Conférence Européenne des Directeurs des Routes

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CRABforOERE

Life Cycle Assessment of CRAB mixtures

Deliverable D7

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Cold recycled asphalt bases for optimal energy and resource efficiency pavements

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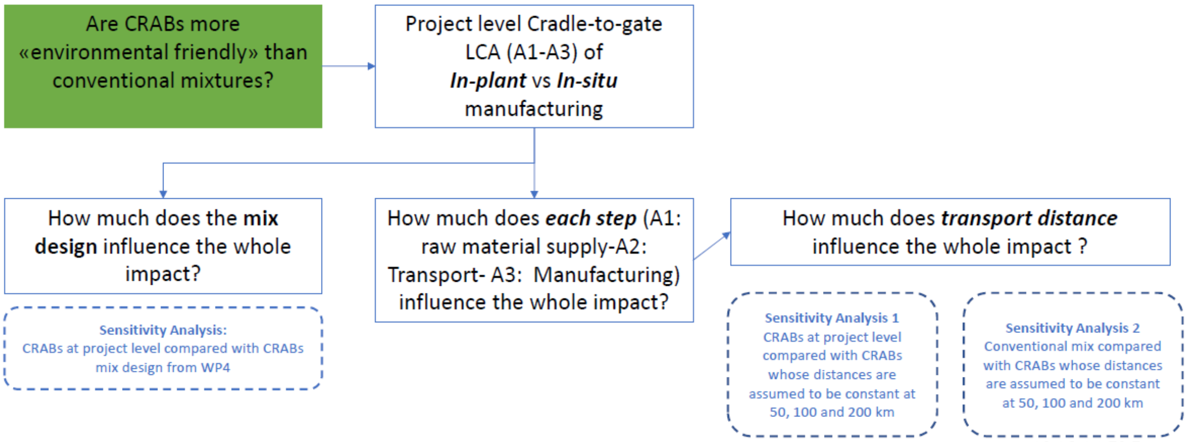
Executive Summary

The aim of Work Package 7 of the Crab4Oere (C4O) Project, is to evaluate the benefits of using cold recycled materials (CRM) rather than using conventional hot mix asphalt. This will be carried out by limiting the investigation to the production of the pavement materials/products (A1 – A3) and on the basis of two case studies representative of two different production scenarios: in-plant recycling (Republic of San Marino) and in-situ recycling (Germany).

For each case study, results have been analyzed in order to address which life-cycle stage between material supply, transport and manufacturing is the most impactful. Furthermore, a sensitivity analysis on the transport distances was undertaken assuming distances up to 200Km.

Finally, for each case study, the investigation also focused on the effect of using different CRAB mix designs by varying the range of cement, bitumen emulsion and water within typical ranges indicated within the other deliverables of the project.

The following “flowchart” provides a summary of the processes followed for the LCA study.



The data collection has been carried out with the support of the partners. Primary data was used when available, secondary data was taken mostly from GaBi database. The LCIA methodology chosen was EF 2.0. The whole exercise was carried out according to the following reports, communications and frameworks:

- JRC (2016). Guide for interpreting life cycle assessment result, EU Joint Research Centre technical report.
- EN 15804:2012 + A1:2019. Sustainability of Construction works. Environmental Product Declarations. Core Rules for the product category of construction products.
- EN ISO 14040 (2006). Environmental management – Life Cycle Assessment – Principles and framework
- EN ISO 14044 (2006). Environmental management – Life Cycle Assessment – Requirements and guidelines
- PavementLCM Guidelines, created within the project funded by CEDR.

Results

- The research shows that, regardless of the manufacturing technology (in-situ recycling vs in-plant recycling), the environmental impact of the manufacturing of CRABs, expressed with 16 different indicators, is on average at least 40% lower when compared with the conventional hot mix asphalt (this is based on an overage of 16 environmental impact indicators).

- The hotspot analysis showed that the acquisition of raw materials (A1) seems to be the most impactful stage for CRABs (higher than 80%). Hence, to further reduce environmental impacts of these technologies, CRAB producers should focus on identifying materials whose extraction and/or supply is less impactful.

- Furthermore, sensitivity analyses revealed that transport distances, related to material supply and CRAB manufacturing, do not play the same main role as they typically have with hot asphalt mixtures. This is due to the significantly reduced amount of materials to be transported at the manufacturing site, which in turns corresponds to a significant lower number of trips, hence an overall reduced impact of the transport phase (A2).

- At last, it was shown that some mix components drive certain impact categories (i.e. it is confirmed that higher cement content leads to a higher value on climate change), however as a general conclusion, the manufacturing of a cold asphalt mix is more environmental friendly than a hot asphalt mix, regardless of the mix design formula.

These results can be used by NRAs for further sustainability assessment exercises and/or in databases providing the life cycle environmental impact of road pavement materials. The authors hope this report can contribute to raise the importance for asphalt contractors to assess sustainability performance of their products at the design stage and to assist road authorities/decision makers moving towards prescribing eco-design as a mandatory practice within the industry.

List of Tables

List of Figures

Table of contents

1. Introduction

Concerns about the environmental, economic, and social impacts related to the activities of the road engineering industry are rising lately among the policy/decision-makers, contractors, stakeholders, and even society. For this reason, the road engineering industry has indirectly been pushed towards adopting and eventually implementing more sustainable ways of producing, constructing, and managing road assets.

A promising approach that can reduce the environmental, economic, and social impacts of said activities is the utilisation of cold mixture recycling for the base layers of asphalt pavements.

In this deliverable, an attempt is being made to better understand the sustainability implications of using Cold Recycled Asphalt Bases (CRAB) in the pavement engineering sector. Thus, as reported in Figure 1, two case studies have been structured and undertaken, one in the Republic of San Marino and one in Germany, to understand the environmental and health impacts of the possible use of 100% cold recycled asphalt mixes for base courses at European level; and perform a comparative life cycle assessment with alternative disposal routes and alternative construction methods, namely: the use of virgin materials to build bituminous bound layers, the use of Hot Mix processes, and within different pavement structures.

The defined pavements were evaluated and compared in terms of their environmental impacts through the utilization of the Life Cycle Assessment framework (LCA). After the definition of the case studies, necessary data was collected (primary and secondary) by the project partners and reputable literature sources where needed). To further understand the impact mechanism of said alternatives, a hot spot analysis was performed and thus, the most impactful life cycle stages of the defined products were pinpointed. Moreover, through a sensitivity analysis performed on the transport distances of the used materials, guidelines and recommendations were drawn that can help NRAs and stakeholders to optimize their overall sustainability approach.

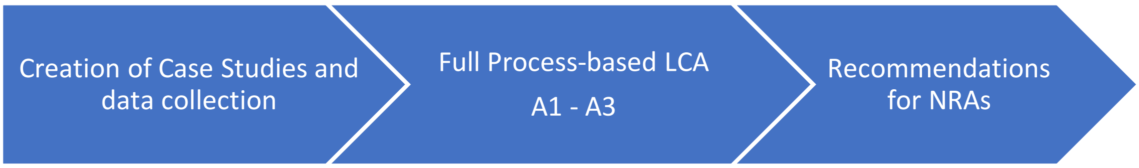


Figure 1- D7.1 structure for the investigation and report

2. Case Studies

The presented case studies have been selected as representative of two different manufacturing processes of CRAB materials as well as for the subsequent installation/construction of road pavement components. The two case studies are real projects recently carried out at the Republic of San Marino and in Germany. Hence, they differ in terms of geographical location, pavement structure, traffic level and above all, construction methods: in-plant recycling for San Marino and in-situ recycling for Germany.

The table below summarizes the main information directly collected from contractors and/or project partners. As it can be seen in both cases the project consists of a major maintenance activity that includes the use of a cold mix asphalt (CRAB), in place of conventional hot asphalt mixtures, for binder layers (San Marino) or for base layers. (Germany).

Table 1 - Main information of Case Studies

Pavement course	In-Plant recycling: Republic of San Marino		In-Situ recycling: Germany	
	original	*with CRABs*	*original*	*with CRABs*
Section Width	4m		12,5m	
Section Length	80m		150m	
Wearing	Asphalt (HMA) 40 mm		Asphalt (HMA-SMA8) 40 mm	
Binder	Asphalt (HMA) 70 mm	CRAB 100 mm	Asphalt (AC16) 80 mm	Asphalt (AC16) 65 mm
Base	Recycled materials treated with cement 150 mm	Recycled materials treated with cement 150 mm	Asphalt (AC32) 220 mm	Asphalt (AC32) 120 mm
Sub-Base	-	-	-	CRAB (bitumen emulsion) 200 mm

2.1 In-plant recycling case study: Republic of San Marino

Location: The case study consists of a repaving operation on a two-lane dual carriageway road section part of Via XXV Marzo. According to the available data, the pavement can be divided into subsections, which differ in terms of materials, distresses and type of interventions. The average daily traffic used for the design of the pavement is 4.000 vehicles per day.

Figure 2- San Marino Site Location

Production and Construction methods:

- In-plant recycled CRAB materials are produced within the asphalt plant facilities of Cooperativa Braccianti and then transferred to the site. Regarding the construction procedure, at first, the reclaimed asphalt was produced by milling the existing pavement and transferred to stockpiling facilities, then the CRAB is produced at the plant, transported and fed into a paver followed by a roller. It's installed over a tack coat made of bitumen emulsions and mineral filler.

- Conventional asphalt mixtures are manufactured at the asphalt plant of Cooperativa Braccianti and then installed by using mineral filler and bitumen emulsion as a tack coat over the binder layer and then a paver and a roller will complete the construction.

The design formula of the materials used in the "in-plant recycling" case study (San Marino) are provided in Table 2.

Table 2 - San Marino asphalt pavement composition

PAVEMENT MATERIALS – San Marino case study	
Mix specifications for all mixes used on the project. These should include (at the very least) aggregate type and content, asphalt content and any modifiers used in the mix.	**Asphalt Concrete- modified bitumen (Surface)** - Aggregate 90.5% - Filler 4% - Total binder content: 5.5% - Type of binder: Bitumen - No added fibres, additive or modifiers

	CRAB mix (Binder) - Aggregate 89.5% (84.5% Reclaimed Asphalt) - Filler 4% - Total binder content: 4.5% - Type of binder: Bitumen emulsion - Cement: 2% - This binder substituted the conventional mix, assumed to be the same of surface. **Cement treated material (Base)** - Aggregate 97% - Total binder content: 3% - Type of binder: Cement - No added fibres, additive or modifiers

Transport distances: locations of interest for the different phases from material sourcing to pavement installation are shown in Figure 3:.

- Conventional
  - Refinery (bitumen, modified binder and bitumen emulsion): Bologna, Italy - 125 km
  - Fine and Coarse Aggregate Quarry: Forlì, Italy (fine) – 65 km / Castel Viscardo, Italy (coarse) - 235 km
  - Filler Quarry: Serra San Quirico, Ancona, Italy - 150 km
  - Asphalt manufacturing and paving equipment storage: Cooperativa Braccianti Riminesi in San Leo, Rimini, Italy – 15 km

- CRABs
  - Refinery (bitumen emulsion): Bologna, Italy – 125 km
  - Fine Aggregate Quarry: Ravenna, Italy – 65 km
  - Filler Quarry: Gubbio, Italy – 145 km
  - Additives storage: Moselice, Padova, Italy – 210 km
  - Asphalt plant, RA processing and Stockpile (asphalt manufacturing and paving equipment storage): Cooperativa Braccianti Riminesi in San Leo, Rimini, Italy – 15 km

Figure 3 - San Marino- Llocations of interest

<u>Selected subsection and maintainance activity:</u>

A conventional pavement, with hot mix asphalt layers, is partially substituted, according to the scheme in Figure 4. The selected subsection 2 showed a series of interconnecting cracks caused by repeated traffic loading, high-severity level of the fatigue cracking, combined with a localised depression due to the settlement of the foundation. The maintenance of subsection 2 (Figure 4) requires the milling of 29 cm of the old pavement, laying and compaction of 15 cm of cement treated recycled materials, spreading of the prime coat (bituminous emulsion with dosage of 1.00 kg/m2 of residual bitumen and saturation with mineral filler), laying and compaction of 10 cm of cold recycled mixture, spreading of the tack coat (bituminous emulsion with dosage of 0.45 kg/m2 of residual bitumen and saturation with mineral filler) and laying and compaction of 4 cm of asphalt concrete (maintenance work code: P-4c)

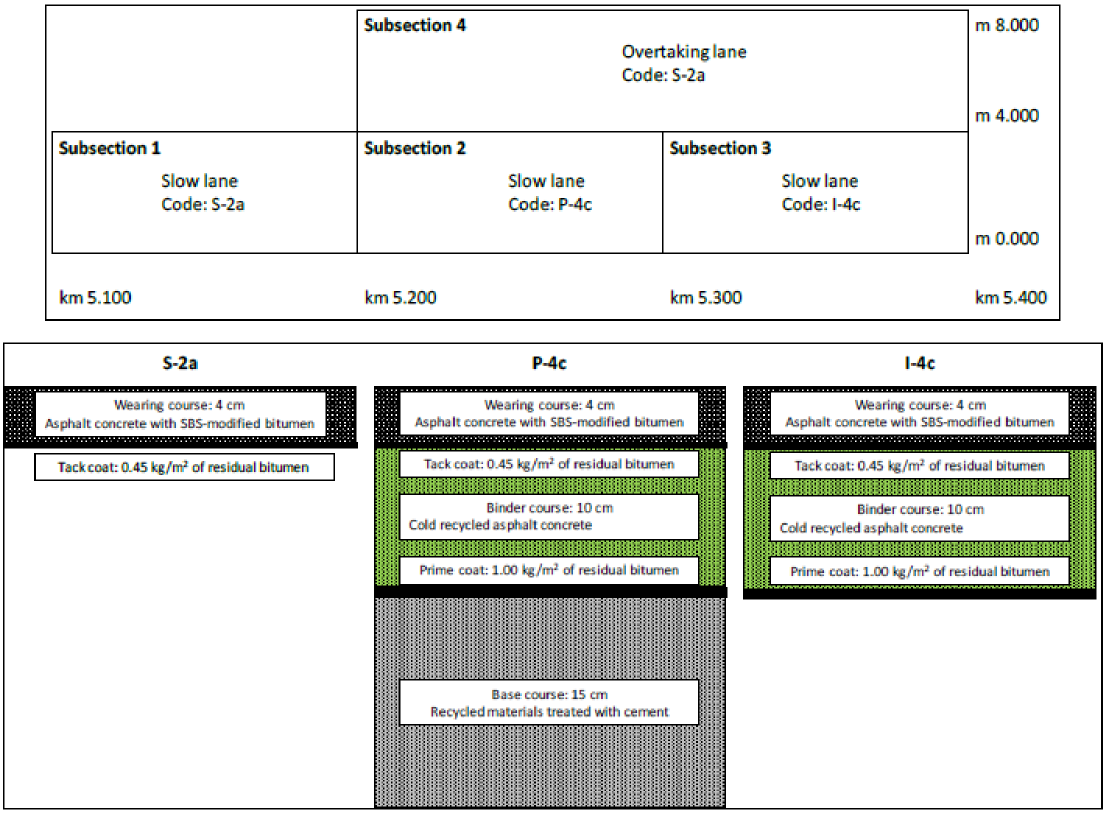


Figure 4 – San Marino - Scheme of the working sections and maintenance methods

2.2 In-situ recycling case study: Germany

Location: The case study consists of a repaving operation on section of 150 m x 12.5 m, which is part of E44 in Trier.

Manufacturing and Construction method:

- In-situ recycled CRAB materials are manufactured on-site, hence allowing to minimize the transport for the reclaimed asphalt milled directly from the site. At first the reclaimed asphalt is milled, then there is a levelling with a grader, tack coat is added with a spreader, then a recycler (mix paver, water tank and bitumen tank) manufactures the CRAB with the addition of bitumen emulsion and cement and lays down the crab material which is then compacted with a roller.

- Conventional asphalt mixtures are manufactured at the Asphalt Plant in Trier and then installed by using bitumen emulsion as a tack coat over the binder layer and then a paver and a roller will complete the construction.

The design formula of the materials used in the "in-site recycling" case study (Germany) are provided in Table 3.

Table 3 - German asphalt pavement composition

PAVEMENT MATERIALS – Germany case study	
Mix specifications for all mixes used on the project. These should include (at the very least) aggregate type and content, asphalt content and any modifiers used in the mix.	**SMA 8 S (Surface)** - Aggregate: 83% - Filler 10% - Total binder content: 7% - Type of binder: Bitumen - No added fibers, additive or modifiers **AC16BS (binder)** - Aggregate 90.5% - Filler 5% - Total binder content: 4.5% - Type of binder: Bitumen - No added fibers, additive or modifiers **CRAB_G (Cold Asphalt Base)** - Reclaimed Asphalt 93.6% - Total binder content: 4% - Type of binder: Bitumen emulsion - Additive (cement): 4 % This CRAB substituted the conventional **base (AC32TS)** - Aggregate 89.5% - Filler 7% - Total binder content: 3.5% - Type of binder: Bitumen - No added fibers, additive or modifiers

Transport distances: locations of interest for the different phases from material sourcing to pavement installation are shown in Figures 6:

- Refinery (bitumen emulsion): Bonn, Germany – 163 km
- Aggregate Quarry: Neumagen-Dhron, Germany – 94 km
- Filler Quarry: Neumagen-Dhron, Germany – 94 km
- Additives Storage: Allmendingen, Germany – 392 km
- Asphalt plant (asphalt manufacturing and paving equipment storage): Basalt-Actien-Gesellschaft, Trier, Germany – 2.9 km

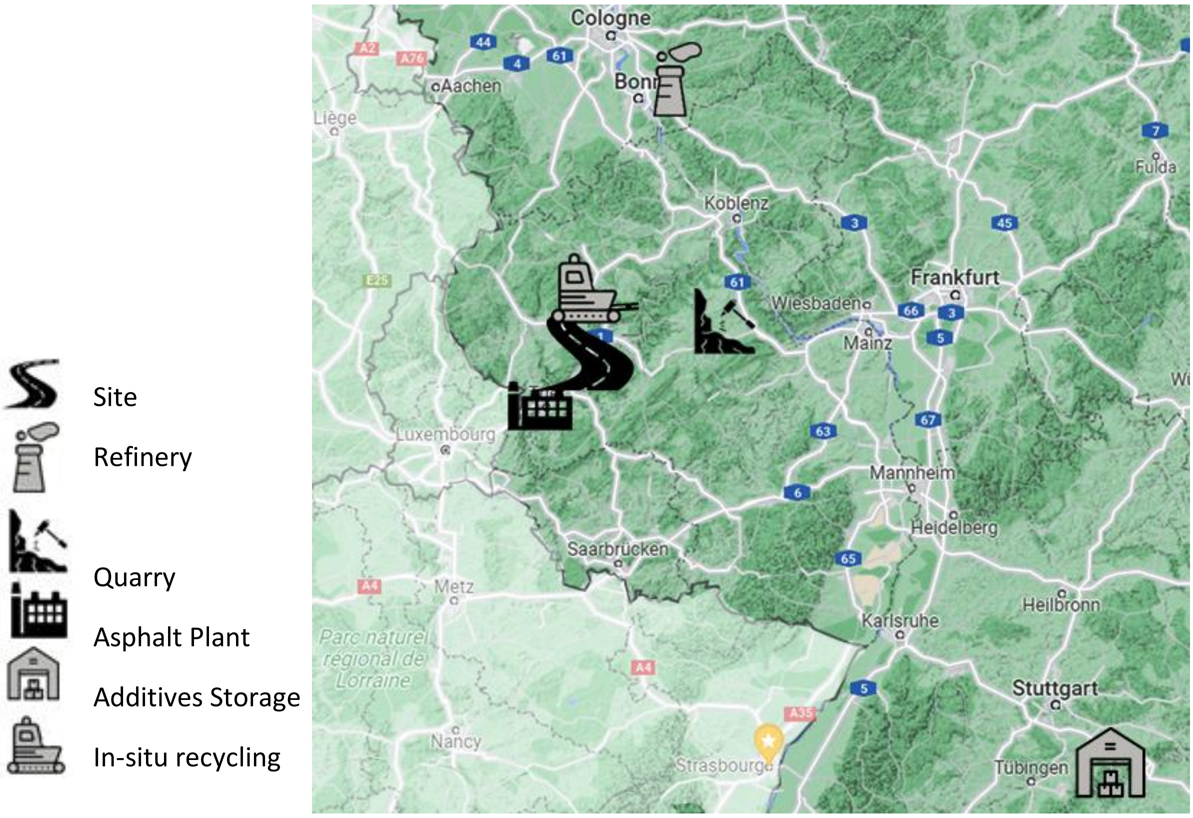


Figure 5 - Germany - Locations of interest

<u>Selected subsection and maintenance activity:</u> For this case study the sub-section III was selected having a total width of 12.50m (currently divided in 4 lanes). According to German design the rehabilitation of this section would have had a pavement structure made of asphalt concrete with 4cm SMA8 over 8cm AC16 and 22cm AC32. The same design method suggests using a solution with CRAB material with bitumen emulsion and the following pavement design: 4cm of wearing course (SMA8), 8 cm of binder (AC16 made), 12cm of base (AC32) and finally 20cm of CRAB materials.

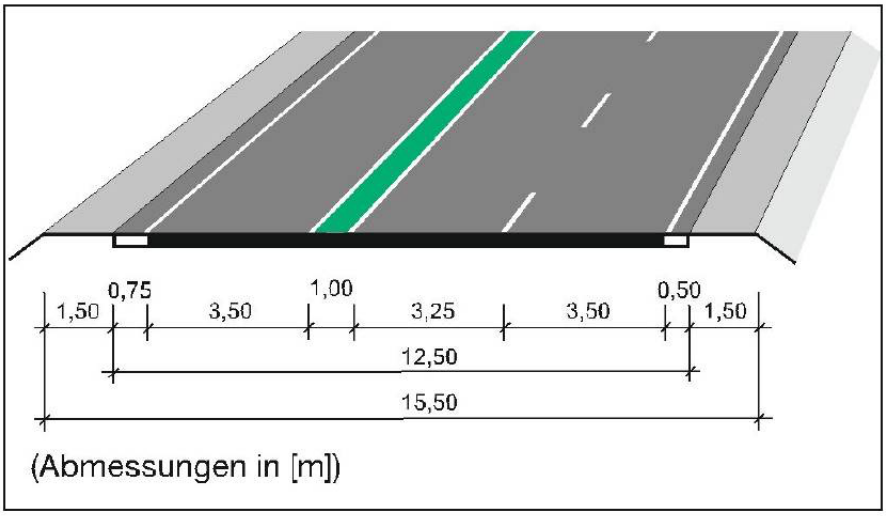


Figure 6 – Germany - Road section width

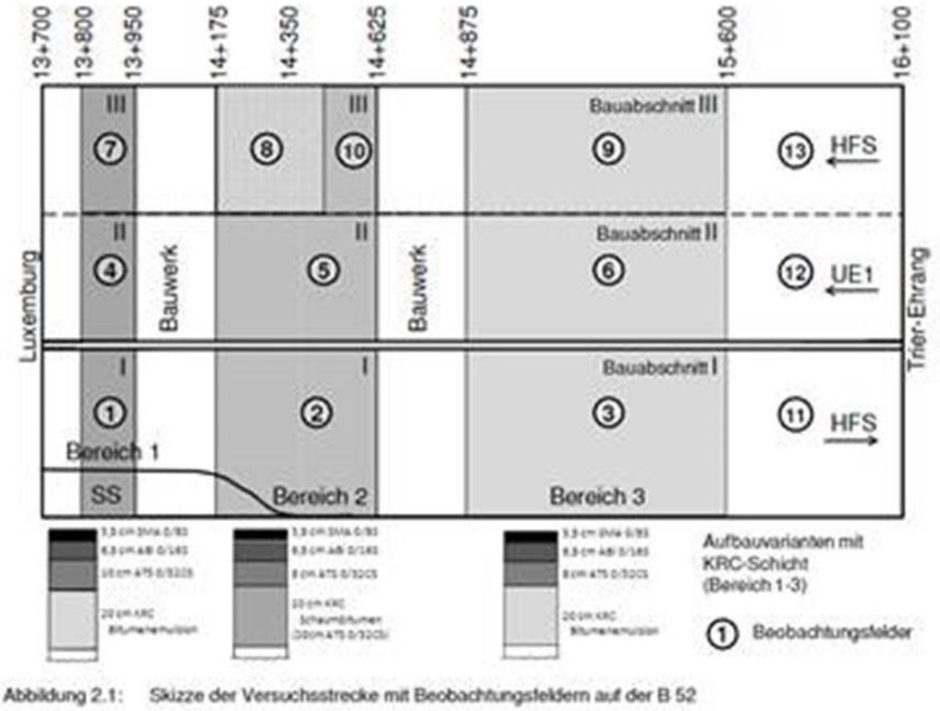


Figure 7 - Germany - Maintenance pipeline

The described case studies were analyzed in terms of environmental impacts in a cradle-to-gate approach.

2.3 Comparative LCA of Pavement Materials

The study performed is an LCA cradle-to-gate used to compare hot asphalt mixes production with CRAB recipes realized with a high content of Reclaimed Asphalt (RA) and used to replace the conventional one.

The study has been carried out to understand if this technique can be "environmentally friendly", so if the impacts emitted are less than a conventional HMA, in relationship to the case studies proposed. In particular, the CRAB mixtures have been compared in both countries mentioned above, which provided recipes both for current mixtures and for cold asphalt.

At first, a comparison has been made at project level to understand if the German "CRAB_G" is behaving environmentally friendlier than the conventional base AC32TS and if the San Marino "CRAB_RSM" produces less environmental impacts when compared with the conventional binder mix.

Furthermore, the C4O project WP4 provided four other CRAB mixtures, that can be used both as base and binder courses. These recipes were used to go further in the research and to deeply understand which aspects influence the results in terms of environmental impacts.

For this reason three research questions were structured and summarized in the following flowchart:

1. how much does each step (A1: raw materials supply- A2: transport- A3: Production) influence the overall values of the impact category indicators?
2. how much does the percentage of each material in asphalt mix cause a variation in terms of emissions?
3. how much do transport distances influence the environmental impact category indicators?

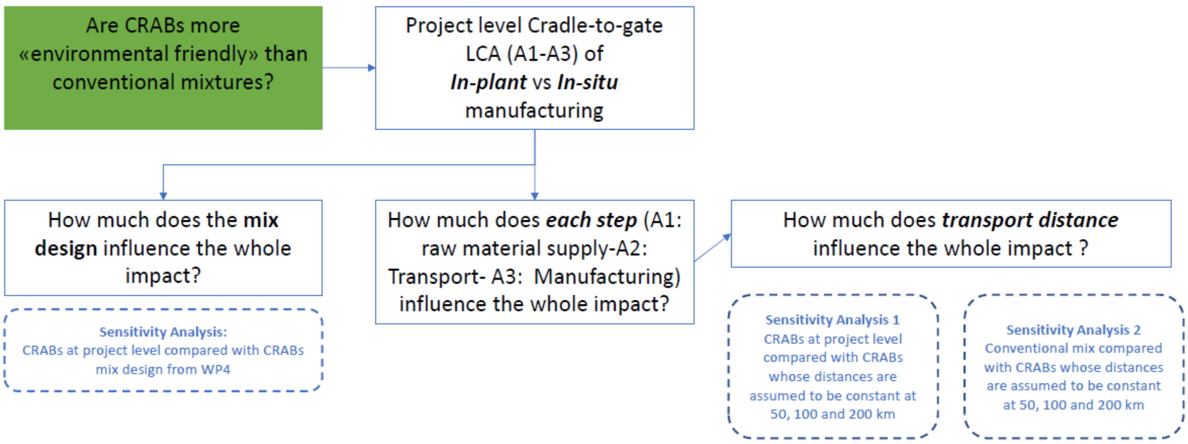


Figure 8 – Flow diagram of the investigation

- For the first question, the overall impacts of the LCA exercise were subdivided into the three stages the cradle-to-gate is composed of (A1, A2, A3), in order to understand the contribution to each one of them.

- For the second question, two different comparisons were made:

  - the first one was made between the binder and all six CRABs (Germany, San Marino, four recipes provided by WP4), assumed to be produced in Republic of San Marino;

  - the second one compared the German base with all the six CRABs (Germany, San Marino, four recipes provided by WP4), assumed to be produced in Germany.

  In detail, the CRABs object of the assessments are here detailed:

  - CRAB_RSM: Composed of 2% of cement and 4.5% of bitumen emulsion.
  - CRAB_G: Composed of 4% of cement, 4% of bituminous emulsion, 3.1% of water.
  - CRAB_1: Composed of 0% of cement, 6% of bituminous emulsion, 4.5% of water.
  - CRAB_2: Composed of 1.5% of cement, 3.3% of bituminous emulsion, 4.5% of water.
  - CRAB_3: Composed of 1.5% of cement, 6% of bituminous emulsion, 4.5% of water.
  - CRAB_4: Composed of 3% of cement, 3.3% of bituminous emulsion, 4.5% of water.

In both cases, the distances were assumed to be constant for each mix design component.

- For the third question, three different scenarios were structured in terms of transport distances from the raw materials acquisition location to the asphalt plant: 50 km, 100 km and 200 km. The distance was assumed the same for each material (aggregates, materials, bitumen, etc)

3. Life Cycle Assessment of C4O Asphalt mixtures

This exercise was carried out concerning the area of materials/products, assessing the environmental impacts related to the C4O mixtures, as can been seen if Figure X.

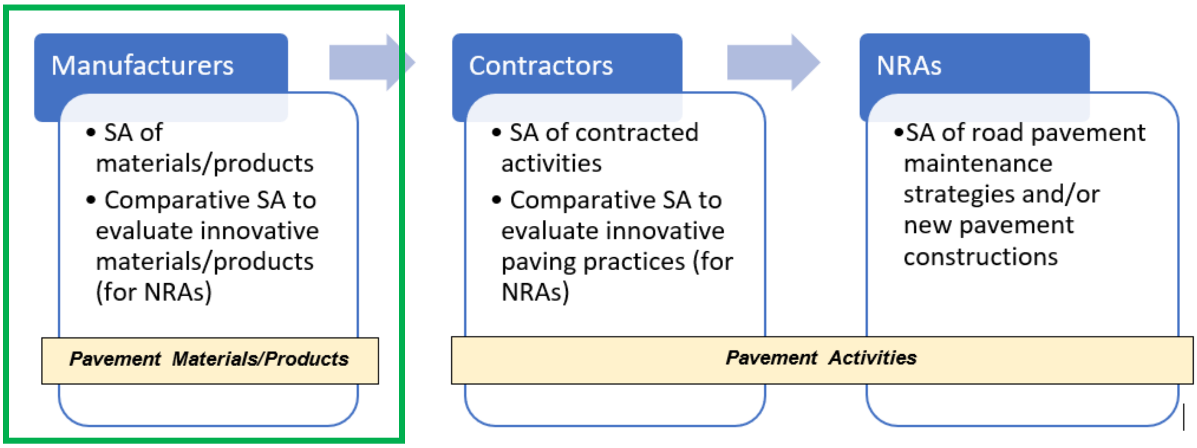


Figure 9 – Selection of LCA exercise according to the PAVEMENTLCM framework (pavementlcm.eu)

3.1 Goal and Scope Definition

The aim of this study is to calculate the environmental impacts of different mixtures during their product stage (cradle-to-gate (A1-A3)). The materials investigated include conventional hot asphalt mixtures (base course (AC32TS HMA) in Germany and the conventional binder course in San Marino) and cold asphalt mixtures derived from WP4 (Crab4Oere mixtures). These mixtures are produced with different manufacturing processes: in-situ recycling for the German case study, in-plant recycling for the one produced in San Marino. The results of the study can be compared to understand how less impactful the use of cold asphalt mixture technologies (comparative LCA) is.

The intended applications of the study are:

- The understanding of the environmental benefits related to cold asphalt recycling;
- The understanding of the pros and the cons of using the C4O technologies when compared to currently used construction methods
- The support of more sustainable decision-making processes of asphalt mixture producers

The study is part of Crab4Oere project, funded by the CEDR within the call 2017 "New Materials" and it is directed to the scientific community (National Road Authority, Academics, etc.) to provide evidence of results the environmental impact of cold recycled asphalt mixtures used for pavement maintenance. The outcomes could also be used for further sustainability assessment extended to pavement activities, as indicated within the PavementLCM framework.

3.1.1 Product description

Detail of two CRABs mixtures have been provided to be compared with conventional hot asphalt mixtures to be used for binder and base course. Here are the details of each case study:

- <u>German Case Study – in-situ recycling CRAB</u>

  The actual base AC32TS HMA, currently used, is a Hot Mix Asphalt and was studied in terms of environmental benefits when compared with the CRAB mixture provided by Germany. This CRAB is directly produced in-situ and was identified in this study as "CRAB_G". It's composed of 4% of cement, 4% of bituminous emulsion, 3.1% of water and contains a high percentage of RAP (936 kg in one ton).

- San Marino Case Study- in-plant recycling CRAB

  The environmental impacts of the conventional binder course were compared to a CRAB mixture whose recipe has been provided by the Road Authority of San Marino. This mixture, called CRAB_RSM, is produced in plant and then transported to the construction site. It is composed of 4.5% of bitumen emulsion, 2% of cement and contains a high percentage of RAP (845 kg in one ton). With regards to the conventional hot asphalt mixtures, in compliance with specifications of the Italian Road Authority (ANAS), it was assumed that both binder and surface courses are composed of 89.5% aggregates, 4.5% binder, 4% filler and 2% additives.

3.1.2 Declared unit and System Boundaries

In both cases, the chosen declared unit is 1t of apshalt mixture produced.
The life cycle approach is a "cradle-to-gate", hence the system boundaries (EN 15643-5) include the product stage (A1-A3). In particular:

- A1- Raw material acquisition: All those processes involved in pavement materials acquisition (e.g. mining, crude oil extraction) and processing (e.g. refining, manufacturing, mixing);
- A2- Transport: All the processes involved in transport of materials to the plant;
- A3- Production: The processing and production of asphalt mixtures.

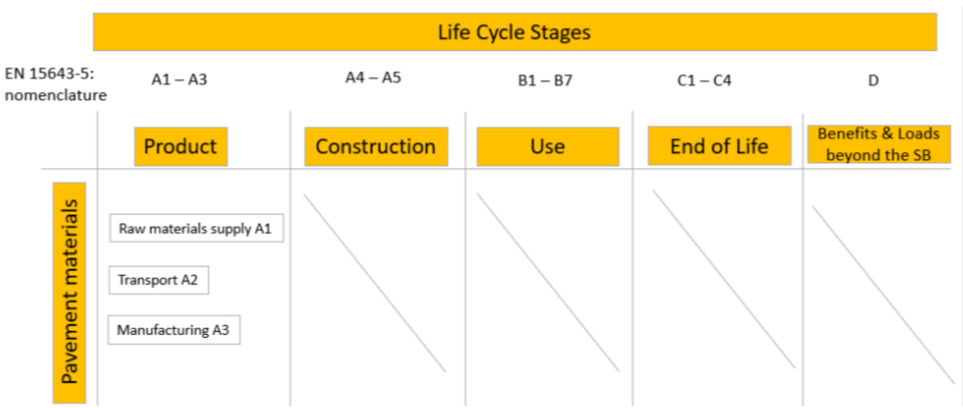


Figure 10 - System boundaries and life cycle stages

3.1.3 Analysis period

This case study refers to a material, that's why any analysis period is taken into consideration.

3.1.4 Cut-off rules

In order to simplify inventory activities, standard EN 15804 allows a cut-off threshold of 99% of the mass of the input flows, provided that substances that are very toxic, toxic, harmful or hazardous to the environment and are intentionally introduced into the manufacturing of the assessed products should be taken into consideration (EAPA, 2016). Therefore, according to EAPA, the following criteria are applied:

1. In case of insufficient input data or data gaps for a unit process, the cut-off criteria shall be 1% of the total (renewable and non-renewable) primary energy usage and 1% of the total mass input of that unit process. The total sum of neglected input flows shall not exceed 5% of energy usage and mass. This applies particularly to material and energy flows known to have the potential to cause significant emissions into air and water or soil during the life cycle of the product; it also applies to processes that are known to be resource intensive.

2. Materials that are less than 1% of the total mass input but are considered environmentally relevant include additives and polymers. There might be data gaps in their publicly available life cycle inventories, but these materials should be included when publicly available data exists.

During the development of this LCA and according to the goal and scope definition of the study, no cut-off rules were applied in order to consider all materials' influence. All data was available and produced when necessary.

3.1.5 Allocation procedures

For the allocation the only aspect taken under consideration was the effect of Reclaimed Asphalt. RA is considered to bring zero emission into the considered system boundaries (EAPA, 2016). Hence, the considered emissions will be only those related to operational procedures for RA treatment, such as those crushing and screening and eventual transport to the asphalt plant. These according to EAPA's Guidance Document for Preparing Product Category Rules (PCR) And Environmental Product Declarations (EPD) for Asphalt Mixtures was assumed 47MJ/t.

3.1.6 Impact categories

The aim of an LCA is the quantification of environmental impacts all along the life cycle of a product, according to the chosen system boundaries. In order to interpret the collected inputs, they are translated into outputs/environmental impact categories thanks to a series of characterization factors. Characterization factors indicate the environmental impact per unit of stressor (e.g. per kg of resource used or emission released).

Impacts are calculated during the third part of LCA, so in the Life Cycle Impact Assessment (LCIA) with a specific methodology called EF2.0, developed by the European Commision in 2018.
In details, the indicators taken into consideration are:

- Global Warming Potential (GWP) with total Climate Change considered as the sum of:
  - Global Warming Potential-Fossil fuels (GWP- Fossil fuels)
  - Global Warming Potential-Biogenic (GWP-biogenic)
  - Global Warming Potential- Land use and land use change (GWP-luluc)
- Acidification
- Eutrophication, taking into consideration:
  - "Eutrophication terrestrial", whose indicator is Accumulated Exceedance
  - "Eutrophication acquatic freshwater", whose indicator is fraction of nutrients reaching freshwater end compartment
  - "Eutrophication acquatic marine", whose indicator is fraction of nutrients reaching marine end compartment potential, fraction of nutrients reaching freshwater end
- Natural Resources, which refers to four midpoint impact categories:
  - "Water use", whose indicator is deprivation potential, deprivation-weighted water consumption (WDP)

- "Land use", whose indicator is Potential Soil Quality index (SQP)
- "Resources use, minerals and metals", whose indicator is Abiotic depletion potential for non fossil resources (ADP- minerals&metals)
- "Resources use energy carriers", whose indicator is Abiotic depletion for fossil resources potential (ADP-fossil)

- Air pollution, which refers to:
  - "Photochemical ozon formation", Trophospheric Ozone Concentration increase.
- Two other indicators were taken into account but direclty provided by the LCI. Hence, any LCIA methodology was applied and they are:
  - Energy use (renewable and non renewable);
  - Secondary materials consumption.

3.1.7 Data requirements and data quality

The data quality requirements were considered following EN 15804 (2012). Primary data was obtained by sending questionnaires about materials, processes and transportation to the different partners of the consortium involved in this stage.
When primary data was not available, secondary data was used from recognized databases (such as GaBi) or collected from literature. The source of all data is detailed in the LCI section. Results of the quality data assessment are shown in below. As mentioned in ISO14040:2006, data have to comply with some requirements and in the next steps a rating score can be assigned, according to their quality with a specific table presented in LCI phase.

3.1.8 Assumptions and limitations of the study

No asphalt plant stack emissions were considered.
When used, RA stockpile and processing are considered to be located at the asphalt plant, therefore, transport distance of RA is zero.

3.2 Life Cycle Inventory

The source of data collection can be divided into two categories: primary and secondary, according to the informations provided by the partners and those taken from the software database. Partners have been interviewed in order to have details on materials, asphalt pavement structure, mix design recipes, transport distances and current manufacturing and installation practices. When there was a lack of information, needed data were taken from GaBi Database.

3.2.1 Data Collection

Primary Data:

- <u>Germany</u>

Here the data linked to the production of conventional hot mix asphalt (AC32TS base in Germany and AC12 for San Marino) and of CRABs are reported.

Table 4 – All case studies - Asphalt mixtures components by weight

	AC32TS	AC12	CRAB_G	CRAB_RSM
Fine Aggregates	600 kg	505 kg	-	50 kg
Coarse Aggregates	295 kg	400 kg	-	-
Reclaimed Asphalt	-	-	936 kg	845 kg
Cement	-	-	40 kg	20kg
Binder	35 kg	55 kg	40 kg	45 kg

Filler	70 kg	40 kg	-	40 kg
Water	-	-	31 kg	29 kg

Table 5 - A1 + A2- - Raw material acquisition + Transport

	AC32TS		AC12		CRAB_G		CRAB_RSM	
	Location	Distan.	Location	Distan.	Location	Distan.	Distances	Distan,
Fine Aggregates	Neumagen-Dhron	28 km	Forlì	65 km	-	-	Ravenna	65 km
Coarse Aggregates	Neumagen-Dhron	28 km	Castel Viscardo	235 km	-	-	-	-
Reclaimed Asphalt	-	-	-	-	In-situ (E-44 Trier)	0 km	In-plant	0 km
3Cement	-	-	-	-	Allmendingen	392 km	Moselice	210 km
Binder	Niederlassung Bonn	163 km	Bologna	125 km	Niederlassung Bonn	163 km	Bologna	125 km
Filler	Neumagen-Dhron	28 km	Serra San Quirico	150 km	-	-	Gubbio	145 km
Water	In-plant	0 km	In-plant	0 km	Trier	2,9 km	In-plant	0 km

Table 6 - A3 - Production

	AC32TS	AC12	CRAB_G	CRAB_SM
Electricity	3,33 kWh/t	6,75 kWh/t	-	0,65 kWh/t
Natural Gas	-	10 m^3	-	
Water	0,55 kWh/t	-	-	
Diesel	-	0.042 kg	0,16 kg	0,17 kg
Other type of energy (heating oil)	116 kWh/t	-	-	

Secondary Data:

All the other data, such as the elementary flows of extraction of raw materials, have been taken from the Professional Database of GaBi ts by Thinkstep, a company of Sphera (Thinkstep, 2019).

3.2.2 Data Calculation

All the collected data was introduced in GaBi ts software, in order to create the processes for the assessment, as seen in Figures provided in the Annex (Figure A 1, Figure A 2, Figure A 3 and Figure A 4).

3.2.

The Data Quality Assessment was performed according to JRC (2016), as shown in Table 7. It consists of attributing a score, related to some quality indicators, to each data (both primary and secondary) used in the LCA. As a result, the average data quality rating was judged satisfactory, being comprised between good and very good.

Table 7 – Quality Rating [JRC 2016]

			Data quality elements					
			Representativeness					
Quality level	Quality rating	Definition	Technological	Geographical	Time-related	Completeness	Methodological Appropriateness and Consistency	Parameter uncertainty
Very good	1	Meets the criterion to a very high degree, without need for improvement.	E.g. Process is same. For electricity from grid, average technology as country- specific consumption mix.	Country specific data	≤ 3 years old data	Very good completeness (≥ 90 %)	Full compliance with all requirements of the PEF guide	Very low uncertainty (≤ 7 %)
Good	2	Meets the criterion to a high degree, with little significant need for improvement.	E.g. average technology as country- specific consumption mix.	Central Europe, North Europe, representative EU 27 mix,	3-5 years old data	Good completeness (80 % to 90 %)	Attributional Process based approach AND following three method requirements of the PEF guide met: (1) Dealing with multi-functionality; (2) End of life modelling; (3) System boundary.	Low uncertainty (7 % to 10 %)
Fair	3	Meets the criterion to an acceptable degree, but merits improvement.	E.g. average technology as country- specific production mix or average technology as average EU consumption mix.	EU-27 countries, other European country	5-10 years old data	Fair completeness (70 % to 80 %)	Attribution Process based approach AND two of the following three method requirements of the PEF guide met: (1) Dealing with multi-functionality; (2) End of life modelling; (3) System boundary.	Fair uncertainty (10 % to 15 %)
Poor	4	Does not meet the criterion to a sufficient degree, but rather requires improvement.	E.g. average technology as country- specific consumption mix of a group of similar products	Middle east, North-America, Japan etc.	10-15 years old data	Poor completeness (50 % to 70 %)	Attributional Process based approach AND one of the following three method requirements of the PEF guide met: (1) Dealing with multi-functionality; (2) End of life modelling; (3) System boundary.	High uncertainty (15 % to 25 %)
Very poor	5	Does not meet the criterion. Substantial improvement is necessary.	E.g. other process or unknown, not available (n.a.)	Global data or unknown	≥ 15 years old data	Very poor or unknown completeness (< 50 %)	Attributional Process based approach BUT: None of the following three method requirements of the PEF guide met: (1) Dealing with multi-functionality; (2) End of life modelling; (3) System boundary.	Very high uncertainty (>25 %)

Table 8 - Assessment of Data Quality

Data	Type	Source	Technological Representativ.	Geographical Representativ.	Temporal correl.	Completeness	Methodological Appropriateness and Consistency	Avarage
EU-28: Crushed rock 16-32 mm	Secondary	GaBi	1	2	1	2	2	1.6
EU-28: Crushed sand grain 0-2 mm	Secondary	GaBi	1	2	1	2	2	1.6
EU-28: Bitumen at refinery	Secondary	GaBi	2	2	1	2	2	1.8
EU-28: Limestone	Secondary	GaBi	2	2	1	2	2	1.8
EU-28: Bitumen emulsion	Secondary	GaBi	3	2	1	2	2	2
EU-28: Cement (CEM II)	Secondary	GaBi	2	2	1	2	2	1.8
Reclaimed Asphalt (RA)	Secondary	GaBi	2	2	2	2	1	1.8
EU-28: Water	Secondary	GaBi	2	2	1	2	2	1.8
EU-28: Diesel mix at filling station	Secondary	GaBi	2	2	1	2	2	1.8
Gas Consumption in Asphalt Plant	Primary	Material Producer	2	2	1	2	1	1.6
EU-28: Electricity Grid mix	Secondary	GaBi	2	2	1	2	2	1.8
Other resources use consumption : EU-28: Oil	Primary	Material Producer	2	2	2	2	1	1.8
Transport Distances	Primary	Real Distances related to the specific case study	1	1	1	1	2	1.2
Transport Mean	Secondary	GaBi Database	2	2	1	2	1	1.6
Total Avarage								1.72

3.3 Life Cycle Impact Assessment

The third LCA step aims to assess a product system and better understand its environmental burden. The results are shown in the tables below and contain the comparison between the hot and cold mixtures.

Once selected the impact categories and the linked indicators, the results of the environmental assessment have been defined and reported below in Tables 9 and 10 and Figure 11 and Figure 12.

Table 9 - San Marino - LCIA Results for Conventional HMA used as binder course and CRAB_RSM

		Conventional HMA used as binder course	CRAB_RSM used for Binder Course
CLIMATE CHANGE	EF 2.0 Climate Change [kg CO2 eq.]	4.90E+01	2.84E+01
	EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	6.02E-02	4.22E-02
	EF 2.0 Climate Change (fossil) [kg CO2 eq.]	4.87E+01	2.83E+01
	EF 2.0 Climate Change (land use change) [kg CO2 eq.]	2.02E-01	4.94E-02
	EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	1.67E-01	8.21E-02
EUTROPHICATION	EF 2.0 Eutrophication freshwater [kg P eq.]	9.90E-05	4.12E-05
	EF 2.0 Eutrophication marine [kg N eq.]	4.23E-02	2.02E-02
	EF 2.0 Eutrophication terrestrial [Mole of N eq.]	4.68E-01	2.21E-01
AIR POLL.	EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	1.36E-01	6.53E-02
NATURAL RESOURCES	EF 2.0 Land Use [Pt]	2.36E+02	1.10E+02
	EF 2.0 Resource use, energy carriers [MJ]	2.81E+03	9.66E+02
	EF 2.0 Resource use, mineral and metals [kg Sb eq.]	7.86E-06	3.63E-06
	EF 2.0 Water scarcity [m^3 world equiv.]	2.86E+00	4.09E+00
ENERGY	Energy use (mJ)	6.01E+25	2.12E+25
	- Non renewable	6.01E+25	2.12E+25
	- Renewable	1.47E+03	2.04E+03
	Secondary Materials Consumption (kg)	0	845

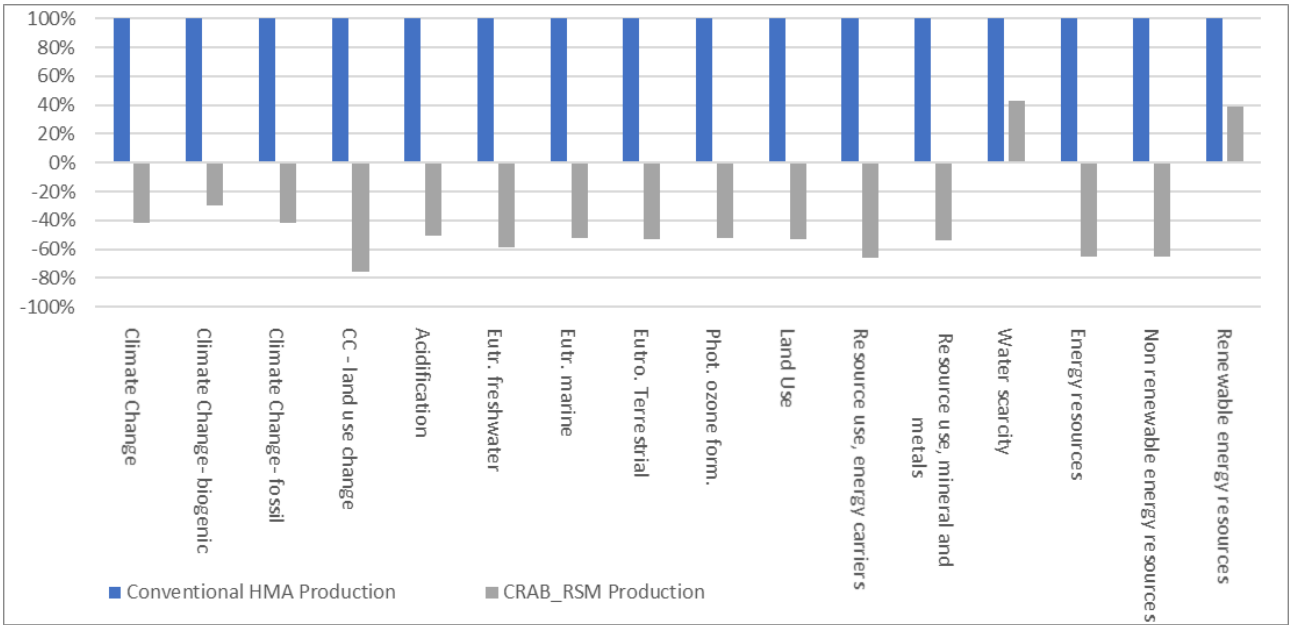


Figure 11 – San Marino - change of environmental impact burden between conventional HMA AC12 and CRAB_RSM

Table 10 - Germany - LCIA Results for Conventional HMA AC32TS and CRAB_G

		Conventional HMA AC32Ts	CRAB_G
CLIMATE CHANGE	EF 2.0 Climate Change [kg CO2 eq.]	6.96E+01	3.99E+01
	EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	1.11E-01	4.06E-02
	EF 2.0 Climate Change (fossil) [kg CO2 eq.]	6.94E+01	3.98E+01
	EF 2.0 Climate Change (land use change) [kg CO2 eq.]	1.11E-01	5.24E-02
	EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	2.09E-01	1.00E-01
EUTROPHICATION	EF 2.0 Eutrophication freshwater [kg P eq.]	1.07E-04	4.12E-05
	EF 2.0 Eutrophication marine [kg N eq.]	4.34E-02	2.70E-02
	EF 2.0 Eutrophication terrestrial [Mole of N eq.]	4.79E-01	2.95E-01

AIR POLL.	EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	1.42E-01	8.41E-02
NATURAL RESOURCES	EF 2.0 Land Use [Pt]	3.45E+02	1.09E+02
	EF 2.0 Resource use, energy carriers [MJ]	2.35E+03	9.13E+02
	EF 2.0 Resource use, mineral and metals [kg Sb eq.]	9.42E-04	3.45E-06
	EF 2.0 Water scarcity [m³ world equiv.]	6.78E+00	4.01E+00
ENERGY	Energy use (mJ)	5.19E+25	2.02E+24
	- Non renewable	5.19E+25	2.02E+24
	- Renewable	1.11E+15	1.95E+03
	Secondary Materials Consumption (kg)	0	936

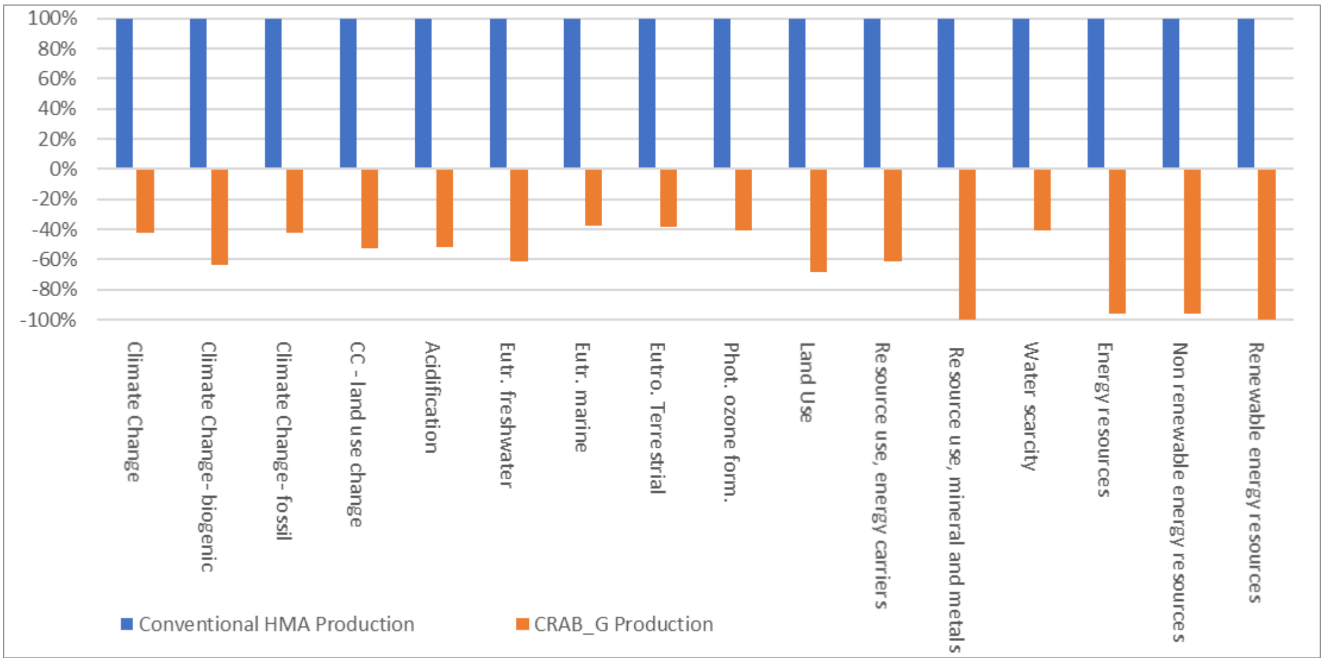


Figure 12 - Germany - change of environmental impact burden between conventional HMA AC32TS and CRAB_G

3.3.1 Optional steps

Standards identify some optional steps in order to deepen the results obtained.

1. **Normalisation**

No normalisation is proposed in this study because adjusting values measured on different scales to a notionally common scale is not necessary.

2. **Weighting**
In relationship to this case study, all the chosen impact indicators have the main importance: that's why no weight were attributed.

3. **Grouping**
No grouping was proposed.

3.4 Interpretation

In this section, the results of LCI and LCIA are summarised and discussed as a basis for further conclusions and recommendations in accordance with the goal and scope definition of the study.

3.4.1. Identification of significant issues

The table below shows the percentage change of the value of each impact category indicator of the C4O technologies with respect to the baseline asphalt mixture. The colour scale is applied to the results in each column from green (lower percentage) to red (higher percentage), for each CRAB material in comparison to the baseline, as shown in Table 11.

Table 11 - All case studies - change of environmental impact burden between CRAB_RSM, CRAB_G and their respective conventional HMAs

		Conventional Hot Mix Asphalt	San Marino CRAB	German CRAB
CLIMATE CHANGE	EF 2.0 Climate Change [kg CO2 eq.]	100%	-42%	-43%
	EF 2.0 Climate Change (biogenic) [kg CO2 eq.]	100%	-30%	-63%
	EF 2.0 Climate Change (fossil) [kg CO2 eq.]	100%	-42%	-43%
	EF 2.0 Climate Change (land use change) [kg CO2 eq.]	100%	-76%	-53%
	EF 2.0 Acidification terrestrial and freshwater [Mole of H+ eq.]	100%	-51%	-52%
EUTROP	EF 2.0 Eutrophication freshwater [kg P eq.]	100%	-58%	-61%
	EF 2.0 Eutrophication marine [kg N eq.]	100%	-52%	-38%
	EF 2.0 Eutrophication terrestrial [Mole of N eq.]	100%	-53%	-38%

CEDR Conférence Européenne des Directeurs des Routes Conference of European Directors of Roads

AIR POLL.	EF 2.0 Photochemical ozone formation - human health [kg NMVOC eq.]	100%	-52%	-41%
NATURAL RESOURCES	EF 2.0 Land Use [Pt]	100%	-53%	-68%
	EF 2.0 Resource use, energy carriers [MJ]	100%	-66%	-61%
	EF 2.0 Resource use, mineral and metals [kg Sb eq.]	100%	-54%	-100%
	EF 2.0 Water scarcity [m³ world equiv.]	100%	43%	-41%
ENERGY	Energy use (mJ)	100%	-65%	-96%
	- Non renewable	100%	-65%	-96%
	- Renewable	100%	39%	-100%

Paying attention to the table, it is possible to underline that:

- In both cases, the CRAB is more environmentally performant than the conventional hot mix, in any environmental impact category, except for CRAB_RSM which is worse according with the water scarcity and and the renewable energy use. These better results are mainly due to the fact that CRAB materials have got a very high quantity of reclaimed asphalt sourced from nearby and/or on-site location.
- For Germany, the highest decreases in terms of impacts can be seen on the Climate Change-biogenic (-635), Land use (-63%), Resource use, minerals and metals (-100%) and Energy use (-96%).
- For Republic of San Marino, the most negatively affected impact categories are the Climate Change-land use change (-76%), Eutrophication (-58% freshwater), the resource use, energy carriers (-66%) and the non-renewable energy resources (-65%).
- German CRAB seems be more environmentally friendly compared with the San Marino one for all the impact categories, except for Climate Change- land use change (-53% Germany vs -76% San Marino), for Eutrophication marine, terrestrial and freshwater (about -40% Germany vs -52% San Marino), Energy Use (-38% Germany vs -65% San Marino). CRAB_RSM is most impactful for the water scarcity and for the use of renewable energy resources.
- Furthermore, German CRAB contains a higher quantity per ton of reclaimed asphalt than the other cold mixture (936 kg vs 845 kg).

The mixture impact results were compared and reported in the graphic here below (Figure 13).

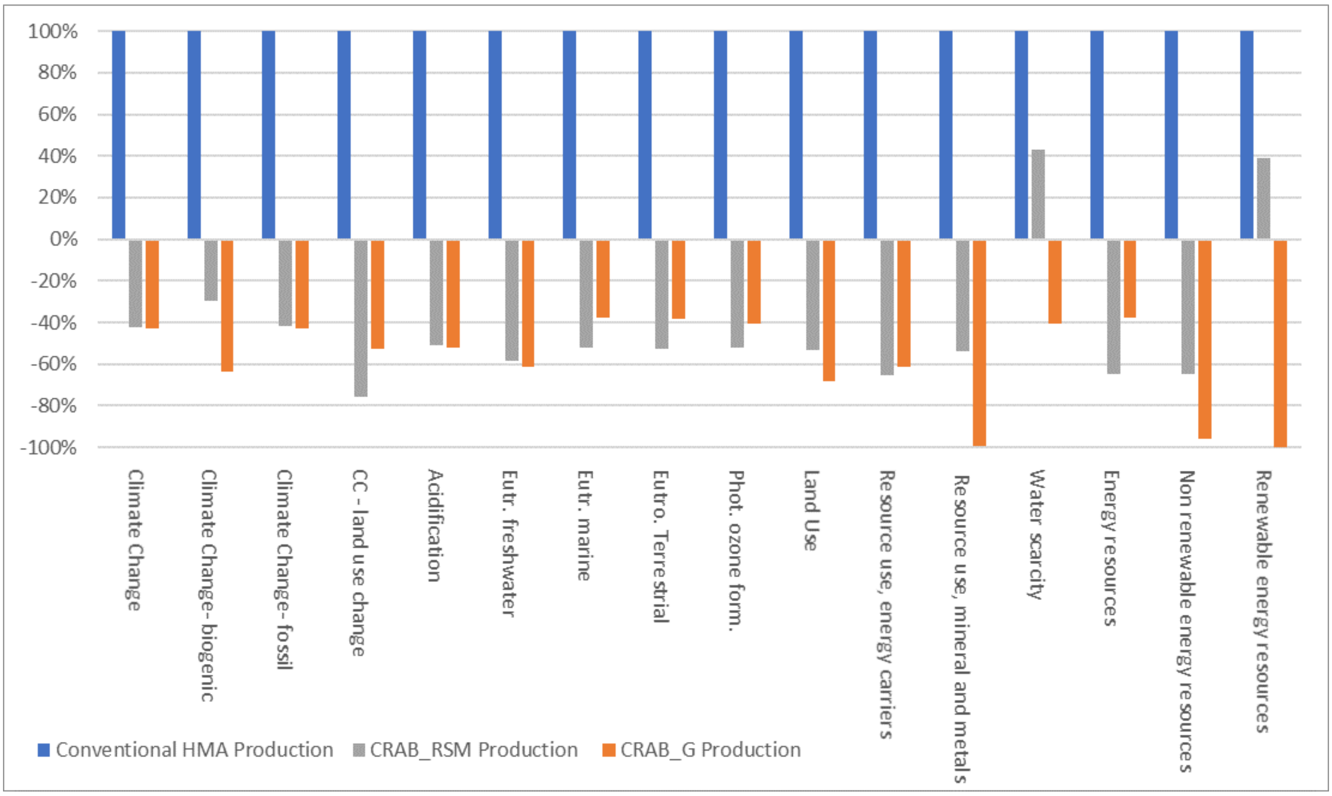


Figure 13 – All case studies - change of environmental impact burden between CRAB_RSM, CRAB_G and their respective conventional HMAs

3.4.1.1 Hotspot analysis

Hotspots in LCA are defined as those life cycle stages or processes which have a great contribution to the environmental impact category indicators. According to SETAC (2016), a life cycle stage or a process is a hotspot when its contribution to the total environmental impact category indicator is >50%, while a process it's relevant when its contribution is >80%. The life cycle stages included in the cradle-to-gate system under analysis are 1) raw material acquisition, 2) transport to asphalt plant and 3) manufacturing. It was studied the contribution of each LC stage for the two conventional mixtures and for CRAB_G and CRAB_SM. In all the four analyses, as shown in the Annex in Figure A 5, Figure A 6, Figure A 7 and Figure A 8, it's evident that raw materials acquisition is the most impactful stage, representing almost always a hotspot or a relevant step in the Life Cycle. In particular this is evident in CRABs mixtures, where the impacts linked to the production are reduced because of the law temperatures during the mixing process.
In fact, for both the CRABs, A1 is always relevant or a hotspot (with contributions from 99% to 74%), except for Climate Change- land use change (34% for CRAB-G and 36% for CRAB_RSM). Concerning CRAB_G, A1 average contribution is of 88%, A2 of 5% and manufacturing of 7%. Instead, for the cold mix producers in San Marino, A3 influences a bit less than in Germany (4%), while A1 is as impactful as in Germany (88%) and transport to plant (A2) is higher (8%). For the conventional hot mixes, A1 is almost always a hotspot/relevant stage, but with the difference that contributions are more fairly distributed between the raw materials supply and the manufacturing steps. In fact, conventional mixes need a bigger quantity of energy to reach the high temperatures needed for the production than a cold asphalt. The transport influences in a very low percentage, as also shown in the sensitivity analysis reported in paragraph 3.4.2.2.

It can be deduced that for the Conventional HMA used as binder course:

- A1 contributes from 58% to 100% (total average: 67%), being an hotspot for the most of the impact categories; excluding five impact categories (Climate Change- biogenic (48%), Climate Change- land use change (18%), Eutrophication freshwater (40%), Land use (33%));
- A2 on average contributes 9%, and specifically from 0% to 33% for all the impact categories, impacting in a bigger way eutrophication marine (33%) and eutrophication terrestrial (32%).
- A3 on average contributes 23%. All the impact categories are affected in a low percentage, except Climate Change (biogenic (52%) and land use change (81%)), Eutrophication freshwater (59%) and Land use (66%).

To show in a clearer way the differences in terms of impacts related to each step, both mixtures percentages were reported in the Figure 14.

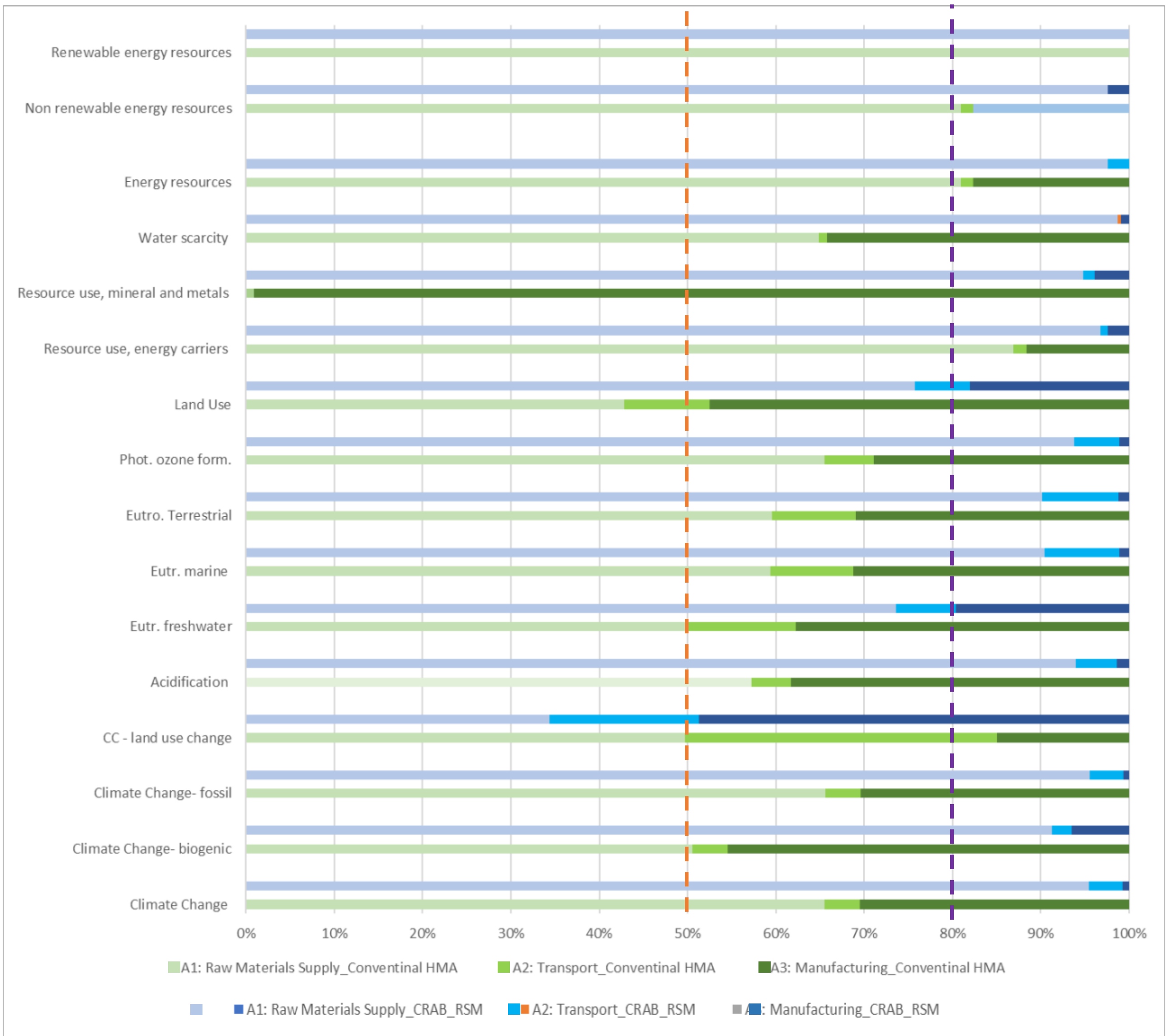


Figure 14 – San Marino - Hotspot Analyses

For the German conventional mixtures used as base:

- A1 is a hotspot for all the impact categories, excluding Land use (43%), Resource use-minerals and metals (1%) and Resource use-energy carriers (87%, it's relevant);
- A2 contributes in a very low percentage (0%-35%) for each impact category. A higher contribution (35%) is linked to Climate Change- Land use change;
- A3 is a hotspot only for Resource use- minerals and metals (99%), and it is caused using heating oil which contributes the most to this impact category.

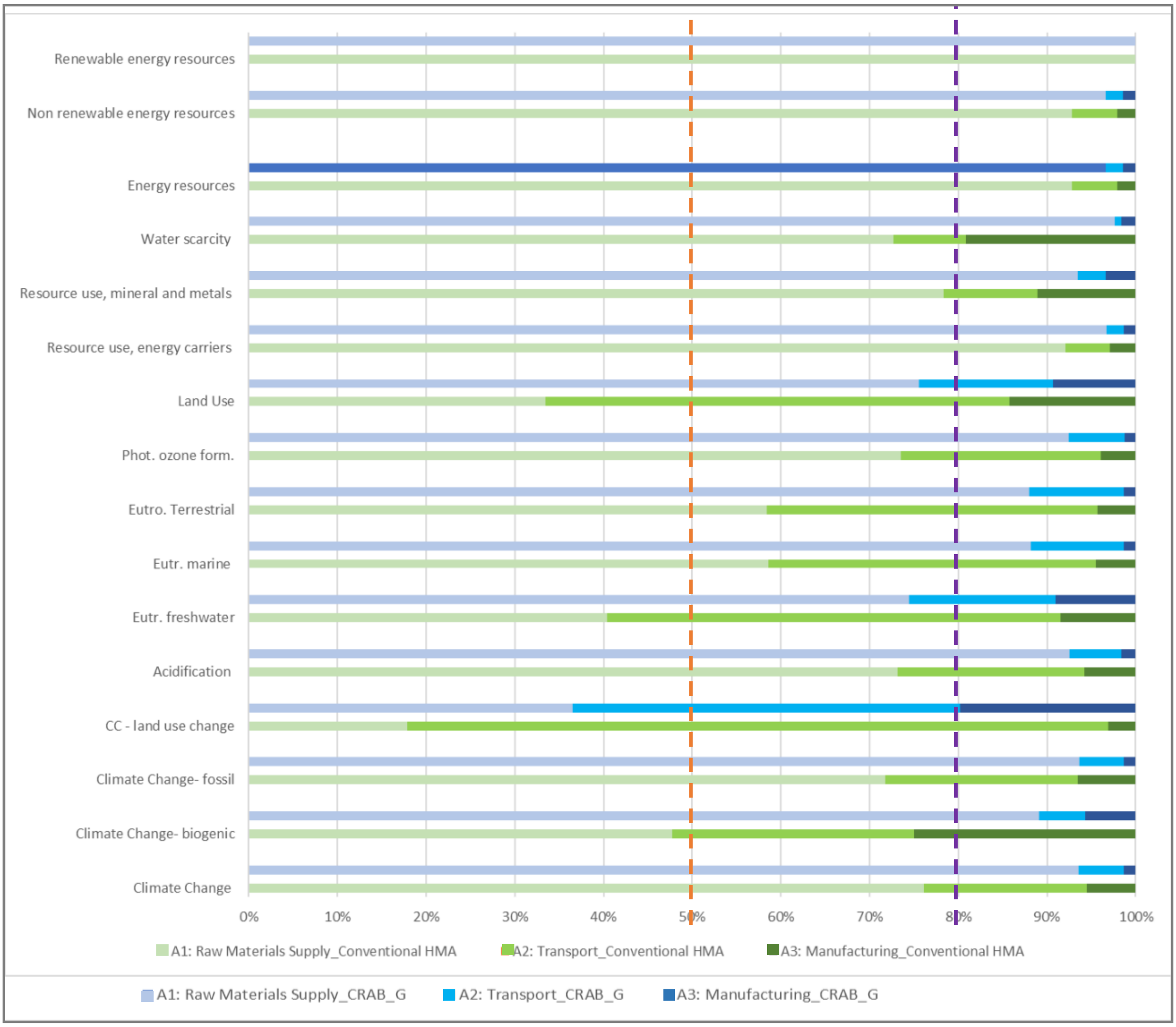


Figure 15 – Germany - Hotspot Analyses

3.4.1.2 Sensitivity Analysis

In order to understand how much the impacts are influenced by choices and parameters and in response to question three, two sensitivity analyses were performed and the following factors were considered:

Contribution of transport distances:

In two previous projects (Lo Presti et al., 2015 and Jimenez del Barco Carrion et al., 2018), the transport stage was found to have a high impact on the results and conclusions of LCA. For this reason, within this investigation, the transport of raw materials to the asphalt plant has been subjected to sensitivity analysis.

To answer this question, three scenarios have been created. In each scenario all the extracted materials (aggregates, bitumen, additives, etc) are sourced at the same transport distance from the asphalt plant and changed for each scenario. The distances considered are 50km, 100km and 200km.

A first sensitivity analysis was made comparing CRABs at project level with CRABs whose distances were assumed to be 50 km, 100 km and 200 km. A second one was carried out comparing the conventional hot mix asphalt with all the CRABs whose distances were assumed to be 50 km, 100 km and 200 km. In both cases, as distances increase, also impacts become bigger, even if the increase of emissions incidence is very low. In fact, the variation range changes on avarage from -1% to 6% for CRAB_RSM and from -7% to 0%, even if the distances are assumed at 200 km. Some impact category are mostly affected, such as Climate Change- land use change (37% in CRAB G and 54% in CRAB_RSM) and Eutrophication freshwater (15% in Germany and 21% in San Marino). From this it was deduced that transport doesn't affect in a huge way the impacts: even if the distances increase, any impact category becomes a hotspot (contribution >50%) or relevant (contribution >80%). This is consistent with the results provided with the Hotspot Analysis, which showed that transport influenced the whole impacts from 6% to 7%.

Otherwise, conventional HMA are more affected by the increase of distances: the impacts are bigger at the increasing of distance. In fact, for German HMA the range goes from 18% to 48%, while for San Marino binder course it goes from -17% to 12%. However, it can be deduced that:

- in German case study, if the distances are within 100 km, any impact categories is a hotspot or relevant, except the Climate Change- land use change. If the distances increase to 200 km, Eutrophication marine and terrestrial and Land Use become a hotpots, while Climate Change- land use change become relevant;
- in San Marino Case Study, any impact category becomes a hotspots, even if the distance increase until 200 km.

Figures in the Annex (Figure A 9, Figure A 10, Figure A 11, Figure A 12, Figure A 13 and Figure A 14) show the contribution of transport in the considered impact categories.

In conclusion,

- As expected, as shown in Figure 16,
- Figure 17, Figure 18 and Figure 19, it can be stated that, the environmental impacts of both German and San Marino conventional HMAs are directly dependent on transport distances. In particular most of the impact categories increase their values whenever transport distances increase.

- On the contrary, CRAB_RSM and CRAB_G seems not be influenced by the increase of transport distances. This is due to the significantly reduced amount of materials to be transported at the manufacturing site, which in turns corresponds to a significant lower number of trips, hence an overall reduced impact of the transport phase (A2).

In more details, this is justified by the fact that:

- CRABs are mostly composed of RA (at least 85%) whose impacts linked to transport are, in both case studies, zero. In fact:
    - in Germany pavement is milled and than processed in-situ, hence the transport distances for RA is null;
    - in San Marino the RA stockpile is on the same site of the asphalt plant, hence also for this case the transport distances for RA is null. Furthermore, it has to be highlighted that due to the allocation rule favouring recycling (100% previous cycle, 0% new cycles), the environmental burdens related to transport freshly milled RA to the stockpile is zero.
- the amount of materials having a transport phase (A2) with a positive environmental burden is significantly reduced. This means that the impact of supplying bitumen emulsion, cement and other additives is minimal. (maximum 9% of the total impact).

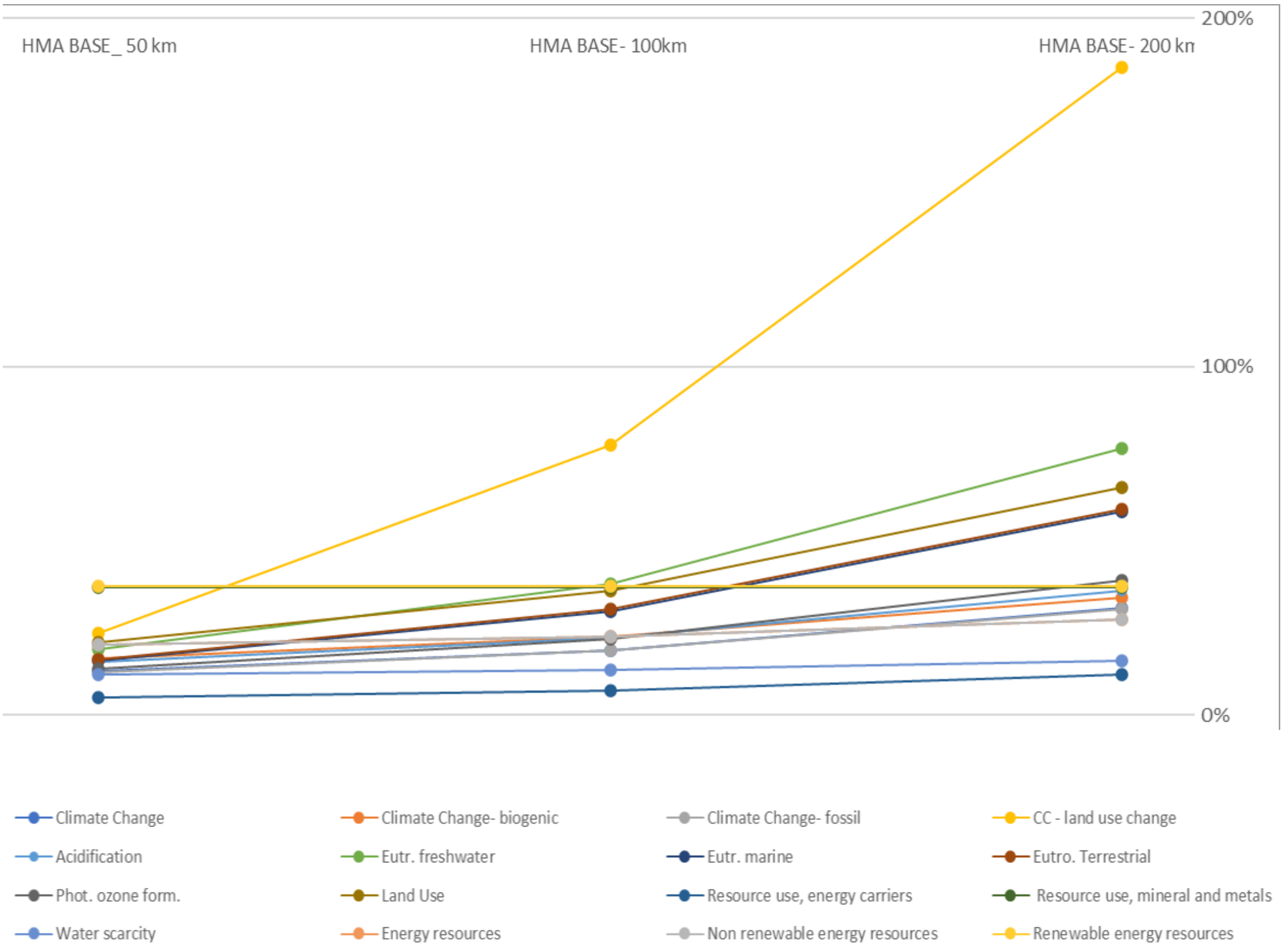


Figure 16 – Germany - How distances affect environmental impact of conventional HMA AC32TS

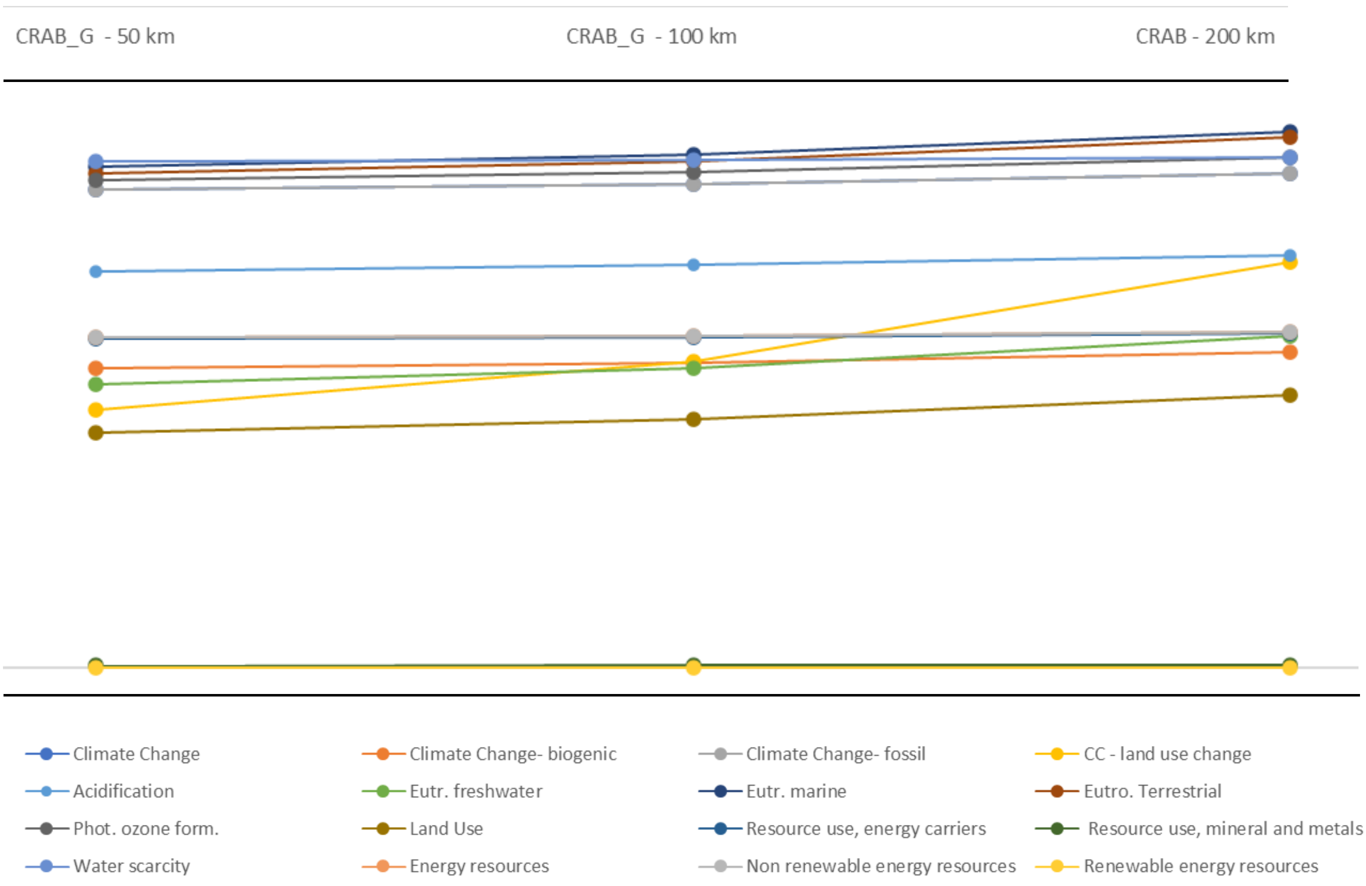


Figure 17 – Germany - How distances affect environmental impact of CRAB_G

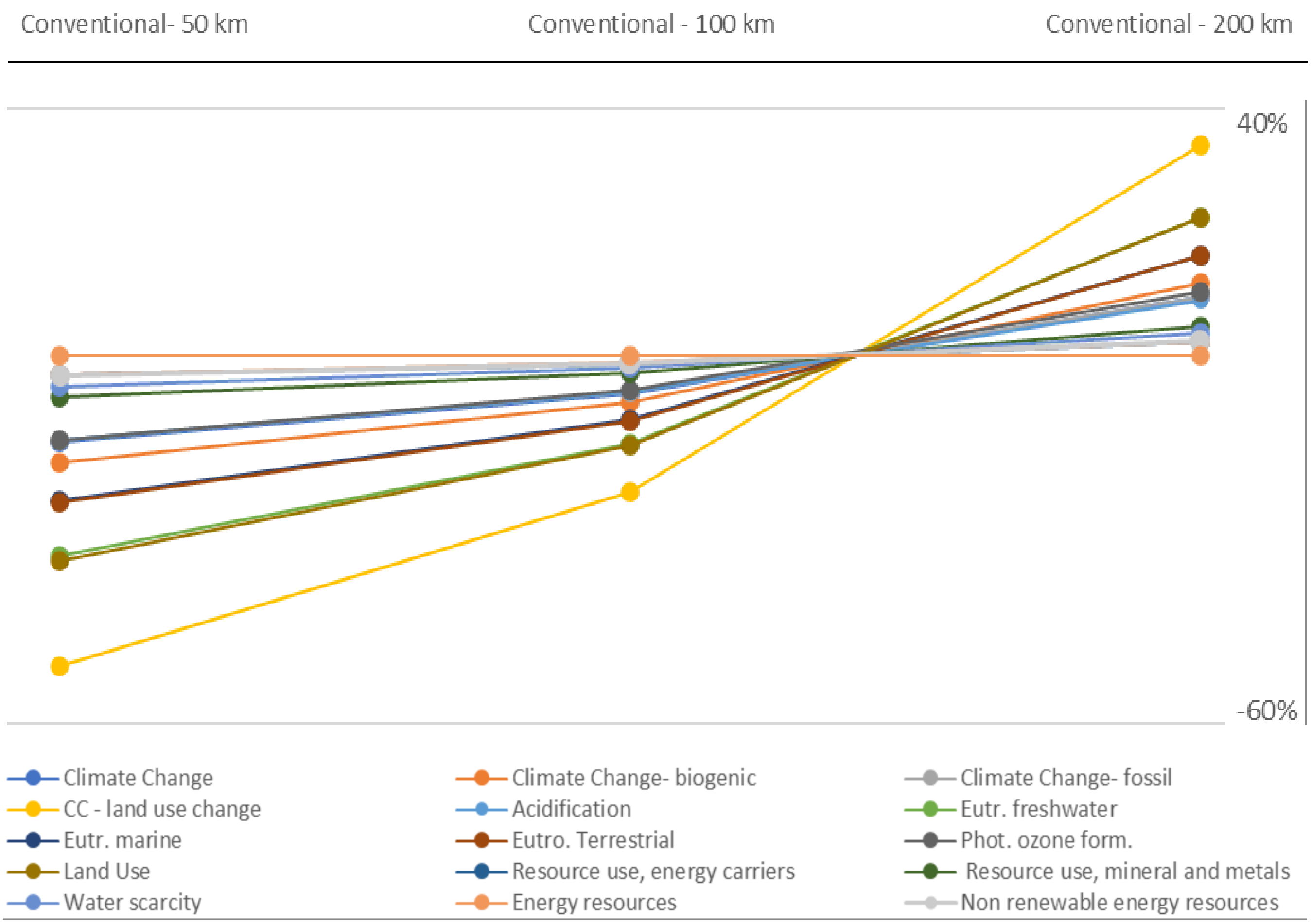


Figure 18 – San Marino - How distances affect environmental impact of conventional HMA AC12

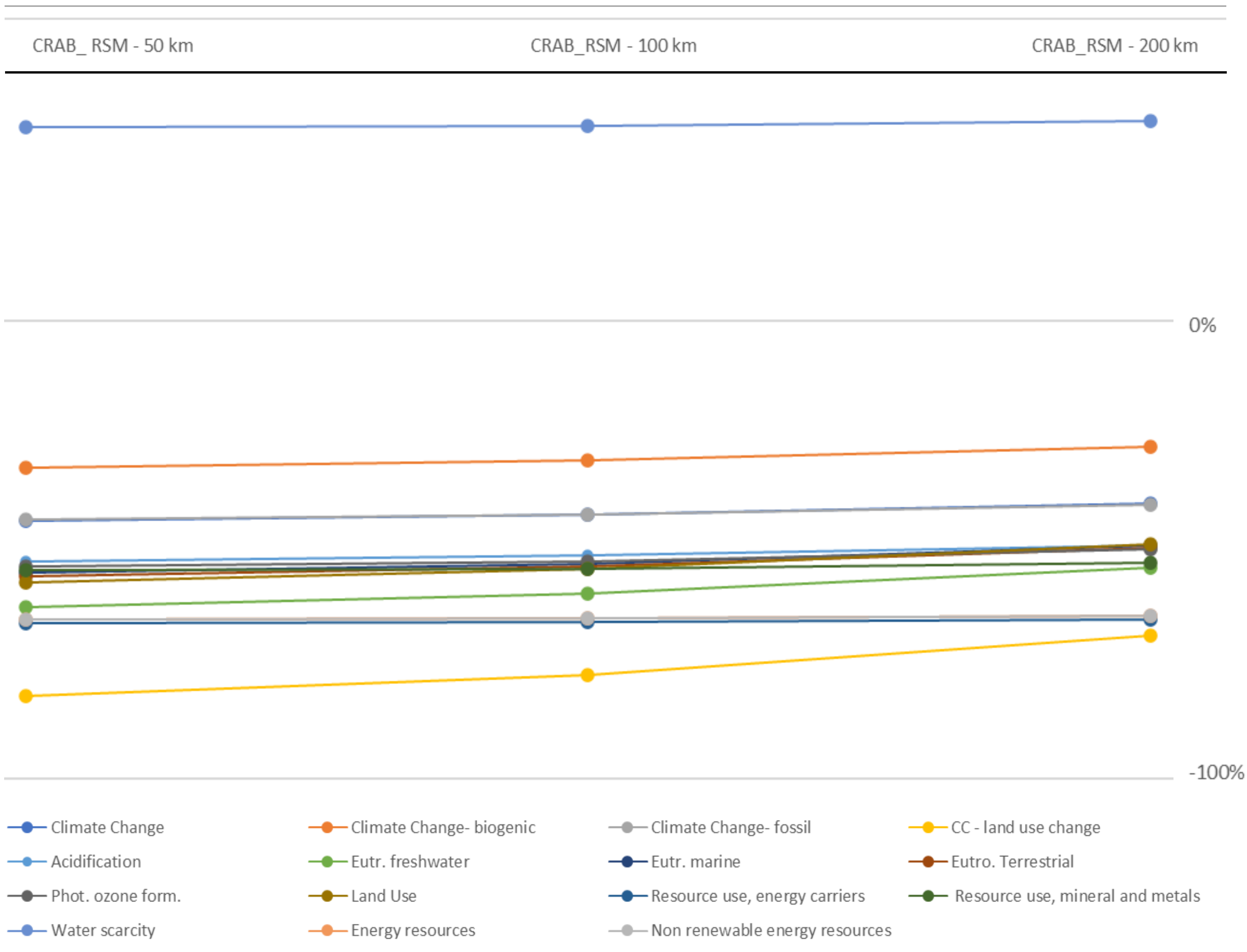


Figure 19 - San Marino - How distances affect environmental impact of CRAB_RSM

<u>Contribution of mix design formula:</u>

The results in terms of emissions might be affected by the composition of the CRAB materials. Therefore, to draw some conclusions, the presented case studies have been enriched also with four other CRABs formulas with varying ranges of cement, bitumen and water, as defined in WP4 of this same project.

In detail, in addition to the CRABs already presented (CRAB_RSM and CRAB_G), four other recipes were studied and here detailed:

a. CRAB_1: Composed of 0% of cement, 6% of bituminous emulsion, 4.5% of water;
b. CRAB_2: Composed of 1.5% of cement, 3.3% of bituminous emulsion, 4.5% of water;
c. CRAB_3: Composed of 1.5% of cement, 6% of bituminous emulsion, 4.5% of water;
d. CRAB_4: Composed of 3% of cement, 3.3% of bituminous emulsion, 4.5% of water.

To answer this question, two comparisons have been made between the binder and all six CRABs (Germany, San Marino, four other recipes) and the base course and the six CRABs, keeping the distances constant (50 km from quarry to plant).

As shown in the tables below, CRAB mixtures, independently of their compositions, are more performant in terms of reduction of emissions, when compared with the conventional asphalt.
It was deduced that the recipes don't influence in a very specific way the impacts for all the categories: it's impossible to select a CRAB whose production implies a reduction of all emissions in air, soil and water.
It can be explained because CRABs are produced at very low temperatures, hence, they need less energy than a conventional HMA. Furthermore, all the impacts related to the extraction for raw materials are reduced, seeing the virgin aggregates are replaced by RA.

However, in both cases:

- a trend is visible in the emissions of CO2eq, linked to the Global Warming Potential: as the cement decreases, the quantity of carbon dioxide is reduced.
- the categories which have a major decrease in terms of impacts, taken into account all the CRABs, are Climate Change (land use change) and the Secondary Materials Consumption.
- according to the CRAB used, some impact categories are affected in different ranges, such as Water Scarcity or Energy Use.

In the German Case Study, when the CRABs are compared with Base AC32TS:

- if all the CRABs are taken into account the most decreased values are for resource use-minerals and metals (-100% for all the CRABs), renewable energy (-100% in all cases, eutrophication freshwater, from -58% to -69%) , land use (from -65% to –76%), Climate change (total and consequently the other three with a decrease of around 64%) and Acidification (from –55% to -70%);
- There are some indicators which are affected in very in different ranges, such as Climate Change (from -73% to -46%), Energy use (from -95 to -50%), water scarcity (-59% to -32%).

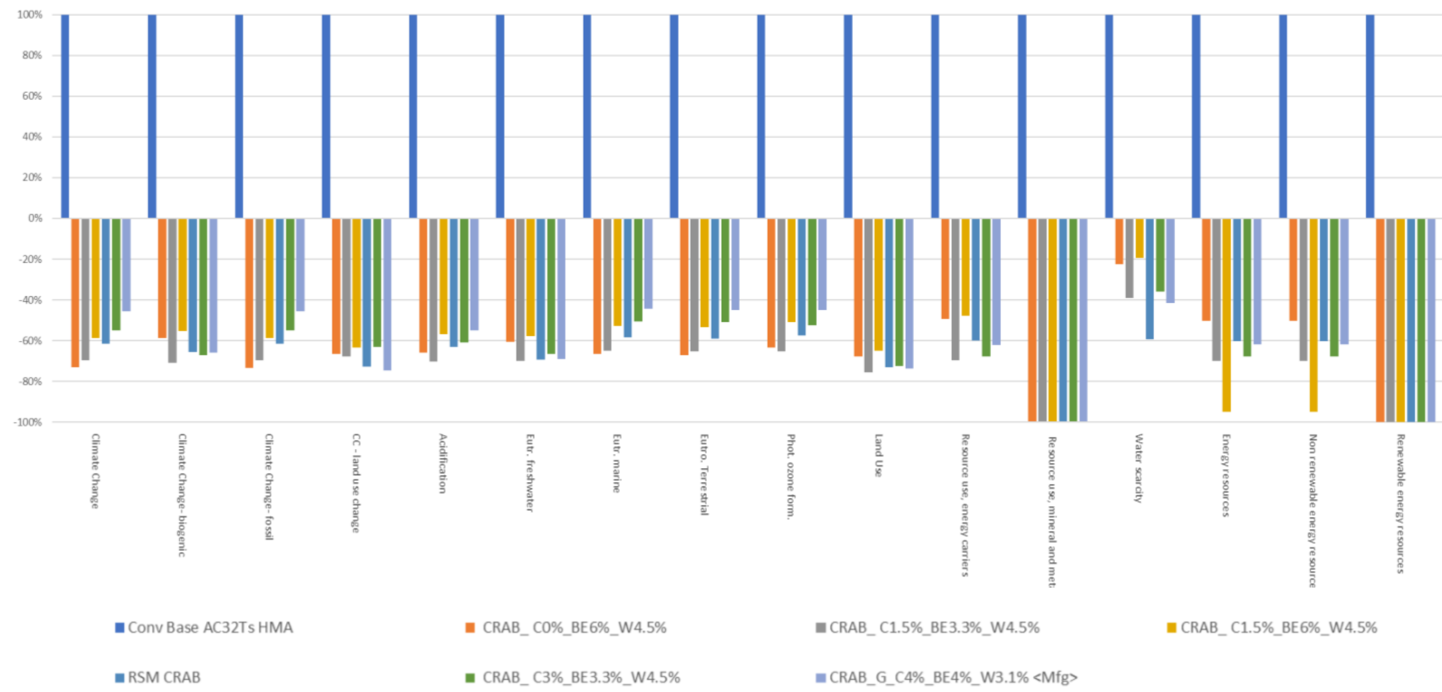


Figure 20 - Germany - Contribution of mix design to impact categories

In San Marino Case Study, when the CRABs are compared with the conventional HMA:

- a visible trend, beyond that one already mentioned, is in Climate Change (fossil).
- if all the CRABs are taken into account, the most negatively affected impact categories are Climate Change- land use change (from -68% to -51%), the resource use- energy carriers (from -72% to 54%) and the energy use (from -53% to -970%);
- There are some indicators which are affected in very in different ranges, such as Climate Change (from -54% to -24%), Climate Change - biogenic (from -31% to -3%), Climate Change- fossil (from -54% to -8%), Resource Use- minerals and metals (from -37% to -62%) Energy use (from -970% to -53%).
- Water Scarcity and Renewable energy use are the only categories which have an increase if compared with the conventional HMA. Climate Change- Biogenic increases of 5% in CRAB C1,5%-BE6%-W4,5%.

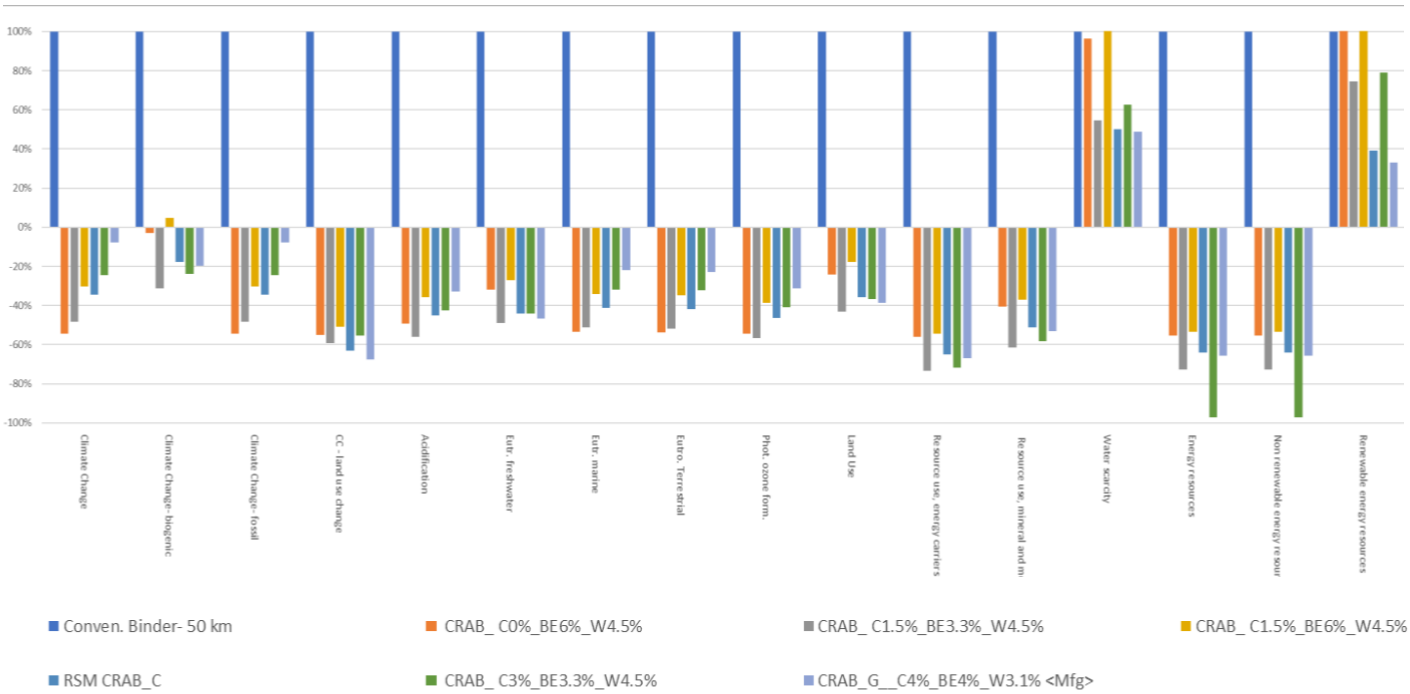


Figure 21 - San Marino - Contribution of mix design to impact categories

3.4.2 Completeness, sensitivity and consistency checks

In order to define the basis for conclusion and recommendations, it's necessary to evaluate the previous phases of LCA through the checks reported below.

3.4.2.1 Consistency Check

According the actual standard, it is important to be sure that all the LCA carried out is consistent throughout.

First of all, the consistency with Goal and Scope is assured. In fact, for instance, we can state that the declared unit defined as 1 ton of asphalt mixture, the impact categories chosen following the Pavement LCM Guidelines and system boundaries as A1-A3 (cradle-to-gate) are all consistent with what stated in Goal and Scope.

Secondly, the consistency with the LCI phase is assured too thanks to the data provided by the partners and specific for the case studies and responding to the requirements (see data quality). All the data were uploaded in GaBi database to perform the assessment.

Thirdly, concerning the consistency for LCIA phase, the methodology and impact categories used are the same of those defined in Goal and Scope Definition. Furthermore, all the processes were included.

3.4.2.2 Completeness Check

According to ISO 14040, it is important to ensure that all relevant information and data needed for the interpretation are complete and available. As stated in the Goal & Definition phase, any cut-off rule was applied.

In detail, it can be stated that:

- all the LCI unit process coverage and system modeling are complete. In fact, the model is exaclty created in GaBi according to the chosen system boundaries. No process was excluded;
- Intermediate and elementary flow coverage are complete. The model is created with GaBi and all the unit processes contain the linked elementary flows;
- Life Cycle Impact Assessment phase is complete. In fact, the following evaluations were done:
    - the selected impact categories are those one suggested by PavementLCM Framework, which is based on the actual suggestions by JRC and they cover the set of most relevant impacts potentially occurring;
    - Completeness of the model's elementary flows recorded in the inventory is assured and no significant elementary flows are excluded in the impacts calculation, as checked in GaBi database.

3.4.2.3 Sensitivity Check with Uncertainty Analysis

No sensitivity analysis was performed.

3.4.3 Conclusions, limitations and recommendations

This study aimed at understanding if the production of CRAB mixtures is more environmentally friendly than a HMA, by limiting the analysis to a cradle-to-gate scenario (A1-A3) and considering both in-situ recycling and in-plant recycling.

In order to carry out the analysis, two case studies were built and presented in the previous sections. These differ in terms of mix design, mix production, location and purpose. In fact, German CRAB material is produced in-situ for a base course, while the San Marino CRAB is produced in-plant for a binder course.

The case studies were built with the collaboration of several stakeholders and data from literature, and show how the use of cold technology is more environmental friendly. The results were calculated by using GaBi software and the EF2.0 methodology and following the Guidelines for Sustainability Assessment provided by PavementLCM Project.

As a result:

- The research shows that regardless of the manufacturing process (A1-A3), the environmental performance of all investigated CRABs are at least 40% lower than a conventional HMA in almost all the impact categories.

- CRAB materials seems to be more environmental friendly than HMA, both for in-situ recycling (base course) and in-plant recycling (binder course). In fact, all the impact categories, for both case studies with CRABs, have an environmental impact on average at least lower than 40% in relation to HMA, excluded the water scarcity which is higher for CRAB_RSM (CRABs contain a a higher percentage of water). This can be explained by the following:
    - CRABs are produced at ambient temperatures, hence, they need less energy than a conventional HMA;
    - CRABs contain a much higher amount of RA, a component with 0% of embodied environmental impacts;
    - CRABs manufacturing requires lower amounts of materials to be transported at the manufacturing site, which in turns corresponds to a significant lower number of trips, hence an overall reduced impact of the transport phase (A2).

- The hotspot analysis showed that the most impactful stage is the acquisition of raw materials, in particular bitumen and cement, for CRAB (at least 80% of total emissions for both CRABs). Hence, in order to further reduce environmental impacts of this technology, CRAB material producers should focus on identify materials whose extraction and/or supply is less impactful.

- Sensitivity analyses revealed that transport distances, related to material supply and CRAB manufacturing, do not play the same main role as they typically have with the environmental impact of conventional HMA.

- In general, appreciable emissions savings (at least 40%) can be observed for both case studies using CRABs. Hence, CRABs are less impactful than conventional HMA regardless of the manufacturing process and mix design formula.

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ANNEX

1. Production models in GaBi ts

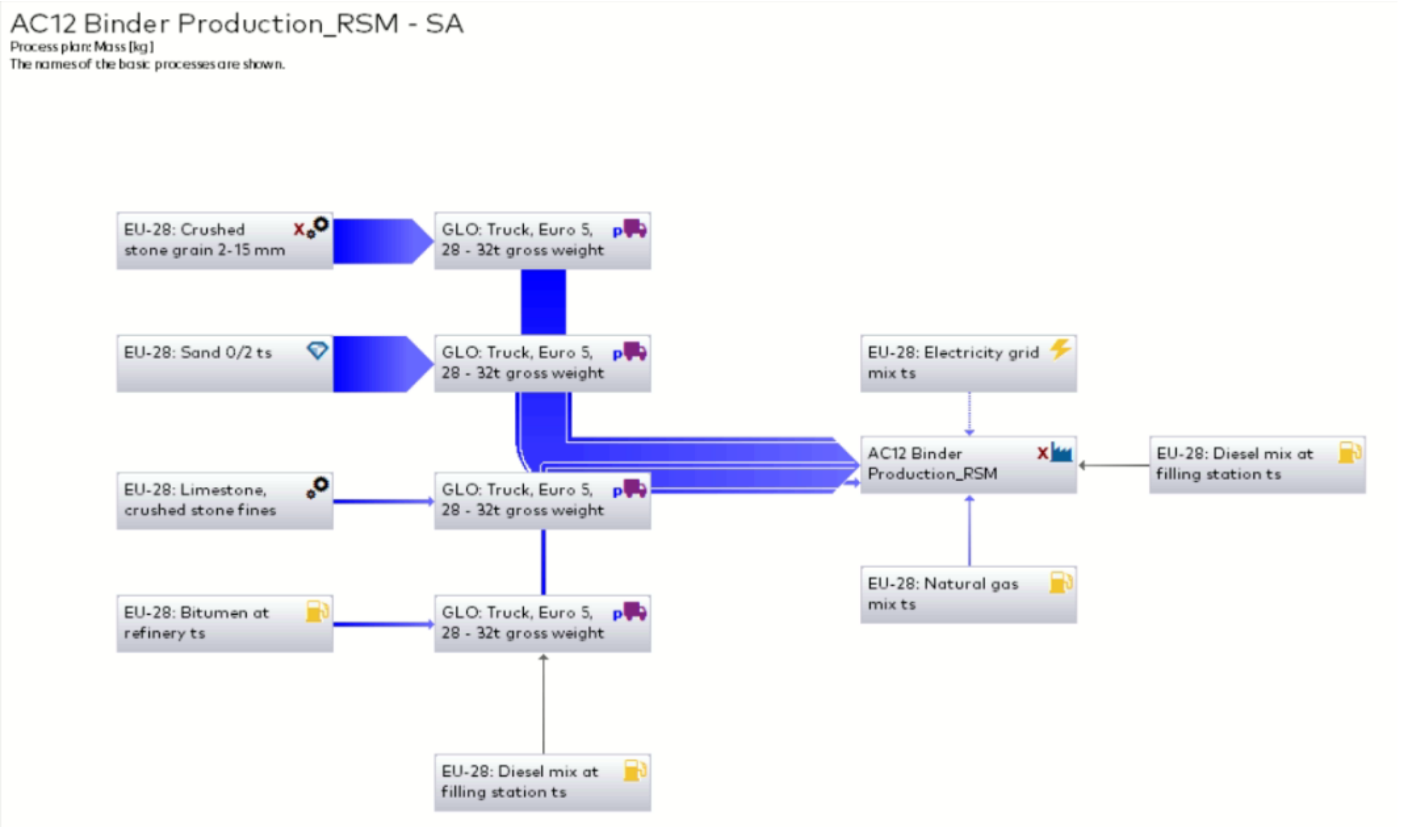

Figure A 1 - San Marino - HMA AC12 production LCA model Plan in GaBi

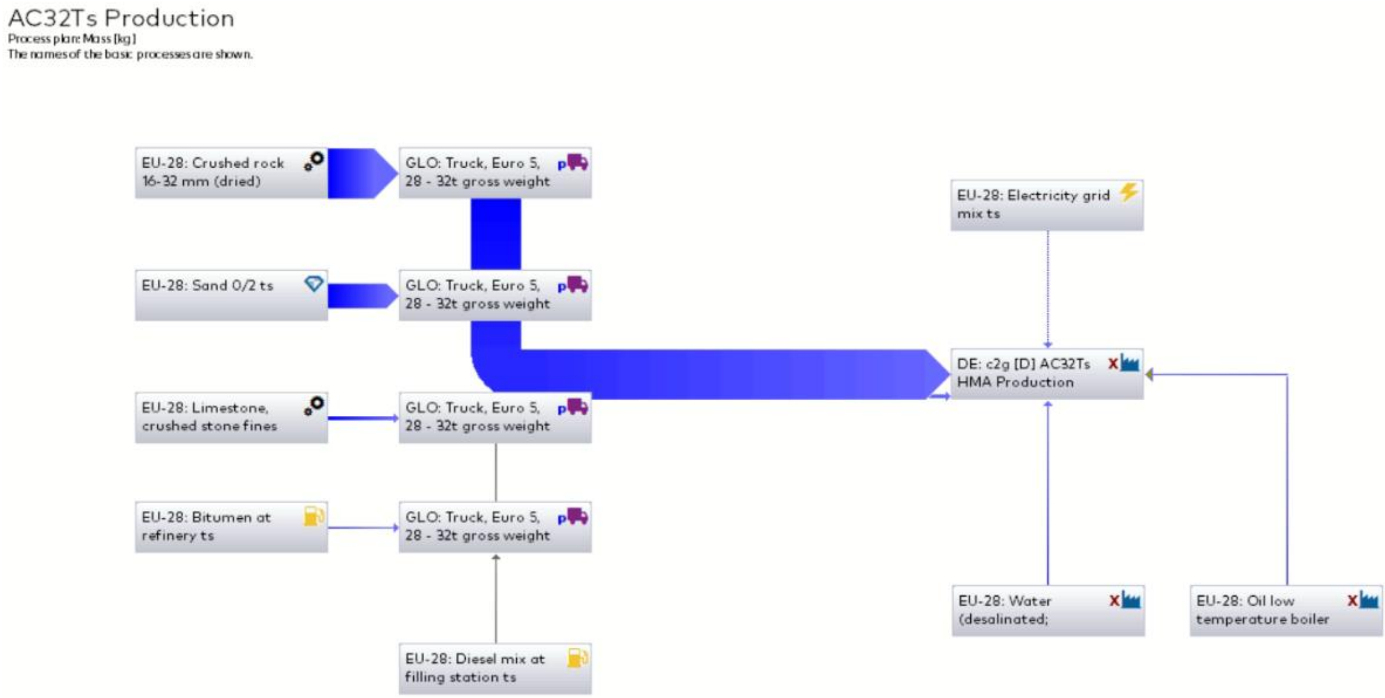

Figure A 2 – Germany – HMA AC32TS production LCA model Plan in GaBi

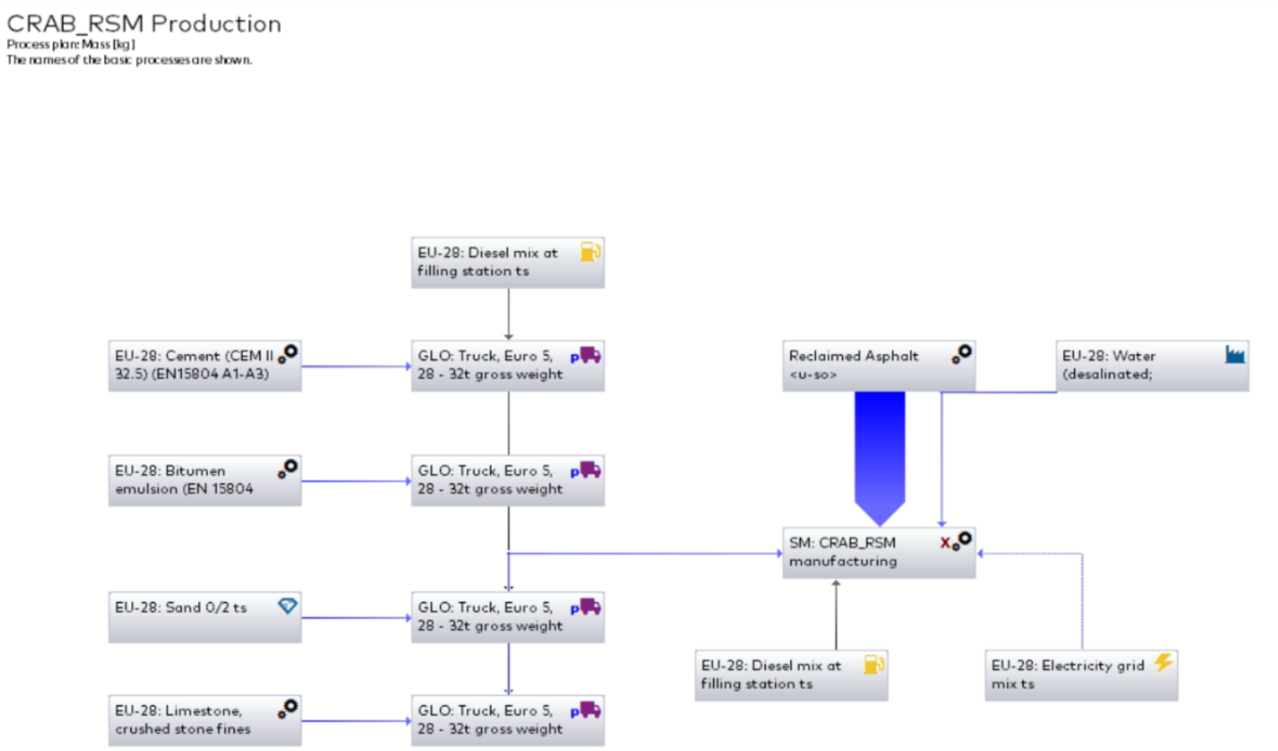

Figure A 3 - San Marino - CRAB_RSM production LCA model Plan in GaBi

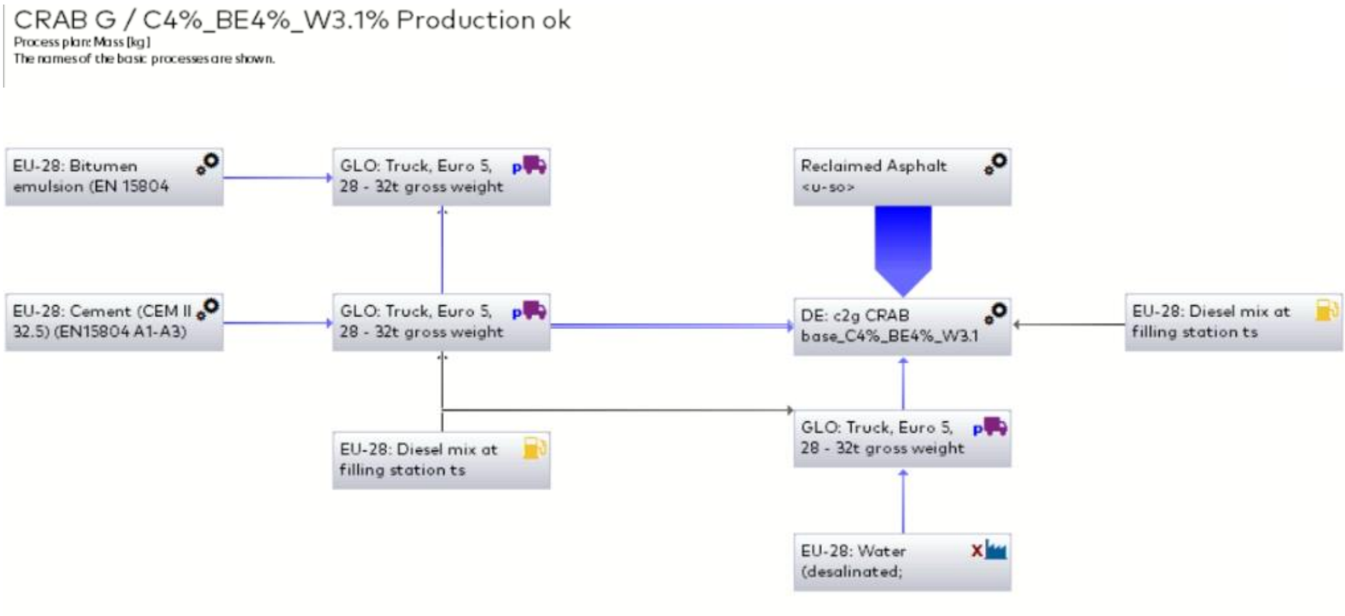

Figure A 4 – Germany – CRAB_G production LCA model Plan in GaBi

2. Hotspot Analysis – Contribution of each step in mixtures production

Figure A 5 – San Marino - Contribution of each stage in CRAB_RSM Production

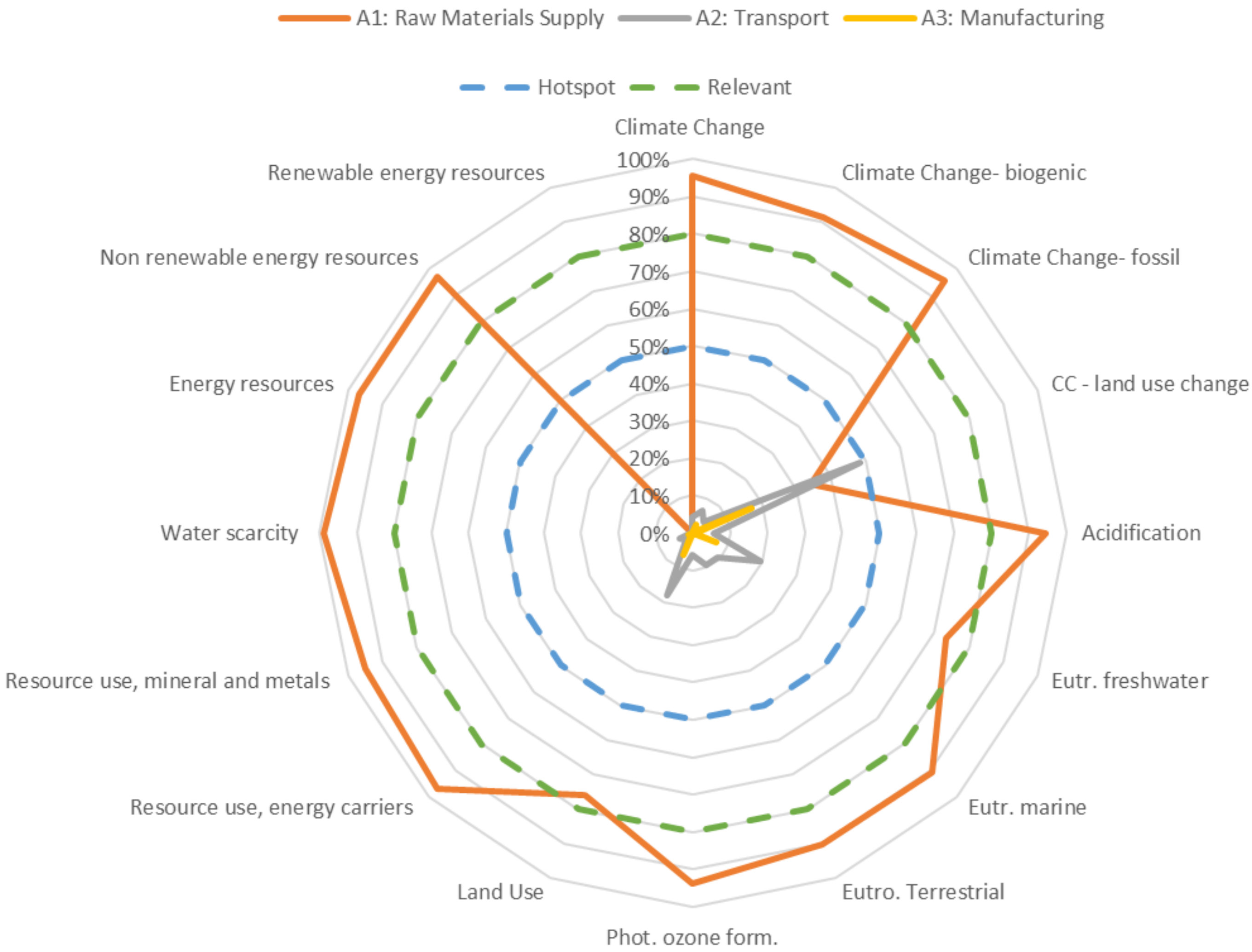

Figure A 6 – Germany - Contribution of each stage in CRAB_G Production

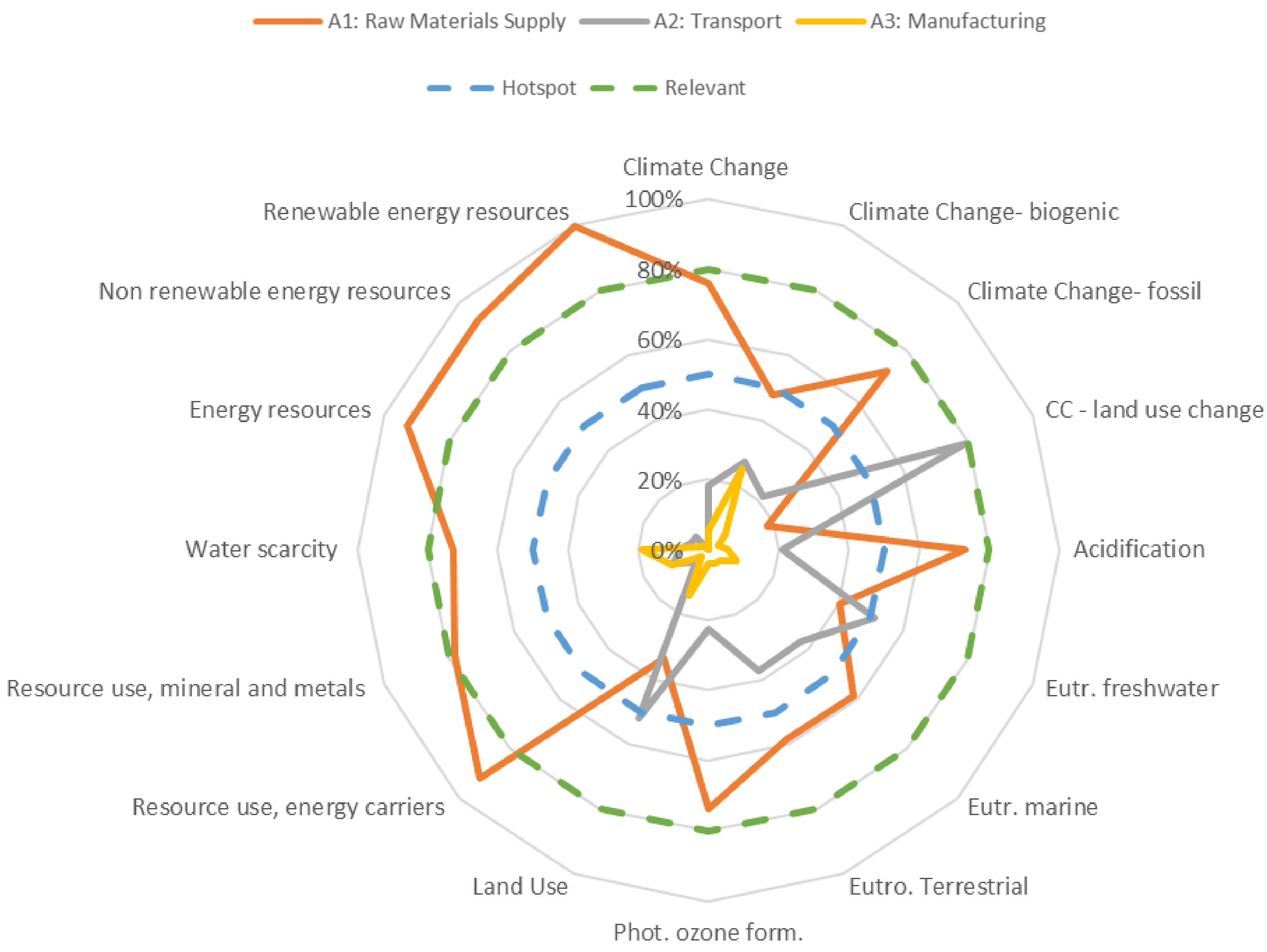

Figure A 7 – San Marino - Contribution of each step on the environmental impact of conventional HMA AC12

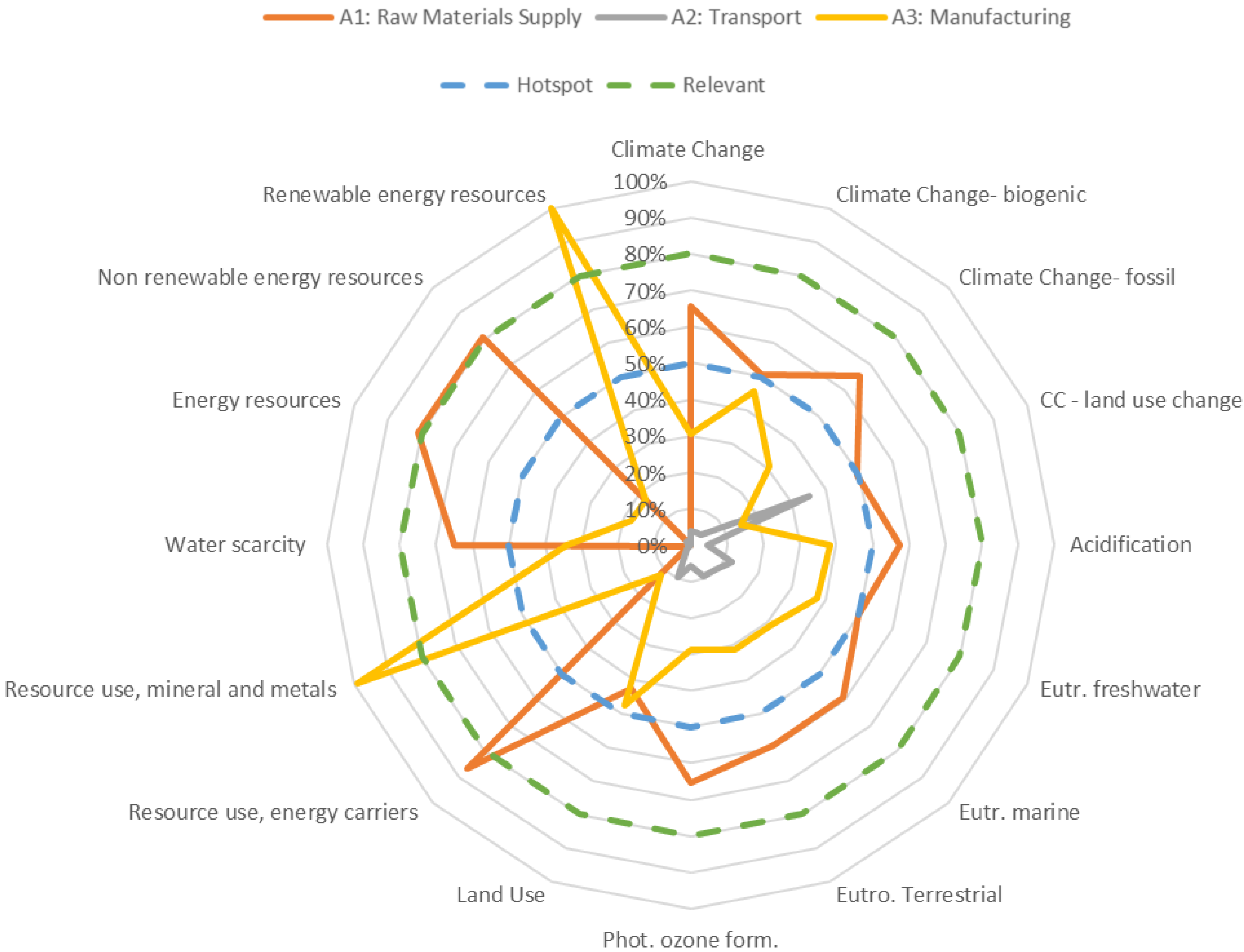

Figure A 8 – Germany - Contribution of each step on the environmental impact of conventional HMA AC32TS

3. Sensitivity Analysis

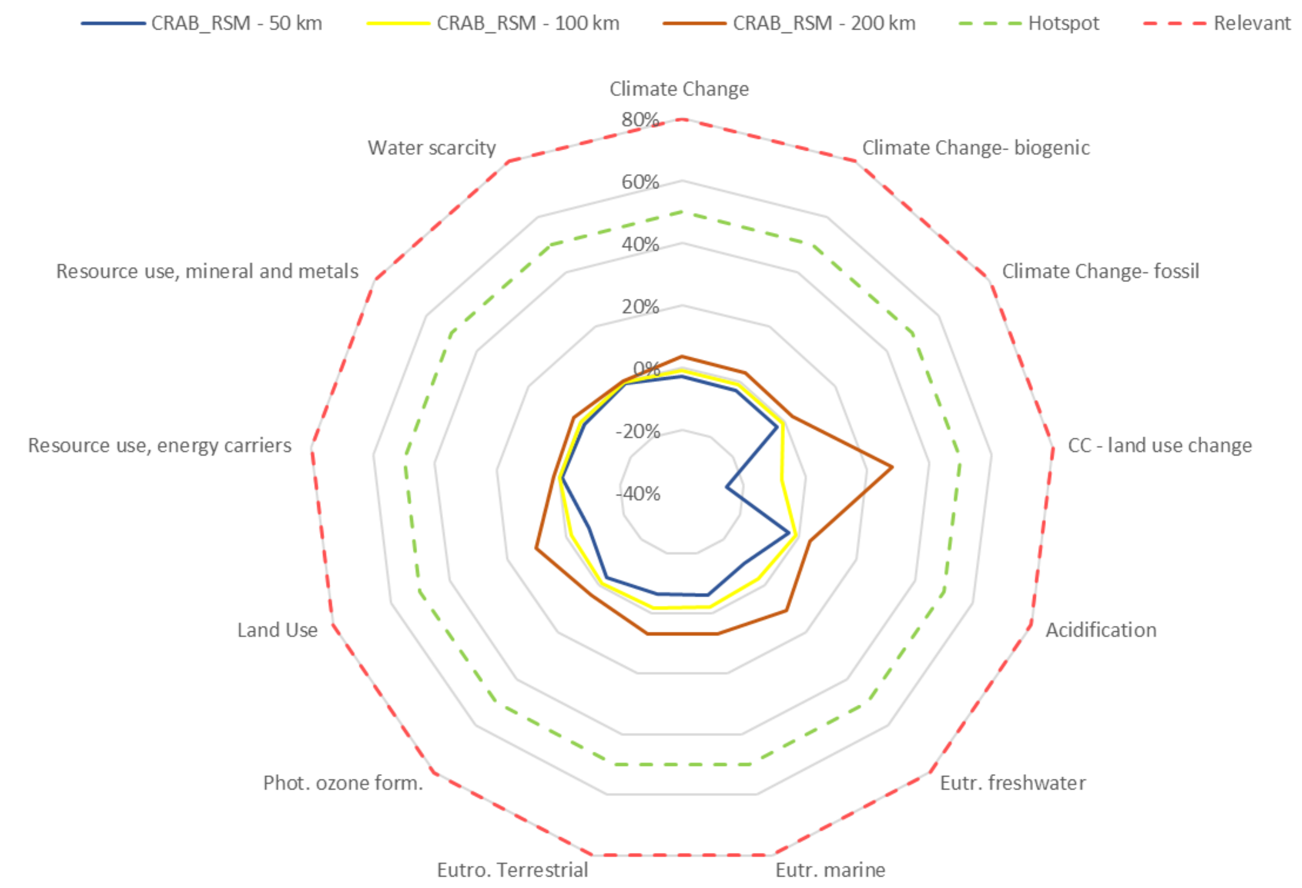

Figure A 9 – San Marino - CRAB_RSM at project level compared with CRAB_RSM whose distances are assumed to be constant at 50, 100, 200 km.

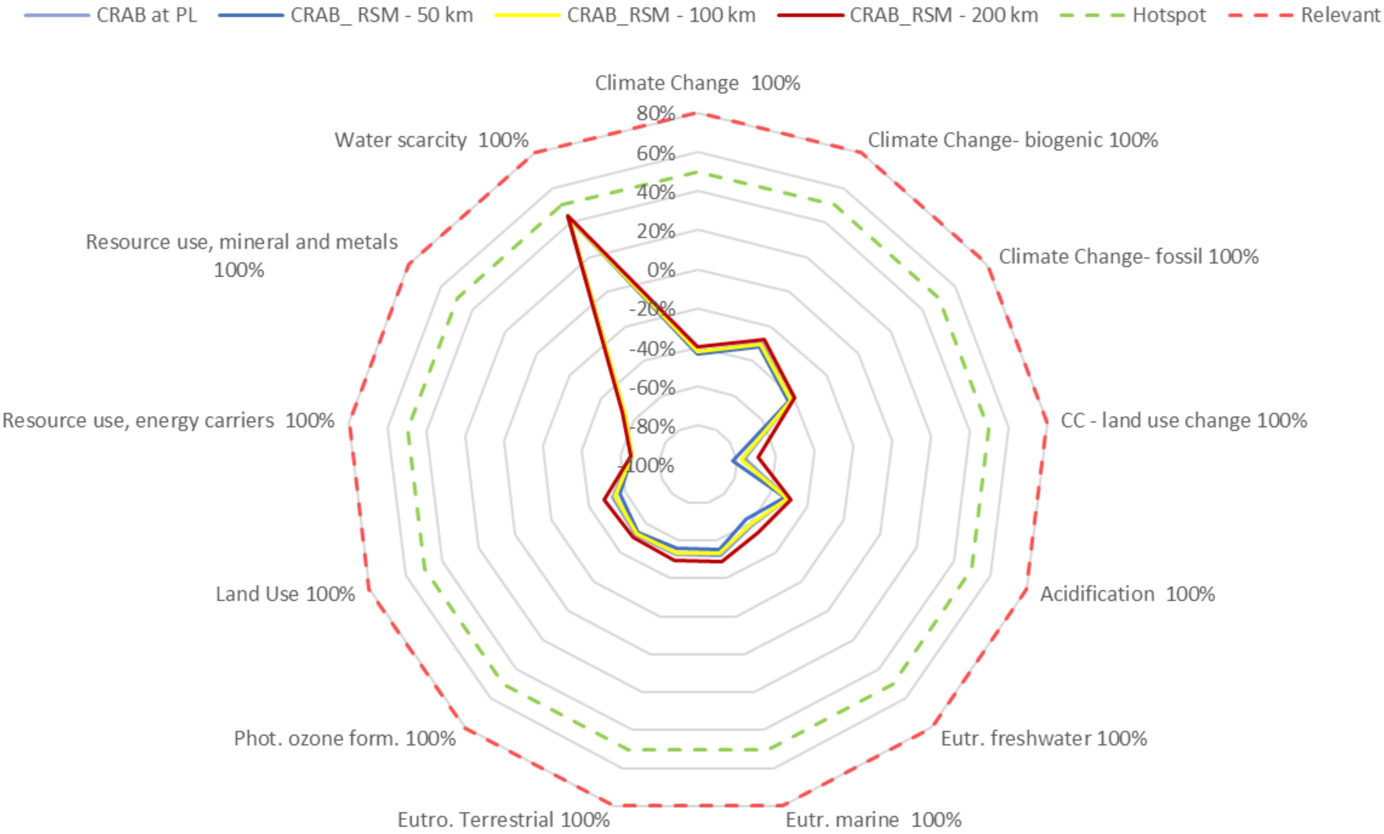

Figure A 10 - San Marino - CRAB_RSM with distances at project level and at 50, 100, 200 km compared with San Marino Conventional HMA AC12.

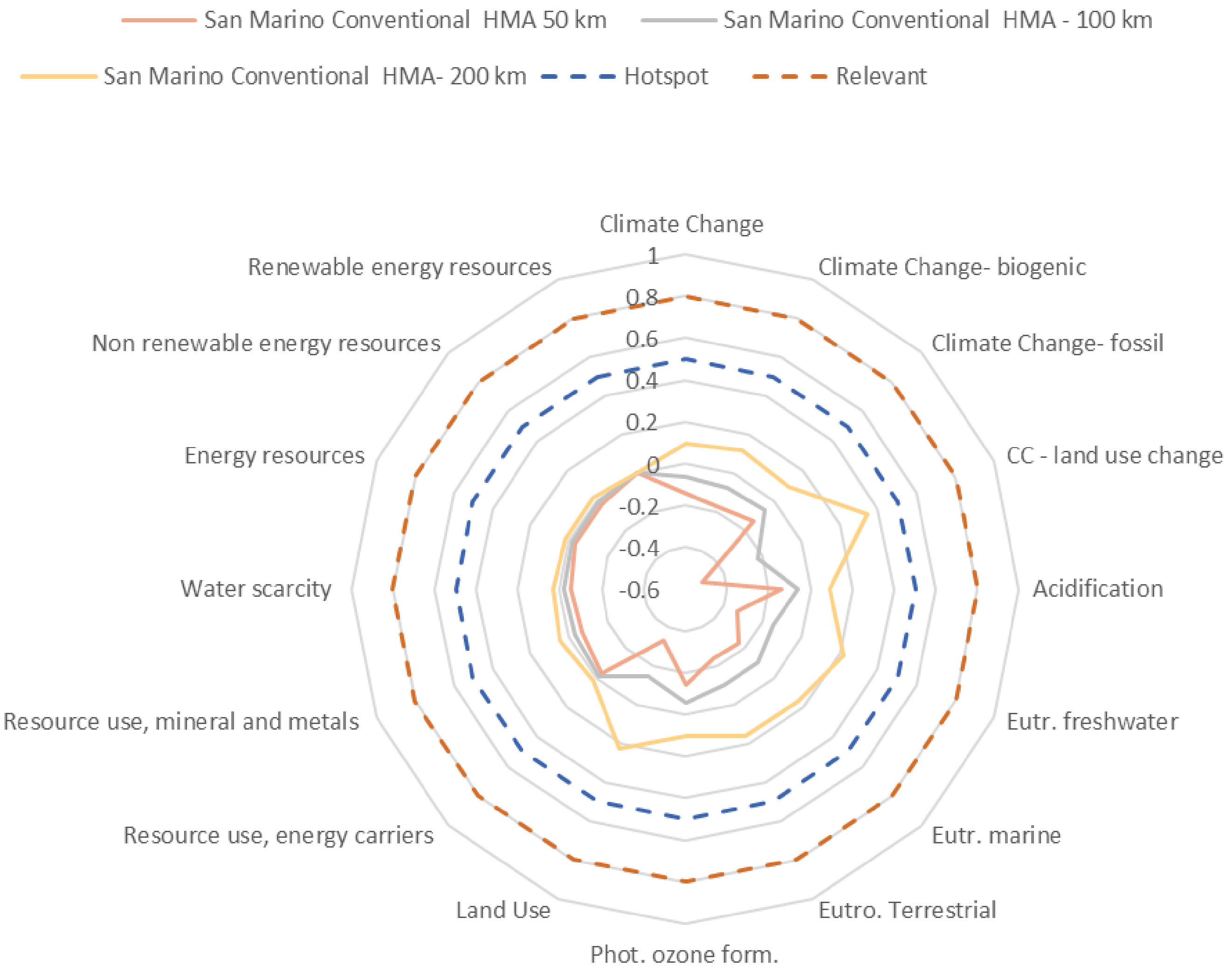

Figure A 11 - San Marino - Conventional HMA AC12 at project level compared with HMA AC12 whose distances are assumed to be constant at 50, 100 and 200 km.

Figure A 12 - Germany - CRAB_G at project level compared with CRAB_G whose distances are assumed to be constant at 50, 100, 200 km.

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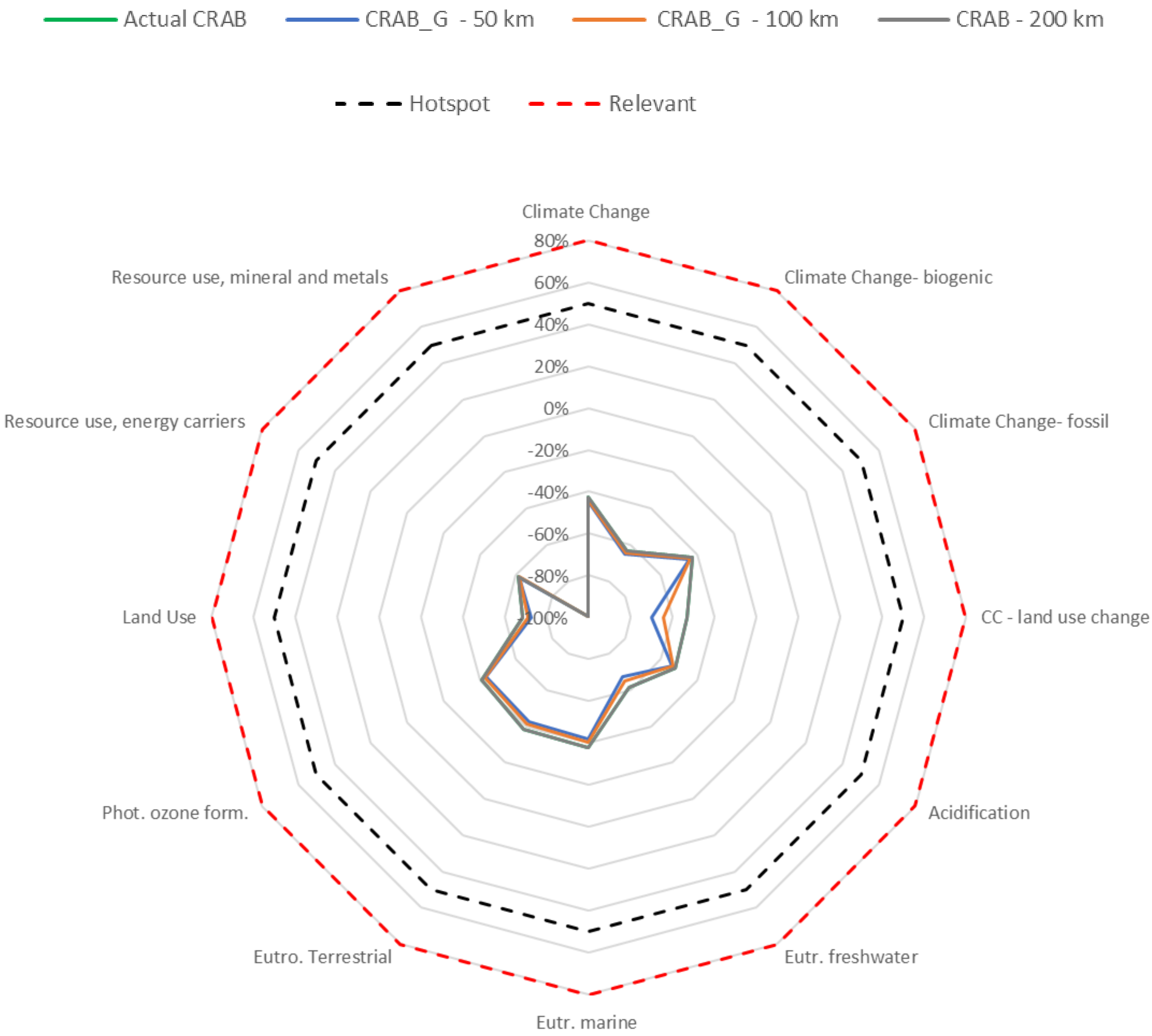

Figure A 13 - CRAB_G at project level and at 50, 100, 200 km compared with Germany Conventiona HMA.

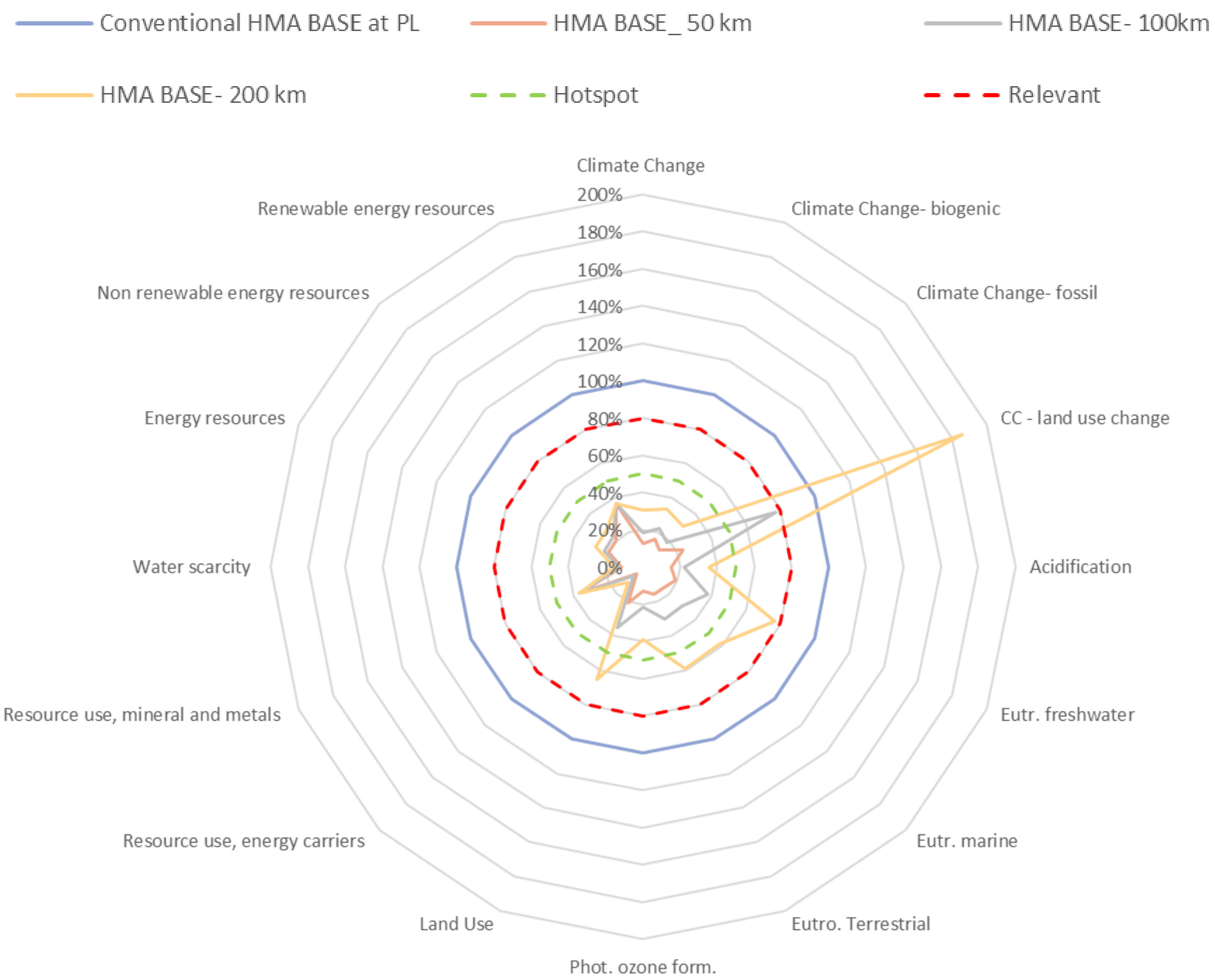

Figure A 14 - German Conventional HMA at project level compared with HMA whose distances are assumed to be constant at 50, 100 and 200 km.