Review and comparison of freely-available tools for pavement carbon footprinting in Europe

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ABSTRACT: This paper wants to raise awareness of LCA/CF tools that have been built within European projects in the last 5-6 years and that are freely-available on the internet: asPECT, ECORCE M and CARBON ROAD MAP. The tools will be compared in terms of their architecture and system boundaries considered, as well as on the basis of the results of a comparative carbon foot printing exercise of several high content reclaimed asphalt wearing courses. This will provide practitioners with clearer ideas on the benefits and limitations of the existing tools, will provide suggestions to perform the carbon footprinting analyses in Europe and through the comparison of the results will allow drawing some guidelines for the final user.

1 INTRODUCTION

Full process-based LCA is certainly the most advisable technique to assess the environmental impact of road components as well as road pavement services. Research and industry should cooperate to build tools that can allow an easy access to these techniques as well as a uniform interpretation of results. However, pavement LCA is still a very young subject and up-to-date still too many uncertainties and lack of primary data makes the full process LCA very difficult to undertake. Furthermore, in many cases, authorities charged with managing transportation infrastructure are concerned mainly with the impacts towards climate change, and are not as concerned with the additional information produced by an LCA. This may be driven by legislative actions that set goals towards the reduction of carbon emissions, such as when countries adopt the goals set forth in the Kyoto Protocol. In response to these goals, many countries also standardize the measurement of carbon emissions linked to the global warming process, such as the UK's PAS-2050 (Huang et al. 2013). Additionally, the process of calculating the carbon footprint (CF) is simplified from an LCA given that the reminder of the environmental impacts associated with LCA (e.g., acidification, eutrophication, etc.) do not need to be calculated in a carbon footprint analysis, leading to a much smaller required inventory. The CF may be seen as a proxy for environmental impacts, and thus displace the need for conducting a full LCA. However, the limitations of using the CF as a proxy for environmental sustainability was thoroughly evaluated in Laurent et al. (2012), and the authors found that limited conclusions can be drawn from carbon footprints regarding other pollutants. However, the authors note that in products, which are dominated by relatively few processes, the correlation between CF and other impact assessment results may become much stronger.

1.1 *Aim of the study*

This paper wants to raise awareness and analyze benefits and limitations of LCA/CF tools that have been built within European projects in the last 5-6 years and that are freely-available on the internet: asPECT (Wayman et al. 2014), ECORCE M (2014) and CARBON ROAD MAP (Spriensma et al. 2014). The study will perform a comparison of the tools in terms of their architecture and system boundaries considered, as well as comparing the results of environmental impact assessment exercise based on a CF study performed within another European project Allback2Pave (2016). This will provide engineers of Road Authorities and practitioners with an idea of which could be the more effective tool for performing environmental impact assessment of road pavement components (e.g. asphalt mixtures) in EU. A final comparison of the CF results will allow drawing some guidelines for the final user.

2 REVIEW OF THE LCA/CF TOOLS IN EUROPE

A recent comprehensive overview of the currently available pavement LCA and carbon footprinting tools allowing an estimate of the environmental impacts of road pavement technologies (i.e. asphalt mixtures) within their lifecycle, is provided by Spriensma et al. (2014). This section presents an overview of suggested tools that could be used from European Road Authorities to perform an environmental impact assessment exercise. These tools have the common characteristics of being:

- Freely available and accessible
- Based on full process LCA
- User-friendly and in any case accompanied by a user manual
- Able to perform at least a cradle-to-laid Carbon foot printing of road pavement technologies

Furthermore some of them also allow to:

- Perform a full pavement LCA, not only providing the carbon footprint
- Perform a cradle-to-grave analysis (up to end of life)
- Use references and databases developed in EU countries

Additionally, other more general, complex professional LCA tools can be used to assess/compare the environmental impact of road pavement technologies to be used in road pavements. These tools are not presented in this report and consist in softwares such as BEES, GaBi and SimaPro, which allows higher flexibility and possibly a more detailed estimation, but are not cost-free and need professional expertise.

2.1 *asPECT*

asPECT (asphalt Pavement Embodied Carbon Tool) is a pavement carbon footprint tool which was developed by the Transport Research Laboratory (TRL), and released in its current version in 2014 (Wayman et al 2014). The tool estimates CO_2e emissions from asphalt paving processes in a cradle to gate scenario, and has been designed to meet the specifications in the UK standard PAS 2050 (Huang et al 2014). Several thorough reviews have been conducted on the capabilities and limitations of asPECT, one of which is presented in Spriensma et al. (2014). One trade off when using asPECT that is noted in Spriensma et al. (2014) is the required input from the user. Other tools contain many default values within the database for processes, such as Hot Mix Asphalt (HMA) plant specifics, which limits the user input to material amounts, material types, construction processes and transportation types and distances. asPECT requires several user inputs, such as the characteristics of the HMA mixing plant (e.g., annual production values, the profile of the power consumed by the plant, etc.). This specificity of data has the benefit of increasing the reliability of the results, due to more accurate information, but has the drawback of considerably increasing the complexity over similar tools.

2.2 *ECORCE M*

ECORCE M (ECO-comparator applied to Road Construction and Maintenance) was developed by the French Institute of Science and Technology for Transport Development and Networks (IFSTTAR), and the international version was released in mid-2014 (ECORCE M. 2014). ECORCE M is a process based LCA tool with an extensive integrated default database used to complement the lifecycle inventory phase. The data used to populate the integrated database is drawn from multiple sources. However, in cases that an international consensus does not exist for data, ECORCE M draws upon research conducted in France to populate values. Inputs into

ECORCE M include: volumetric data, equipment type (e.g. roller, paver, etc.), layer composition data, the type of mixing plant, and the transport distances and modes. Based on these inputs, several default values that are stored in the ECORCE M LCI database are used to populate an inventory of environmental data. The input data is then combined with inventory data to develop environmental impact values. The following indicators are presented as results from ECORCE M: Total Energy Consumption (MJ), Total Water Consumption (m^3), Greenhouse Effect (kg eq.CO_2), Acidification (kg eq.SO_2), Eutrophication (kg eq.PO_4), Tropospheric Ozone Formation (kg eq. ethylene), Ecotoxicity and Chronic Toxicity (both measured in terms of kg equivalent of 1,4 dichlorobenzene).

2.3 *Carbon Road Map (CEREAL)*

Royal Haskoning DHV BV, in a consortium with KOAC*NPC, The Netherlands and the Danish Road Directorate (DRD) in Denmark, initiated the research and development of a European Carbon footprinting tool for more sustainable road management and construction in the project called "CEREAL": CO2 emission Reduction in road lifecycles (Spriensma et al. 2014). The consortium of CEREAL evaluated data of several popular national tools and finally created a tool, "Carbon Road Map", which concentrates on maintenance and rehabilitation of in service roads and was harmonized in the Western-European Countries that funded the project: Germany, Denmark, Ireland, The Netherlands, Norway, Sweden and The United Kingdom. When compared to asPECT, Carbon Road Map has the strong points of being as user-friendly but needs fewer data easily accessible by engineers of road authorities and it is able to include lifecycle maintenance strategies for road pavements allowing calculating a full lifecycle carbon footprint. The tool is programmed in Excel and already includes all CO_2 data for materials, transports and equipment for UK, Denmark and the Netherlands. Furthermore, the tool allows customization to other regions.

3 COMPARISON OF THE TOOLS: SYSTEM BOUNDARIES

The purpose of a pavement LCA is to quantify the total environmental impact of the pavement throughout the pavement's life, which is generally divided into the following five phases (Santero et al. 2011); (*1*) raw materials extraction and production, (*2*) construction, (*3*) use, (*4*) maintenance and (*5*) end of life. Ideally an LCA should be considered a cradle to grave analysis that accounts for the entire life of the materials, all the processes involved with the system, as well as other processes directly impacted by the system.

Nevertheless, a lack of information, such as the impact of infrastructure decisions on what are considered secondary systems, leads to a constraint on the system boundaries for a pavement. Thus, in the case of pavements, typical LCA boundaries are constricted to cover only the time period from material extraction through the end of the construction phase of the project also referred to as cradle to laid analysis. asPECT and ECORCE M are designed to perform CF/LCA considering this type of reduced lifecycle for road pavement which includes a cradle-to-laid + end-of-life scenario (Figure 1). These tools allow obtaining a much more detailed CF/LCA of new designed road pavement components, such as new asphalt mixtures, and a more accurate final outputs (e.g. KgCO_2/t of mix). However, this type of analysis can't be considered a comprehensive road pavement CF/LCA, because it does not allow taking in consideration the Use phase, which is a fundamental phase of the road pavement life cycle (Trupia et al 2016).

Furthermore, in order to use LCA/CF tools for decision-making, these must be more related to asset management rather than road pavement technologies. In other words, the CF of the pavement components (e.g. asphalt mixes) should be a mere input and the overall methodology should focus mainly on dealing with data such as road geometry, maintenance strategies, traffic, pavement conditions and statistical parameters to account for data changing over the analysis period. An ideal tool to account for environmental impact within asset management should overcome these limitations. This would provide a methodology for decision-making which is composed by lifecycle stages that are different from those considered in the other two tools, so to allow accounting for the CF of maintenance of existing road pavements. This type of analysis is far more complex than the one related to only pavement components. Furthermore the standard on Sustainability of Construction Works EN 15804:2012, reports that the Use phase of LCA incorporates the maintenance, repair, replacement "…including provision and transport of all materials, products and related energy and water use, as well as waste processing up to the end-of-waste state or disposal of final residues during this part of the use stage". From this it can be interpreted that the Use phase is equal to the analysis period and should include pavement layers dismantling, replacement and also stockpiling, so that the End-of-life phase, as intended for pavement components as asphalt mixtures (Figure 2), might not occur or it occurs only when the whole road pavement is dismantled or changes functionality (this is the reason of the "?" on Figure 2). CARBON ROADMAP (CEREAL 2014) is built upon this philosophy and it was also conceived to be a tool able to account for CF of maintenance of existing road pavement at EU level.

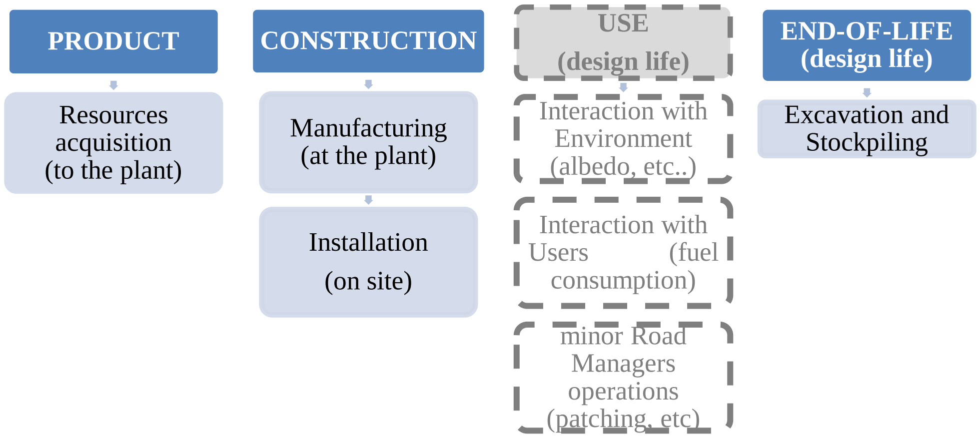

Figure 1: Proposed system boundaries for CF/LCA of road pavements components such as asphalt concrete. Use phase not included as in asPECT and ECORCE M.

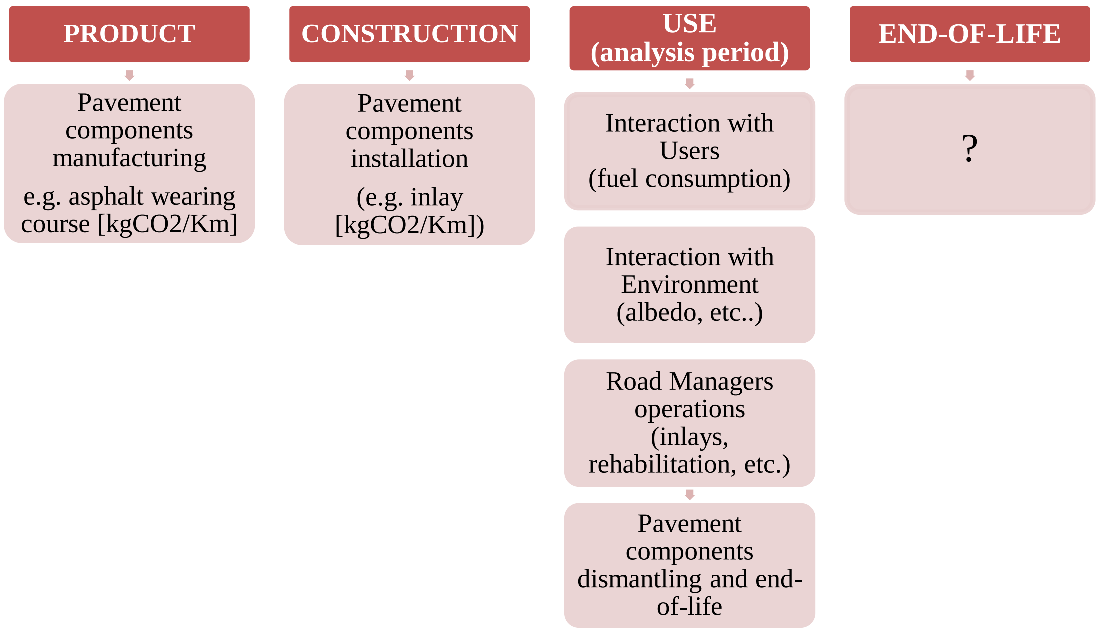

Figure 2: Proposed system boundaries for CF/LCA of maintenance of existing road pavement (e.g. CARBON ROAD MAP)

4 COMPARISON OF THE TOOLS: CARBON FOOTPRINTING RESULTS

In order to compare the outcomes and user-friendliness of the selected CF/LCA software, a LCA study conducted within the AllBack2Pave (AB2P) 2013 – 2015 project, funded by the Conference of European Road Directorate, was selected. More details of the LCA study will be published elsewhere and can be found on the project website (http://allback2pave.fehrl.org). The strategic aim of the AB2P project was to elevate asphalt recycling levels across Europe, on the basis that recycling surface into surface course would yield the greatest benefits, since this would best utilize the properties of the high grade aggregates used in the original surface course. This was funded on the premise that recycling asphalt into wearing courses was able to best utilize the preserved properties of the recycled material, both aggregate and binder. The Work Package (WP) 5 of the project aimed at providing results of the difference in the environmental performance over 60 years, between the currently maintained typical European major road asphalt pavements and scenarios in which the currently used asphalt mixtures are replaced by the AllBack2Pave (AB2P) asphalt mixes: eight asphalt mixtures for wearing course containing up to 90% Reclaimed Asphalt (RA). In order to take into account the European level of the project, three case studies were considered: Italy for South Europe, Germany for Central Europe and UK for North Europe.

4.1 *CF Baseline scenarios, Maintenance strategies and general assumptions (LCI)*

Each case study was crafted with the help of the interested Road Authorities and was intended to be representative of "typical" inter-urban roads of the selected countries (Table 1). Results from the other WPs of the project, direct data collection from the asphalt production plant in Germany and Italy and tailored questionnaires completed by the interested Road Authorities, were the sources of information on the key variables, such as the asphalt mixes recipes, energy and fuel consumption and transport distances. When needed, reports, standards and reputable data sources were utilized to provide emissions factors for fuels, transport and embodied carbon values for constituent materials. Gathered data including more detailed such as mix recipes, site locations and other information are presented elsewhere (AllBack2Pave 2016). Maintenance strategies for a 60 years analysis period and practices are reported in Table 2.

Table 1: Asphalt pavement geometry, structures, traffic and durability

Pavement course	South EU - IT (Anas 2015)	Central EU - D (Bast 2015)	North EU - UK -10
Section Width	9.50m	11.80m	11.00m
Section Length	2000m	800m	720m
Wearing	Asphalt 30 mm	Asphalt 30 mm	Asphalt 40 mm
Binder	Asphalt 40 mm	Asphalt 80 mm	Asphalt 50 mm
Base	Asphalt 100 mm	Asphalt 140 mm	Asphalt 100 mm
Foundation	Cement treated sand 300 mm	Unbound gravel +frost blanket 350 mm	Cement treated limestone 258 mm
Traffic levels	High Traffic	Medium Traffic	Low Traffic
Durability of wearing c.	5 years (AC)	16 years (SMA)	10 years (SMA)
Durability of binder c.	25-30 years		
Durability of base c.	50 years		

The philosophy behind the development of the AB2P technologies is to allow maintenance of existing roads through inlay treatments that re-use as much as possible of the milled material so to reduce RA stockpiling and downgrading to base or unbound layers, and avoid depletion of new natural resources. For this reason, in this exercise, in order to account for the potential lifecycle environmental benefits of the AB2P technologies, all the case studies will consider a similar maintenance strategy consisting of the repeated inlays of the wearing courses, complemented with binder course inlays and rehabilitation over an analysis period of 60 years. Of course this will consider as a common assumption that the road pavement foundation and sub-layers will not deteriorate and the difference between the maintenance plans will be strictly linked to the estimated service lives of the wearing courses provided by primary data (ANAS 2015, BAST 2015; Spray 2014) or extrapolated from other similar investigation (EARN 2015; Re-Road 2013). Furthermore, for the purpose of modelling, it is assumed that the asphalt will only last for its full estimated lifetime with no under/over performance. The equipment, schedule and production rate are provided elsewhere (AllBack2Pave 2016).

Table 2: Maintenance treatments, mix durability and assumptions

Maintenance treatment	• Surface treatments with periodic inlay of wearing course and occasional inlay of binder and base course • Maintenance is undertaken in one carriageway (two lane), or one lane (single lane road) at a time, with the traffic diverted onto the other carriage/lane. • Workzones are extended for the whole length and the width of the full carriage • In the case studies with dual carriageway, maintenance event is considered only in one direction.	
Materials	Current asphalt mixtures for each case study will be compared with the following asphalt mixes for wearing course and occasionally binder and base course: AB2P mixes technologies	
	1. AC16 30%RA+additives	4. SMA8S 30%RA
	2. AC16 60%RA+additives	5. SMA8S 30%RA
	3. AC16 90%RA+additives	6. SMA8S 60%RA+additives
Analysis period	60 years	

4.2 *Modeling Carbon Footprinting over 60 years*

The selected tools were all used to calculate the environmental performance of the AB2P technologies through a carbon foot printing exercise carried out for each case study. This exercise focuses mainly on comparing the CF generated from using the AB2P technologies in place of the currently used asphalt mixes over the entire analysis period of 60 years The total amount of tonnes of CO_2e over 60 years is the final outcome considered to evaluate each design alternative and is calculated as explained in Figure 3.

Table 3: number of interventions per case study over the 60 years

	South EU - IT	*Central EU - D*	*North EU - UK*
Inlay Wearing Course	9	2	2
Inlay Wearing Course + Base Course	2	1	2
Rehabilitation	1	1	1
TOTAL	12	4	5

It has to be highlighted that whenever the maintenance intervention involves also binder and base courses, it is assumed that these asphalt mixes are the same of the considered wearing course. In fact, it looks not realistic that future interventions will make use of RA only in wearing courses. The obtained CF was then multiplied for the number of interventions included within the current maintenance scenarios of existing road sections in South, Central and North Europe (Table 3).

4.3 *asPECT 4.0*

asPECT is in the authors' opinion the most flexible and customizable free tool for road pavement components CF. Its main benefits come from its extreme flexibility: it allows inserting and/or changing almost all inputs, from the energy and resources consumed at the plant to the constants related to the grid electricity, fuels, transport, etc. and this increases the reliability of the results. asPECT allows implementing new design of the mixtures in the plant and understanding CF in each operation. Although requiring very detailed inputs, it also allows higher level of customization of CF.

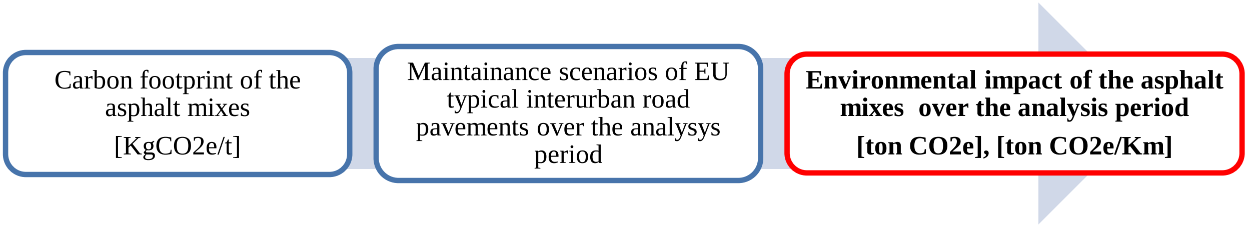

Figure 3: Environmental Impact Assessment of the AB2P technologies

At the same time this has the drawback of considerably increasing the complexity of the analysis over similar tools, especially for new users. However, other parts of the tool are not as detailed as those above discussed. In particular for the part concerning the laying and compaction on site, it would be more rigorous to import the specific CO_2e value from other sources, instead of using the default value. Furthermore, this tool does not carry out a complete LCA analysis but is limited to the carbon footprint, and does not take into account the Use phase. Despite its complexity and some limitations, asPECT comes with a very well explained manual so that it was possible to understand, replicate all the calculations and double check all the outputs. Results of the analysis performed by using asPECT are shown in Table 4.

Table 4: Calculated total tonnes CO_2e footprints (and percentage of variation with respect to the Baseline) over 60 years for the all case studies with aspect

Case study	*South Europe: Italy*		*Central Europe: Germany*		*North Europe: England*	
Baseline	2361	-	953	-	649	-
SMA IT-RA30add	2356	-0.20%	741	-22.30%	573	-11.70%
SMA IT-RA60add	2295	-2.80%	614	-35.50%	555	-14.50%
SMA IT-RA90add	2236	-5.30%	492	-48.40%	539	-17.00%
SMA D-RA30	2595	9.90%	822	-13.70%	656	1.10%
SMA D-RA60	2410	2.10%	670	-29.70%	598	-7.90%
SMA D-RA60add	2512	6.40%	697	-26.80%	628	-3.20%

Table 5: Calculated total tonnes CO2e footprints (and percentage of variation with respect to the Baseline) over 60 years for the all case studies with ECORCE M

Case study	*South Europe: Italy*		*Central Europe: Germany*		*North Europe: England*	
Baseline	1492	-	739	-	502	-
SMA IT-RA30add	1400	- 6.1%	552	-25.4%	418	-16.6%
SMA IT-RA60add	1310	-12.2%	448	-39.4%	391	-22.0%
SMA IT-RA90add	1250	-16.2%	356	-51.8%	375	-25.3%
SMA D-RA30	1638	9.8%	632	-14.5%	501	-0.1%
SMA D-RA60	1509	1.2%	525	-29.0%	462	-8.0%
SMA D-RA60add	1509	1.2%	525	-29.0%	462	-8.0%

4.4 *ECORCE M*

ECO-comparator applied to Road Construction and Maintenance is a full process, customizable road pavement LCA tool based on a database populated with data coming from researches conducted in France. The main inputs concern pavement volumetric data, transport distances and modes, and mixtures recipes. All the other data included in the database, are average data obtained from current manufacturing and maintenance operations in France and the tool does not allow

modifying them. On the one hand, this makes the tool really easy to use for non-expert users, even without a manual. On the other hand, not having a quick access to the database's references makes it more difficult to fully understand results obtained; for the same reason, it is not possible to change CO_2e values of the mixture components or to add some specific element such as fibers, adhesive enhancers, emulsifiers, thickeners, fluxing agents, etc. Therefore, ECORCE M is very much user-friendly and it possibly needs the addition of a universal/open features allowing higher level of customization to expert users. However, despite these limitations, the tool provides benefits such as including the analysis of the earthworks and soil treatments, it can be used for comparison between maintenance operations and above all it carries out a full process LCA analysis, not restricted only to CF. In order to have a comparison with the other tools, Table 4 shows only the results CO_2e emissions for all case studies (Baselines and AB2P mixtures).
From Table 4 and Table 5 it can be noticed that, even though absolute values obtained from ECORCE M are lower than asPECT's ones, the trend line and ratios between scenarios are very close to each other, especially for the German and English case studies. ECORCE M shows always lower absolute values of CO_2e. However, it has to be highlighted that the authors were not able to input additives and fibers present in the mixes, so that results from the two software can't be fully comparable. In conclusion, ECORCE M doesn't allow great level of customization, but it is very much user-friendly, provides similar results to asPECT, in terms of CF, and it is the only freely available tool (over those analyzed) that allows performing a full process LCA of road pavement in both scenarios: new construction and maintenance of existing assets.

4.5 *CARBON ROAD MAP*

CARBON ROAD MAP allows estimation of the CF of maintenance operations of existing road pavement at European level. Its database is filled with information acquired from West-European Countries (Netherlands, Denmark and United Kingdom); however the software allows using an "expert mode" with which it is possible to customize the database through Excel. Its strength lies in the few amount of data required that makes it a user-friendly tool, especially for inputs concerning maintenance strategies. Furthermore, as explained before, this tool is the only one that includes the possibility of considering the entire life cycle analysis period (e.g. 60 years), including maintenance strategies and traffic change. The outputs, also in form of graphs, allow comparing the total amount of CO_2e obtained by considering different maintenance strategies in different countries. Despite the concept and architecture of the tool are remarkable, unfortunately the tool is not recommendable because the copy received from the authors of the CEREAL project, is not free from bugs and this makes the software not stable and therefore not recommendable. Furthermore, the tool shows also many limitations and drawbacks:

- The User manual is not exhaustive,
- Users can't change the specific CO_2e inventory values,
- It is not possible to define precise length of the road sections (1 km and multiples).
- Users should access the database to enter CO_2e values of customized pavement components and these that would need to be calculated separately (for instance using asPECT).

Table 6: Calculated total tonnes CO2e footprints (and percentage of variation with respect to the Baseline) over 60 years for the all case studies with Carbon Road Map

Case study	*South Europe: Italy*		*Central Europe: Germany*		*North Europe: England*	
Baseline	1206654	-	191764	-	404942	-
SMA IT-RA30add	1206643	-0.001%	191621	-0.074%	404856	-0.021%
SMA IT-RA60add	1206561	-0.008%	191534	-0.120%	404836	-0.026%
SMA IT-RA90add	1206481	-0.014%	191453	-0.162%	404817	-0.031%
SMA D-RA30	1206968	0.026%	191677	-0.045%	404950	0.002%
SMA D-RA60	1206716	0.005%	191571	-0.100%	404884	-0.014%
SMA D-RA60add	1206854	0.017%	191590	-0.091%	404919	-0.006%

For these reasons, in order to carry out the analysis, as performed with the other two tools, authors needed to first modify the database by entering in the expert mode and introducing the $kgCO_2e/t$ values of each asphalt mixture as calculated with asPECT. The software then requires details of project definition (case study details and analysis period), construction data (pavement structure, design life and traffic data), maintenance strategies and road dimensions. Authors created one file for each alternative and run the software to obtain the summary of the total CO_2e emissions, also grouped per type of maintenance intervention. Results obtained were not satisfactory as shown in Table 6. In fact, it can be noticed that the total tonnes of CO_2e are of one order of magnitude bigger and also the proportions of CO_2e values between operations are really different from those obtained from asPECT and ECORCE M; in particular Use of equipment and Production materials look over-proportioned relative to the Transport. As a result, CARBON ROAD MAP needs to be "labeled" as well structured and very promising tool, but under development. Its use is still not recommended due to several software bugs and above all, results are not comparable with those obtained with the other tools and with other researches in literature.

5 COMPARISON OF THE TOOLS: SUMMARY

Freely-available road pavement specific LCA/CF tools built in Europe in the last 4-5 years were presented. Each tool has its own benefits and limitations, however results obtained for specific AB2P case studies were very different (Tables 4,5,6). It can be quickly noticed that, results coming from Carbon Road Map are over-estimated compared to the other tools and this leads to the suspicion that there are some mistake in the tool database. On the other hand, results obtained from asPECT and ECORCE M are comparable and they lead to similar considerations and recommendations. The only issue of using ECORCE M in the analyzed case studies is restricted to the limitation of specifying the incorporation of fibers and additives within asphalt mixtures. Nevertheless, this can't justify the difference in results considering that from the results obtained with aspect, the emissions due to fibers account for less than 1% of the total. Table 7 provides a summary of all features including pro and cons of the tools compared in the present study. This information can be useful to select the tool that best fit interest of practitioners or decision makers while helping further developments of such tools within European framework. LCI for material and processes include the embedded value and is available within library of each software.

Table 7: Key information of LCA/CF tools analyzed

	asPECT	*ECORCE M*	*Carbon Road Map*
Full LCA	Only CF	Yes	Yes
Materials and processes LCI	Tool library (asPECT manual)	Tool library (ECORCE M manual)	Tool library (www.ce-real.dk.)
Customization	High	Medium	High
User-friendly	Medium	High	High
Entire life-cycle period within the tool	No	No	Yes
Reliability	High	High	Low

6 CONCLUSIONS

Based on this investigation the following recommendations can be drawn out for practitioners:

- For its flexibility, asPECT is the best tool for performing cradle-to-grave carbon footprinting analyses of road pavement components in EU. If maintenance strategies and end-to-life phase are needed, then system boundaries can be widened as explained in Figure 3.

- ECORCE M is the most user-friendly tool and allows performing a full LCA, which takes into account several environmental impact indicators. Also in this case, maintenance and end-of-life can be added by widening the system boundaries.
- In terms of system boundaries CARBON ROADMAP is the tool better structured to perform decision-making based on environmental impact within pavement asset management. However, despite the tool is well structured, it is not reliable yet and would need further development.

Overall, this paper provides a comprehensive comparison between three free-available road pavement LCA/CF tools. This analysis was able to highlight advantages and disadvantages of the considered tools and it also highlighted the issue of benchmarking these LCA/CF studies at the countries level inside Europe. As a result, the authors believe that any other attempt to build continental-wide LCA tools should first of all pay attention on the definition of the tool architecture so to include appropriate system boundaries. Furthermore, enhancing cooperation between the involved countries could allow decreasing issues related to geographical benchmarking by the definition of common databases and impact assessment methodologies. Such step would be fundamental to encourage a greater deployment of LCA within the road engineering and asset management industries.

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