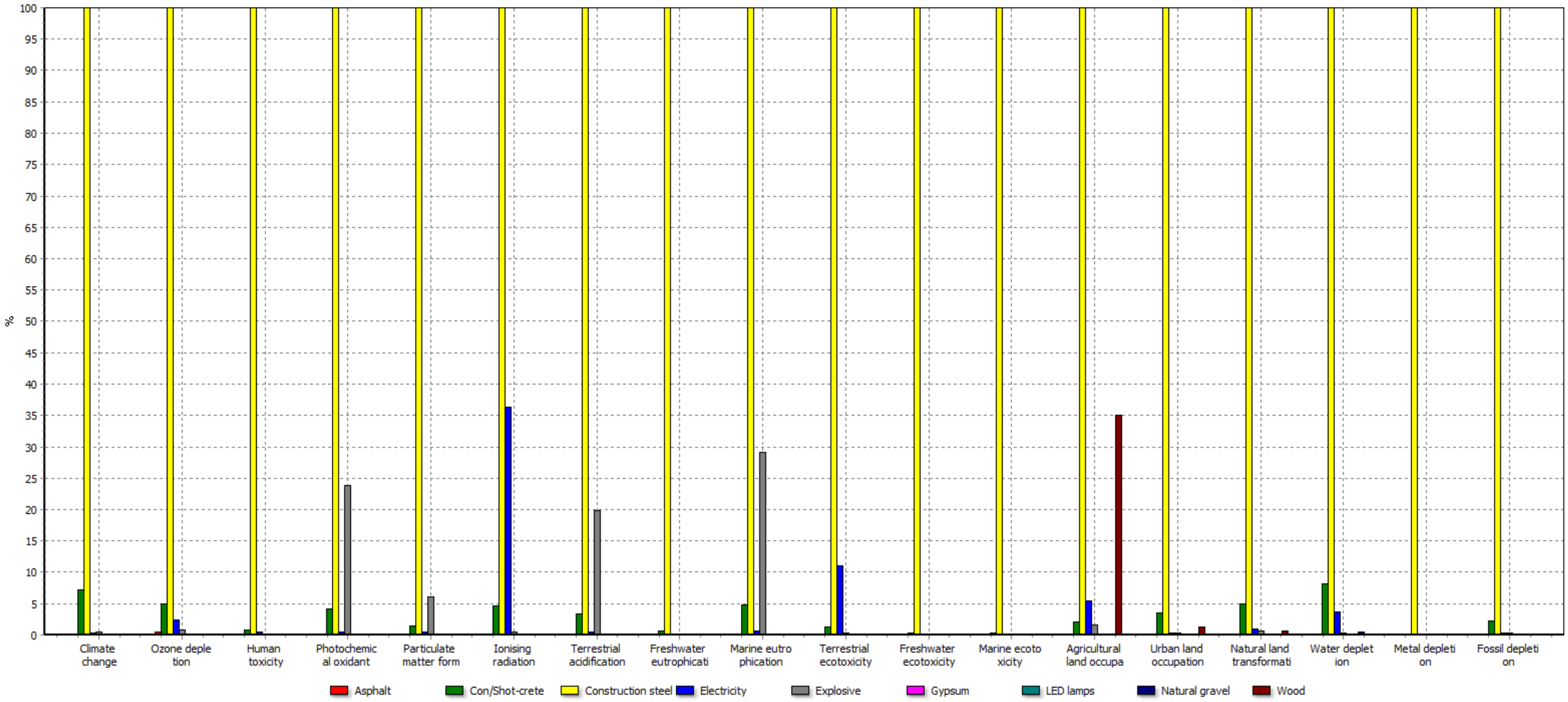

Figure 6 Impacts of the components of the tunnel structure during the construction phase

3.1.2. Importance of steel in the life cycle

As described before, the SimaPro modelling shows that the “construction steel” has by far the biggest share in the impacts of the Citybanan. In the following section, the reasons why the impacts of this steel are so important are exposed.

In SimaPro, this “construction steel” has been built as an assembly of “Steel, low-alloyed, at plant”, and it is transported partly by lorry and partly by boat. The following figure shows the repartition between the impacts for the assembly.

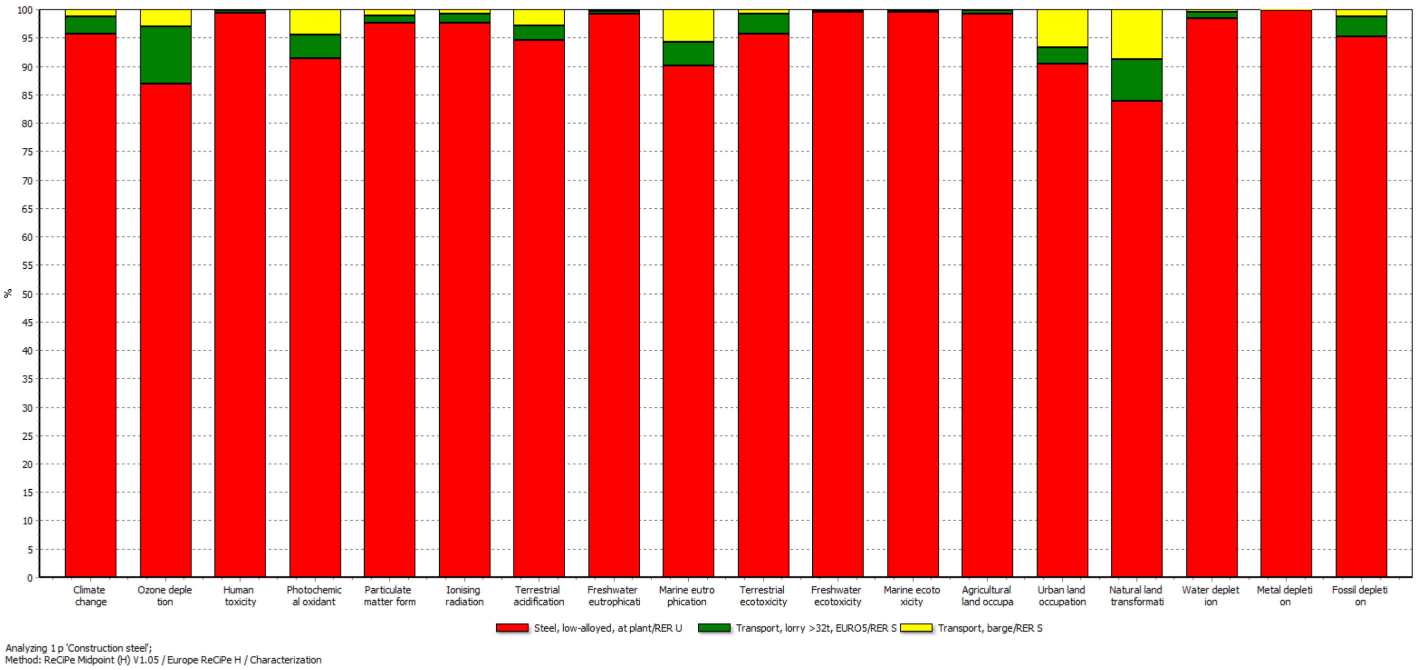

Figure 7 Repartition into impacts for the assembly “construction steel”

This figure shows clearly that the material steel itself brings the biggest impact for the assembly “construction steel” (red bars on the Figure 7). It is interesting then to look more into details to this material steel, modelled as “steel, low-alloyed, at plant” with SimaPro, using the material unit (U) instead of the process (S).

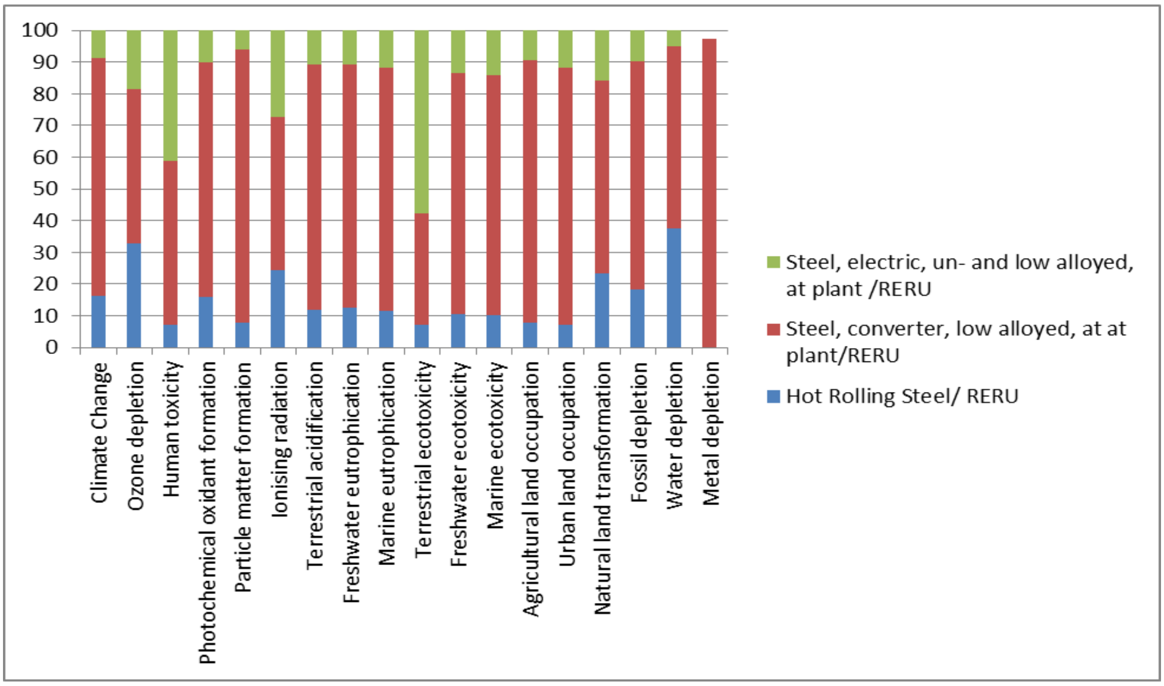

Figure 8 Repartition between impacts for the material "steel, low-alloyed, at plant"

In SimaPro, this low-alloyed steel material is made of the material "hot rolled steel", a converter to transform the primary steel (hot rolled steel) into low-alloyed steel and the electricity needed for transforming the steel. It was studied which of these three components is the main contributor to the impacts for producing the low-alloyed steel (see Figure 8). It seems quite clear that the converter contributes for the most important part to the impacts. This process includes the transports of hot metal and other input materials to converter, the steel making process and casting (Ecoinvent 2.0 database as implemented in SimaPro (Frischknecht et al., 2007).

By going more into details, the "steel, converter, low-alloyed, at plant" can now be studied. Figure 9 shows how the steel converter impacts the environment. The results are in this case not as clear as in the previous situations. However, the pig iron seems to be the most important contributor to the different impacts, followed by the ferronickel.

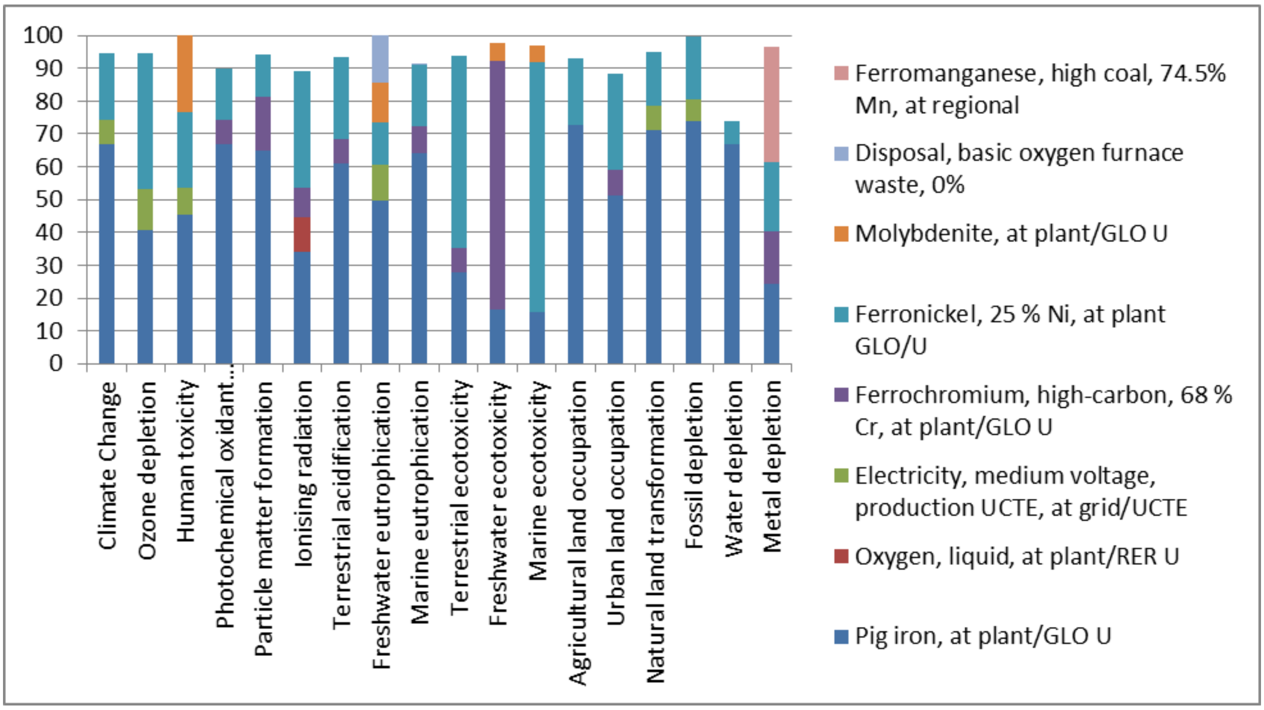

Figure 9 Repartition between impacts for the material "steel, converter, low-alloyed, at plant"

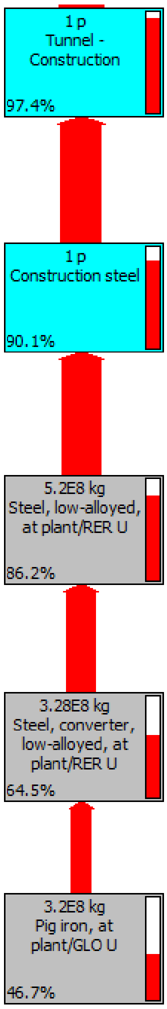

Figure 10 Pig iron as the main contributor to climate change

Figure 10, plotted for the climate change impact, shows also the direct link between the construction of the tunnel and the pig iron itself (cut-off of 20%). The pig iron contributes to 46.7% of the total release of greenhouse gases for the whole Citybanan project. The main effort for improving the whole life cycle of the Citybanan should therefore be emphasized on the production of the pig iron. Looking at the pig iron in SimaPro, it seems that important quantities of sinter and coal are used for producing it, and are the main impact contributors to the pig iron production. Improving the life cycle of the Citybanan could consequently consists of using less hard coal for the production of pig iron, or making the pig iron production process more efficient.

3.2. Data uncertainty

In the model, there are many types and sources of data uncertainty. Uncertainties occur in all phases of the LCA: goal and scope definition, inventory analysis, choice of impact categories, classification and characterisation. Data uncertainty originating from values that are not precisely known can be reduced by additional research (Björklund, 2002). This uncertainty is related to basically all data described in section 2.2. One reason for this is that the tunnel is still under construction and the total amount of material needed is therefore not known. Even though efforts have been made to use site specific data in first hand, many assumptions have been made. There is also uncertainty related to data variability corresponding to inherent differences between individual places, times, and processes and this uncertainty cannot be reduced (Björklund, 2002).

There are also uncertainties regarding future types of materials, processes, fuels and electricity. In this study, it has for example been assumed that components replaced during maintenance are produced and transported in the same way as the original material in construction. The electricity used for lighting and pumping water is also the same for the whole time-frame analysed. There are also uncertainties when real-world processes are modelled as not all aspects can be put in the model, such as temporal and spatial aspects.

It should also be noted that the modelling of tracks, tunnel structure and power supply is very simplified, including only few of the components that are actually included in the tunnel. In this case, the biggest impacts are related to steel manufacturing and the biggest amount of steel is related to construction of the tunnel structure. This amount is directly taken from the environmental reports and represents the amount of steel that has actually been used for construction so far. A major uncertainty is consequently related to steel. In order to install this tunnel section between Riddarholmen and Södermalm, the water has to be removed using a big steel structure. The amount of steel used for this structure has not been documented sufficiently so that it is possible to distinguish between the steel used for the tunnel itself and the steel used for this structure. Seeing the big amount of steel used in the construction, it is unlikely that more detailed information regarding other components will significantly alter the results. Concrete has the next highest impacts. This data is however more uncertain since it is assumed that the amount of concrete used represents both concrete and shotcrete.

Major gaps in data and knowledge lies (in general – not only for our own case) on the suppliers' ability to present reliable data. Obviously it is difficult to have exact data before construction is complete. Also there are different levels of accuracy for different types of material/components. Smaller resources and waste is not documented as well as bigger material inputs so it is necessary to improve documentation during construction, maintenance and operation. For Citybanan, not even the environmental reports included the same type of data from year to year. All the data used presents also a part of uncertainty by reporting quantities, since mistakes can also be made.

3.3. Sensitivity analysis

Sensitivity analysis determines how different values of an independent variable will impact a particular dependent variable under a given set of assumptions (Investopedia, 2012). In the case of this study, it is important to perform a sensitivity analysis on the steel used for construction.

The first sensitivity analysis performed aims at understanding the effects of a change in the amount of steel used for the construction. Two cases have been studied: the normal case, using the amount of steel actually used for the Citybanan, and a hypothetic case, in which 50% less steel is used during the construction. Normalization results have been analysed, and a ratio between the results of the normal case and the hypothetic case has been made. The plot of this ratio is shown in Figure 11. A decrease of 50% in the amount of steel used leads to a mean decrease of 56% in the impacts. This confirms the fact that a change in the amount of steel used for the construction changes almost automatically the whole results of the LCA.

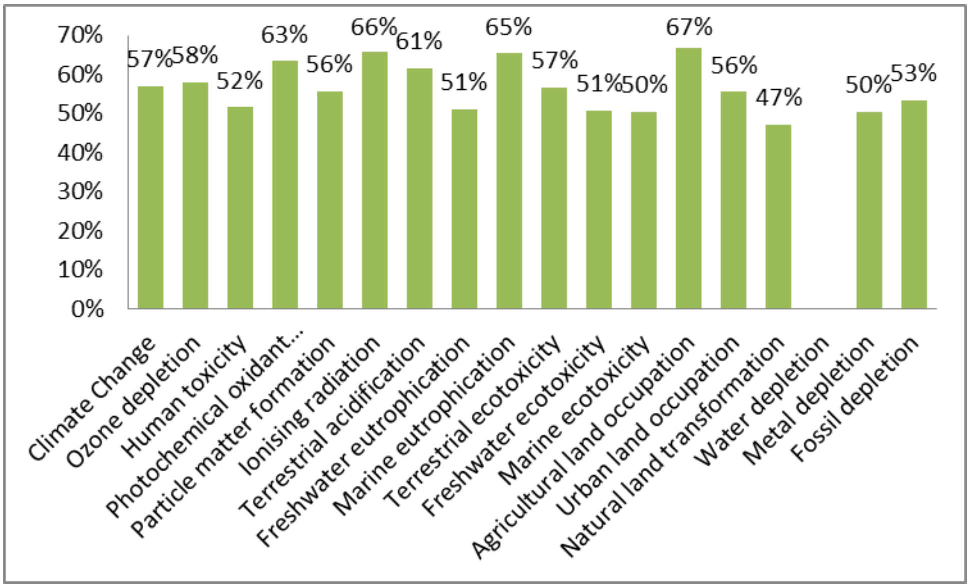

Figure 11 Effects on the normalization of a 50% decrease in the amount of steel used

A second analysis can be performed looking more into details in the production of steel. The investigation about the steel production has shown that the pig iron is one of the main contributors to the impacts on the whole life cycle. As suggested before, an improvement on the life cycle of pig iron should lead to an improvement of the whole life cycle of Citybanan. Therefore, it has been tried to replace the energy coming from hard coal used for the production of pig iron by hydropower energy. This saves 10^6 kg $CO_{2\text{-eq}}$, which represents the amount of CO_2 released by 143 inhabitants from West Europe over one year (Elektor, 2007). Compared to the total amount of CO_2 released from Citybanan, this represents only 0.001%.

A third analysis was then performed since the results for the change from hard coal to hydropower did not reduce significantly the impacts. This analysis consisted of decreasing the amount of pig iron needed for the converter of steel for producing low-alloyed steel. This could be possible assuming that the process of converting low-alloyed steel could be improved and use less pig iron (converting process more efficient). Instead of a need of 0.9 kg of pig iron for producing 1 kg of low-alloyed steel, 0.8 kg are assumed to be needed. This change leads again to a decrease of

0.001% in the greenhouse gases released.

3.4. Conclusions and recommendations

In general, the construction phase of Citybanan is causing more impacts than maintenance and operation phase. The maintenance phase comes second after the construction phase. Impacts caused during the operation phase do not even represent 1% of the impacts caused during the construction phase. However, it should not be forgotten that electricity for operating the trains and the trains itself are not included in the operation phase. Maintenance phase could also present more impacts if the lifetime is increased.

Looking at the results of the construction phase, the tunnel part of Citybanan causes the most important part of the impacts. The track part comes second, and then the power supply, but seem negligible compared to the impacts caused by the construction of the tunnel part. This result could be significantly different if construction activities such as excavation needed for laying cables and cable ducts have been included in the study.

The impacts caused by the construction of the tunnel structure are mainly due to the large amounts of steel used. Explosives also have a large share in the impacts, especially by looking at the eutrophication and acidification. Concrete has also a relatively small but constant share in the total impacts. Electricity can be considered as a contributor to the main impacts, especially by looking at the ionising radiation and terrestrial ecotoxicity. As steel had so high impacts compared to the other materials, sensitivity analysis were performed for steel. Steel will also be the main subject for the discussion that follows, however the discussion could be easily applied to any other material.

The first sensitivity analysis performed shows clearly that the first way to reduce the global impacts of the Citybanan is to reduce impacts from steel. One can:

- Reduce the total amount of steel needed. In this case, the main part of the steel is used for building the tunnel part between Riddarholmen and Södermalm. One could therefore work on the design of this tunnel and eventually wonder if this steel made tunnel can be avoided, by for instance build the tunnel deeper.
- Reduce steel related CO2-emissions by for example using more energy efficient processes in the steel manufacturing, more recycled steel (requires availability of recycled steel in the first place), use more renewable energy (we saw in our analyses that some energy production contributed quite much to total steel impacts). This has to be done by the steel producer while the infrastructure management is responsible for procurement requirements.

The two other sensitivity analysis do not lead to any big reduction in the impacts. It does not seem therefore very efficient to replace the hard coal used for the steel production by hydropower, or to use less pig iron as input for the steel production (if this might be possible).

Reduction and optimization of the use of steel requires management of infrastructure planning and maintenance. Guidelines for planning of railway tunnels should highlight the choice of steel quality and quantity. Procurement routines should be defined, making it obligatory to choose suppliers with low greenhouse gas emissions for instance. This can cause problems as data from suppliers may not always be comparable. For example, a construction company wants to buy steel with low contribution to greenhouse gas emissions and compare different suppliers. However, it is sometimes difficult to know what the information about the amount of CO_2-eq actually represents as this data will depend on system boundaries used and other factors.

Steel is also used for reinforcing concrete, so diminishing the amount of reinforced concrete has a direct effect on the amount of steel needed. Guidelines for planning and dimensioning of tunnel structures have to emphasise the importance of optimizing the amounts of material needed. It is also important to wonder about the whole life cycle of some materials. For instance, one can have to choose between a low quality steel which will have to be replaced after a short time and high quality steel which can lasts for a very long time. In some case, it could be worth to choose higher quality material and thereby extending the life-time. When different components and materials are exchanged, it is also necessary to consider the environmental impacts of this new product so that environmental burdens are not shifted to another place. It could be so that it is produced in a way or contains raw materials that will increase the total impacts of the tunnel. In every case, different reduction measures have to be put in a larger perspective also, so that safety and reliability in operation of the railway tunnel does not decrease.

Even though the analysis describes the environmental impacts of Citybanan, it is still important to remember the reasons for why it was built – to reduce the environmental impacts from transportation in the Stockholm region and also facilitate increased train traffic in the rest of Sweden. However some impacts are not evaluated and therefore not shown in the LCA. For example environmental consequences of changed hydrology which is affected by the environmental impacts. The fact that more passengers are going to use trains instead of other transportation systems such as cars or even flights is also not included in the LCA. These external impacts should be taken into consideration when one wants to get an overall picture of the impacts of Citybanan. The LCA as such is therefore not enough to assess the full environmental impacts of the tunnel. It should also be complemented with an EIA and social LCA for example.

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APPENDIX A

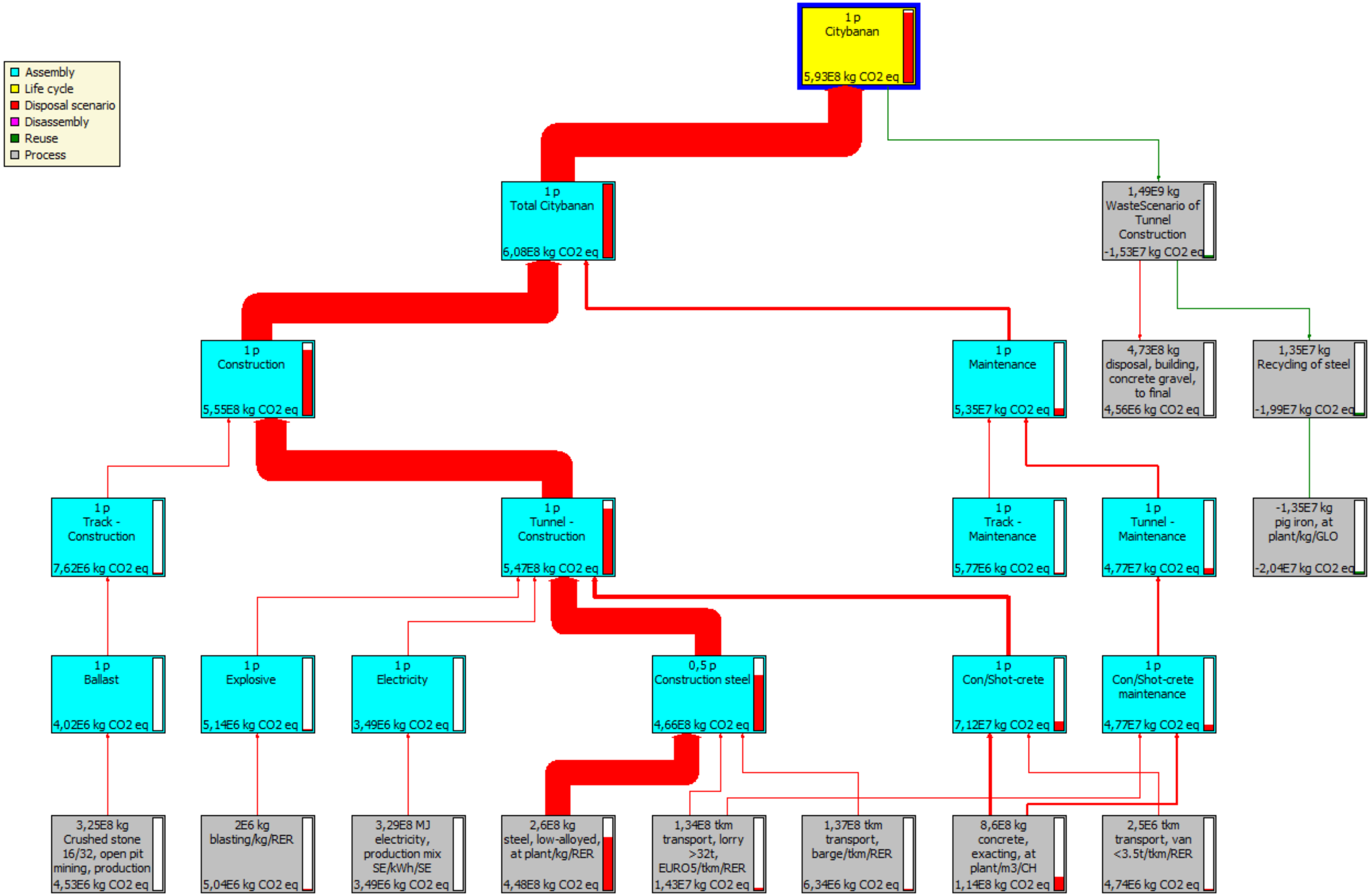

Figure 12 Part of SimaPro network for climate change (kg CO2 eq) The cut-off is 0,5%

APPENDIX B

Table 8 Assumptions made when calculating material and fuel quantities for construction of the tracks

Component	Assumptions	Reference
Rails	Total rail length 12 800 meter and weight of rails 60.4 kg/meter	Banverket (2007b)
Sleepers	The sleepers are composed of the same materials and put in place with the same distance (0.6 meter) as the sleepers in Botniabanan.	Stripple and Uppenberg (2010)
Macadam	200 000 tons used in total for the tunnel	Banverket (2007b)
Sound protection mat	Surface area of 60 000 m^2. Densities vary between 140 and 162 kg/m^3 and thickness between 60 and 180 mm. An average density of 157 kg/m^3 and average thickness of 0.12m is used for calculations.	Trafikverket (2012b); ELCD Database 2.0 (2008)
Geotextile	Assume same surface area as sound protection mat, i.e. 60 000 m^2 and that it is made of polypropylene with a weight of 227 g/m^2.	Miliutenko, et al (2012)
Diesel for rail lying train	Diesel consumption is 117 MJ/meter track	Stripple and Uppenberg (2010)

Table 9 Assumptions made when calculating material and electricity need for construction of the tunnel structure

Material/component	Assumptions	References
Explosives	2000 tons	Trafikverket (2010a)
Rock-bolts	The bolts are between 2.4 and 5.0 m long and manufactured in steel with a weight of 3.85 kg/meter. For calculations an average value of 4.0 m is assumed and the number of bolts is estimated to 60 000 bolts.	Lindfors, et al., (2007); Miliutenko, et al (2012)
Concrete and shotcrete	A total of 350 000 tons concrete will be used and it is assumed that this includes both shotcrete and concrete but without steel reinforcing	Trafikverket (2010a)
Construction steel[1]	Sum of steel reported in environmental reports 2008-2011	Banverket (2009b); Trafikverket (2010b; 2011b; 2012c)
Material/component	**Assumptions**	**References**

1 All steel for tunnel construction excluding the steel structure for the tunnel under Söderström

Steel structure for tunnel under Söderström	3 tunnel elements of 900 tons each	Trafikverket (2011a);
Wood	Sum of wood reported in environmental reports 2008-2011	Banverket (2009b); Trafikverket (2010b; 2011b; 2012c)
Asphalt	Sum of asphalt reported in environmental reports 2008-2011	Banverket (2009b); Trafikverket (2010b; 2011b; 2012c)
Natural gravel	Sum of natural gravel reported in environmental reports 2008-2011	Banverket (2009b); Trafikverket (2010b; 2011b; 2012c)
Fire doors	Dimensions 2x1.4 meters. Distance between doors is 300 m. Thickness of steel and gypsum is assumed to be 0.02 meter respectively	Vägverket (2004); Banverket (2007b)
Emergency exit signs	Distance between signs 30 m and it is assumed that there is one sign on each side of tunnel. Assume that there is 2 kg of polycarbonate/sign and 9 LED-diodes/sign.	Vägverket (2004)
Electricity for drilling and ventilation	Electricity consumption is 7 kWh/m^3 of excavated rock for Stockholm Bypass and it is assumed that it is the same for Citybanan.	Stripple (2009)
Electricity for pumping water	Amount of water that needs to be removed is calculated from the EIA. The amount of energy needed for pumping the total amount of water for 10 years of construction has been estimated. The pump was assumed to have an efficiency of 0.6 and the mean differential head is assumed to be 33 meters.	Banverket (2007a)

Table 10 Assumptions made when calculating material consumption for construction of the tunnel structure

Material	Assumptions	References
Copper wire	Assume that the wires will be of the same type as for Botniabanan. Cross sectional area 200mm^2 and it is assumed that the wire length is the same as the rail length.	Stripple and Uppenberg (2010)
Copper cables	0.605 kg/km track	Swärd (2006)
Contact rail	Weight of aluminium is 6.1 kg/meter and it is assumed that it has the same length as the rail length	Balfour Beatty Rail (n. d.)

Table 11 Service-life of infrastructure components and need for material during maintenance

Component	Service-life (years)	Times exchanged	Comments
Rails	50	1	Material input same as for construction
Sleepers	50	1	Material input same as for construction
Ballast	30	2	20% of the ballast is replaced each time
Shotcrete and concrete	50 - 100	1	71% of the original concrete amount is replaced (50 mm of 70 mm)
LED-diodes	10	6	Material input for each time is same as for construction

Table 12 Waste amount, type of waste treatment and modelling in SimaPro for different materials

Waste type	Amount	Waste treatment	SimaPro
Steel	5% of all steel input + steel in complete set of rails + steel in complete set of sleepers	Recycling of steel	Recycling steel and iron/RER S
		Avoided burden: steel production	Pig iron used as avoided product
Concrete	30% of all concrete input + concrete in complete set of concrete sleepers + 71% of tunnel lining	Crush and reuse as ballast in e.g. asphalt	Disposal, building, concrete gravel, to final disposal/CH S - lca07
		Avoided burden: gravel mining	Gravel, crushed, at mine/CH S
Rubber	5% of input	Recycling	Recycling rubber and leather/RER S
Nylon	5% of input	Incineration	Waste incineration of plastics (Nylon 6 GF 30, Nylon 66 GF 30), EU-27 S
Macadam, natural gravel and excavated rock	5% of all macadam input + 40% of remaining ballast; 5% of gravel input; all excavated rock	Reuse as ballast	Not found in SimaPro (blasting process does not imply any output)
		Avoided burden: gravel mining	
Rockwool	5% of input	Disposal	Disposal, building, mineral wool, to recycling/CH S

Waste type	Amount	Waste treatment	SimaPro
Polypropylene	5% of input	Disposal	Disposal, polypropylene, 15.9% water, to municipal incineration/CH S
Wood	5% of input	Disposal	Disposal, building, waste wood, untreated, to final disposal/CH S
Asphalt	5% of input	Landfill	Disposal, asphalt, 0.1% water, to sanitary landfill/CH S
Copper	5% of input	Incineration	Disposal, copper, 0% water, to municipal incineration/CH S
Aluminium	5% of input	Recycling	Recycling aluminium/RER S
Gypsum	5% of input	Disposal	Disposal, building, plaster board, gypsum plaster, to sorting plant/CH S

Table 13 Assumptions made when calculating transportation distances and modelling of transportation in SimaPro

Material	Distances and assumptions	SimaPro
Steel for rails	Rails are manufactured in Austria (Stripple and Uppenberg, 2010), and a distance of 1800 km is assumed	Transport, freight, rail/RER S
Steel tunnel structures for tunnel under Söderström	Produced in Estland and transported by sea (Trafikverket, 2011a). A distance of 500 km is assumed.	Transport, barge/RER S
All other types of steel (bolts, doors, reinforcing steel)	Transported from Poland, approximately 530km by boat and 500km by truck (Miliutenko, et al., 2012).	Transport, barge/RER S Transport, lorry >32t, EURO5/RER S
Concrete for sleepers	Distance is assumed to be 150 km, the same as for concrete in (Miliutenko, et al., 2012).	Transport, lorry >32t, EURO5/RER S
Shotcrete and concrete	Transportation distance 5km and 5 m^3 per load (Linder and Kilic, 2011)	Transport, van <3.5t/RER S

Material	Distances and assumptions	SimaPro
Crushed aggregates (macadam and natural gravel)	Assume same type of transportation of gravel in as excavated rock out (Banverket, 2009a). Distance 20 km, from (Miliutenko, et al., 2012).	Transport, lorry 3.5-16t, fleet average/RER S
Rock wool	The mat is produced in Hedenehause, Denmark (Trafikverket, 2012b) a distance of 680 km from Stockholm.	Transport, lorry >32t, EURO5/RER S
Explosives	Assume the same distance as in (Miliutenko, et al., 2012) – 240 km	Transport, lorry 20-28t, fleet average/CH S
Wood	Assume the same distance as in (Miliutenko, et al., 2012) – 500 km	Transport, lorry >32t, EURO5/RER S
Asphalt	Assume the same distance as in (Miliutenko, et al., 2012) – 10 km	Transport, lorry >32t, EURO5/RER S
LED-diodes	Assume manufacturing in Europe and transportation distance of 1700 km	Transport, lorry >32t, EURO5/RER S
Gypsum	Assumed to be manufactured in South-America (KnaufDanoline, n.d.). Transportation distance is assumed to be 11000 km.	Transport, barge/RER S

Table 14 Densities assumed in calculations

Material	Density	Reference
Rock	2970 kg/m^3	Stripple (2001)
Gypsum (plaster)	849 kg/m^3	Simetric (2011)
Steel	8000 kg/m^3	National Physical Laboratory (2004)
Wood	450 kg/m^3	Simetric (2011)
Copper	8960 kg/m^3	Swärd (2006)
Concrete	2400 kg/m^3	Miliutenko, et al. (2012)

Table 15 Assumptions for materials and processes in SimaPro modelling

Material/Process	SimaPro	Database
Steel	Steel, low-alloyed, at plant/RER S	Ecoinvent
Concrete and shotcrete	Concrete, exacting, at plant/CH S in kg	Ecoinvent
Wood	Sawn timber, Scandinavian softwood, raw, plant-debarked, u=70%, at plant/NORDEL S	Ecoinvent
Asphalt	Mastic asphalt, at plant/CH S	Ecoinvent
LED	Light emitting diode, LED, at plant/GLO S	Ecoinvent
Polypropylene	Polypropylene fibres (PP), crude oil based, production mix, at plant, PP granulate without additives EU-27 S	ELCD
Nylon	Nylon 66 GF 30 compound (PA 66 GF 30), production mix, at plant RER	ELCD
Rubber	Synthetic rubber, at plant/RER S	Ecoinvent
Copper	Copper, primary, at refinery/RER S	Ecoinvent
Aluminium	Aluminium sheet, primary prod., prod. mix, aluminium semi-finished sheet product RER S	ELCD
Gypsum	Gypsum plaster (CaSO4 alpha hemihydrates) DE S	ELCD
Natural gravel	Gravel, round, at mine/CH S	Ecoinvent
Rockwool	Rock wool, packed, at plant/CH S	Ecoinvent
Explosives	Blasting/RER S	Ecoinvent
Diesel lying train	Diesel, burned in building machine/GLO S	Ecoinvent
Electricity for pumping water and construction activities	Electricity, production mix SE/SE S	Ecoinvent