Environmental Life Cycle Assessment (LCA) of Road Pavements: Comparing the Quality and Point of Application of Existing Software Tools on the basis of a Norwegian Case Study

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Abstract

Various software tools have been developed to evaluate the life cycle performances of roads to provide decision supports for road authorities and contractors. It is therefore important to compare the strengths and limitations of these software tools to understand the appropriate application and to identify the points for optimization. This study evaluated EFFEKT 6.6, EKA, and LICCER software tools, by applying the environmental life cycle assessment following the ISO 14040 standard. The assessment was based on an open-air road (excluding tunnels and bridges) with a functional unit of one kilometer and greenhouse gas emissions as well as embodied energy indicators were evaluated in the considered software tools. The open-air road was modeled for each software tool with respects to road class H9 characteristic in Norway, classed as a national road. The assessment showed that the system boundary and purpose of use differed between the considered software tools. This resulted in performing the assessment only over A1 – 4 and B6 modules according to EN 15978 standard for the hypothetical open-air road to provide a comparable boundary condition. The results demonstrated that EFFEKT overall yielded higher values for greenhouse gas emissions and embodied energy compared to the two other software tools, while, the three software tools quantified nearly the same amount of asphalt use within the 20-year analysis period.

Key words: LCA, asphalt, GHG emissions, embodied energy, road

1. Introduction

Roads as part of the transport infrastructure contribute to job creation and growth of GDP. However, roads are also corresponding to natural resource use, land usage, emission and waste creation. And, every year new roads are built, maintained and rehabilitated due to an increased demand for new roads and deterioration of existing roads. This growth in demand and increase in cumbersome issues (like availability of resources, environmental awareness etc.) puts decision-makers in a challenging position to address and comply with the various challenges.

Environmental life cycle assessment (LCA) is a well-established and standardized method and has been widely used due to the increased awareness in importance of environmental stewardship (ISO, 2006). LCA is a method that evaluates potential environmental impacts for a product or service over its full life cycle (ISO, 2006). And so far, different LCA studies have been conducted in the area of road infrastructure in order to better understand the environmental impacts associated with roads and road products such as ECORCE2, DuboCalc, PaLATE, SEVE, etc. (Zukowska E. A. et al., 2014). In spite of availability of different road LCA software tools (Hammervold, 2014), different areas of coverage could be found in the domain of software that might be due to various system boundaries and intended applications. This leads to the fact that some LCA software tools may show unexpected results.

The present work is aiming to evaluate three currently used software tools based on a hypothetical Norwegian road, especially regarding the results achieved in terms of embodied energy and greenhouse gas emissions. The considered software tools are EFFEKT 6.6[1], EKA[2] and LICCER[3]. The hypothetical road is chosen from manual 017 "Road and street design" (NPRA, 2013b) and categorized as road class H9 with a total distance of one kilometer with annual daily traffic above 15 000 vehicles.

2. Methodology

Environmental Life cycle assessment (LCA) is a well stablished method and has been widely used due to the increased awareness of importance of environmental stewardship (ISO, 2006). LCA is a methodology that analyzes and evaluates the environmental impacts associated with a product system, service or activity in a systematic way through its entire life cycle (Baumann and Tillman, 2004, Lindfors et al., 1995, ISO, 2006). The entire life cycle or "cradle-to-grave" refers to the whole value-chain of a product that can be simply comprised of extraction, manufacturing, transportation, use, and disposal activities. These stages are explicitly illustrated by EN 15978 standard in figure 1.

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[1] http://www.vegvesen.no/
[2] http://www.trafikverket.se/
[3] http://www.eranetroad.org/

LCA is often performed to compare different product systems with a same functional unit, to find critical stages and/or processes (hot spots), or to document environmental performances as internal reports (Robèrt K. H. et al., 2002, Baumann and Tillman, 2004).

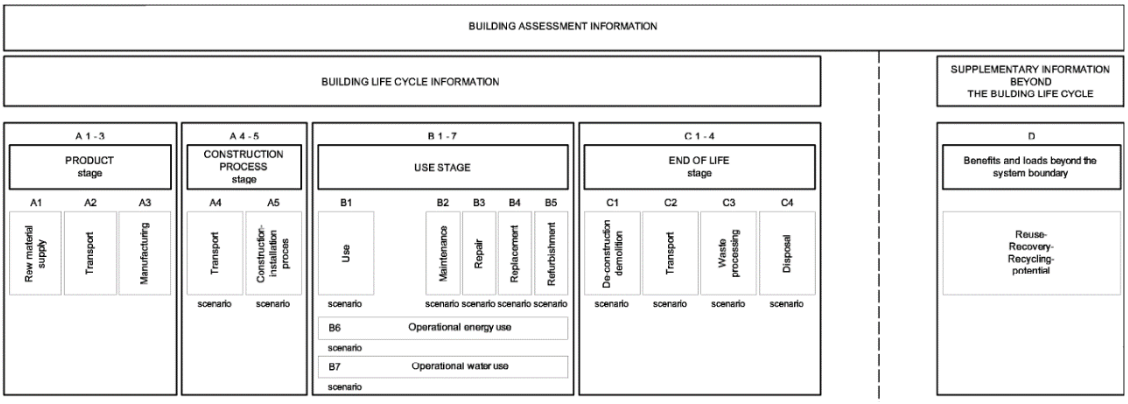


Figure 1: Modular information for building life cycles (CEN, 2011).

Based on a description that has been provided by International Organization for Standardization (ISO) within ISO 14040:2006 standard (ISO, 2006), a LCA is comprised of four main stages: goal and scope, inventory analysis, life cycle impact assessment, and interpretation (see figure 2) (ISO, 2006).

- Goal and scope describes what the target, purpose, and relevant choices are.
- Inventory analysis identifies input/output material, energy, and corresponding emissions.
- Life cycle impact assessment measures the potential impacts from the developed inventory in a qualitative way.
- Interpretation explains the results in each stage to increase the transparency and to help make more informed decisions.

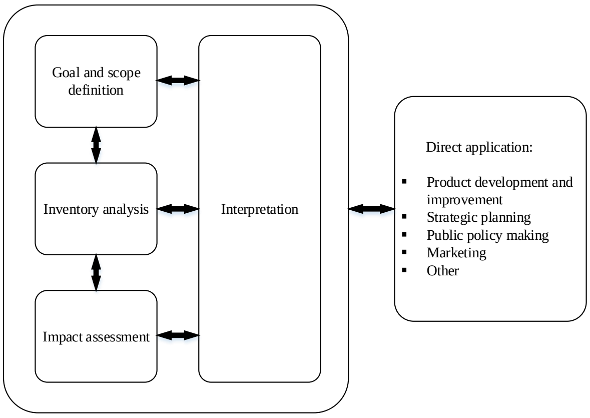


Figure 2: Four stages of an LCA (ISO, 2006)

3. LCA tool

The three software tools, which are in the scope of assessment of this paper, are EFFEKT6.6, LICCER and EKA. Here, a brief description for each software tool is provided to represent the focus area of the LCA tools.

3.1 EFFEKT 6.6

EFFEKT is a software program that is developed by the Norwegian Public Road Administration (NPRA) (Hammervold, 2014). It is a tool that assesses cost-benefit and socio-economic analyses of road infrastructures. EFFEKT is particularly developed for and regularly used during early stages of road infrastructure planning (Miliutenko S. et al., 2014a), aiming at roughly estimating the consumption of inputs, cumulative energy use and GHG emissions in a context when little data for a new road project are actually available. EFFEKT is carried out to assess the impacts from alternative routes of a road projects compared with a reference scenario (baseline) that helps for selection of solutions or prioritization of route alternatives within a road project (NPRA, 2007, Martinsen J. A., 2008). EFFEKT includes *production*, *construction* and some modules of *use* life cycle stages as shown in figure 1, but it excludes *end-of-life* and *potential benefits and loads* life cycle stages from its assessment (Liljenström, 2013). The main focus of the calculations is on impacts from major material production activities and selected construction activities.

3.2 EKA

EKA was developed by the Swedish Transport Administration to calculate inputs, cumulative energy and GHG emissions of different road maintenance activities for various asphalt types (Martinsson, 2014). The tool covers the entire asphalt production value chain (from input materials to the finished products) based on Swedish production techniques. This means EKA incorporates submodules A1 – 4, and also, it covers some parts of *use*, *end-of-life* and *potential benefits and loads* life cycle stages in its assessment. The final asphalt products in EKA tool are: hot mix asphalt, warm mix asphalt, half-warm mix asphalt, remixing (recycled asphalt), tank coating (surface treatment), and thin-layer coating (Martinsson, 2014).

3.3 LICCER

LICCER was a research project funded by ERA-NET with the aim at developing "an easy to use model based on existing tools and methodologies for Life Cycle Assessment of road infrastructure" (Brattebø H. et al., 2013). LICCER was to a certain extent motivated by EFFEKT and it evaluates inputs, GHG-emissions (in ton CO_2-eq/year) and cumulative energy demand (energy use in GJ/year) in early planning of road infrastructure (open-air roads, bridges, and tunnels), as well as road furniture (O'Born R. et al., 2013, Brattebø H. et al., 2013, Liljenström, 2013, Miliutenko S. et al., 2014b, O'Born R. et al., 2015). LICCER includes *production*, *construction* and some modules of *use* as well as *end-of-life* stages, but it excludes *potential benefits and loads* life cycle stage from its assessment.

4. Case study

Manual 017 (NPRA, 2013b) entitled "Road and Street Design" was a guideline used in this study. The manual developed by the Norwegian public road administration (NPRA) provides technical requirements for the design of roads and streets and it does not discusses non-traffic related conditions (like landscape condition, geology, etc.) (NPRA, 2013b).

Based on the manual 017 (NPRA, 2013b), there are various road classes for construction of national main roads. Here, road class H9 is selected for the assessment, which is classed as the national main road. The road class H9 has a motorway standard with the speed limits of 100 km/h. The road must be built as a 4-lane road with driving lane and hard-shoulder of 3.5 and 3 meters wide, respectively, and it consists of a 23 meter wide roadway in total (NPRA, 2013b). Figure 3 illustrates the schematic view of the road cross-section.

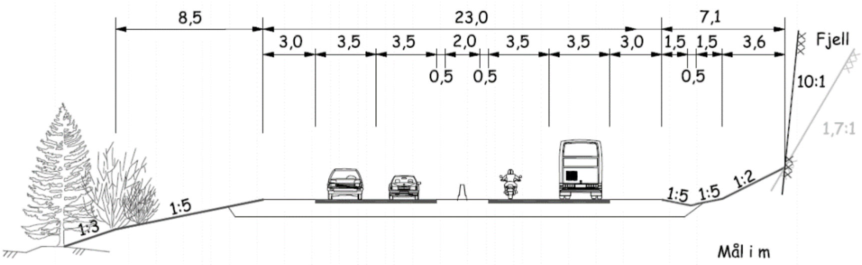
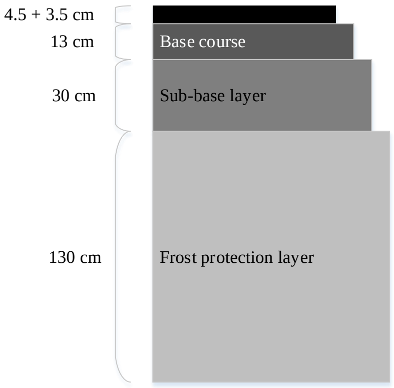


Figure 3: The cross section of national main road H9 (NPRA, 2013a)

Due to the fact that there was no reference model for a typical pavement structure corresponding to design class H9, it was necessary to design a hypothetical road first in order to assess the environmental impacts from the road in a next step. To do so, empirical pavement design is selected based on chapter 51 in the manual N200 (NPRA, 2014). By means of manual N200, it is possible to design an empirical road pavement with some prerequisite input data such as subgrade condition, traffic load, road construction materials, climate condition and standard structure.

Table 1: The structure of designed pavement for road class H9

Layer	*Material type / thickness*
Wearing course	*4.5 cm asphalt concrete*
Binder course	*3.5 cm asphalt concrete*
Base course	*13 cm asphalted gravel*
Sub-base	*30 cm crushed rock*
Frost protection	*130 cm crushed rock*
Total thickness	*181 cm*



In the designing stage of a hypothetical road pavement, it is assumed that the road is located in Malvik municipality. The ADT in the opening year is assumed to be 15 000 vehicles[4] (with 12% share of heavy vehicles) and it is assumed that annual heavy vehicles traffic growth is 1.4%. The frost amount F100 is 18 000 h°C (it is assumed that the maximum correction factor is 1.3; annual mean temperature is 5.4°C and average frost amount F_{100} is 18 000 h°C) and road subgrade

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[4] Annual daily traffic (ADT) above 20 000 vehicles is suggested for the road class H9 (according to manual 017); however from a hypothetical viewpoint in this paper, it is assumed the road provides service to ADT above 15 000 vehicles in its initial operation year.

consists of clay with Cu T4. Table 1 presents a theoretical pavement layers that designed for the hypothetical road.

5. Results

Although the introduced software tools have intentions to quantify GHG emissions and embodied energy associated with road projects, they slightly differ where they draw their system boundaries. EFFEKT 6.6 on the one hand covers production, construction and (some modules of) use stages (B1, B2 and B6) in its system boundary. And, LICCER covers more life cycle stages compare to EFFEKT 6.6 by including production (A1 – 3), construction (A4 – 5), use (B1, B2 and B6) and end-of-life (C1 – 3) phases. EKA on the other hand has a more limited coverage. EKA does not consider construction phase of a new road (stage A5) like earthworks, drainage system, unbound layers etc. in its assessments. Instead, it only evaluates embodied energy and GHG emissions associated with bound layer products within maintenance activities.

With respect to the described dissimilarities between the LCA software tools, it became clear that performing a full lifecycle “cradle-to-grave” was not applicable due to limitation in the system boundary of the EKA tool and not full lifecycle coverage by EFFEK 6.6 (as it is explained in EN 15978 standard (CEN, 2011)). Thus, in order to run a fare comparison between these three software tools, it has been decided to evaluate them based on the *stages* and the *modules* that they have in common. By doing so, it could be said that the maintenance module from the *use* stage (B2) as well as A1 – 4 modules are mutually covered by these three software tools (see figure 4).

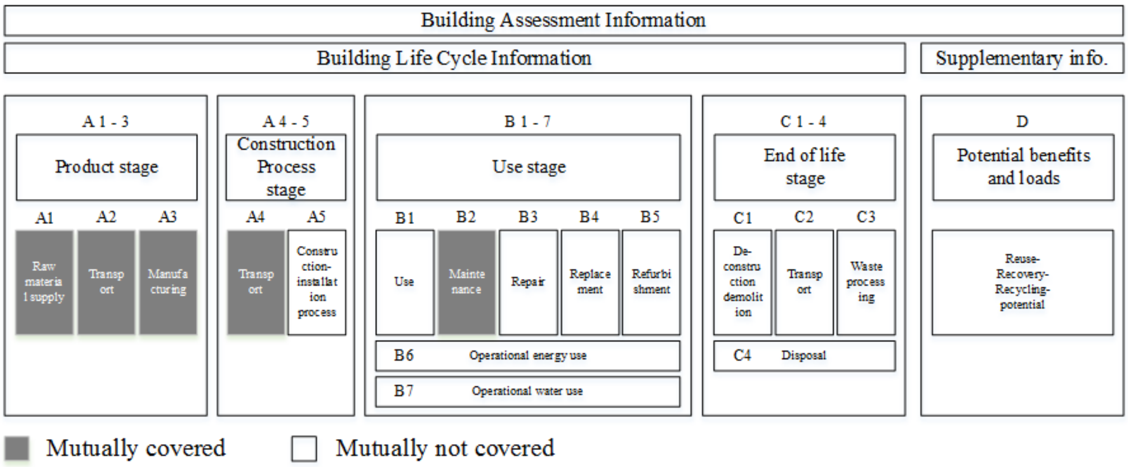

Figure 4: Life cycle stages and modules shared mutually between the three software tools.

EFFEKT 6.6 in general does not require any calculations regarding the amount of material inputs for the maintenance of a road. Instead, it only demands information on the length, number of lanes, layer thicknesses, widths, traffic volume etc. that were all described in the case study of this paper (see chapter 4). LICCER in this regard inquires inputs similar to the EFFEKT tool, but as an alternative the user can insert project-specification data in LICCER if such data are available. Nonetheless, the condition is different for EKA. EKA needs more detailed data (like, production rate, tons and corresponding thickness of materials etc.) to calculate the GHG emissions and embodied energy. Therefore, in order to quantify the masses of input data for each maintenance activity, the following equation is conducted to quantify tonnage of asphalt pavement.

$$AS[ton] = (\mathrm{T} \times \mathrm{L} \times \mathrm{B} \times 2.5) \qquad (1)$$

In formula (1), AS is the total tonnage of asphalt wearing course; T is the thickness of wearing course; L is the length of road; B is the width of road; and 2.5 (ton/m^3) is material density of asphalt.

Formula (1) is the same equation that is introduced by EFFEKT 6.6 in its manual (Straume A. and Bertelsen D., 2015) to calculate the amount of an asphalt wearing course. LICCER also proposes almost a similar formula, the only difference is the asphalt density. LICCER considers a density of 2.24 ton/m^3 as a default for asphalt product, instead of 2.5 ton/m^3 in EFFEKT[5]. Whereas both tools assume that a typical hot mix asphalt (corresponding to 96% of production of asphalt product in Norway) consists of 94% aggregates and 6% bitumen.

As many roads are designed based on certain standards to fulfil the pavement serviceability, various influential parameters influence the maintenance intervals (like traffic volume, climatic zone, subgrade strength, frost depth etc.) over years (Garbarino E. et al., 2014). In this paper, maintenance intervals are taken from report no. 358 (Straume A. and Bertelsen D., 2015) that suggests pavement lifetimes with respect to different traffic volume. It is also assumed in each maintenance activity, 0.04 meter of road is milled and replaced by new asphalt wearing course.

By inserting all the input values to the three LCA software tools, the following results can be observed (table 2):

Table 2: Results of the Norwegian hypothetical national road within a 20-year analysis period with three LCA tools.

	EFFEKT 6.6	*EKA*	*LICCER*
Greenhouse gas emissions (ton CO_2.eq)	*487*	*344*	*296*
Embodied energy (GJ)	*28 108*	*5 786*	*27 400*
Amount of re-asphalting (ton)	*8 330*	*8 400*	*7 526*

6. Discussion

With respect to table 2, it became clear that the application of three different LCA tools to compare the hypothetical Norwegian national road (over a considered period of 20 years), led to different absolute and sometimes conflicting results. EFFEKT 6.6 showed higher GHG emissions compared to EKA and LICCER. However, by comparing embodied energy and asphalt, LICCER

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[5] As a simple solution to calculate asphalt consumption, it is proposed by NPRA that 1 cm of asphalt has approximately 25 weight per square meter (kg/m^2) (NPRA, 2005).

and EFFEKT 6.6 showed a close similarity in their results. Also, EKA and EFFEKT showed the amount of consumed asphalt with only small differences (less than 1%). Due to the differences in absolute numbers gained by the application of the three LCA tools, the main drivers need to be identified

A more in detail analysis reveals that the level of details in data compilation and assessment were not the same in the software tools. EFFEKT showed its results in an integrated approach to indicate GHG emissions and energy as well as materials consumption (might be due to this fact that EFFEKT is intended to have a more informative way to communicate its results). Such a limitation in EFFEKT is because of high level of aggregation that makes it hard to see what the attribution of different attributors are for each material. For instance, a typical asphalt pavement consists of different input materials (like aggregates, bitumen and other additives) that have different transportation patterns and corresponding embodied energy, which in EFFEKT all attributors are aggregated and shown as one representative attribute. Nevertheless, LICCER and EKA showed an advantage over EFFEKT 6.6 due to giving a possibility to their users to go through different spreadsheets in their software tools in favour of finding the reference assumptions.

Concerning the illustrated disparity in the magnitude of the results (table 2), a possibility to do calculations manually would be seen as a large benefit. Equation 1 represents how the tonnage of asphalt wearing course can be quantified for all the three software tools. By replacing variables with their representative values, the tonnage of asphalt pavement during each maintenance activity can be quantified. The results from the calculation showed that LICCER and EKA quantify 1881 and 2100 tons of asphalt pavement are consumed in each maintenance cycle, respectively. The results demonstrate (if the maintenance activities are happening 4 times in the period of 20 years) that the numbers are aligned with the results shown from LICCER and EKA in table 2.

However, the calculation of consumed asphalt for EFFEKT was not straight forward because it is based on cost principles in its analysis. This means EFFEKT considers a yearly cost for every year in the analysis period due to expected future maintenance activities, which might be based on expert opinions. In the road example taken in this paper, EFFEKT calculated two different maintenance cycles through the analysis period of 20 years. It considered one-sixth of maintenance in the first maintenance cycle[6] that would be attributed to the first year after construction of the road. However, in the remaining years (from the 2nd year till the 20th year), EFFEKT considered the maintenance activity would happen every other fifth year over the following 19 years (Kroksæter A., 2015).

$$Year\ 1: ((0.04 \times 1000 \times 21 \times 2.5))/6$$

$$Year\ 2\ -\ 20: ((0.04 \times 1000 \times 21 \times 2.5))/5 \times 19$$

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[6] This mean that the first maintenance cycle is taking place after six years.

In the above formulas, 0.04 is the thickness of wearing course; 1000 is the length of road; 21 is the width of road; 2.5 (ton/m^3) is material density of asphalt; 5 and 6 are maintenance cycles after five years and six years, respectively; and 19 is the number of years between year 2 and year 20.

One reason that LICCER shows a lower value in GHG emissions is because of the lower asphalt concrete density that is assumed in the section of material specification. In EKA and EFFEKT, the density of asphalt concrete is assumed to be 2.5 ton/m^3; however, LICCER considers asphalt density of 2.24 ton/m^3 as its default value. By only adding 0.26 to the presumed asphalt concrete density in LICCER tool, i.e. assuming the asphalt concrete is 2.5 ton/ m^3, the amount of bitumen consumption in each maintenance activity increases from 112.9 tons to 126 ton. This alteration in the amount of bitumen usage can correspond to additional 5.63 ton CO_2.eq. In addition, LICCER considers 5.99 kg CO_2.eq/ton corresponding to asphalt mixing plant in its assessment, which has the lower ratio compare to the other software tools. EKA considers approx. 21 kg CO_2.eq/ton for asphalt mixing plant, while, EFFEKT only shows one aggregated number (58.5 kg CO_2.eq/ton) for ‘asphalt’ that consists of GHG emissions from material extraction to placement on the road.

EKA showed a disproportional embodied energy compared to the two other software tools within the analysis period of 20 years. One of the rationales for such a deviation in the result is due to differences between values of bitumen embodied energy. EKA considers energy value of 720 kWh/ton (2.59 GJ/ton) for bitumen, but LICCER considers 52 GJ/ton (almost 20 times greater). This inconsistency in the result for the embodied energy of bitumen might be due to dissimilarity in the boundary of bitumen values chain. If we compare the results more in depth, it can be said that bitumen corresponded to approx. 85% of energy consumption in LICCER, but bitumen only had approx. 20% of contribution in EKA embodied energy. Furthermore, the results were compared with ecoinvent version 3.01 ‘Pitch’ production process[7] (ecoinvent Center, 2013). The process by means of CML V4.01 impact assessment method showed the embodied energy is approx. 51 GJ/ton for bitumen production at the refinery. Given results and comparison with ecoinvent value show that the calculation done by LICCER is aligned with ecoinvent assessment. However, one should be consider is that the result in addition to data input consists in methodology of choice because the result may differ if another methodology is chosen. It is hence very important to carefully control for this dissimilarity via a systematic approach (as it is explained in the European Standard 15804:2012+A1 (CEN, 2013)) to reduce any miscalculation and successive misperception of results.

It became obvious that the three LCA tools have a focus only on greenhouse gas emissions and resource consumption, which raises the question why other environmental metrics (impact categories) are not considered. In fact, having a shorter list of impact categories makes the interpretation of LCA results easier for decision-makers, as it is all about comparing different product systems with a same functional unit. However, taking decisions on only a few LCA indicators carries multiple risks. In addition, it was not clear (except for EKA[8]), how the greenhouse gas emissions have been calculated in terms of considered greenhouse gases and

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[7] Pitch (Europe without Switzerland) | petroleum refinery operation | Alloc Def, U.

[8] EKA includes solitary three climate gases in its greenhouse gas emissions that are: CO_2, CH_4 and N_2O.

impact factors. Due to this fact that Kyoto Protocol only covers six greenhouse gases in its first commitment period, which results in excluding short lived climate gases (e.g. black carbon) from its target. In fact, these short lived climate gases cause approx. 60% of overall global forcing (Rhodes S. P. and Schultz T., 2014). Hence, this is essential to be aware of climate gases that are not included in the assessment of GHG emissions, as they may have significant influence in the overall results.

Although this study by means of the three LCA software tools showed a range of results, it was essential to compare the results (from this study) with an Environmental Product Declaration (EPD) report (Nielssen C. S. and A., 2011) to evaluate the magnitude of similarities. The report showed that production and placement of asphalted gravel concrete (Agb 11) contributes to 56 kg CO_2.eq and 1141 MJ per ton of asphalt pavement. By scaling up the result of the EPD based on the assumptions given earlier in this paper, the greenhouse gas emissions from the asphalt manufacturing in the 20-year period sums up to approximately 470 tons of CO_2.eq, which shows roughly similar to what has been shown by EFFEKT 6.6 tool. However, the result of embodied energy shows 9584 GJ during the same time period, which is not aligned with the results of the three software tools in this study. The reasoning of having similarity or dissimilar results for the embodied energy and the GHG emissions has not been possible to be farther assessed. Due to the fact that the EPD report used another way of demonstrating the results, which made it impossible to compare the values with the other software tools.

7. Conclusions

To conclude, it can be stated that LCA needs a critical review in order to diagnosis any possible hidden errors in life cycle inventory and LCA results. Given the fact that a small error can accumulate through the life cycle assessment and consequence a substantial error in the overall results. This study was performed with the intention to evaluate three LCA software tools (EFFEKT 6.6, LICCER and EKA) to magnify the area of their coverage, strength and limitation of each software tool.

This paper assessed the software tools by comparing the results for a hypothetical road. The assessment covered resource consumption and greenhouse gas emissions as its proxy and considered road class H9 as it is hypothetical road. Although the supporting tools were intending to assess environmental performance of road projects, they had dissimilarities in their system boundary conditions. Therefore, the system boundaries for assessment were narrowed down to the maintenance phase within a 20-year analysis period.

In spite of the fact that the assessed tools addressed GHG emissions and embodied energy, there was no consistency in the results. These variations in the magnitude of results may lead to decisions on false grounds when it comes to making a comparison between different road options for decision makers. Therefore, having a transparent scope in LCA and explicit documentation make it possible for readers and future decision-makers to have a better insight into and therefore make more informed decisions based on LCA analysis. In addition, limitations and recommendations are additional pieces of information that need to be delivered at the end of LCA works to declare and highlight the accuracy level for the intended users and readers.

It will be necessary that future LCA software tools integrate more details and additional data into their inventories in favor of making the LCA results more comprehensive and transparent. In addition, it would be beneficial to consider the pavement-vehicle interaction and the effect on energy consumption due to rolling resistance and geometry of roads as well. Winter service and effect of it on winter maintenance strategies, especially in cold climatic zones, can bring more dimensions to the scope of assessment. Including more environmental impact categories and using comprehensive database as well as impact assessment methods are very critical and need to be carefully handle in order to provide more thorough and fair environmental impact assessment. End-of-life material policy should include more than material transport after maintenance activities. It should cover more data like; amount of waste asphalt generated and stored in storage sites, maximum permissible storage time of waste asphalt in depots, etc.

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