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Quantifying the effect of RAP on the environmental impact

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Joke ANTHONISSEN

Promotoren: Prof. Dr. Ing. Wim Van den bergh
Prof. Dr. Johan Braet

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MEMBERS OF THE JURY

Prof. Dr. Ir. Amaryllis Audenaert Chair
University of Antwerp – faculty of Applied Engineering
Research group Energy and Materials in Infrastructure and Buildings (EMIB)

Prof. Dr. Ing. Wim Van den bergh Promotor
University of Antwerp – faculty of Applied Engineering
Research group Energy and Materials in Infrastructure and Buildings (EMIB)

Prof. Dr. Johan Braet Promotor
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University of Antwerp – faculty of Design Sciences – department Product Development

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Research group Energy and Materials in Infrastructure and Buildings (EMIB)

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Ir. Matt Wayman Industrial expert
Transportation Research Laboratory, United Kingdom

Dr. Ir. Amlan Mukherjee Academic expert
Michigan Technological University – Department of Civil & Environmental Engineering
Michigan Technological University – Service Systems Engineering Program

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SUMMARY

BITUMINOUS PAVEMENTS IN FLANDERS

Quantifying the effect of RAP on the environmental impact

In this thesis the environmental impact of bituminous road pavements and the use of reclaimed asphalt pavement (RAP) in asphalt mixtures are investigated according to the current practice in Flanders.

A preliminary research was set up to determine the research gaps. The literature review has a wide scope, from road engineering up to environmental topics. Different approaches to increase the service life of pavements and to reduce the material and energy consumption have been discussed. Both the technologies themselves (i.e., using RAP and warm mix asphalt) and results of LCA studies in literature have been discussed. The preliminary research also includes three case specific LCA studies of the construction of different Flemish road test sections. The Carbon Free-ways pilot project is subject of one of the case studies. It is concluded that taking into account only CO_2-emissions leads to a significant underestimation of the full environmental impact by excluding impact categories such as fossil depletion, particulate matter, land transformation, etc. In a comparative study, the ranking of products can differ if only a single environmental impact is considered (i.e., climate change) compared with an assessment including multiple environmental indicators.

Three research topics, influenced by the use of RAP, were selected from the results of the preliminary research i.e. (1) service life of bituminous pavements, (2) transport processes, and (3) energy consumption for asphalt production. These topics mainly involve data collection and statistical analysis within the scope of the current research. The research scope is limited to the current practice in Flanders. Data for 2013-2016 are used. The technical research results of the three topics contribute to the exploration of different scenarios used in the environmental assessment.

Three different research levels are implemented to investigate the service life of pavements and the effect of RAP: (1) mechanical performances tested in the laboratory, (2) mechanical performances of base courses tested with measurements in situ, and (3) service life of pavements in situ by inventory of historical construction, maintenance, and rehabilitation interventions. Despite the research conducted at different research levels and the collaboration with experts in the field, few conclusions were drawn from these research parts. There is not enough data available for a meaningful analysis related to the durability of pavements in situ. Based on laboratory test results, it is concluded that it is possible to design asphalt mixtures with RAP with equivalent performance characteristics as compared to the mixtures with only virgin raw materials.

A questionnaire was addressed to the Flemish asphalt plants for the inventory of transport distances between the asphalt plant and the road worksite. The road transport distance between the asphalt plant and the road worksite is shorter compared to the road transport distance for the delivery of virgin raw materials. Therefore, less transport (tkm) for raw material delivery to the plant is needed if RAP is used in the asphalt mixture. However, it appears that the transport processes between plant and worksite are inefficient. Optimization would be possible by the definition of service areas to assign road worksites to the nearest plant, taking into account the production capacity of the specific plant.

Data on moisture content in aggregates were collected from both asphalt and concrete laboratories, and research centres. The analyses did not reveal any statistically significant difference in moisture content between (1) mixtures with only virgin raw materials and mixtures with RAP, and (2) RAP stored under a shelf and RAP stored in open air. The grain size fraction of the aggregates has an important influence on the moisture content.
The daily registration of production parameters in 2013 to 2016 was used to collect information on the energy consumption for asphalt production. All variances by means of switchover in mixture type, interruption in production, variable weather conditions, and special circumstances are actually part of the asphalt production in situ and hence included in the dataset. A statistically significant increase of the energy consumption (natural gas) was measured if asphalt with RAP is produced. However, the causal connection has to be investigated in future (e.g., moisture, additional drum, higher temperature of virgin aggregates, etc.).

These data and results of the three research topics were used in an environmental assessment. Since no similar research was carried out before, it is necessary to develop a reference frame or a benchmark. The life cycle assessment (LCA)

methodology is used. The attributional, cut-off modelling approach is applied in which RAP is a burden free raw material. The end-of-life (EOL) stage is reached just before the pavement is deconstructed, and the end-of-waste (EOW) stage is reached after the RAP has had a treatment (e.g. crushing and sieving or thermal cleansing) and is ready to be reused in different applications (in another life cycle).
The functional unit is an average Flemish road worksite: 250 m long with 2x2 lanes, including the surface and base course (12 cm thick) inlay construction. Different scenarios were generated to calculate the environmental impact and the effect of using RAP, of reduced transport distance between plant and worksite, and of reduced durability of the pavement.

Results of the uncertainty assessment show that limiting the transport distances between the plant and the road worksite to the maximum necessary distances lead to a reduction of the environmental impact with 36%. This result is robust and not sensitive for data uncertainties. The average use of RAP at this moment in Flanders leads to a reduction of the environmental impact with only 0.9% compared to the use of only virgin materials. This reduction is sensitive to data uncertainties.
For the specific scenarios in this study, the environmental benefit from using RAP will change into an environmental load if the use of RAP induces a reduction in the durability that should be compensated by an increased layer thickness of 1 cm or more in order to reach the same service life.

It is concluded that the most important potential to reduce the environmental impact is by reducing transport distances. In practice, it will be necessary that the contracting authority takes the lead in this, for example by an alternative procurement strategy.

SAMENVATTING

ASFALTVERHARDINGEN IN VLAANDEREN

Inschatten van het effect van AG op de milieu-impact

In deze thesis wordt de milieu-impact van bitumineuze wegverhardingen en het gebruik van asfaltgranulaat (AG) in asfaltmengsels onderzocht op basis van de huidige praktijk in Vlaanderen.

In deze studie wordt eerst een uitgebreid vooronderzoek uitgevoerd om de hiaten in het onderzoeksdomein te bepalen. De scope van de literatuurstudie is breed, gaande van wegenbouwkunde tot milieukundige onderwerpen. Toepassingen om de levensduur van verhardingen te verhogen en het materiaal- en energieverbruik te reduceren komen aan bod. Zowel de technieken zelf, bijvoorbeeld gebruik van AG en asfaltproductie bij verlaagde temperatuur, alsook resultaten van LCA studies in de literatuur worden besproken. Ook drie verschillende, case specifieke, LCA studies, over de aanleg van proefvakken in Vlaanderen, maken deel uit van het vooronderzoek. Het Vlaamse pilootproject CO_2-bestek is één van de drie case studies. Er kan worden besloten dat de totale milieu-impact sterk onderschat wordt wanneer er enkel CO_2-emissies in rekening genomen worden, en impact categorieën als uitputting van fossiele grondstoffen, fijn stof, functiewijziging van gronden, en dergelijke buiten beschouwing gelaten worden. Bovendien kan in een vergelijkende studie de volgorde van de producten of scenario's veranderen wanneer men slechts één impact beschouwt in vergelijking met een analyse waarbij meerdere milieu-impacts onderzocht worden.

Op basis van de resultaten van de voorstudie, worden er drie onderzoeks-onderwerpen geselecteerd, die allen worden beïnvloed door het gebruik van AG in asfaltmengsels: (1) de levensduur van asfaltverhardingen, (2) transportprocessen, en (3) energieverbruik voor de productie van asfalt. Voor deze onderzoeksonderwerpen is het voornamelijk belangrijk om data te verzamelen en deze data statistisch te analyseren binnen de reikwijdte van dit onderzoek. De reikwijdte van dit onderzoek is beperkt tot de huidige praktijk in Vlaanderen. Data voor 2013 tot 2016 worden gebruikt. De technische resultaten van de drie onderzoeksonderwerpen zullen bijdragen tot de uitbouw van verschillende scenario's in het onderzoek naar de milieu-impact.

Om de levensduur van asfaltverhardingen en de invloed van AG hierop te kunnen bepalen, wordt er onderzoek uitgevoerd op drie verschillende niveaus: (1) mechanische eigenschappen van asfaltmengsels worden getest in het labo, (2) mechanische eigenschappen van onderlagen worden getest door metingen op de asfaltverhardingen uit te voeren, en (3) de levensduur van asfaltverhardingen wordt

bepaald door de inventarisatie van informatie over de aanleg, onderhoud en herstellingsingrepen. Desondanks dat het onderzoek op deze verschillende niveaus gevoerd werd en er samen gewerkt werd met experten uit de sector, konden er slechts weinig besluiten getrokken worden. Er is te weinig data en informatie beschikbaar om een betekenisvolle analyse van de levensduur van verhardingen te maken. Op basis van de resultaten van de labotesten kunnen we enkel besluiten dat het mogelijk is om mengsels met AG te ontwerpen die gelijkwaardige prestaties vertonen in vergelijking met mengsels met enkel nieuwe grondstoffen.

Er werd een enquête verzonden naar de Vlaamse asfaltcentrales om transportafstanden tussen de asfaltcentrale en de wegenwerken die ze uitvoeren te verzamelen. De transportafstand via de weg tussen de centrale en de werf is korter in vergelijking met de transportafstand via de weg voor de levering van nieuwe grondstoffen aan de asfaltcentrale. Dit betekent dat er minder transport (tkm) nodig is voor de aanvoer van grondstoffen wanneer er AG gebruikt wordt in de asfaltproductie. Toch blijkt dat de transportafstanden tussen de centrales en de werven erg inefficiënt zijn. Deze transportprocessen zouden geoptimaliseerd kunnen worden wanneer de wegenwerken toegewezen worden aan de dichtstbijzijnde asfaltcentrale, rekening houdend met de productiecapaciteit van de centrales.

Testresultaten van de berekening van vochtgehaltes in aggregaten worden verzameld via de laboratoria op asfalt- en betoncentrales en via onderzoeksinstellingen. Er werden geen betekenisvolle verschillen gevonden wanneer de vochtgehaltes vergeleken werden (1) in de totale mix van aggregaten voor mengsels met enkel nieuwe grondstoffen en voor mengsels waarin AG gebruikt wordt, en (2) in AG dat buiten opgeslagen wordt en in AG dat opgeslagen wordt onder een afdak. De resultaten tonen aan dat de korrelmaat van de aggregaten wel een grote invloed heeft op het vochtgehalte in de aggregaten.
Op de asfaltcentrale worden dagelijks een aantal productieparameters geregistreerd. Deze werden gebruikt om een dataset op te bouwen voor het energieverbruik voor de asfaltproductie. Hierdoor worden alle variaties in het asfaltproductieproces mee opgenomen in de dataset, bv. afwisseling tussen mengseltypes, onderbrekingen in de productie, veranderlijke weersomstandigheden, etc. Er werd een statistisch betekenisvolle toename van het energieverbruik (aardgas) gevonden als asfalt met AG geproduceerd werd. Het oorzakelijk verband tussen een aantal parameters en de toename van het energieverbruik moet echter nog verder in detail onderzocht worden, bv. vochtgehalte in aggregaten, extra paralleltrommel, hogere temperaturen voor nieuwe grondstoffen als AG toegevoegd wordt, etc.

De data en resultaten van de drie onderzoeksonderwerpen worden gebruikt in de analyse van de milieu-impact. Omdat er niet eerder een gelijkaardig onderzoek werd uitgevoerd, is het nodig om te starten met een referentiekader. De levenscyclusanalyse (LCA) methodologie wordt gebruikt. Er wordt gekozen voor een bepaalde methodologische aanpak (attributional, cut-off) waarbij AG als grondstof in de productiefase geen milieu-impact heeft. In de levenscyclus wordt het einde van de levensduur (EOL) bereikt net voordat de verharding wordt afgefreesd, en het einde van de afvalfase wordt bereikt nadat het AG een voorbehandeling heeft ondergaan (bv. breken en zeven of thermische reiniging) en zo klaar is voor hergebruik in verschillende, nieuwe toepassingen (in een volgende levenscyclus).
Als functionele eenheid wordt een gemiddelde Vlaamse asfaltwerf genomen: een 250 m lange wegsectie, 2x2 rijstroken waarbij de top- en onderlaag (samen 12 cm dik) in rekening genomen worden. Verschillende scenario's worden opgebouwd om de milieu-impact te onderzoeken en het effect van het gebruik van AG in asfaltmengsels, van kortere transportafstanden tussen de centrale en de werf, en van een mengsel met verminderde mechanische duurzaamheidsprestaties.

Resultaten van de onzekerheidsbeoordeling tonen aan dat het beperken van transportafstanden, tussen de asfaltcentrale en de werf tot de maximaal noodzakelijke afstanden, voor een daling van de milieu-impact met 36% zorgt. Dit is een zeer robuust resultaat en weinig gevoelig voor onzekerheden in de gebruikte data. Het gemiddeld gebruik van AG, zoals momenteel in Vlaanderen wordt toegepast, resulteert in een daling van de milieu-impact met 0.9% in vergelijking met het gebruik van enkel nieuwe grondstoffen. Deze daling is echter wel gevoelig aan onzekerheden in de data.
Specifiek voor het onderzochte scenario in deze studie werd er gevonden dat het milieuvoordeel door het gebruik van AG zal veranderen in een milieunadeel wanneer het gebruik van AG een vermindering van de duurzaamheid van het asfaltmengsel impliceert en een wegopbouw nodig is van minstens 1 cm dikker om dezelfde levensduur te bereiken.

Er wordt besloten dat de belangrijkste mogelijkheid om de milieu-impact te verminderen is door de transportafstanden te beperken. In de praktijk zal het nodig zijn dat de aanbestedende overheid hierin de leiding neemt, bijvoorbeeld door een aangepaste aanbestedingsstrategie.

TABLE OF CONTENTS

ABBREVIATIONS

%O/N	Percentage old binder from RAP in the total binder blend
AC	Asphalt concrete
ALCA	Attributional life cycle assessment
AMT	Asphalt mixture type
APO	Asphalt mixtures with performance characteristics for base courses (translated from Dutch: asfaltbeton met prestatie-eisen voor onderlagen)
ART	Agency for Roads and Traffic of the Ministry of the Flemish Community
BAT	Best available technique
BC	Binder content
BENOR	Mark of quality on products in compliance with Belgian standards (NBN) or technical requirements
BRRC	Belgian Road Research Centre
CI	Confidence interval
CLCA	Consequential life cycle assessment
COPRO	(Control of products) Belgian impartial certification body in the construction sector
Certipro	Certification and inspection service incorporated by VITO
CRCP	Continuously Reinforced Concrete Pavement
EAPA	European Asphalt Pavement Association
EME	High modulus asphalt mix (translated from French: Enrobé à Module Élevé; AVS in Dutch: asfalt met verhoogde stijfheid)
EOL	End-of-life
EOW	End-of-waste
EU ETS	European Union emissions trading system
ESAL	Equivalent single axle load
FU	Functional unit
FWD	Falling Weight Deflection
GIS	Geographic information system
GPP	Green public procurement
GVW	Gross vehicle weight
GWP	Global warming potential
HMA	Hot mix asphalt
ISO	International Organization for Standardization
LC	Life cycle
LCA	Life cycle assessment
LCI	Life cycle inventory

LCIA	Life cycle impact assessment
LTPP	Long Term Pavement Performance (research program in United States and Canada)
OVAM	Public Waste Agency of Flanders (translated from Dutch: Openbare Vlaamse Afvalstoffenmaatschappij)
PMB	Polymer modified bitumen
PMS	Pavement management system
RAP	Reclaimed asphalt pavement
SB250	Flemish Road Standard
SCI	Surface curvature index
SMA	Stone mastic asphalt
SSD	Saturated surface dry
st. dev.	Standard deviation
st. error	Standard error
VITO	Flemish institute for technological research
VLAREMA	Flemish regulations on the sustainable management of material cycles and waste (translated from Dutch)
WMA	Warm mix asphalt

APPENDED PAPERS

This thesis is based on the following eight papers which are appended in Part II of the thesis.

Paper I	Anthonissen, J., Van den bergh, W., Braet, J., 2016. Review and environmental impact assessment of green technologies for base courses in bituminous pavements. Environ. Impact Assess. Rev. 60, 139-147. doi:10.1016/j.eiar.2016.04.005	*Published*
Paper II	Anthonissen, J., Van Troyen, D., Braet, J., Van den bergh, W., 2015. Using carbon dioxide emissions as a criterion to award road construction projects: a pilot case in Flanders. J. Clean. Prod. 102, 96–102. doi:10.1016/j.jclepro.2015.04.020	*Published*
Paper III	Anthonissen, J., Van den bergh, W., Braet, J., 2016. Climate change impact compared to life cycle assessment results: a pilot case in Flanders. 6th Eurasphalt & Eurobitume (E&E) Congress, June 1-3, 2016. Prague.	*Published*
Paper IV	Anthonissen, J., Braet, J., Van den bergh, W., 2015. Life cycle assessment of bituminous pavements produced at various temperatures in the Belgium context. Transp. Res. Part D Transp. Environ. 41, 306–317. doi:10.1016/j.trd.2015.10.011	*Published*
Paper V	Anthonissen, J., Van den bergh, W., Braet, J., 2014. Cradle-to-Gate Life Cycle Assessment of Recycling and Impact of Reduced Production Temperature for the Asphalt sector in Belgium. International Symposium on Pavement LCA 2014. Davis, California, pp. 61–74.	*Published*
Paper VI	Anthonissen, J., Braet, J., Van den bergh, W., 2016. Effect of RAP on the mechanical properties of registered asphalt mixtures in Flanders. The fifth International Symposium on Life-Cycle Engineering (IALCCE 2016), 16-20 October 2016, Delft, The Netherlands. DRC Press/Balkema, Leiden, The Netherlands, pp. 399-405.	*Published*
Paper VII	Anthonissen, J., Buyle, M., Van den bergh, W., Braet, J., Audenaert, A. Analysis of the Belgian electricity mix used in environmental life cycle assessment studies: How reliable is the ecoinvent 3 mix? Energy Efficiency.	*Submitted*

Paper VIII	Anthonissen, J., Van den bergh, W., Braet, J. Reuse of bituminous pavements: a mini-review of research, regulations and modelling. Waste Management & Research. Prepublished December 5, 2016. doi:10.1177/0734242X16678064	*Published (online first)*

PART I: COMPREHENSIVE RESEARCH

This doctoral thesis is a description of the extensive research work over four years, at University of Antwerp. The first part of this doctoral thesis explicates the research, the motivation and the contribution of the papers to the research. In this part, certain research topics that are included in the papers are elaborated in depth. Some results are exclusively presented in this first part of the thesis, but can be published in separate articles in the future since the findings are also very important for the Flemish industry.

1 INTRODUCTION

Infrastructure plays a vital role in the society for moving people and goods. Roads in particular offer service without fixed departure times and without limited service schedule and are therefore experienced as mobile freedom. Furthermore, roads are the crucial connection between other transport services (e.g., airports, railway stations, bus stops), services, health facilities, etc. (International Road Research Board, 2013).

Roads are used for both freight and passenger transport. According to figures for 2014 from the European Commission, 49% of all tonne-kilometres freight transport within EU28 were performed using roads (European Union, 2016). In Belgium, in 2014, transport by road represents 71% of freight transport on land. For the same year, passenger transport using roads (including passenger cars, powered 2-wheelers, busses, and coaches) represents 82% of all person-kilometres passenger transport for EU28 and 92% for all passenger transport on land for Belgium.

The figures from the European Commission also showed that 3.1% of all employed Belgians had a job in the transport sector in 2014 and there was a turnover of €48.2 billion in the sector in 2013 in Belgium.

From the environmental point of view, use of public (rail) transport is encouraged for person transport[1], and transport via rail and inland water ways is beneficial for freight transport (see Figure 1, findings in paper V, and (Organisation for Economic Co-operation and Development (OECD), 1997)). However, the importance of the road infrastructure for transport is proven by the figures above.

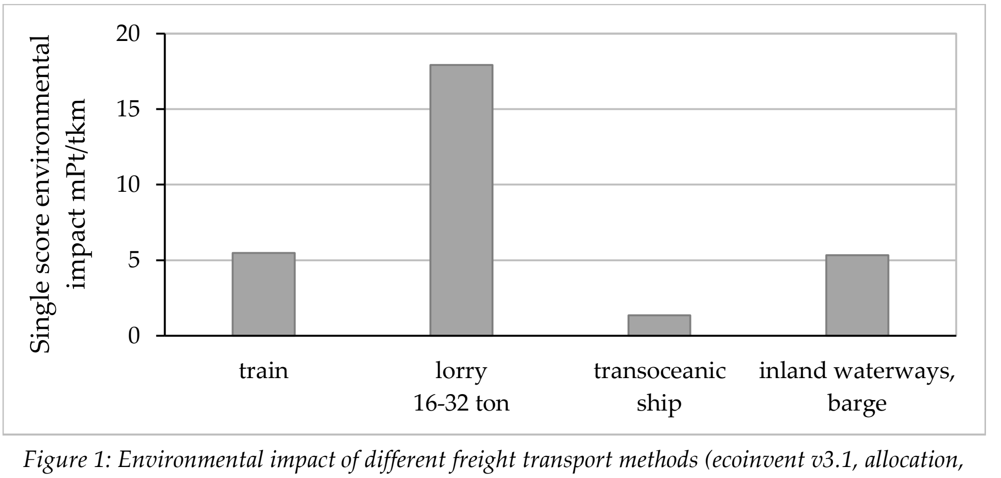


Figure 1: Environmental impact of different freight transport methods (ecoinvent v3.1, allocation, recycled content, ReCiPe Endpoint H/A v1.12)

[1] According to collective bargaining agreement number 19 octies from 20.02.2009, defined by the Belgian National Labour Council, a financial refund must be given by Belgian employers to their employees for the commuter traffic when public transport is used (Belgian National Labour Council (NAR), 2009).

1.1 The Flemish public road sector

Multiple organisations are involved in the Flemish public road sector. This research focuses mainly on the public road works with bituminous pavements. A minor part (less than 20% in 2014) of the asphalt produced by COPRO-certified plants is not registered according to SB250 and can hence not be used for surfacing of public works in Flanders (COPRO, 2015a). Different rules are into force for public road works compared to private surfacing works. Different important organisations in the sector are described in this chapter with an indication of their working area.

In Belgium, the competent authorities for the public roads are the regions. Belgium has three regions: the Flemish Region (Flanders), the Walloon Region (Wallonia), and Brussels (the Capital Region); each with their own road standard specification: '*Standaardbestek voor de Wegenbouw*' (SB250) in Flanders, '*Cahier des Charges Type Qualiroutes*' (2016) in Wallonia, and '*Typebestek*' (TB 2015) in Brussels. The present research focuses on the region Flanders. The current version of the Flemish road standard is SB250 v3.1, entered into force since the first of May 2015. More information on the SB250 and registration of asphalt mixtures for use in public road works is described in section 3 of paper VI.

The Agency for Roads and Traffic (ART) in Flanders is responsible for the management of the primary and secondary road network, comprising motorways, including approach ramps, and the main or national roads. This part of the Flemish road patrimony comprised 6 270 km in 2001, increased to 6 964 km in 2013, and levelled in 2015 (Communicatiecel Planning en Coördinatie Agentschap Wegen en Verkeer, 2016, 2014; Vanhout, 2002). The Belgian paved road network, including all road types (motorways, main or national roads, regional roads, and other roads) was 148 216 km long in 2001, increased to 155 210 km in 2010, and then remained unchanged till 2012 (most recent data (European Union, 2015)). It is remarked from these figures that the length of the Belgian road network is stabilising. This means that most road works are (structural) maintenance works instead of the construction of new roads at new locations.

ART defined the structural design life of pavements as 20 years for asphalt pavements, 30 years for asphalt pavements with a high modulus asphalt mix (EME) in base courses, and 30 years for concrete pavements. The number of equivalent single axle load (ESAL) for a road section over its service life determines the construction class of the road. One ESAL is defined as a load of 100 kN with 7 bar. Calculation guidelines for the number of ESAL for a particular road section are published by ART (Agentschap Wegen en Verkeer, n.d.). ART published a series of standard structures for road constructions in different construction classes from B1, highest loading, till B10, lowest loading.

The use of bituminous pavements is proposed for any construction class. The thickness of the asphalt pavement is related to the construction class (thus the total loading during its service life) and the foundation type. For road constructions with a high number of ESAL (B1-B5), standard structures with EME base courses and bituminous surface courses and standard structures with continuously reinforced concrete pavement (CRCP) are recommended. The current policy of ART is to construct road sections for class B1-B2 in CRCP (Agentschap Wegen en Verkeer, 2010), however, this is often omitted in practice due to its higher cost and longer execution time at the construction stage.

The current version of the Flemish road standard SB250 v3.1 prohibits the use of reclaimed asphalt pavement (RAP) in asphalt mixtures for surface courses. Therefore, this research focuses on base courses since the use of RAP is only allowed in these mixtures. SB250 v3.1 specifies the following asphalt mixtures for use in base courses:

- APO-A = AC-20 according to standard EN 13108-1 (2006);
- APO-B = AC-14 according to standard EN 13108-1 (2006);
- AVS-B = EME-14 according to standard EN 13108-1 (2006);

with, APO = asphalt mixtures with performance characteristics for base courses, AC = asphalt concrete, and AVS = EME = high modulus asphalt.

In Belgium, there are 38 asphalt plants of which 18 in Flanders, 1 in Brussels, and 19 in Wallonia (Belgian Road Research Centre, 2014; European Asphalt Pavement Association, 2015). All asphalt production plants in Flanders are batch plants, meaning that the production process is discontinuous. The nominal production of Flemish plants is 100 to 350 ton per hour (average 222 ton/h) (Leyssens et al., 2013). Figures related to the annual asphalt production in Belgium for 2012-2014 as published by the European Asphalt Pavement Association (EAPA) are presented in Table 1 in the columns 'total'. The 18 Flemish plants are part of 11 different companies.

Table 1: Figures of asphalt production in Belgium in 2012, 2013, and 2014

	2012		2013		2014	
	total	COPRO	total	COPRO	total	COPRO
number of production sites	38	21	38	21	38	22
HMA and WMA production (million tons)	5.6	3.7	5.3	3.3	5.2	3.3
available amount of RAP used in asphalt (million tons)	1.5	0.9	1.5	0.9	1.5	1.0
available amount of RAP used in foundations (million tons)		0.9		1.2		0.6
part of available RAP used in asphalt (%)	61	50	61	43	72	61
mixtures containing RAP (%)	49	58	51	58		61
average RAP content in mixtures with RAP (%)		39		45		43

References: (COPRO, 2015a, 2014, 2013, European Asphalt Pavement Association, 2015, 2014, 2013)

With, HMA = hot mix asphalt, WMA = warm mix asphalt

The contracting authority (ART) must verify that all products processed on the worksite comply with SB250. SB250 v3.1 specifies the type of quality mark to be used for each of the materials: virgin granulates, filler, and tar containing RAP need a BENOR quality mark, while paving grade bitumen, polymer modified bitumen (PMB), RAP (without tar), and bituminous mixtures need a COPRO-quality mark (Vlaamse Overheid, 2015).

COPRO is a Belgian impartial certification body in the construction sector. The main working area of COPRO is road construction. COPRO is accredited for the BENOR certification of some selected construction materials for road construction, including natural stone and filler. In the scope of the quality control on asphalt mixtures by COPRO, the asphalt plants have a continuous production registration. The continuous production registration is a digital registration and print out of the inventory of all batches produced at the plant, date and time stamped, mixture composition, production temperature, and mixing duration.

The columns 'COPRO' in Table 1 present the figures concerning the number of asphalt plants certified to produce bituminous mixtures, the annual production volumes, and the use of RAP as published by COPRO for 2012-2014. In May 2017, 21 plants are certified by COPRO to produce asphalt mixtures (17 in Flanders and 4 in Wallonia), and 22 plants are certified to produce (pre-treatment) certified RAP

(17 in Flanders, 4 in Wallonia, and 1 in Brussels) (COPRO, 2016a). Compared to the data for 2014 (Table 1), one Dutch plant discontinued the COPRO-certification, indicating an unaltered number of Belgian COPRO-certified asphalt plants from 2014 to June 2016. Only one asphalt plant in Flanders is not COPRO-certified for asphalt mixtures and RAP. Comparing the data from EAPA with the data from COPRO, differences are mainly explained by the scope of the data. It is important to note that the numbers published by COPRO are exactly quantified while the numbers published by EAPA are the result of a questionnaire. Therefore, the data from COPRO are assessed to be more accurate.
Data on the total annual asphalt production volume strictly for the Flemish plants are not available. The data as published by COPRO are considered to be most reliable and representative for the Flemish asphalt sector.

The last important organisation in the sector is the Belgian Road Research Centre (BRRC). BRRC is an impartial research centre serving all different partners in the Belgian road sector. BRRC is often involved or is the requestor to construct test sections on the road.

1.2 Outline of the thesis

This thesis consists of two parts: Part I is an extensive description of the research and Part II contains the full version of the appended papers. Part I includes 7 chapters: Introduction, Analysis of current practice and gap analysis, Objectives and scope, Research approach and methodology, Results and discussion, Conclusions, and Recommendations. Most of these chapters are subdivided in at least three or four sections, handling the four main aspects in this study (explained in chapter 2), which are (1) the service life of pavements, (2) transport processes over the life cycle of bituminous road pavements, (3) moisture content in aggregates and energy consumption at the asphalt plant, and (4) the environmental impact assessment.

Chapter 1, the Introduction, describes the importance of roads, the different actors in the Flemish public road sector, and the outline of the thesis.
Chapter 2 includes an analysis of the current practice regarding green technologies, the determination of the general focus of the study based on important findings from own preliminary research, and a gap analysis.
The objectives and scope of the research are described in Chapter 3, including information related to the area and time frame. An overview of the research questions is also included in this chapter.
Chapter 4 presents the research approach and the research methodology, discussing the environmental assessment and the data collection for the three main research

topics, a description of the life cycle assessment methodology in general and explaining and justifying the selected system model.

Next Chapter 5 includes four sections. Research results on the service life of pavements and the influence of RAP are given in section 5.1. Section 5.2 gives the results of the research on transport distances, both for the delivery of raw materials to the asphalt plant and for the transport of the asphalt mixture from the plant to the road worksite. The effect of using RAP on the moisture content in aggregates and on the energy consumption at the asphalt plant is investigated in section 5.3. Final section 5.4, gives the results of the environmental assessment for the Flemish sector.

Chapter 6 includes the main conclusions of the research and the answers to the research questions.

Finally, Chapter 7 contains recommendations addressed to research institutes, authorities, and contractors and asphalt producers.

Part II in this thesis includes the full version of the eight selected articles.

Additional background information is included in different appendices.

2 ANALYSIS OF CURRENT PRACTICE AND GAP ANALYSIS

There is a growing environmental awareness in the last few decades, among which targets for sustainable growth by 2020. The Kyoto Protocol was adopted and signed in 1997 and sets binding obligations on industrialized countries to reduce greenhouse gas emissions. At this occasion, the European Union emissions trading system (EU ETS) was introduced in 2005. The EU ETS works based on the "cap and trade" principle (see paper I) and thus emission allowances are subjected to a market price. This leads to a correlation between environmental and economic issues. Energy-intensive industrial installations and the electricity sector are obliged to monitor and report CO_2-emissions from fuel combustion. 13 Flemish asphalt plants have been subjected to this EU ETS since 2013. The allocation of free allowances (distributed by the EU) gradually decreases and in 2015, allowances allocated were only 79% of the allowances allocated in 2013 and will further reduce to 33% in 2020. The total emission permits (both the free allocated and the tradeable) of the 13 plants together have decreased by 10% in 2015 compared to that in 2013, while the asphalt production by the COPRO-certified plants increased by 2.4% from 2013 to 2015 (COPRO, 2016b, 2014). 12 of the 13 Flemish asphalt production plants subjected to the EU ETS are COPRO-certified. It is hence seen that the desired effect of reduced CO_2-emissions is achieved in practice as a consequence of environmental beneficial measurements implemented at the asphalt production plants.

A new international climate convention has been signed by 195 countries and the EU at 12 December 2015 at the 21st session of the Conference of the Parties (COP 21) in Paris. The Paris Agreement sets new targets to reduce CO_2-emissions and limit global warming for the 21st century.

Triggered by economic benefits, some technologies such as warm mix asphalt production and the use of RAP were introduced in the bituminous road pavement sector earlier, and are nowadays considered to have also a beneficial impact on the environment. Both these technologies and the possibilities for the government to reduce the environmental impact of bituminous road pavements in Flanders are discussed in the next section.

2.1 Possibilities to reduce the environmental impact

In this section, the possibilities to reduce the environmental impact in the Flemish bituminous road sector are discussed. Paper I addresses the possibilities for the industry and paper II describes an approach applied by the government.

Paper I is an extensive literature review concerning the different approaches applied in the Flemish asphalt sector for reducing the environmental impact of bituminous road pavements. In paper I, the focus is set on the three main pillars as presented in Figure 2: (1) increasing the service life of road pavements, (2) reducing the virgin material consumption, and (3) reducing energy consumption. The technique itself and how it is applied in Flanders are described, and the potential reduction of the environmental impact induced by the technique is analysed based on LCA results.

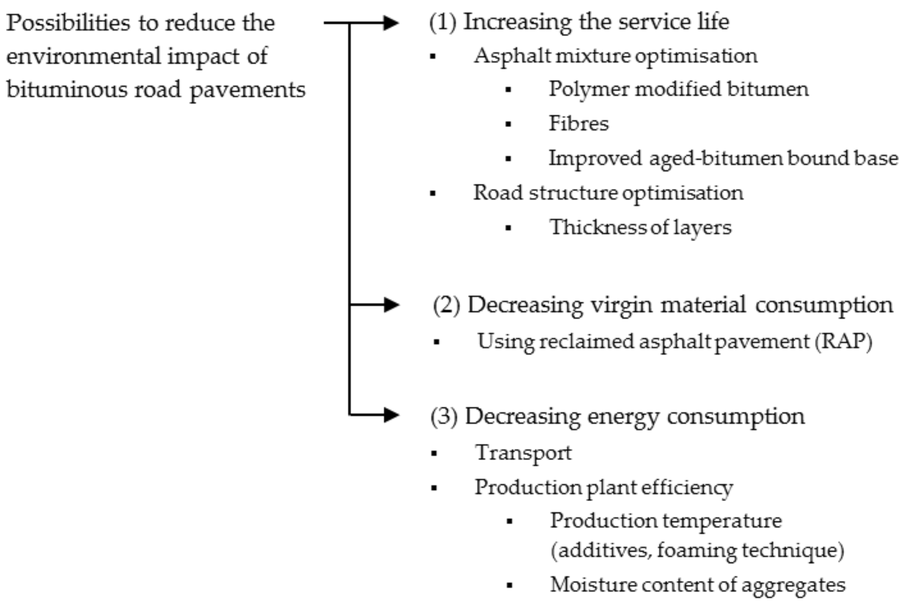


Figure 2: Schematic presentation of main topics to reduce the environmental impact, included in literature review (paper I)

Main conclusions paper I

Various studies in literature state that, irrespective of the asphalt mixture used, the durability of the asphalt pavement significantly affects the total environmental impact. Further research on the service life of pavements is recommended for an adequate inclusion in LCA.

According to literature, the use of RAP in new asphalt mixtures yields significant environmental advantages due to virgin material savings and reduced transport distances.

Concerning WMA, the adopted production technology is a determining factor for the environmental impact. Besides, there is not much practical experience with the WMA production and the durability of the pavement in Flanders. The burners at the Flemish asphalt plants are at this moment not adjusted for the lower production temperatures.

It is necessary to further investigate on key areas like the moisture content in virgin and recycled aggregates, the effect of storage under a shelter, and the influence of both the moisture content in aggregates and the use of a parallel drum on the energy consumption for asphalt production.

As described in paper I, based on the results reported in literature (Rubio et al., 2013; Ventura et al., 2009), the stack emissions during asphalt production depend, amongst others, on the burner adjustment. Results of stack emission measurements in two Flemish asphalt plants are analysed. These data are confidential. Despite the small number of measurements, it was found that the CO-emissions (mg/m_0^3) during WMA production tend to be higher compared to the emissions during HMA production.[2] Since the fine tuning of the burners in the drums influences the CO-emissions, the results might be explained by the fact that the Flemish asphalt plants are currently not designed for WMA production. The burners have a higher thermal capacity, designed for HMA production. However, there are other parameters influencing the CO-emissions: geometry, position and wear of the drums, particulate matter in aggregates, and moisture content in the aggregates.
Due to a lack of an extensive practical experience, other benefits from WMA described in literature cannot yet be validated for the Flemish sector, for example: up to 35% reduced energy consumption, increased RAP content in WMA, improved

[2] It is important to note that CO is not the sole emission. The single score environmental impact of 1 g SO_2 is almost 30 000 times higher compared to the impact of 1 g CO (ecoinvent v3.1, allocation, recycled content, ReCiPe Endpoint H/A v1.12). No trend is found in the SO_2-emissions when comparing WMA with HMA production. SO_2-emissions are currently mainly associated with the sulphur content in fuel, not with the burner adjustment. SO2-emissions from natural gas combustion are low compared to fuel combustion.

workability and compaction efficiency, and quicker turnover to traffic due to shorter cooling time (D'Angelo et al., 2008; Mallick et al., 2008; Rubio et al., 2012).

Paper II describes the Flemish pilot project Carbon Free-Ways that was a first scoping exercise from ART towards the implementation of green public procurement (GPP) in road work tenders. It was concluded by ART that the methodology of the pilot project Carbon Free-ways is not applicable on a regular basis due to various reasons:

- the work load and costs for ART are too high;
- the system boundaries of the study induced increased environmental impacts behind the scope of the study (i.e. transport);
- and including only economic and environmental parameters can negatively affect the durability.

Nevertheless, the project is a first, important attempt and considered useful for further investigating the possibilities to approach to GPP in the public road sector. Different approaches are possible: (1) a detailed analysis of a few large road works each year, (2) implementing some standard sustainability parameters in each tender, or (3) evaluation of the asphalt plant instead of the road work. A work group was created in 2016, led by BRRC with members from different organisations in the sector from the three Belgian regions, aiming to further investigate the possibilities concerning GPP.
In June 2016, the European Commission published EU GPP criteria for road design, construction, and maintenance and a draft version of the "procurement practice guidance document" (European commission, 2016; Garbarino et al., 2016). The EU GPP criteria state that a life cycle assessment is preferred over a carbon footprint analysis, but an LCA is associated with a higher technical complexity (European commission, 2016). Two other EU GPP award criteria address specific phases in the life cycle of a road and are hence less technically demanding: using recycled and re-used content, and reducing emissions from heavy transport. However, important to note, if a contracting authority decides to reward the two latter criteria, it shall consider setting criteria that take into account the specific conditions in the local market for construction materials (European commission, 2016).

Currently, the analysis of the environmental impact of a product, process, or service is often limited to the analysis of CO_2-equivalent emissions related to the presumed climate change impact e.g., EU ETS. However, carbon footprint itself cannot justify environmental sustainability (European Committee for Standardization, 2012; European Union, 2013). Therefore, it is necessary to investigate a larger number of

environmental impact categories. Besides, the analysis of only one life cycle phase of a product, e.g. the asphalt production process, is an incomplete analysis. A shift of environmental impacts from one phase to another is not captured in such analysis (e.g. WMA additives with high environmental impact (Vidal et al., 2013)).
Life cycle assessment is seen as the appropriate method to assess the environmental impact of products, processes, or services. It allows including different life cycle phases and multiple environmental impact categories. The environmental issues included in the analysis are determined by the selection of the life cycle impact assessment method. Ideally, all processes associated with a product, from raw material extraction to the end-of-life (EOL) disposal (cradle-to-grave) are included.

The numerical results of the environmental assessment of the pilot project as described in paper II are presented and discussed in paper III. The climate change impact based on CO_2-equivalent emissions is compared to the results of an assessment that takes into account multiple environmental impacts. The main goal of the LCA case study is to analyse in which way the used method in the pilot study (CO_2-emissions calculated with the Carbon Counter) is representative for the assessment of the environmental impact.
The results reveal clearly that taking into account only CO_2-emissions leads to a significant underestimation of the full environmental impact by excluding impact categories such as fossil depletion, particulate matter, land transformation, human- and ecotoxicity, ionising radiation, eutrophication, etc. Climate change is not the dominant impact factor in bituminous pavement LCA. It is seen in this case study that fossil depletion has a major contribution to the single score impact. The fossil depletion impact mainly stems from the raw material bitumen and transport processes by lorry. Moreover, in a comparative study, the ranking of products can differ if a single environmental impact is considered (i.e., climate change) compared with an assessment including multiple environmental indicators. This is seen in the results, calculated with SimaPro: the climate change impact of transport processes is higher than the climate change impact of materials (Figure 50, p.204), but the single score environmental impact of materials is higher compared to the single score environmental impact of transport (Figure 53, p.206).

2.2 Focus of the study determined by preliminary research

Paper IV presents the results of an LCA case study comparing four surface course test sections: (1) HMA, (2) cold asphalt mix with emulsion, (3) WMA with a synthetic zeolite, and (4) WMA with an organic Fischer-Tropsch wax. Analysis of the baseline scenario highlights that the life cycle impact of the pavement depends on the type of additive (see Figure 58, p.223) and the service life (see Figure 65, p.229). From the results of this analysis, no preference can be given to either HMA or WMA. The contribution analysis of the baseline scenario shows that the production of bitumen, transport processes, and energy for heat mainly contribute to the total environmental impact (see Figure 60, p.226). More information on the life time of different asphalt pavements is necessary for accurate LCA results.

Paper V presents the results of an LCA case study comparing (1) a reference HMA (REF), (2) a WMA, and (3) a HMA with RAP. The three asphalt mixtures have similar gradation and composition and hence only the influence of a reduced production temperature and the use of RAP is investigated. Compared to the used additives for WMA production in paper IV, this paper analyses the WMA production with bitumen foaming by injecting water. Only the latter WMA production technique is applied in Flanders. Cradle-to-gate analysis of the baseline scenario highlights that the mixture with RAP has a significant lower impact compared to REF and WMA (see Figure 67, p.243). Mainly the production of bitumen, the transport of raw materials to the asphalt plant, and the energy for drying and heating aggregates contribute to the total environmental impact (see Figure 68, p.245).

The results of the three preliminary LCA case studies (paper III-V, see also section 2.1) are only representative for these particular cases due to the specific LCI data used. Generalisation of these results for the Flemish situation is not possible. However, similar trends are found in the different case studies and the results set the focus for the following part of this research.
It is concluded in both paper I and paper V that using RAP is more effective to reduce environmental impact compared to WMA techniques. Besides, the durability is unknown due to the little practical experience in Flanders, and the reduction of energy consumption and emissions could not be measured in practice. The little practical experience makes it impossible to obtain statistically significant results. Therefore, WMA is not included further in this research.
The importance of the service life of the pavement, influencing the LCA results is emphasized by both papers IV and V (Figure 65, p.229 and Figure 74, p.251), and the findings from the literature review (paper I in section 2.1).
The results presented in paper III-V show that the used environmental data source influences the results (Figure 50, p.204, Figure 62, p.228, and Figure 69, p.247). This

strongly indicates the importance of verifying the relevancy of data in existing LCI databases for the particular circumstances of a research and the goal setting of the underlying project.
The three LCA studies indicate the same major contributors to the environmental single score impact: the production of bitumen (55 to 67%), the transport processes (13 to 38%), and the energy consumption for drying and heating aggregates (7 to 25%).

Similar results were found in literature:
"*The environmental performance of asphalt recycling is very sensitive to transportation distances, hence the comparisons that can be done are very site specific.*" (Miliutenko et al., 2013)
"*The main environmental impacts arise from daily traffic (fuel consumption by cars and heavy trucks) during the use phase of a road. … The road life cycle stage with the second largest environmental impacts is indicated to be the construction phase, in which the hot-spots are related to the resources used and the emissions and ecosystem impacts associated with materials production, including extraction and transportation. … If a contracting authority decides to reward recycled or re-used content or reduced transport emissions, it should consider setting criteria that take into account the specific conditions in the local market for construction materials.*" (European commission, 2016)

Based on these findings, the current research focuses on three important topics

- service life of bituminous pavements;
- transport processes;
- and energy consumption for drying and heating aggregates;

which are quantified in this research in order to be able to use them in the calculation of the environmental impact of bituminous road pavements with and without RAP in Flanders.

2.3 Conclusions and gap analysis

Research on the environmental impact of bituminous road pavements was found in literature, however, local context influences the results. First example: different recycling techniques exist. All asphalt plants in The Netherlands are fit for hot and warm recycling, while less than 5% of the asphalt plants in Norway are (European Asphalt Pavement Association, 2015). The applied technique and plant infrastructure (batch, drum mixer, parallel drum) influence the energy consumption for asphalt production with RAP. Another example: the area of a region or country may affect the asphalt production process. Belgium covers 30 528 km² for 38 stationary asphalt production plants in 2014, while for France 50 stationary and 23 mobile plants are distributed over 551 500 km² (European Asphalt Pavement Association, 2015). The use of mobile asphalt production plants reduces the cumulated transport distance between the asphalt plant and the road construction site.

At this moment it is not possible to give a well-founded answer on the question: "Is the current practice of using RAP having a beneficial effect on the environmental life cycle performance of bituminous pavements?" This is a problem for the Flemish road sector with regard to the general aim for sustainable development. A specific and detailed environmental assessment is lacking and therefore it is unsure which processes are suited for ecological optimization.

The main gap is the environmental assessment of using RAP according to the current practice in Flanders. Furthermore, specific, quantitative information on service life, transport processes, moisture content, and energy consumption is missing in literature. Continuous monitoring of these aspects is not common practice in the Flemish asphalt sector. Besides, asphalt mixture compositions, emissions measurements etc. are trade secrets. Publicly available data are sometimes outdated or do not reflect the current technologies in a specific region. Hence, the data collection for the purpose of this environmental assessment is also an important research gap.

3 OBJECTIVES AND SCOPE

3.1 General

The objective of this research is to give a scientifically based answer on the following, main research question: Is the current practice of using RAP having a beneficial effect on the life cycle performance of bituminous pavements in Flanders?

The results of an environmental assessment are influenced by geographical and case specific parameters such as applied techniques, available infrastructure, distances, legislation etc. The scope of the present research will therefore be limited to Flanders. As described in the gap analysis (section 2.3), similar research for the Flemish situation was not carried out before. As a first step, it is therefore necessary to develop a reference frame or a so called benchmark for the current practice, before further research can be introduced i.e. on the environmental assessment of future developments. Hence, the study focuses on the current practice of using RAP in the bituminous road sector in Flanders by using information and data from the period 2013-2016. The scope of the study is limited to paving works at public roads (see section 1.1). Private asphalt mixtures are hence outside the scope of the current research. Since RAP is currently not allowed in asphalt mixtures for surface courses according to SB250 v3.1, the research focuses on base courses. Table 2 presents the annual asphalt production by COPRO-certified plants in 2014. 1.37 million ton asphalt is applied for base courses in public road works. This is 41% of all asphalt produced by COPRO-plants.

Table 2: Annual asphalt production in 2014 subdivided according to application

total asphalt production in 2014 (ton)				**3.311.838**
not applied for road construction (ton)			75.529	*2%*
applied for road construction (ton)			**3.236.309**	*98%*
private (ton)		650.248	*20%*	*20%*
registered SB250 (ton)		**2.586.061**	*80%*	*78%*
surface (ton)	1.141.566	*44%*	*35%*	*34%*
base (ton)	**1.373.970**	*53%*	*42%*	*41%*
other (ton)	70.525	*3%*	*2%*	*2%*

References: (COPRO, 2015a)

Excluding surface courses also induces that certain impacts in the use stage of the pavement are outside the scope of the present research e.g., impacts related to the pavement-vehicle interaction, albedo, lighting etc. since these are influenced by the surface course of the pavement. The present study mainly focuses on processes at the level of the industry, which can be adjusted or improved by the industry for decreasing the environmental impact.

The goal of sustainability encloses the triple bottom line, concisely described by People-Planet-Profit. The scope of the current research is limited to the sole aspect, Planet, representing the environmental and ecological framework. It is recognized that also the social (e.g., fair trade) and financial aspects must be included in a full sustainability assessment. A life cycle cost (LCC) analysis and a social LCA are outside the scope of this research, but useful methods to apply in further research.

In addition to the main research question, some sub questions represent the objectives of the research. Are there other techniques or processes, besides using RAP, with a higher potential to decrease the environmental impact of bituminous road pavements? Which processes or materials are the main contributors to the environmental impact?
The results of the research will apply across limited stretches of time since updated versions of SB250 induce new regulations influencing the current practice. Since this research is specific for the Flemish sector, it is recognized that the results obtained from this research are not generally applicable for other regions. The results are relevant for the Flemish asphalt producers, who might consider some possibilities for environmental impact reduction. The Agency for Roads and Traffic of the Ministry of the Flemish Community (ART) can use the results as a benchmark, to conduct further research for the implementation in green public procurement (GPP) and development of new legislation. Furthermore, other researchers can use the methodology and results for comparison.

Different standards and guidelines describe the approach for environmental assessment. Different modelling approaches can significantly influence the results. What is the appropriate approach for modelling the environmental analysis of bituminous road pavements with use of RAP?
The results of this research sub question are significant for practitioners of environmental assessment. Results of this research question will importantly contribute to better understanding appropriate modelling approaches for environmental assessment of bituminous road pavements. Provided some adjustments, the modelling approach might also apply for other research subjects. The results will be universal applicable across long stretches of time.

Besides, a chapter with recommendations addressed to the different stakeholders in the Flemish bituminous road sector is considered to be an important objective of the present applied study.

The three research topics defined in section 2.2 (service life of pavements, transport processes, and energy consumption for asphalt production) are expected to be influenced by the use of RAP and can therefore be seen as important parameters for the environmental assessment. The scope of these three research topics is the same as the general scope of the research: Flanders, current practice represented by information and date from 2013-2016, base layers, public road works, and maintenance interventions. The objectives of these three research topics are presented in the following sections. It mainly involves the collection of accurate data in the scope of the current research. These technical results are used for the environmental assessment of using RAP.

3.2 Service life of bituminous road pavements

The objective of this research topic is to define a service life of pavements and the effect of using RAP in asphalt mixtures in base courses on the service life of pavements. The service life of bituminous road pavements significantly influences the life cycle environmental impact (see paper I).
It is expected that there is an influence on the service life of pavements when using RAP instead of exclusively virgin raw materials. However, the use of RAP in asphalt mixtures is not new and the composition of mixtures with RAP can be adjusted in order to reach equal performance characteristics. The effect of using RAP on the mixture composition (e.g. bitumen content in the mix) is also investigated since the environmental impact of virgin bitumen is high (see Figure 29, p.94). An increased virgin binder content might hence importantly affect the environmental impact.

3.3 Transport distances

The goal is to quantify the transport distance for the delivery of raw materials to the asphalt plant and the road transport distance between the asphalt plant and the road worksite. The influence of using RAP on the transport distances is investigated as well. Is the transport distance for the delivery of RAP to the asphalt plant significantly different from the delivery of virgin raw materials? Transport distances importantly vary from one region to another. When including RAP in the asphalt mixture, transport processes in the life cycle are influenced since less raw materials need to be transported to the plant. This research topic mainly involves the collection of appropriate data to be used in the environmental assessment.

3.4 Moisture content and energy consumption

The objectives of this research topic are to quantify the moisture content in virgin and recycled aggregates, quantify the energy consumption for asphalt production at the plant, and assess the effect of using RAP.

Moisture content is a parameter that influences the energy consumption for drying and heating. It is found in literature that the moisture content in RAP is higher compared to the moisture content in virgin aggregates since the milling machine for removing the old pavement is cooled, using water. The virgin aggregates used in asphalt production for Flemish public road works are washed in order to remove small particles. Therefore, both virgin and recycled aggregates are wet when delivered to the asphalt plant. The effect of both washed virgin aggregates and a shelf to protect stored aggregates from rain is unknown and needs further investigation in relation to the moisture content in aggregates.

It is found in literature that the energy consumption for asphalt production is higher when RAP, preheated in a parallel drum, is used in the mixture (see paper I (van den Berk, 2004)). This is an important parameter to be further investigated in situ at Flemish asphalt plants.

3.5 Overview research questions

The research questions as formulated in the previous sections are numbered, grouped, and structured below. Typically there is a main research question for a particular research topic with some sub questions supporting the main question. All research questions concern the Flemish practice.

1. What is the service life of pavements and the effect of using RAP in asphalt mixtures in base courses on the service life of pavements?
    - 1.1. Are performance characteristics of asphalt influenced by the use of RAP?
    - 1.2. Is the mixture composition (e.g. total bitumen content in the mix) adjusted when RAP is used?
2. Are transport processes for the delivery of raw materials to the asphalt production plant influenced by the use of RAP? In other words: Is the transport distance for the delivery of RAP to the asphalt plant significantly different from the delivery of virgin raw materials?
    - 2.1. What are the transport distances for the delivery of virgin raw materials to the asphalt production plant?
    - 2.2. What is the transport distance between the asphalt production plant and the road worksite?
    - 2.3. How is the real practice compared to the theoretical optimal situation for transport distance between plant and road worksite?

3. What is the energy consumption for asphalt production at the plant?
   3.1. Is the moisture content in aggregates affected when stock piled under a shelf?
   3.2. Is the moisture content in recycled aggregates higher compared to virgin aggregates?
   3.3. What is the effect of using RAP on the energy consumption for asphalt production?
4. Is the current practice of using RAP having a beneficial effect on the environmental life cycle performance of bituminous pavements?
   4.1. What is the appropriate approach for modelling the environmental analysis of bituminous road pavements with use of RAP?
   4.2. Which processes or materials are the main contributors to the environmental impact?
   4.3. To what extent do transport processes contribute to the environmental impact?
   4.4. To what extent does energy consumption contribute to the environmental impact?
   4.5. To what extent is the environmental impact influenced by the service life of pavements?
   4.6. Are there other techniques or processes besides using RAP, with a higher potential to decrease the environmental impact of bituminous road pavements?

4 RESEARCH APPROACH AND METHODOLOGY

4.1 Research approach

As described in chapter 2, results of a preliminary study determine the focus and scope of the further research (see Figure 3). This preliminary research includes a literature review and some case specific LCA calculations.

Paper I summarizes the literature review, describing different technologies that potentially reduce the environmental impact and the results of LCA studies on these technologies. The main focus is set to aspects related to the industry: (1) reusing reclaimed asphalt pavement, (2) reducing the asphalt production temperature, and (3) prolonging the service life of pavements. The results are described in section 2.1. Three case-specific LCA calculations are incorporated in papers III-V and described in sections 2.1 and 2.2. These LCA studies aim to (1) determine the main contributors to the environmental impact, (2) define lacks in available data, and (3) explore different LCA modelling possibilities. The case studies contain the construction of different Flemish road test sections.

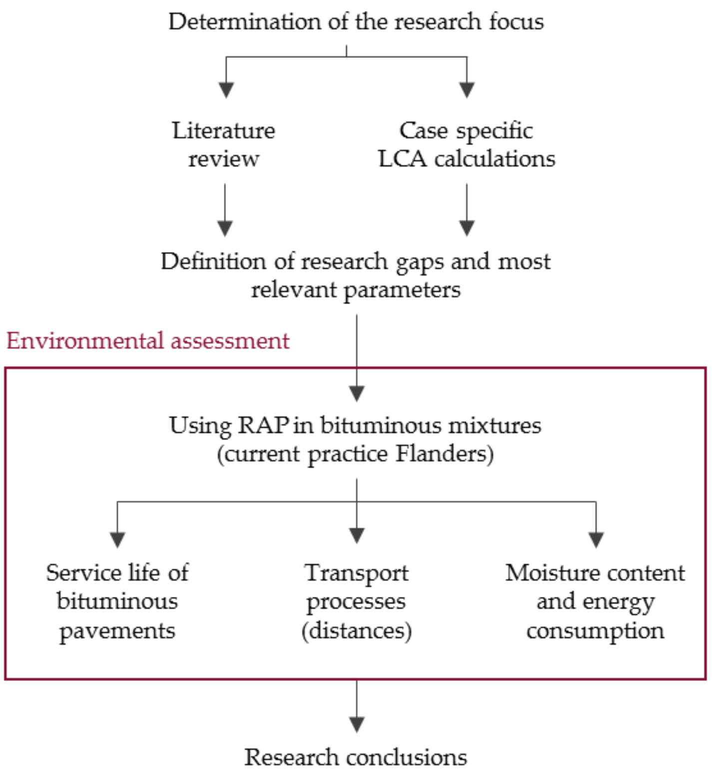


Figure 3: Research approach

The preliminary research ascertained the main focus of the study, being the environmental assessment of using RAP in bituminous mixtures according to the current practice in Flanders (described in chapter 3). Three important research topics, selected from the results of the preliminary research, mainly involve important data collection within the scope of the current research. The technical research results of the three topics contribute to the exploration of different scenarios used in the environmental assessment.

Difficulties in environmental assessment of bituminous pavement are related to the complexity of the asphalt sector and the variability in numerous related parameters (paper IV). Firstly, the complexity of the asphalt sector and the variability in different parameters is avoided by choosing specific case studies in a preliminary research (papers III-V). Secondly, these complexities and variabilities are further investigated for a number of selected processes (sections 5.1 to 5.3).

4.2 Research methodology

Life cycle assessment methodology is applied for the environmental assessment. The various LCA case studies included in papers III-V have different goal and scope definitions and hence different LCA methodological choices are made. Different versions of software, dataset, and impact assessment method are used as well. The version is reported where appropriate. In §4.2.1.1 and §4.2.1.2, the general LCA methodology and the methodological choices as applied in the final LCA study are described and where appropriate compared with the preliminary research.
The SimaPro software version 8.1, developed by PRé-consultants BV in the Netherlands, is used for LCA calculations.
Data collection is an important part of life cycle assessment studies. The general methodology applied for data collection and data analysis in this thesis is described in the following paragraphs.

Personal communication (interviews) with experts from different institutions, agencies, and companies is often used in the current research. The current study is applied for a specific Flemish sector and hence the validity of information in international literature must always be verified with the current research scope. In the first stage of the research, personal communication with experts helped to obtain a clear impression of the operation of the Flemish asphalt sector. These experts also importantly contribute to the collection of crucial information and data.
Despite the regional scope of the study, the international literature remains as an important research source. A review of the international literature is applied multiple times in order to explore the different research topics and to compare own

results with published results. A variability of resource types is referred to: academic and scientific literature (PhD thesis (Butt, 2014), journal papers (Giani et al., 2015), conference proceedings (Leroy et al., 2012)), reports describing results of applied research (Wayman et al., 2012), sector reports (COPRO, 2015a), software manuals (Goedkoop et al., 2016), and standards (European Committee for Standardization, 2012; International Organization for Standardization, 2006a).
The working range of certain institutions (i.e., COPRO, EAPA, and ENTSO-E) goes beyond the Flemish region. Therefore, data exclusively representative for Flanders are not always available or calculable. However, the aim is to use only data that are the most representative and the used data source will be reported for all calculations. At the time of calculating, the most recent data published by both COPRO and EAPA were dealing with the year 2014. It is aspired to use data for 2014 or more recently dated for making a representative analysis of the current real practice. Besides, measurements and data collection in situ are part of the research and essential to compile a representative dataset.

Statistical analysis is applied for large datasets. The IBM SPSS Statistics 23 software is used. A wide range of different analysis techniques and tests are used for statistical analysis. The used statistical test is always mentioned in the particular section of the thesis and more information on these tests and the preconditions to select particular tests is given in appendix 1.

4.2.1 Life cycle assessment

4.2.1.1 General

The first international standard on LCA was published in 1997 by the International Organization for Standardization (ISO). Currently, the ISO series on LCA includes ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework and ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines (International Organization for Standardization, 2006a, 2006b). The life cycle assessment framework consists of four stages that are described in this subsection (International Organization for Standardization, 2006a) (paper IV).
Another series of standards is written by the technical committee CEN/TC 350 and describes standardised methods for the assessment of the sustainability aspects of construction works, including environmental product declaration (EPD) for construction products. The standard EN 15804 is used as a guideline in the current research (European Committee for Standardization, 2012). However, in some points, the applied methodology for environmental assessment in this research deviates from the standard (see §5.4.3.2).

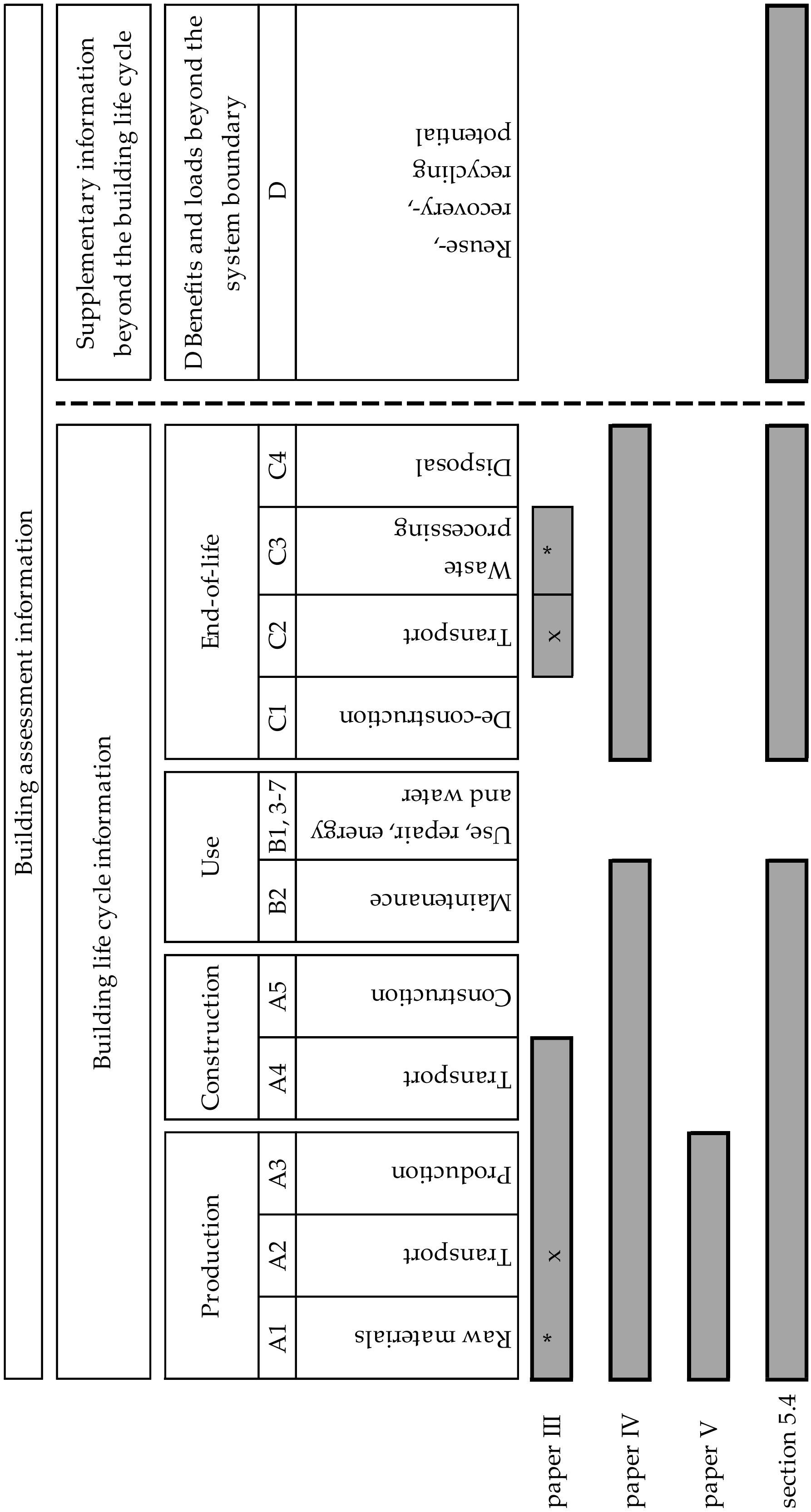


Figure 4: Comparison of LCA calculations in preliminary research and final LCA in the scope of this research.
** = deviation with LCA methodology related to impact for materials; x = deviation with LCA methodology related to transport processes*

Stage 1: goal and scope definition of the LCA study. A common pitfall when trying to implement an LCA is the lack of a clear purpose and intended application of an LCA (Goedkoop et al., 2016). For performing an LCA, a product, service, or system life cycle has to be modelled. It is important to realize that a model is a simplification of a complex reality and as with all simplifications this means that the reality will be distorted in some way. The challenge is to develop the model in such a way that the simplifications and distortions minimally influence the results. The best way to deal with both problems is to carefully define the goal and scope of the LCA study. Defining the goal includes a description of both the application and intended audiences, and the reasons for carrying out the study (Goedkoop et al., 2016). The scope of the study consists of the most important methodological choices, assumptions, and limitations e.g., functional unit (FU) and reference flow, system boundaries, thresholds for inclusion of inputs and outputs, and type of allocation (Goedkoop et al., 2016).

For road pavements, the most common system boundaries of an LCA study are (paper VIII):

- Cradle-to-gate: all impacts until the asphalt mixture reaches the gate of the asphalt plant (paper V, (Blomberg et al., 2012));
- Cradle-to-laid: variant of cradle-to-gate specific for road pavements; all impacts until the road is constructed (Huang et al., 2012);
- Cradle-to-grave: all impacts until the road reaches end-of-life (paper IV, (Hoang et al., 2005));
- Cradle-to-cradle: all impacts, including the reuse, recovery and/or recycling potential (Silvestre et al., 2014).

Figure 4 gives an overview of the system boundaries of all LCA calculations included in the current research. The grey beams indicate the life cycle stages that are included in the different studies. The structure of Figure 4 is based on Figure 1 in standard EN 15804. The preliminary LCA case study in paper III follows the specific system boundaries of the pilot project. The asterisks (*) and 'x' for paper III indicates a deviation from the LCA methodology as described in this chapter[3]. The LCA in paper IV is a cradle-to-gate study with options of a pavement with different WMA mixtures. Similar as the LCA calculation in section 5.4, the maintenance of the pavement is included, but any other process related to the use phase (stage B in

[3] The LCA study in paper III includes the impact from crushing and sieving RAP in life cycle stage A1, while the recycled material RAP should be burden free included according to the cut-off methodology (see paper VIII in §4.2.1.2). However, in the LCA study elaborated in section 5.4 of the thesis, the impact from life cycle stage C3 only accounts for 1.5%, so the influence from this modelling deviation on the LCA results is small.

EN 15804) is not included in the study. Paper V is a preliminary LCA case study with a typical cradle-to-gate system boundary. Finally, the LCA study in section 5.4 of this research also includes the supplementary information in module D as recommended by the standard EN 15804 (European Committee for Standardization, 2012). More information on this module D is given at the end of §4.2.1.2.

The goal and scope of the final LCA calculation in this research are described in section 5.4.

Stage 2: life cycle inventory. This second step is the data collection and is often considered to be the most demanding part of the LCA. It includes both the data collection and a detailed description of the used data. Both quantitative and environmental data are necessary to develop a life cycle inventory (LCI). A distinction between foreground (or primary) and background (or secondary) data is often made (European Union, 2013; Goedkoop et al., 2016; Ingwersen and Subramania, 2013; Miliutenko et al., 2013). Foreground data are related to core processes in the product life cycle for which direct access to information is available e.g., from measurements. Background data are related to the processes in the product life cycle that are more generic and for which no direct access to information is possible.
Data that are measured and calculated in this research and described in sections 5.1 to 5.3 importantly contribute to the general life cycle inventory as part of the foreground data. Environmental background data are mostly taken from an existing database. The ecoinvent 3.1 database is mostly used and is included in the SimaPro software. Ecoinvent is an international life cycle inventory database for energy systems, materials, transports and chemicals. More information on the LCI for the final LCA is included in subsection 5.4.3.

Stage 3: life cycle impact assessment. The first step in the impact assessment is selecting appropriate impact categories (see Figure 5). An impact category is a "*class representing environmental issues of concern to which life cycle inventory analysis results may be assigned*" (International Organization for Standardization, 2006a). Once the impact categories are defined and the LCI results are assigned to these impact categories (classification), it is necessary to define characterization factors. This is the last obligated step in an LCA study according to the standards.

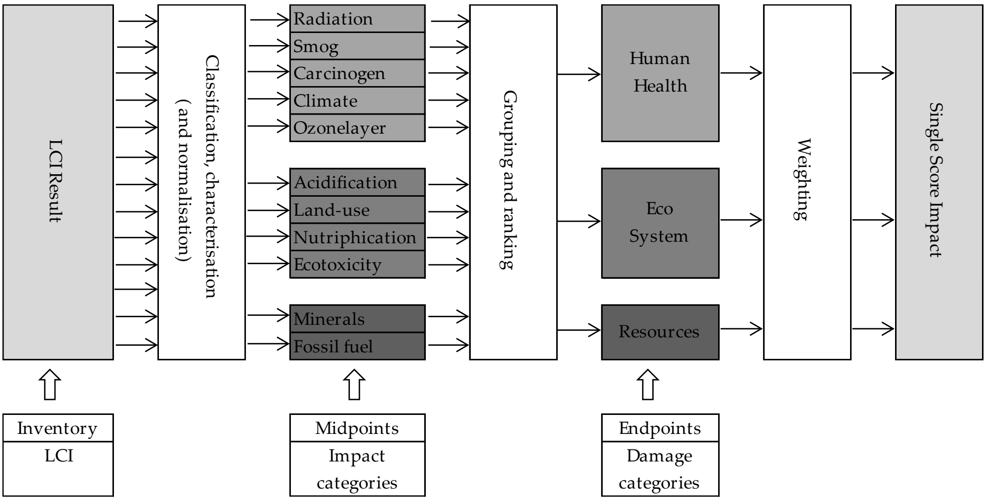


Figure 5: Life cycle impact assessment methodology

Characterization factors reflect the relative contribution of an LCI result to the impact category. For example, on a time scale of 100 years the contribution of 1 kg CH_4 to global warming is 25 times as high as the emission of 1 kg CO_2. This means that if the characterization factor for global warming of CO_2 is 1, the characterization factor for global warming of CH_4 is 25. Multiplying the inventory result by the characterization factor gives the impact category indicator. Characterization uses science-based conversion factors, numerous of them were found through European research (Scientific Applications International Corporation (SAIC), 2006). An optional step to generate midpoint or endpoint results[4] is the use of normalization. This is a procedure to show to what extent an impact has a significant contribution to the overall environmental problem in a defined region (e.g. Europe) for a specific impact or damage category. Normalization is performed by dividing the impact or damage category indicators (at the midpoint or endpoint level respectively) by a ‘’normal” value. The most common procedure to define the ‘’normal” value is the determination of the impact or damage category indicators for a region per year and, if desired, divided by the number of inhabitants in that area. Normalization is used to express the data in a way that can be compared among impact categories. Another optional step to facilitate interpretation of the results is to group and rank the impact category indicators. Impact category indicators that have some common features may be presented as a group. Ranking refers to a procedure, where impact categories are sorted by a panel in a descending order of significance. Afterwards, fate, exposure, and effect steps in modelling are applied to present the results in damage

[4] A midpoint is a problem oriented indicator that is somewhere along the environmental mechanism and the LCI parameter, grouped in impact categories. An endpoint is a damage oriented indicator referring to the final outcome of an environmental mechanism, grouped in damage categories.

categories or as endpoints (Goedkoop et al., 2013). Weighting is the most controversial and most difficult step in life cycle impact assessment (LCIA). However, in the current research, weighing is often applied (paper III, IV, V, VII) by using existing weighting methods since a single score environmental impact simplifies the interpretation of the results in a comparative LCA study.

These different steps are embedded in the LCIA method. Different LCIA methods are developed by various scientific (research) institutions (PRé, 2014). A comparison of LCA results calculated with different LCIA methods is included in paper IV (Table 28, p.230) and paper V (Figure 73, p.249 and Table 30, p.249). Based on the findings in paper III, as described in chapter 2, it is concluded to include multiple impacts in the environmental assessment instead of including only global warming potential. ReCiPe is chosen as LCIA method. ReCiPe provides a recipe to calculate life cycle impact category indicators and the acronym represents the initials of the institutes that were the main contributors to its development and design (RIVM and Radboud University, CML, and PRé). The regional validity is for Europe. The environmental impacts that must be included in an Environmental Product Declaration according to EN 15804:2012 (European Committee for Standardization, 2012) are included in ReCiPe. Besides, it implements both midpoint (impact categories) and endpoint (damage categories) results, with the possibility for normalisation on both categories. Normalisation at the global and European level are included in ReCiPe as described by Sleeswijk and the figures used in SimaPro are recalculated per citizen (PRé, 2014; Sleeswijk et al., 2008). Environmental impacts calculated with ReCiPe Endpoint are dimensionless figures, but expressed in points (pt). With regard to calculating a single score impact from the three damage categories, ReCiPe Endpoint contains a set of weighting factors determined by a panel. The ReCiPe LCIA method is developed according to three different perspectives. The default perspective is the hierarchist, based on the most common policy principles with regards to time frame (100 years) and other issues. The individualist perspective takes into account a short time frame (20 years) and the egalitarian perspective takes into account a long time frame (500 years). Both the normalization and the weighting indicators change with the selected perspective.
The hierarchist ReCiPe version 1.12 with European normalization and average weighting set was chosen. In this LCIA method, the weighting indicators for damage categories human health, ecosystems, and resources are respectively 400, 400, and 200. More information about the chosen LCIA method can be found in literature (Goedkoop et al., 2013; PRé, 2014; Sleeswijk et al., 2008). Both midpoints and endpoints are used to present the results in section 5.4.

Stage 4: interpretation. This is the last of the four steps in an LCA and includes a number of checks on the reliability of the results: uncertainty analysis, sensitivity analysis, contribution analysis and inventory analysis (Goedkoop et al., 2016). In the current research both contribution and sensitivity analysis are included and a baseline scenario is defined to distinguish between the original case study and other scenarios with different assumptions on some parameters as applied in sensitivity analyses.

4.2.1.2 LCA modelling approaches

Kluts and Miliutenko, and Stripple and Erlandsson presented three decision stages in the road infrastructure planning: (1) network level: choice of transport modality at the national level, (2) corridor level: choice of localization and construction type of a specific project, and (3) project level: choice of specific design (Kluts and Miliutenko, 2012; Stripple and Erlandsson, 2004). Kluts and Miliutenko mention that it is likely to use one single environmental assessment process to evaluate both the second and third decision level. Based on this idea, Butt et al. suggested a framework including two complexity levels (network and project level) and two decision situations (early planning and late planning/design) (Butt et al., 2015). The decision level and the goals of the study determine the selection of a certain LCA approach.

In general, two main types of LCA approaches are distinguished: accounting/descriptive type or attributional LCA (ALCA) and change/effect oriented or consequential LCA (CLCA). However, Baumann and Tillman distinguished a third LCA type: Stand-alone LCA (Baumann and Tillman, 2004). These three LCA types are described as follows:

- *"Stand-alone LCA is used to identify the environmental hot spots within a system and it reports the actual environmental declaration of a particular product. It could be used to identify the most energy consuming phase in a road's life cycle."* (Butt, 2014)
- *"Linearly modelled ALCA provides input and output flows attributed (associated) to the delivery of a specified functional unit. It is a comparative approach that could be used as a decision support tool in a network or a project level, depending on how goal and system boundaries have been defined."* (Butt, 2014)

  "Attributional modelling: LCI modelling frame that inventories the inputs and output flows of all processes of a system as they occur. Modelling process along an existing supply-chain is of this type." (European Commission, 2010)
- *"CLCA is appropriate to use when changes within or outside the life cycle are studied by a change within a life cycle system."* (Butt, 2014)

  "Consequential modelling: LCI modelling principle that identifies and models all processes in the background system of a system in consequence of decisions made in the foreground system." (European Commission, 2010)

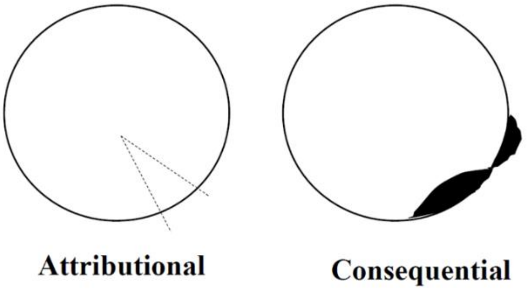


Figure 6: The conceptual difference between ALCA and CLCA (Weidema, 2003)

The stand-alone LCA is always an ALCA.
Figure 6 is often used to present the conceptual difference between attributional and consequential LCA, as published by Weidema. "*The circles represent the total global environmental exchanges. In the left circle, attributional LCA seeks to cut out the piece with dotted lines that belongs to a specific human activity. In the right circle, consequential LCA seeks to capture the change in environmental exchanges that occur as a consequence of adding or removing a specific human activity.*"
In general, ALCA is defined by its focus on describing the environmentally relevant flows within the chosen temporal window (Curran et al., 2005). This is exactly the aim of the current research (see section 3.1). In other words stated: defining the environmental hot spots in the current practice. Therefore, recent, but historical data are used. The consequential LCA on the other hand, aims to describe how environmentally relevant flows will change in response to possible decisions.
There is no prior environmental analysis of the current practice in the Flemish asphalt sector, there is the need to do first a benchmark of the current practice. Therefore, the ALCA modelling approach is the best choice for the current research. Later, another LCA methodology might be applied to assess the environmental impact of future developments.
A stand-alone attributional LCA approach is applied in paper III, while the other are attributional, comparative LCA studies. A comparison between the attributional and consequential LCI was made in paper VII for the Belgian low voltage electricity mix. Buyle et al. compared the results of ALCA and CLCA for a case in the Flemish construction sector (Buyle et al., 2016). It was found that the applied modelling approach importantly influences the results of the environmental assessment, both the absolute values and the ranking of different optimization scenarios.

Especially when analysing life cycle stages with recycling, involving an interaction between different life cycles, a well-considered modelling approach is necessary. It is recognized that the modelling approach in the preliminary LCA studies is not always consistent with the standard EN 15804, as indicated by * and x in Figure 4. The environmental impact of RAP used as secondary raw material in the asphalt mixture (life cycle stage A1) is modelled in different ways:

- a default reduction of the environmental impact from virgin materials in the Carbon Counter tool (paper III);
- environmental impact related to the RAP processing (crushing and sieving) (paper III);
- or a burden free material (paper V).

Two different attributional system models are included in ecoinvent. A system model is a collection of different modelling choices. For further research, the cut-off system model is selected. The cut-off system model is the most basic attributional approach, relevant in a market situation where there is a surplus of recycled material available. The definition of the end-of-life (EOL) and the end-of-waste (EOW) stage is important when modelling in accordance with the standard EN 15804 (European Committee for Standardization, 2012). Paper VIII describes how the cut-off modelling approach is applied for bituminous road pavements, using RAP. The main result of paper VIII is presented and applied in the LCA study in section 5.4.
It is seen in Figure 7 that the environmental impact of virgin materials, various impacts during the life cycle and the impact of the waste treatment are included within the system boundaries. The waste treatment processes (crushing and sieving RAP) are included in life cycle stage C3. After these treatment processes, the EOW stage is reached and the cut-off point in the system model. Any non-waste by-products of a waste treatment are cut off. In this case, the RAP is a non-waste by-product of the sieving and crushing and hence, the EOW defines the point of cut-off. The RAP in the life cycle stage A1 is burden free available to use as a raw material. Besides, the transport of RAP from the road worksite to the asphalt plant is included in C2 and hence, no transport for RAP to the asphalt plant is included in stage A2. The latter inconsistency in preliminary LCA studies is indicated with 'x' in Figure 4.

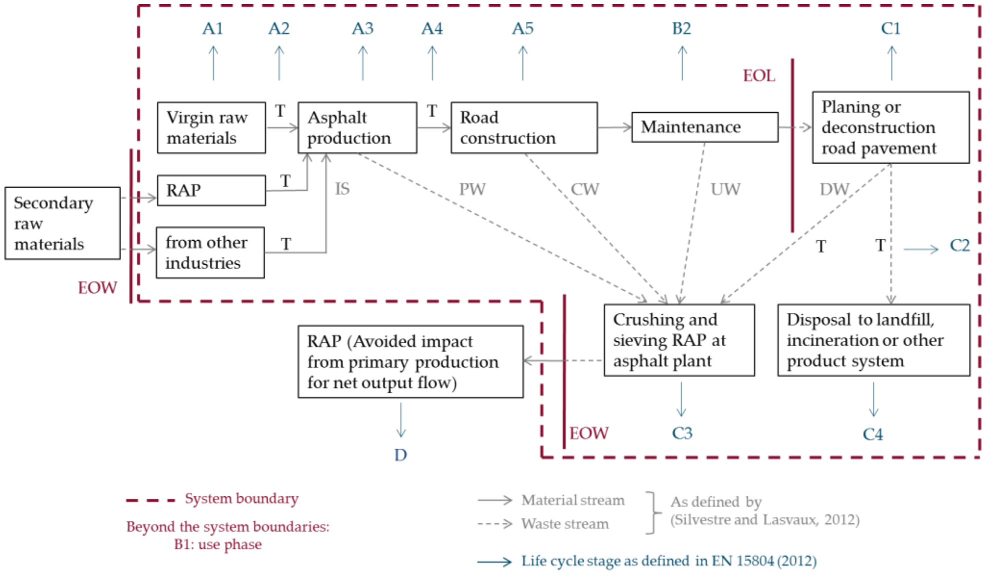


Figure 7: Life cycle of bituminous road pavement with the indication of the stages as defined in EN 15804

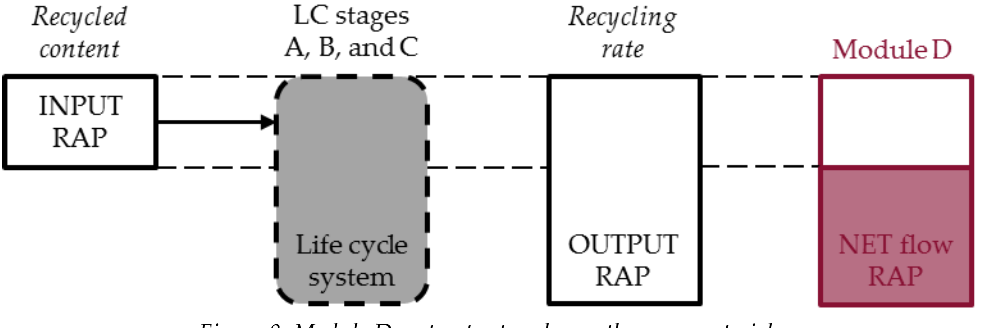


Figure 8: Module D: net output replaces other raw materials

There is an additional module D in the standard EN15804, outside the system boundary (see Figure 4), reporting on the environmental benefits and loads. The environmental savings on virgin materials, which are replaced by the net RAP output of the system under study, are reported in module D. Module D takes only into account the net output flow, calculated as presented in Figure 8.

The modelling approach applied in the life cycle stages within the system boundaries (allocation) differs from the modelling approach in module D (system expansion). It is therefore important to note that the result calculated in module D cannot be added to the impact from the life cycle stages within the system boundaries (A up to and including C). This would cause double counting of environmental impacts, in this case environmental benefits related to the use of recycled materials (that are burden free available in raw materials stage A1) and the recyclability of the material (environmental impact of substituted virgin material is subtracted).

4.2.2 Data collection

Figure 9 schematically presents the different fields of data collection within the scope of the current research. The applied methodology in the different research topics is described in the following paragraphs.

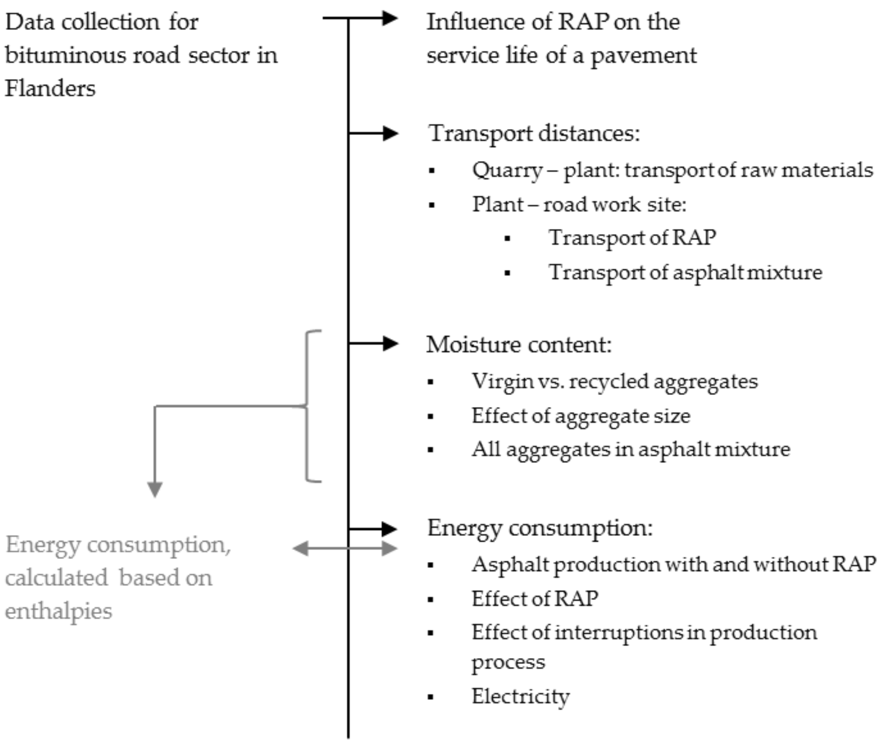


Figure 9: Different fields of data collection within the scope of the current research

4.2.2.1 Service life

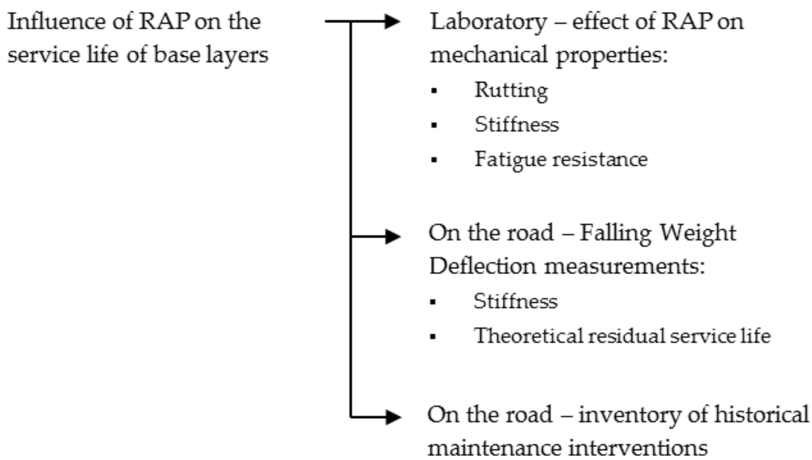


Figure 10: The influence of RAP on the service life of a pavement – three different research levels

Three different research levels were implemented to investigate the service life of pavements. As presented in Figure 10, this includes the analysis of laboratory test results and the analysis in situ on the road.

The first level includes an analysis of the effect of RAP on the performance characteristics (rutting, stiffness, and resistance to fatigue) of a large number of bituminous mixtures. These performance characteristics for base courses are required as input parameters for pavement design calculations in Flanders. It is acknowledged by the authors that there are other important characteristics, which are not included in the current research. For example, healing characteristics are influenced by the presence of RAP (Van den bergh, 2011), and used in pavement design calculations in The Netherlands, but these are not included at this stage in this research. Laboratory test data on registered mixtures according to SB250 v2.2 and newer versions were collected at ART and in this research used to evaluate the mechanical performances of asphalt mixtures. Data from 65 hot mix asphalt samples for base courses, with a RAP content ranging from 0 to 63% were analysed. More details concerning the research setup are described in paper VI.

The second level includes the analysis of Falling Weight Deflection (FWD) measurements on a selected series of test sections, constructed in 2006 at a motorway, the E19 in Kontich, Flanders. The test sections were constructed to investigate the use of EME in base courses on motorways and were monitored by BRRC (De Backer et al., 2007). The test sections included two pairs of sections in which EME mixtures were used with similar composition with both a variant with RAP and a variant without RAP. The road structure was 3.75 m wide and the following thicknesses of courses were measured: 3 cm stone mastic asphalt (SMA) surface course, 9 to 10 cm EME base course, 15 cm asphalt concrete (AC) base course, 26 cm crushed stone foundation, and subsoil (De Backer et al., 2007).

FWD measurements were executed in April 2006: (1) directly on the base course (without the surface course), 2 to 4 days after construction, and (2) on the total pavement, one day after finishing the surface course construction, before the road was opened to traffic. In October 2015, new FWD measurements were requested in the scope of the current research and executed by ART (see Figure 11). For each test section, three FWD measurements were executed. The FWD measurements were applied to determine the strength of the road pavement and to calculate a theoretical residual service life. In this test, a load of 65 ± 5 kN is dropped on rubber buffers placed on the pavement. The response of the pavement is measured with nine geophones located at 0, 30, 60, 90, 120, 150, 180, 210 and 240 cm from the load point. The measurements from the nine points together form a deflection curve, influenced by the thickness and stiffness of the different courses in the road pavement. The results of the FWD measurements are described in a master thesis (Moras, 2016).

The third level of the research determining the effect of RAP on the service life of pavements, includes the set-up of an inventory of service lifes of pavements from road sections, with and without RAP. Historical data on road sections, including: (1) date, mixture, and materials for initial construction, (2) date, mixtures, and materials for maintenance interventions, (3) results of routine analyses of the road, and (4) evolution of the traffic load, were collected in this inventory. Different authorities in charge of road construction and maintenance (ART and 9 cities) and road contractors were contacted for information collection. This research part was also the subject of a master thesis (Moras, 2016).

Figure 11: FWD measurements at E19 Kontich

A theoretical LCA scenario with reduced durability for asphalt mixtures with RAP in the base course is included in section 5.4. The thickness of the base layer is adjusted based on a default reduction of 20% of the fatigue resistance. The minimal required deformation property (ε_6) is decreased from 93 micro strain (μS) to 74 μS, which is still within the technical specifications of construction class B4 according to SB250 v.3.1.

The calculations were made with the software Qualidim 2.4.0.0 (2013). This software calculates the strains in the structure and uses standard fatigue laws for asphalt. The calculations of stresses and strains are based on the Burmister multilayer model (Burmister, 1945). In this study, the deformations at the lowest position of the asphalt were selected and a modified fatigue law (74 and 93 μS) was used to calculate the number of ESAL. The rule of Miner was applied taking into account three different seasonal conditions (winter, summer, autumn-spring) since asphalt stiffness is affected by temperature (Weise and Blasl, 2010).

The only failure for the APO mixture that was considered was fatigue damage.

Therefore, the road construction was designed to fail by fatigue, which allowed to analyse the effect of a possible decrease in this property when using RAP.

4.2.2.2 Transport

For the delivery of raw materials to the asphalt plants, Google Maps © was used to calculate transport distances between Belgian quarries and Flemish asphalt production plants. It is recognized that this method is a simplification of the real practice since the delivery of raw materials is not limited to only Belgian quarries. Besides, intermediate storage at the site of a distributor is also possible, but this was not considered. A more detailed analysis was not available and a comprehensive data collection related to this research topic is not included in current research.

The transport distance between the asphalt plant and the road worksite was more extensively investigated. A geographic information system (GIS) was used, (Wieczerok and Delmerico, 2009). The software package Esri ArcMap v10.2.2 was used in combination with the Network Analyst extension.

As a first step, the service areas of the 18 Flemish asphalt plants were generated. A service area is represented by a polygon, enclosing all the area that is closer to the plant in the polygon than any other plant. The polygons for the 18 plants were calculated based on the shortest transport distance by road, and based on one-way traffic and traffic routes suitable for trucks.

Secondly, in each service area, the road surface area was compared with the production capacity of the plants. The GIS database was used to calculate the paved surface areas.

In addition, a questionnaire was addressed to the Flemish asphalt plants for an inventory of the worksites of each plant. A file with contact information is included in appendix 2. The Flemish asphalt plants were asked to make an inventory of all locations of the road worksites for which they produced asphalt for a time period of one year.

The GIS software was used to calculate transport distances between the asphalt plants and their road worksite locations. Statistical analysis was applied to these data and gave more insight in transport distances between plant and road worksite, and the size of the road works. Besides, the results of the questionnaire were compared to the calculated theoretical service areas, to get more insight in the efficiency of the transport processes (distances) in current practice in Flanders.

4.2.2.3 Moisture and energy

For the inventory of moisture content in virgin and recycled aggregates, multiple laboratories on both asphalt and concrete production plants were asked for mass balance data on moisture content in aggregates. Results of laboratory tests of moisture content determinations were collected for different fractions of virgin aggregates and for RAP. For asphalt production, it is less important to know the exact moisture content of aggregates, compared to the production of concrete, since all moisture will be evaporated during the asphalt production process. In case of a higher moisture content in the aggregates, the temperature of the materials exiting the drum, continuously read at the monitor in the control room at the asphalt plant, will be lower and consequently the heating capacity of the burners in the drum will be adjusted and the temperature will increase. To produce concrete, on the other hand, aggregates are not dried and hence it is more important for the production process to know the moisture content in the aggregates. The moisture content in the aggregates influences the water-cement ratio and leads to different strength and durability characteristics of the concrete.

Therefore, data on moisture content in aggregates were collected from both asphalt and concrete laboratories and research centres. The data were grouped in the size fractions similar to the fractions after warm sieving (see Figure 23, p.61) in the asphalt production process (i.e., 0/3, 3/8, 8/16, and 16/40).

The moisture content in aggregates was tested in the laboratory by proportion of weight. All moisture contents were expressed in %m/m.

Since the tests on moisture content in aggregates were executed by different laboratories and not by researchers involved in the current research, the circumstances of sample taking and test methods were not known. Sampling of aggregates was conducted according to EN 932-1:1997.

For the data collection related to energy consumption of processes at the asphalt plant, measurements were executed in situ on one Flemish asphalt plant. This asphalt production plant was built in 1994 by the company Benninghoven and has a nominal production capacity of ± 300 ton/h. The plant is equipped with a drier drum for drying and heating virgin aggregates and a parallel drum for drying and heating RAP. The parallel drum is installed at the top of the installation and the exhaust gases are led to the drum that is installed in the lower part of the plant for re-combustion at higher temperatures and partial recuperation of the residual heat. The exhaust gasses of the drum pass through a dust filter before being emitted to the environment. The two oldest bitumen tanks (date of building 1994) are heated by thermic oil. Thermic oil is heated by a combustion installation fed with natural gas. Five newer, insulated bitumen tanks (date of building 2004) are electrically heated during the night (lower electricity cost). Some other elements at the asphalt plant are provided with wall heating by thermic oil. In 2012-2013 the asphalt plant was converted from the use of fuel oil to the use of natural gas as energy source for the drums. The laboratories and the offices are electrically heated.
This asphalt plant is considered to be representative for the Flemish asphalt industry. The average nominal production capacity for Flemish plants is 235 ton/h and 94% of the Flemish asphalt plants are able to use heated RAP in new asphalt mixtures (Belgian Road Research Centre, 2014).

The following paragraphs describe the different research attempts that have been made to collect data on the energy consumption at the asphalt plant, including these that yielded insufficient results. The unsuccessful attempts are described to obtain a complete outline of the research process.

The first measurement campaign for the energy consumption at the asphalt plant was executed by COPRO in May 2014 as part of the Flemish pilot project Carbon Free-Ways described in paper III. Natural gas (for heating materials in the drums) and electricity (for heated storage of bitumen) consumption were read at the general meter at the plant during the production of the various asphalt mixtures. Due to the small number of measurements (4 results for mixtures with RAP and 4 results for mixtures without RAP), no statistically significant difference is found in the energy consumption for the asphalt production with and without RAP.
The second measurement campaign was performed in April 2015 during WMA production for test sections at Scheldelaan in Antwerp. The general gas meter was repeatedly read during continuous asphalt production of one single asphalt mixture type. Due to large variations in the production temperatures of the mixtures, the energy measurements were not representative for a particular mixture. Besides, for both the first and second measurement campaigns, the gas meter should have been

read at the very specific moment when the production is switched between different mixtures. For a specific energy measurement, there cannot be a mix of WMA or HMA production or a mix of mixtures with and without RAP. Therefore, only a few measurements were selected for comparison.

In November and December 2015, a third similar measurement campaign was set up with more frequent gas meter reading to collect an extended dataset for statistical analyses. It is important to note that these measurements were executed in a period in fall, while measurements of the second campaign were executed in spring. The weather conditions influence the parameters (ambient and initial temperature of aggregates, and moisture content of aggregates) related to the energy consumption. No statistical difference in weather conditions for the two periods was found based on KMI data. However, both datasets are kept separate and are not compared, since uncontrolled parameters might affect the energy consumption.

Again, few measurements included the production of only one asphalt mixture (without switchover, without a break in the production, without special circumstances).

Finally, instead of trying to exclude all possible inconsistencies in the production, it was decided to embrace all the variances by means of switchover in mixture type, break in production, variable weather conditions, and special circumstances since they are actually part of the asphalt production in situ. At the asphalt plant, some production parameters are registered in a daily production record e.g.

- natural gas consumption (m^3), read from the gas meter;
- asphalt production with RAP (ton), extracted from the continuous production registration;
- and total asphalt production (ton), extracted from the continuous production registration.

These data for 2013 to 2016 were collected and used for further analysis (see subsection 5.3.2). In this way, a dataset with 772 production days comprising different kinds of asphalt mixtures and seasonal variances was available for analysis.

5 RESULTS AND DISCUSSION

In this chapter, the research results of the three main research topics are presented and discussed in the first sections. These results are input data for the environmental assessment of bituminous road pavements using RAP. An LCA study is elaborated in the fourth section of this chapter.

5.1 Service life of bituminous pavements

5.1.1 Effect of RAP on the mechanical properties of asphalt mixtures

The results of the analysis of the laboratory performance tests on asphalt mixtures with and without RAP are presented in paper VI. It is important to note that this analysis is based on reported test results. Uncertainties related to these tests are not included. For example, the average value of rutting was calculated from two test results for each mixture. The deviation of these two values from the average was not taken into account, as well as, the accuracy of the measurements in the laboratory tests.

Main conclusions of paper VI

It is not possible to formulate robust conclusions based on the current analysis since, for the same amount of RAP, the distribution of the results is very large for each performance characteristic. The large variance is due to the effect of other mixture properties (like granulometry and binder characteristics) on the investigated performance characteristics. Based on the results of the current analysis, it is not possible to define significant differences in binder content or binder type in relation to the recycling rate.

However, important to conclude is that it is possible to design mixtures with high RAP content with identical mechanical performances (rutting, stiffness, and resistance to fatigue).

Additional calculations to paper VI are described here, focusing on the percentage of the total amount of binder that comes from RAP (%O/N in paper VI). This is assumed to be relevant since the binder is not an inert material and the amount of aged binder from RAP may have the largest influence on the performances of the asphalt mixtures with recycled materials.

As stated in section 4.1 of paper VI, using the Spearman's rho correlation test, a statistically significant (α = 0.05), but weak correlation is observed between %O/N and rutting (r_s = -0.295 and p = 0.020), and between %O/N and stiffness (r_s = 0.251 and p = 0.046). The resistance to rutting and the stiffness of the mixture increased if %O/N is higher. No statistical significant correlation was found between %O/N and fatigue (p = 0.621). The results of the dichotomous analysis remained the same in the analysis based on %RAP and %O/N and show that the mixtures with RAP have a significantly ($\alpha = 0.01$) higher resistance to rutting and a higher fatigue life. Results of the graphical analysis are presented below. It is seen from Figure 12, Figure 13, and Figure 14 that the variation in the results is large, since for the same percentage of old binder, the mechanical performances vary and are widely distributed along the y-axis.

The total binder content (BC) on the aggregate mixture, is indicated by different colours in the following figures. The deviation of the binder content from the average binder content for a particular mixture type is used to form three groups. For each mixture type, mixtures with a binder content within the 68% confidence interval[5] (CI) are indicated with a grey label, mixtures with a lower binder content are indicated in red, and mixtures with a higher binder content are indicated in blue. Combining deviations in binder content and mixture type resulted in nine different groups as illustrated in Figures 12-14. It is seen from the results that both higher and lower binder contents – compared to the mean binder content for that mixture type – are found in both higher and lower performance characteristics for the three tested performances. Hence, no robust conclusion can be drawn from the results related to the influence of binder content and %O/N on the performance characteristics.

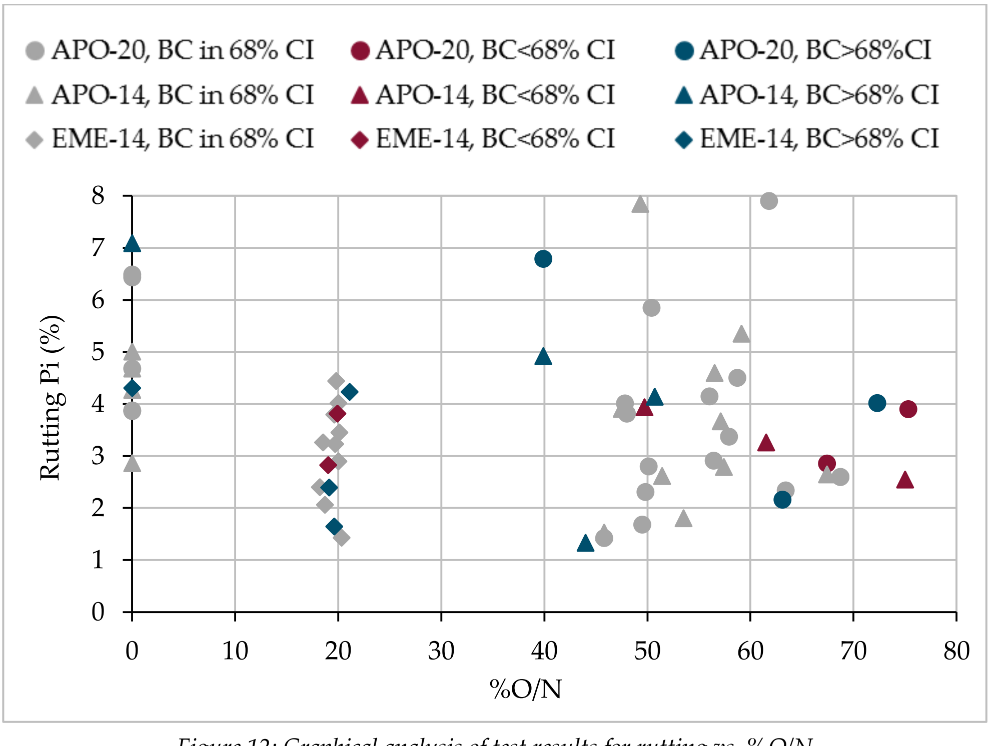


Figure 12: Graphical analysis of test results for rutting vs. %O/N

[5] Mean ± 1 standard deviation.

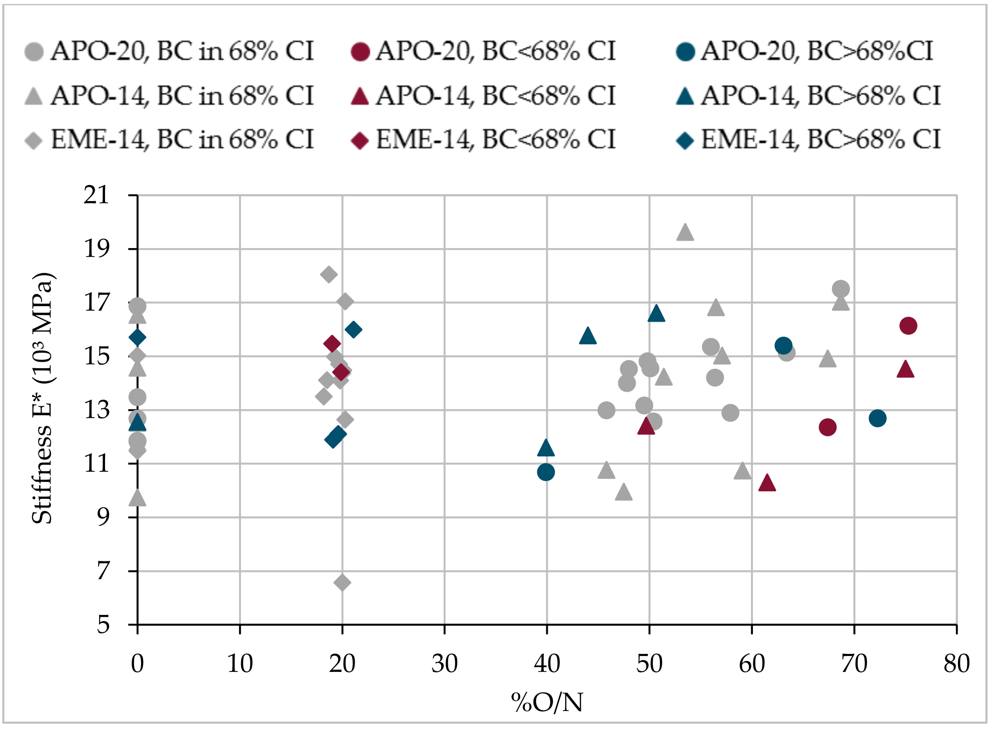


Figure 13: Graphical analysis of test results for stiffness vs. %O/N

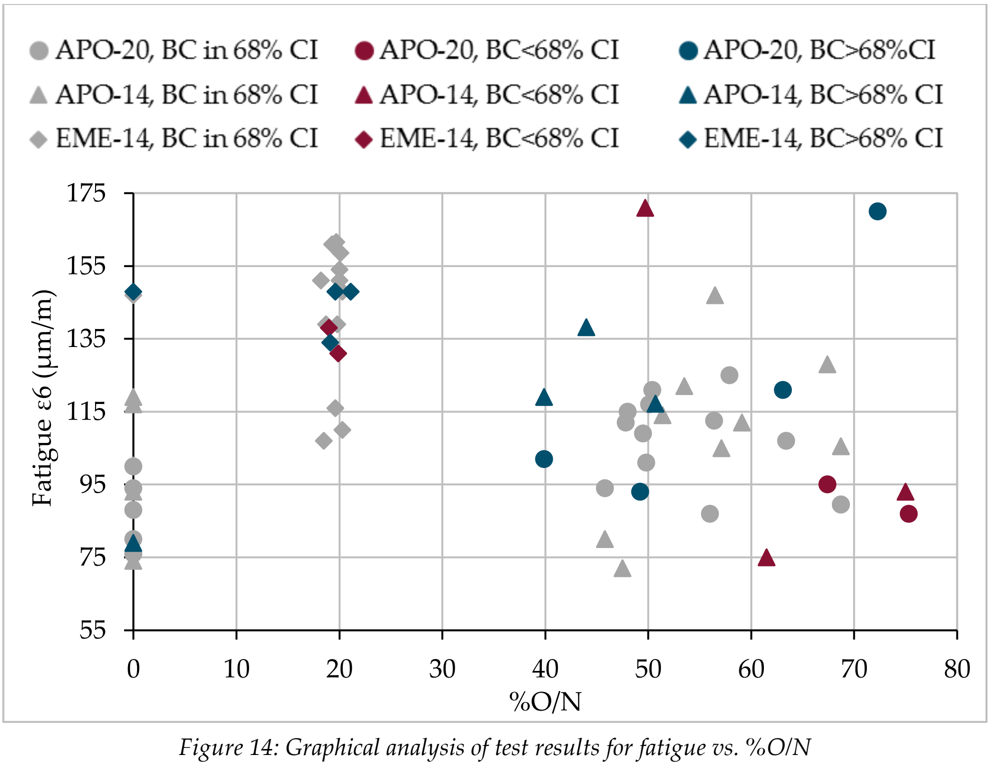


Figure 14: Graphical analysis of test results for fatigue vs. %O/N

Further research on the effect of RAP on the mechanical performances is recommended since the mechanical performances influence road construction dimensions i.e., thickness.

5.1.2 Effect of RAP on the mechanical characteristics of the base course in a road pavement

The results of Falling Weight Deflection (FWD) measurements on a selected series of test sections, constructed in 2006 at a motorway, the E19 in Kontich, Flanders are analysed in a master thesis (Moras, 2016). Although the analysis of FWD results was conducted under the supervision of experts in the sector, based on several software tools, and considered several performance characteristics, no meaningful results within the goal and scope of this research were found.
It is concluded that the FWD test method is not suitable for short test sections. In the current analysis, FWD measurements were executed approximately every 50 m and hence there are only three results for each test section (Moras, 2016). Besides, it is noted that for nine years, no FWD measurements were executed on the test sections. Research on the evaluation of the mechanical performances in time would benefit from more frequent measurements.
However, FWD has been successfully applied before on longer road sections, resulting in a large number of test results that could be used in the iterative calculation for stiffness and residual service life. Unfortunately, the mixture compositions of the pavements that are not registered as official test sections, were not exactly known and the concentration of RAP had not been recorded. Therefore, the results of those FWD measurements were not useful to differentiate between the service life of virgin and recycled asphalt mixtures. The lack of accurate mixture composition registration will continue to importantly hinder this type of research evaluations in the future.

In literature it has been reported that when using cold foamed asphalt stabilized bases, curing of foamed asphalt bonds is an important element in the stiffening as a function of time (Khosravifar et al., 2013). It was found that the stiffness of the investigated material strongly increases within a week after construction. Even four months after construction, the material had become stiffer compared to seven days after construction. Despite the fact that this study relates to a different type of asphalt mixture, it might confirm the findings in the master thesis (Moras, 2016) i.e., the development of adhesive bonds between the binder and coated aggregates causes an increased stiffness during a certain time range after the road construction. Besides, the traditional way of back calculation might be inaccurate and yields an underestimation of the actual strain occurring in the road structure since the load and the peak deflections do not occur at the same time (Salt et al., 2002). However,

the study by Salt revealed that this delay in deflection peak is less pronounced for stiffer pavements compared to more weak pavements and may hence be less important for pavements with an EME base layer.
Additional FWD measurements on the same test sections and extensive literature review are necessary to analyse the further evolution of the pavement performance.

5.1.3 Effect of RAP on the maintenance interventions and service life of road pavements

The results as obtained within the master thesis are described in this paragraph (Moras, 2016). The pavement management system (PMS) used by ART is recording the date of the initial construction, the results of routine analyses of the road, and the evolution of the traffic load (Briessinck and Van Troyen, 2013a, 2013b). The only distinction in road construction materials is set between asphalt, concrete, or composite, without more information on the mixture type, mixture composition, and the use of RAP. The necessary information for a profound analysis of the service life of road pavements in situ was not available. None of the contacted organisations (regional authorities, local authorities, and contractors) seems to collect or store this information. Hence, at this moment, it is impossible to determine a service life of road pavements with and without RAP based on historical information. Moreover, as the practice of not collecting those data appears to be continued even in current days, research in the near future is also limited, i.e. the comparison between mixtures with and without RAP based on actual field performances.

In literature, extensive laboratory studies evaluating the effects of RAP on pavement performance are found, but the actual field performance of asphalt pavements with RAP, however, is rarely reported. "*Particularly lacking is information on the long-term performance of RAP-containing asphalt pavements side-by-side compared with pavements that only use virgin mixtures. Such information would not only be useful in understanding the engineering performance of RAP mixtures, but also be critically important for life-cycle cost analysis (LCCA) and/or life cycle assessment (LCA) of pavements containing RAP.*" (Wang, 2016) The Long-Term Pavement Performance (LTPP) program is one of the few projects collecting data on the actual field performance of multiple (more than 2 500) pavement test sections throughout the United States and Canada (Federal Highway Administration, 2016). Wang uses data from 18 test sites under the LTPP project to compare the long-term performance of AC overlays using only virgin materials with AC overlays using 30% RAP (Wang, 2016). The study includes only overlay, while RAP is not allowed in surface courses according SB250 v.3.1. Hence, the effect of using RAP on the fatigue performance of base courses is not included in the study by Wang. For thin overlays (51 mm) with minimal pre-overlay treatment[6], Wang found that RAP-containing mixtures perform undesirable compared to virgin mixtures due to the high influence of cracks from existing pavement. On the other hand, when a thicker overlay (127 mm) and intensive pre-overlay treatment[7] are applied, mixtures with RAP outperform virgin mixtures in rutting and roughness, without inducing additional cracking-related distresses. The study by Wang provides another insight into the service life of pavements with and without RAP, however, an actual service life, as needed in LCA studies is not quantified.

5.1.4 Conclusions

Despite the research conducted at different research levels (see subsections 5.1.1, 5.1.2, and 5.1.3) and the collaboration with experts in the field, very few conclusions could be obtained from these research parts. It was proven, based on the findings as presented in paper VI, that it is possible to design asphalt mixtures with RAP with equivalent performance characteristics as compared to the mixtures without RAP. Similar results were found in literature:

"*Several studies show that if asphalt recycling is performed properly, hot mix asphalt containing RAP has the same qualities as asphalt produced from virgin material.*" (Miliutenko et al., 2013)

"*Changes and differences in the inherent properties of recycled materials may also result in differences in the performance even if the mix is properly designed and engineered. … There are many factors that can affect the performance of pavements, and it does not seem there is a consensus on the performance of AC pavements contain RAP at this point due to lack of field performance data.*" (Yang et al., 2015)

However, the service life of bituminous pavements could not be quantified based on these research findings. This is a problem since the service life of a product is an essential parameter in LCA studies. It is therefore only possible to include a theoretical scenario with a durability reduction by default (ε_6 reduced by 20%, see §4.2.2.1 and §5.4.4.4) to assess the effect on the environmental impact.

Since it was impossible to find a statistically significant effect of RAP on the service life of bituminous road pavements, it was decided to exclude most processes in the use stage of the bituminous pavements in further analysis (see Figure 4). In this way, the need for assumptions on the influence of RAP on e.g., fuel consumption of cars, lighting, albedo etc. is avoided. An identical functionality of mixtures with RAP and mixtures with only virgin raw materials is assumed in all other life cycle stages.

[6] A minimal pre-overlay treatment includes milling, patching and levelling of the old pavement.

[7] An intensive pre-overlay treatment is similar, but includes crack sealing instead of levelling.

5.2 Transport distances

Transport was mentioned earlier as one of the relevant parameters, contributing to the total environmental impact of bituminous pavements. Road transport distances were analysed, both for delivery of raw materials to the asphalt plant and for the transport processes between the plant and the road worksite.

5.2.1 Quarry to asphalt plant

In the preliminary LCA case studies, the transport distances for the delivery of raw materials were case specific (paper III), based on assumptions (paper IV), or calculated based on a first version of this research (paper V).

Road transport distances for the delivery of virgin aggregates were calculated based on the location of the 18 Flemish asphalt plants and 13 Belgian quarries (excluding transhipment yards) as presented in Figure 15 (Belgian Road Research Centre, 2014; Sagrex, 2016). The transport distance for filler supply was calculated for the four main suppliers in Belgium and The Netherlands. For bitumen, the road transport distance calculated from the port of Antwerp to the asphalt plants since it is an important distribution point of crude oil and bitumen for Flanders (Blomberg et al., 2012).

Results of the data analysis are presented in Table 3. It is recognized by the authors that this modelling approach is a simplification of the real practice since the average, the minimum, or the maximum transport distance for the delivery of raw materials to the asphalt plant is not the real practice. In practice, the transport distances for delivery of raw materials mainly depend on price agreement and contracts between the supplier and the plant. Besides, aggregates are sometimes imported from foreign countries (e.g., Bremanger Quarry in Norway), which are excluded from the analysis since an overview of all international raw material resources is not available. The three bottom rows in Table 3 present transport distances as found in literature. The values are widely divergent, which underlines the importance of data, inventoried in accordance with the scope of the research.

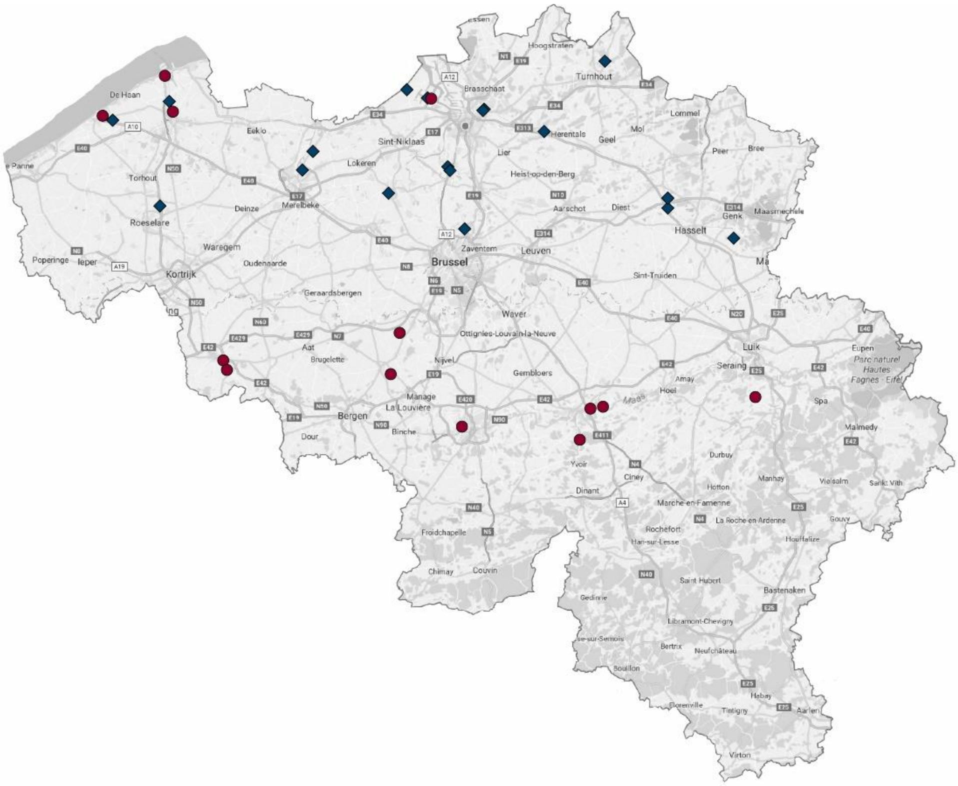


Figure 15: Map of Flemish asphalt plants (red diamond) and Belgian quarries (blue dot)

Table 3: Number of plants and quarries included in the calculations and transport distances for the delivery of raw materials to the asphalt plant for Flanders and findings from literature

	all quarries aggregates	crushed aggregates	round aggregates	filler	bitumen
number of asphalt plants	18	18	18	18	18
number of quarries	13	9	4	4	1
average transport distance (km)	118	128	95	124	61
median transport distance (km)	118	123	96	122	61
minimum transport distance (km)	5.7	46.5	5.7	3.0	15
maximum transport distance (km)	234	234	215	250	123
transport distances found in literature					
(Mirzadeh et al., 2014)	5				100
(Huang et al., 2009b)	193				129
(Celauro et al., 2015)	10			100	100

5.2.2 Asphalt plant to road worksite

In the preliminary LCA case studies, the transport distances between plant and road worksite were case specific (paper III and paper IV), or outside the scope of the study (paper V).

10 out of the 18 Flemish asphalt plants collected the information and responded to the questionnaire. Only 9 of the received datasets were useful, since one asphalt plant grouped the asphalt production per day instead of per construction site and hence for these transport distances it was not possible to obtain a mass weighting. The distribution of the results of transport distance is presented in Figure 16. The data are analysed with SPSS and the descriptives are presented in Table 4. The average transport distance between asphalt plant and road worksite is 43 km. Other results are found in literature: 25 km by average based on expert opinions in a Swiss study (Gschösser et al., 2014), 50 km for a specific case in Switzerland (Mirzadeh et al., 2014), 6.4 km for a specific case in United Kingdom (Huang et al., 2009b), 30 km by average in an Italian study (Celauro et al., 2015), and 24 km (15 miles) for a specific case in Washington State (Pavement Interactive, 2011a).

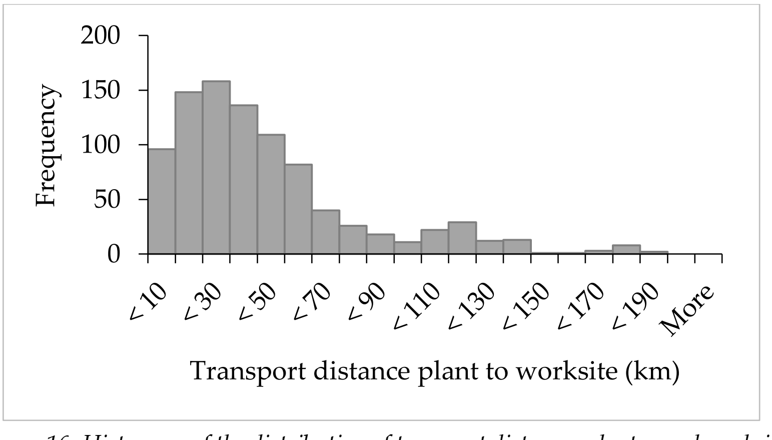


Figure 16: Histogram of the distribution of transport distances plant - road worksite

Table 4: Data analysis transport distances plant – worksite and worksite magnitude (mass asphalt)

number of asphalt plants	9
total number of worksites	915
total amount of asphalt (ton)	888 751
average transport distance to worksite (km)	43.3
median transport distance to worksite (km)	34.6
minimum transport distance to worksite (km)	0.5
maximum transport distance to worksite (km)	182
95% confidence interval for mean distance (km)	41.0 – 45.5
average asphalt mass for one worksite (ton)	944
median asphalt mass for one worksite (ton)	251
95% confidence interval for mean mass (ton)	701 – 1 188
average transport for one worksite (tkm)	27 087
median transport for one worksite (tkm)	8 548
95% confidence interval for mean transport (tkm)	21 495 – 32 680

In the scope of further analysis of the transport distances, the service area in Flanders of each asphalt plant in Flanders is searched. The map depicted in Figure 17 is established with a geographic information system (GIS) [map and data generated by Dries Anthonissen, GIS Consultant at SIGGIS].
The different service areas are indicated with a different colour. It is noted that there are only 17 service areas visible in Figure 17. This is due to the fact that plant 9 (in Puurs) is located in a dead end road and very close to plant 13. Therefore, the service area for plant 9 is really small. It is assumed that both plant 9 and plant 13 are attributed to one and the same service area. The map is included in appendix 3 as a PDF file and can be used for further analysis of the location of the asphalt plants, service areas, worksites, and routes between the asphalt plant and the road worksites.

For the nine asphalt plants, 79% of the inventoried worksites are located outside the theoretical service area of that particular plant. This means that the transport distance could become shorter if another asphalt plant produces the asphalt for these road worksites. For the 9 asphalt plants analysed over a period of one year, it was found that the unnecessary transport distance is 26 551 km, which is 67% of all transport kilometres in the inventory or 14 million ton*kilometre (tkm), which is 57% of the total inventoried transport (tkm). Generalized for the 18 Flemish asphalt plants over one year, this would be 28 million tkm.
These results indicate that there is an important potential for efficiency improvement of the transport scenario in the Flemish bituminous road sector and hence decrease the associated environmental impact.

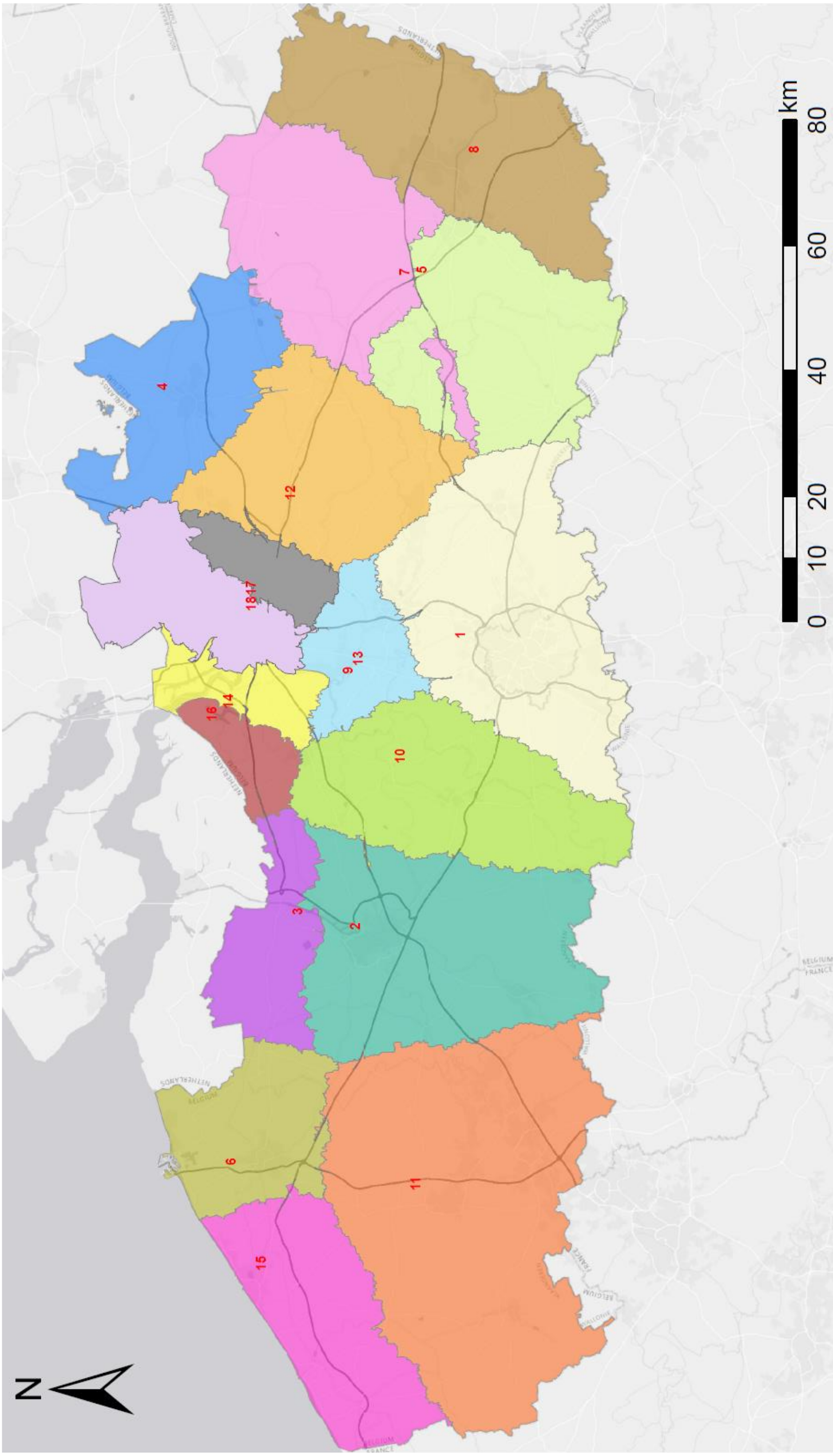
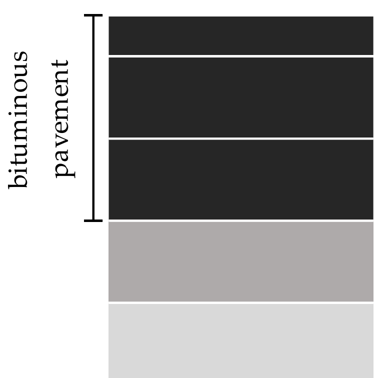


Figure 17: Service areas in Flanders for all 18 Flemish asphalt plants

The definition of the service areas is a theoretical measure to reduce transport, but other parameters play an important role in practice, e.g. the production capacity of the asphalt plant to provide construction and maintenance works in the whole service area. For this purpose, the GIS database and software are used to calculate the length of the road network. The total length of the road network in Flanders, including all service areas, is 72 652 km, which is in accordance with the length of the Flemish road network as published by the Belgian FPS Mobility and Transport (FPS Mobility and Transport, 2011). Three road types are included in the analysis i.e., motorways, dual carriageways (that are not motorways), and single carriageways. Together these three road types represent at least 90% of all roads within the service area, while roundabouts, approach ramps, footpath, cycle path, unpaved roads, etc. are excluded. The width of each road segment is taken from the GIS database as well and so the total paved surface area is calculated.

It is necessary to make assumptions for the analysis of the production capacity of the asphalt plants to assess the feasibility of service areas. Based on expert opinion, a rough division is made: 30% of all Flemish roads are paved with concrete and 70% are paved with bituminous mixtures (Briessinck, 2017). A pavement thickness of 20 cm is assumed, including 4 cm surface course, 8 cm base course 1, and 8 cm base course 2 (see Figure 18). Over 50 years, the surface course is (re)constructed four times, base course 1 is (re)constructed two times, and base course 2 is constructed once (see Figure 18). Using this information, and assuming an equal staggering of construction and maintenance works over 50 years, the annual amount of asphalt (m^3) that is needed within each service area is calculated, and presented in Table 5.



course type	thickness (cm)	replacements over 50 years
asphalt surface course	4	4
asphalt base course 1	8	2
asphalt base course 2	8	1
subbase course		
natural soil (subgrade)		

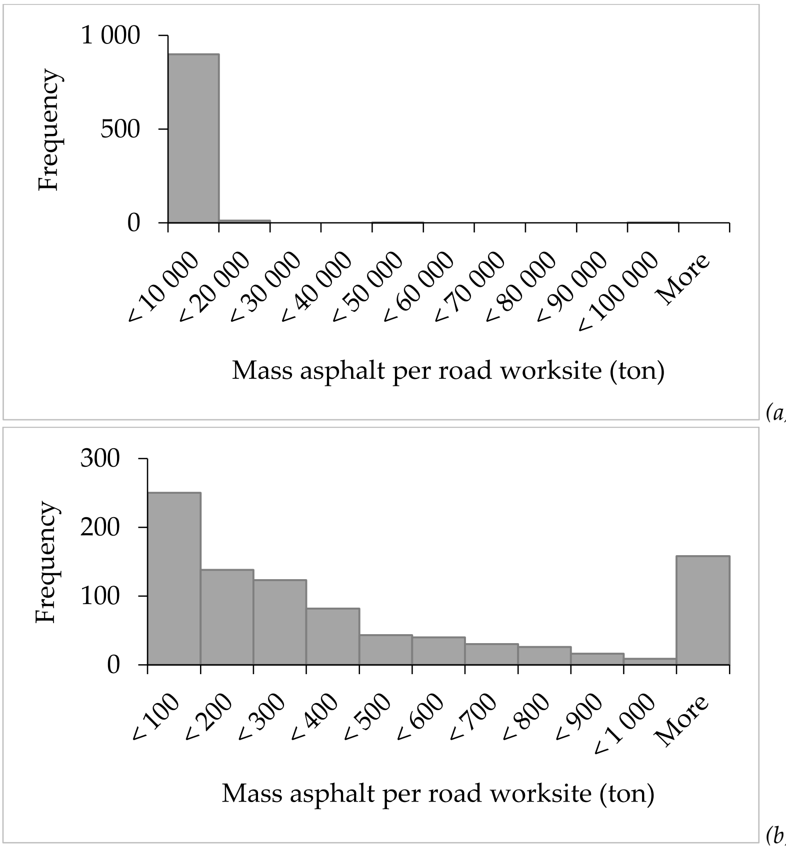
Figure 18: Assumptions on course thicknesses and replacement rates over 50 years for bituminous road pavements

The nominal production capacity of each asphalt production plant was taken from the BAT study (Leyssens et al., 2013). The annual number of production days is 193, which is the average for the reference asphalt production plant over four years. There are assumed to be 7 daily production hours, being the average calculated from the dataset used in §5.3.2.1. The density of the asphalt mixture is 2.4 ton/m^3. With this information, the annual asphalt production (m^3) of each plant is calculated and presented in Table 5.

These results show that the production capacity in 7 out of 17 service areas is not sufficient to provide all road works within the service area. Service areas 9 and 13 were combined, but anyway both plants on their own would be able to produce sufficient asphalt to serve the whole service area. Based on the total Flemish road network and the total Flemish asphalt production capacity, the rearrangement of road worksites in adjusted service areas is possible in this particular theoretical scenario. Similar research can be conducted in more detail by deviating the pavement structure and maintenance frequency for the different road types.

Table 5: Analysis of asphalt production capacity within each service area for the specific theoretical scenario

asphalt plant / service area	road network			plant		
	paved surface area (m^2)	bituminous surface area (m^2)	annual asphalt needed for road works (m^3)	nominal production capacity (ton/h)	annual asphalt production (m^3)	sufficient production capacity?
1	49 581 240	34 706 868	277 655	300	168 875	no
2	34 562 694	24 193 886	193 551	320	180 133	no
3	7 644 929	5 351 450	42 812	350	197 021	yes
4	13 000 574	9 100 402	72 803	120	67 550	no
5	20 613 766	14 429 636	115 437	320	180 133	yes
6	14 162 875	9 914 013	79 312	320	180 133	yes
7	23 049 083	16 134 358	129 075	320	180 133	yes
8	25 901 508	18 131 056	145 048	150	84 438	no
9	0	0	0	160	90 067	yes
10	23 754 493	16 628 145	133 025	140	78 808	no
11	49 569 283	34 698 498	277 588	210	118 213	no
12	21 881 891	15 317 324	122 539	150	84 438	no
13	11 572 823	8 100 976	64 808	150	84 438	yes
14	7 916 372	5 541 460	44 332	150	84 438	yes
15	16 708 236	11 695 765	93 566	320	180 133	yes
16	3 625 913	2 538 139	20 305	240	135 100	yes
17	6 847 175	4 793 023	38 344	250	140 729	yes
18	19 391 673	13 574 171	108 593	350	197 021	yes
total Flanders			1 958 793		2 431 800	



(a)

(b)

Figure 19: (a) Histogram for distribution of the mass of asphalt per road work; (b) Idem (a) with cut off on x-axis and smaller bins

As can be seen in Figure 19(a) the magnitude of the road worksites is very variable. The histogram over the full range of the mass per road work is not representative. Figure 19(b) is a histogram with a cut off on the x-axis and smaller bins. Analysis of the data showed that 82% of road worksites involved less than 1 000 ton asphalt. The skewness of the data is also noticed from the difference between the average and median mass asphalt per road worksite as presented in Table 4.

In LCA studies, the unit of transport is ton*kilometre (tkm). In Figure 20, the transport (in tkm) is represented by the hatched area A for point 1 and the hatched area B for point 2. In this graphical representation of transport, it is clear that the transport and hence the related environmental impact can be identical for two road works with different quantity of asphalt and different transport distance.

It is found from data analysis that the variation in the transport (tkm) data is very large, and therefore presented in the histogram with a cut off on the x-axis (Figure 21).

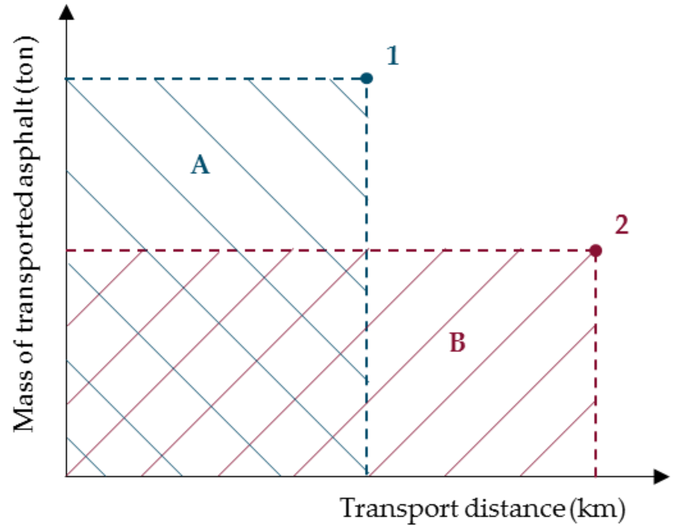


Figure 20: Graphical representation of transport (tkm)

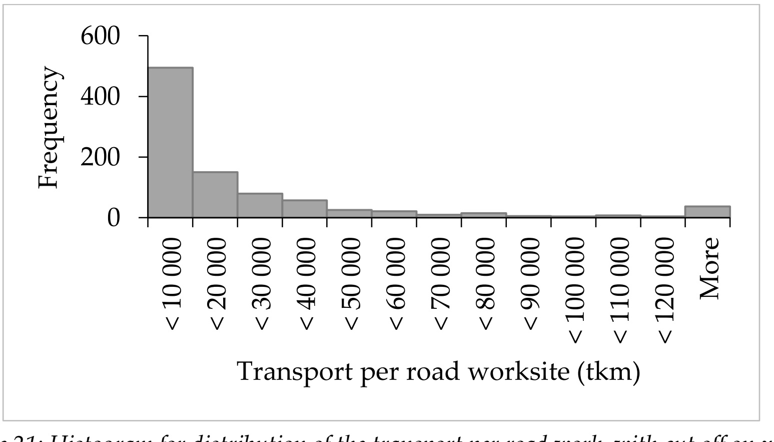
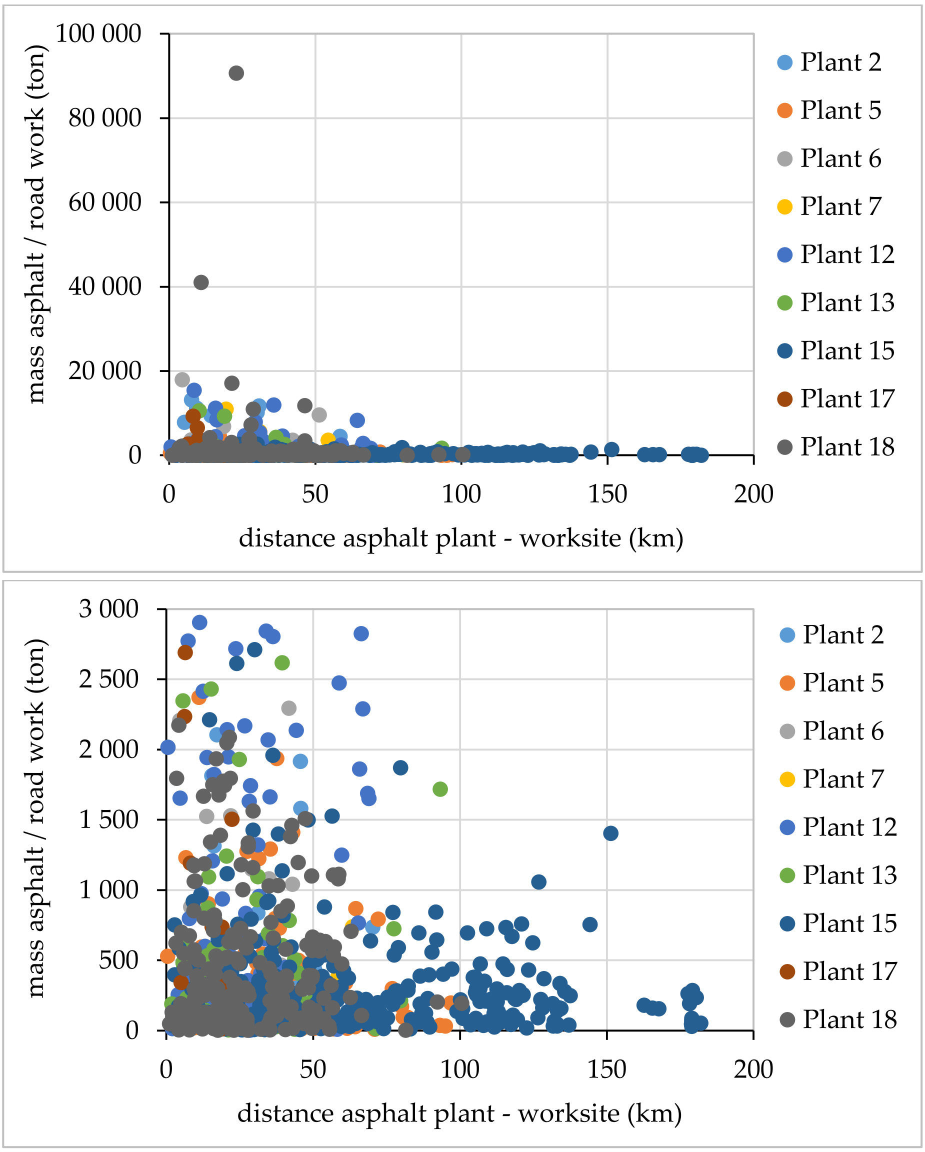


Figure 21: Histogram for distribution of the transport per road work, with cut off on x-axis

The influence of the magnitude of the road work (mass asphalt per road worksite) on the transport distance between plant and road worksite is investigated. Results are presented in Figure 22 (a) and (b). A trend can be seen in the results i.e., worksites a long way from the plant are mainly small works, while large road works are mainly located closer to the asphalt plant.



(a)

(b)

Figure 22: (a) Transport distance between asphalt plant and road worksite, without cut off (b) Transport distance between asphalt plant and road worksite, with cut off on y-axis

5.2.3 Conclusions

Table 6: Distance in Flanders for the transport of materials to the asphalt plant

materials	average distance (km)	standard deviation on distance (km)
crushed aggregates	128	36.5
natural aggregates	95	51
filler	124	58,1
bitumen	61	35
HMA	43.3	34.7
RAP	43.3	34.7
RAP waste from thermal cleansing	143	34.5

An overview of the results of section 5.2 with all transport distances related to the bituminous road sector is presented in Table 6. As a simplification, it is assumed that the released RAP at the road worksite is directly transported to the asphalt plant, without being stock piled in another location. The road transport distance between the asphalt plant and the road worksite is shorter as compared to the road transport distance for the delivery of virgin raw materials. Therefore, less transport (tkm) for raw material delivery to the plant is needed if RAP is used in the asphalt mixture. The transport distance between the plant and the installation for thermal cleansing of tar containing RAP (see appendix 4) is also included in Table 6.

Improvements are possible for the transport distances for delivery of HMA and RAP. 79% of all road worksites are provided with asphalt from a plant that is not the closest Flemish plant to that worksite. Based on the production capacity of all Flemish plants and a theoretical approach to estimate the yearly demand for asphalt pavement construction and maintenance, a reorganisation of worksites in adjusted service areas would be possible to assign a worksite to the closest asphalt plant.

5.3 Moisture content in aggregates and energy consumption at the asphalt plant

The moisture content in aggregates is highly variable and depending on weather conditions and grain size, amongst others. Finer fractions generally contain more moisture because of the small voids between the aggregates that can induce capillary water suction if stored on a wet ground. In addition, the specific surface of the aggregates per volume unit is higher for small grain sizes and hence more water can adhere to the surface of the stones.

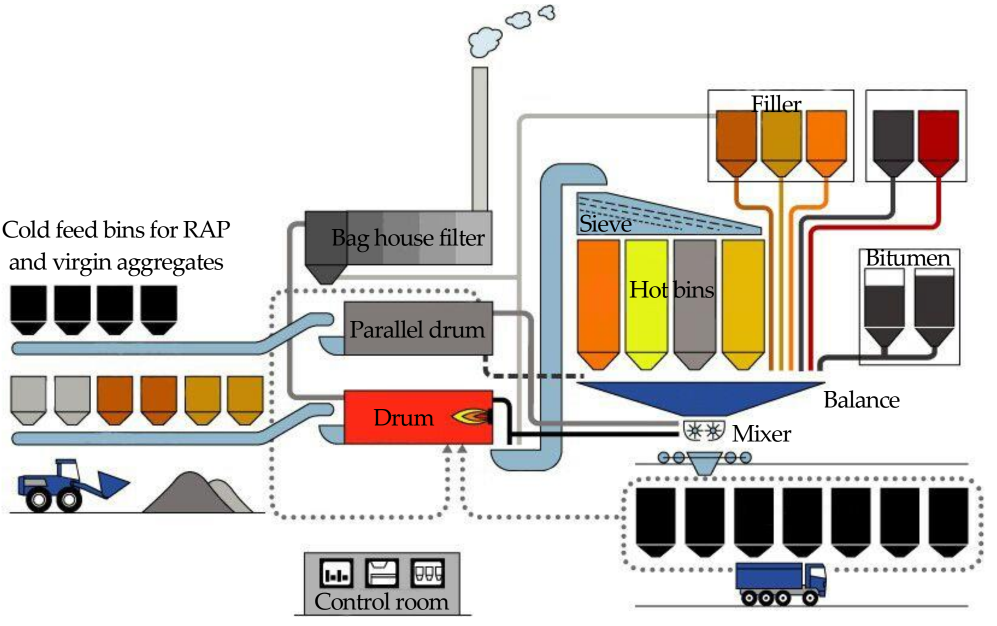


Figure 23: Schematic presentation of an asphalt production batch plant (Van Bentum Recycling Centrale, n.d.)

At the asphalt plant, different virgin stone fractions (e.g., round sand 0/1, sandstone 0/2, sandstone 5.6/8, limestone 6/14, limestone 14/20 etc.) are stored in the cold feed bins for virgin aggregates (see Figure 23). Subsequently a calculated amount of these aggregates enters the drum for drying and heating. Then these warm aggregates are sieved and stored in the hot bins according to the grain size (i.e., 0/3, 3/8, 8/16, and 16/40). A measured mass of these four size fractions is inserted to the mixer. After a short mixing time, filler and bitumen are added to the mixture.

5.3.1 *Moisture content*

5.3.1.1 Virgin aggregates compared to recycled aggregates and effect of shelter

Laboratory test results of one particular plant which were sufficiently detailed could be used for a first analysis of the moisture content of virgin aggregates compared to the RAP. A statistically significant difference between the moisture content of 3 different groups of aggregates is looked for:

- Virgin aggregates (all grain sizes) (1);
- RAP:
    - Stored (uncovered) outside (2);
    - Stored under a shelter (3).

Table 7: Description of dataset of moisture content for virgin vs. recycled aggregates

	virgin	RAP outside	RAP shelter
number of plants/laboratories	1	1	1
period of measurements	01/2014 - 03/2015	03/2012 - 08/2014	03/2012 - 08/2014
number of measurements	59	274	70

Table 8: Results of moisture content analysis in recycled aggregates stored outside vs. under shelter

moisture content (%m/m)	mean	st. dev.	median
RAP outside	3.82	1.55	3.89
RAP shelter	4.09	1.71	3.96

Table 9: Results of moisture content analysis in virgin vs. recycled aggregates

moisture content (%m/m)	mean	st. dev.	median
virgin aggregates	1.86	0.91	1.90
RAP	3.88	1.58	3.90

More information on the data is given in Table 7. Results are presented in Table 8 and Table 9. The data in each group are normally distributed. Using the Levene's test the homogeneity of variances is tested, and using the Anova test the significance of the difference in means for different groups is tested. Following findings are reported:

- There is no statistically significant (α=0.05) difference in mean of the moisture content for RAP stored under a shelf or stored uncovered.
- There is a statistically significant (α=0.01) difference in mean of the moisture content for virgin aggregates (all grain sizes) compared to RAP (both covered and uncovered).

Since the measurements of moisture content in aggregates for virgin aggregates and for RAP were executed in different periods, the monthly weather conditions are compared for these two periods. The non-parametric Mann-Witney test is used. No statistically significant difference in the median precipitation, temperature, wind speed, and sunshine for the two different periods is found.

The influence of the number of days the RAP is stored under the shelter on the moisture content is investigated with a dataset including 70 measurements. The duration of storage varies from minimum 0 days (the RAP was stored and tested on the same day) to maximum 180 days. These are inversely proportional quantities as expected, meaning that the longer the RAP is stored under the shelter, the lower the moisture content is. However, the correlation is weak and statistically insignificant ($r = -0.157$).

Similar and different results were found in literature concerning the moisture content in RAP and virgin aggregates. As described in section 3.4, it is important to note that the virgin aggregates used in asphalt production for Flemish public road works are washed to remove small particles. Hence, both virgin and recycled aggregates are wet when delivered to the asphalt plant. Literature sources discussed below do not mention whether virgin aggregates are washed or not.

A Dutch study reported a moisture content of 3.2% in RAP and 2.7% in virgin aggregates, measured at the asphalt plant between March and November 2012 (Arbeider et al., 2016). Covering aggregate stockpiles is recommended in different studies in literature, especially for fine aggregates and RAP (Ang et al., 1993; Young, 2008). The report from the Re-Road project on the other hand states that: "*However, providing shelter from the rain may not be the primary issue with regards to avoiding moisture content in RA, since the water may have accumulated as a result of planing-off in the previous lifetime and may therefore be difficult to expel from the material without the application of heat.*" (Wayman et al., 2012). Thijssen et al. differentiate between fine aggregates (river sand) and RAP (granulated recycled asphalt) (Thijssen et al., 2011). The authors found that the moisture content in sand benefits from an increased drainage effect, being increasing pile capacity (longer residence times) and decreasing pile height. They found that RAP behaves opposite and the moisture content benefits from measures that limit or prevent the effect of precipitation, including decreasing pile capacity and increasing pile height (area decrease), and precipitation prevention by roofing. It is important to note that the results reported by Thijssen are valid for piles on a porous bottom. Grabowski et al. conclude the opposite by stating that the moisture content in fine aggregates can reduce when they are delivered only shortly before the start of the asphalt production and so the exposure to moisture in case of unfavourable weather conditions is shorter (Grabowski et al., 2013).

5.3.1.2 Influence of aggregate size

The influence of the grain size (of fractions of the virgin aggregates) on the moisture content is investigated based on all data collected from different plants. Four groups of grain size for virgin aggregates are distinguished in analogy with the groups used for dosing aggregates from the hot bins at the plant.

According to SB250 v3.1, only homogeneous RAP (class HE or H+) is allowed for use in mixtures for base layers. The maximal grain size fraction is limited to 40 mm (Vlaamse Overheid, 2015), but there is no minimal grain size fraction defined. Therefore, RAP always contains the finest fractions (e.g., 0/20, 0/40 etc.)

The data in the different groups (as presented in Table 10) are not normally distributed. The Kruskal-Wallis test shows a statistically significant difference in median between the groups. Levene's test of homogeneity of variances shows that the variances are not homogeneous and hence Anova with Games-Howel post hoc test is applied. For both the fraction 0/3 and the RAP, the mean moisture content is significantly (α=0.01) different from all other groups. The mean difference is significant with α=0.05 for fraction 8/16 and 16/40. No statistically significant difference in means is found between 3/8 and 8/16. Considering the grain size fractions, it is understandable that the mean moisture content of RAP is in between the mean moisture content of virgin 0/3 and virgin 16/40.

Results in Table 11 are used for further analysis in subsection 5.3.3.

Table 10: Analysis of dataset of moisture content for different grain size fractions

	0/3	3/8	8/16	16/40	RAP
number of plants/laboratories	4	3	1	1	2
number of measurements	76	32	20	9	359

Table 11: Moisture content of all fractions virgin aggregates and RAP

	moisture content (%m/m)				
	mean	st. dev.	median	min	max
virgin 0/3	7.39	3.85	7.40	1.00	17.86
virgin 3/8	1.96	0.98	1.90	0.10	4.60
virgin 8/16	1.30	0.73	1.15	0.30	3.40
virgin 16/40	0.73	0.21	0.67	0.41	1.07
RAP	3.92	1.58	4.00	0.38	8.30

The moisture content in aggregates depends, among others, on the specific surface of the aggregates (surface of the aggregate per volume of the aggregate). Different moisture conditions are defined for aggregates: oven-dry, air-dry, saturated surface dry (SSD) and wet (see Figure 24) (Pavement Interactive, 2007). In the following analysis, the difference in moisture quantity between wet aggregates and SSD aggregates is modelled. SSD aggregates have a dry surface, but all pores connected to the surface are filled with water. Wet aggregates have excess moisture on the surface. The moisture content of aggregates in SSD condition varies according to the nature of the aggregate, dependent on the porosity of the grain (Loong, 2015). Aggregates in SSD condition have a moisture content identical to the potential absorption (Komastka et al., 2003). Pavement Interactive defined a typical absorption in aggregates used in HMA production ranging from just above 0% to 5% (Pavement Interactive, 2011b). In general, the absorption level (moisture content at SSD) for coarse aggregates is in the range of 0.2% to 4% and for fine aggregates in the range of 0.2% to 2% (Komastka et al., 2003). The moisture content omitted in the following model is hence very variable, dependent on the aggregate type and source. The free-water content is analysed in this section of the study and ranges from 0.5% to 2% for coarse aggregates and from 2% to 6% for fine aggregates (Komastka et al., 2003). As a simplification, the aggregates are considered to be perfect spheres for a mathematical approximation. Equations 1 to 3 are applicable.

$$surface\ area\ A = 4\,\pi\,r^2 \qquad (Eq.\ 1)$$

$$enclosed\ volume\ V = \frac{4}{3}\,\pi\,r^3 \qquad (Eq.\ 2)$$

$$moisture\ content \cong specific\ surface\ area\ \frac{A}{V} = \frac{3}{r} = \frac{6}{D} = 6\,D^{-1} \qquad (Eq.\ 3)$$

With: r = radius

D = diameter

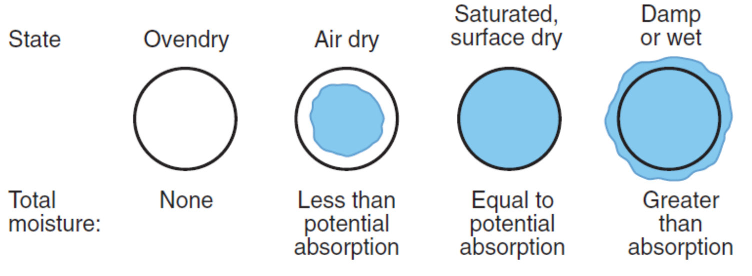


Figure 24: Moisture conditions of aggregates (Komastka et al., 2003)

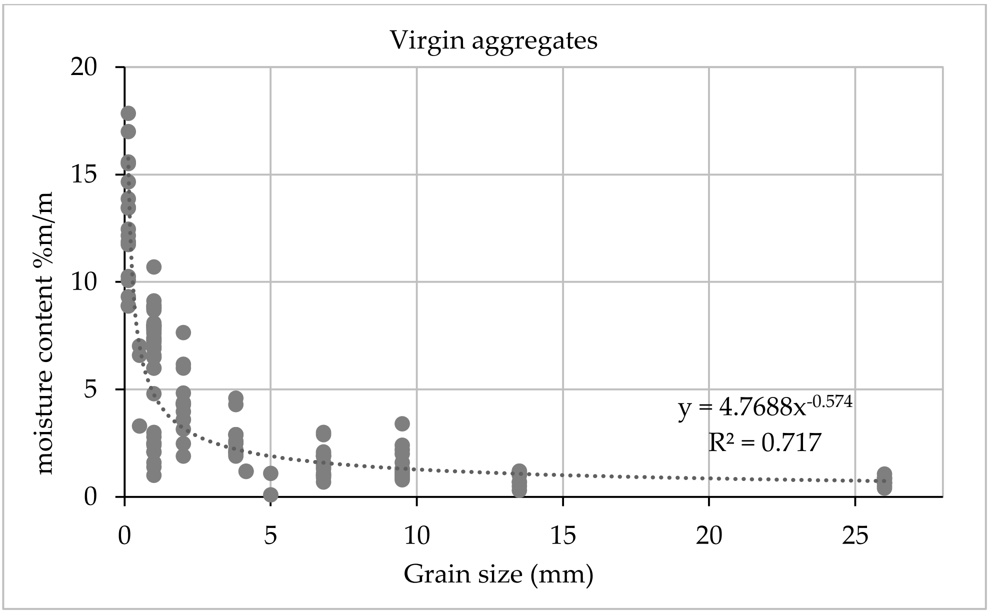


Figure 25: Fitting of a power trend line to measured moisture contents in virgin aggregates

It is seen from Figure 25 that the laboratory measurements of moisture contents fit the theoretical model with a good correlation coefficient ($R^2 = 0.7$). Both the results presented in this graph and in Table 11 indicate that the moisture content in aggregates remarkably increases if the grain size decreases below 5 mm. The same result is found in literature (Ang et al., 1993; Grabowski et al., 2013).

Based on the analyses of the influence of the aggregate size (including both grain size fractions and specific surface), it is not possible to decide on the hypothesis that RAP contains more moisture compared to virgin aggregates. Another research approach is applied and described in the next subsection.

5.3.1.3 Moisture in aggregate mixtures for asphalt production with and without RAP

In this subsection, the moisture content in the aggregate mix of asphalt mixtures is investigated rather than the moisture content in specific grain size fractions. Mixture compositions without and with (15 to 50%) RAP as produced in practice are used for the analysis of the total moisture content in the mix instead of looking at only one grain size fraction. Based on the average moisture content for each virgin fraction and RAP as presented in Table 11, the total amount of moisture (%m/m) in the aggregate mix is calculated. The amount of filler and bitumen in the mixture composition was disregarded in this analysis since these raw materials do not contain moisture. Different analysis approaches are applied.

Table 12: Moisture content in aggregate mix for mixture families with and without RAP

mixture family	fineness of asphalt mixture	moisture content (%m/m) in asphalt mixture 0% RAP	moisture content (%m/m) in asphalt mixture with RAP
1	A	3.1%	
1	A		3.6%
1	A		3.5%
1	A		3.5%
2	B	3.5%	
2	B		4.0%
2	B		4.2%
3	C	3.3%	
3	C		3.4%
3	C		3.4%
4	C	3.8%	
4	C	3.6%	
4	C		3.5%
5	A	3.7%	
5	A		3.5%
6	C	2.5%	
7	C	2.4%	
8	D	2.8%	
9	B	3.4%	
10	B		3.4%
11	B		3.2%
12	D	3.7%	
13	D	3.2%	
14	C	3.8%	
15	C		3.9%
16	C	3.5%	
17	C	3.4%	
18	D	3.6%	
19	C		3.5%
20	A		3.6%
21	B		3.3%
22	C		3.6%

First, mixtures families are searched with at least one variant with RAP and one variant without RAP. These mixture families are similar asphalt mixtures with a slightly varying mixture composition. Considering all HMA productions of 2015, five mixture families are found (mixture family 1 to 5, see Table 12). For mixture families 1, 2, and 3 the mixture with RAP contains more moisture compared to the mix with only virgin aggregates, while for the mixture families 4 and 5 the opposite result is observed.

Second, the means are analysed for the moisture in mixtures with RAP and the moisture in mixtures without RAP, independent of mixture families. 32 mixtures are taken into account as presented in Table 12 (16 mixtures with RAP and 16 mixtures without RAP). Using both parametric and non-parametric tests no statistically significant difference in moisture content is found.

As it is seen in Table 11, the grain size fraction has an important influence on the moisture content. Accordingly the fineness of the aggregates in the asphalt mixture will have a major influence on the total moisture content in the mix of virgin and recycled aggregates. The Flemish road standard for public road works defines the nominal grading of asphalt mixtures with a capital letter (maximal grain diameter D in mm: A=0/20, B=0/14, C=0/10, D=0/6.3, and E=0/4). The finest mixtures D and E are typically only used for surface courses, where the use of RAP is not allowed.
Third, the investigated mixtures are divided according to the nominal grading (A, B, C, and D). In this way, the number of results in each group decreases (A=7, B=7, C=14, and D=4). Within these groups, the differences in moisture content for mixtures with and without RAP are not statistically significant.

Based on the findings in this research, it is not possible to conclude that the moisture content in RAP is unambiguously higher or lower compared to the moisture content in virgin aggregates. Based on the findings in §5.3.1.1, a higher moisture content in RAP compared to virgin aggregates is expected, but the findings in §5.3.1.2 indicate the important influence of the grain size fraction on the moisture content in the aggregates. When considering all (virgin and recycled) aggregates in the mixture composition, with an average moisture content for each grain size fraction as found in §5.3.1.2, no significant difference in total moisture content in the mix is found when comparing mixtures with and without RAP. The fact that virgin aggregates are washed to remove small particles may have an influence on this result.

5.3.2 Energy consumption for drying and heating aggregates

Based on the daily production records at the reference asphalt production plant, absolute values of energy consumption are used for the analyses. The natural gas consumption in m^3 is converted to MJ with the calorific values monthly published by VREG[8], specific for the location of the reference plant (Flemish Regulator of the Electricity and Gas market, 2014). Multiple linear regression is used to model the relationship between two predictor variables (x_1 = asphalt without RAP in ton, x_2 = asphalt with RAP in ton) and a response variable (y = absolute energy consumption in MJ) by fitting a linear equation to the observed data set.

[8] VREG is the Dutch abbreviation for the Flemish Regulator of the Electricity and Gas market

772 production days with an average production of 1 166 ton per day in 2013 to 2016 are taken into account for the development of the model. The average energy consumption is 214 MJ/ton asphalt over these four years.

The following multiple linear regression equation is found.

$$NG = 36\,488 + 202 * M_{RAP} + 158 * M_{0\%} \qquad \textit{(Eq. 4)}$$

With: NG = natural gas consumption (MJ)
M_{RAP} = mass asphalt production with RAP (ton)
$M_{0\%}$ = mass asphalt production without RAP (ton)

The coefficient of determination R^2 is 0.93 for equation 4, meaning that 93% of the variability in the response variable (natural gas) is explained by the two predictor variables (asphalt with RAP in ton and asphalt without RAP in ton).
Based on the two coefficients in equation 4 (202 for asphalt production with RAP and 158 for asphalt production without RAP), it is concluded that the energy consumption is statistically significantly higher if RAP is included in the asphalt mixture and hence the parallel drum is used.

This equation is a model to calculate the energy consumption. Since all production days of 2013 to 2016 are included in the analysed dataset, the model is representative for production days including mixtures other than HMA, for all time periods of the year with associated variations in moisture content and ambient temperature, and for all daily production quantities. However, if the total production volume (M_{RAP} + $M_{0\%}$) strongly deviates from an average daily production amount, equation 4 should be adapted. Equation 4 is based on daily production quantities of minimum 4.5 ton and maximum 3 000 ton. For deviating production volumes, the number of production days was calculated by dividing the particular production volume by the average daily asphalt production in the model (1 166 ton).

$$NG = PD * (36\,488 + 202 * M_{RAP} / PD + 158 * M_{0\%} / PD) \qquad \textit{(Eq. 5)}$$

With: PD = number of production days considered

5.3.2.1 Effect of RAP on the energy consumption

For further analysis of the effect of RAP on the energy consumption for traditional HMA production data for 2015 is used, but all days with asphalt mixture production other than HMA (e.g., mastic asphalt, cold mix asphalt, warm mix asphalt, etc.) and all days with daily asphalt production quantity less than 170 ton (see appendix 5) are removed from the dataset.

All data presented in §5.3.2.1 and §5.3.2.2 are tested for homoscedasticity, and if necessary the standard error in the linear regression model is adapted to be heteroscedasticity-consistent.

Analogous to the interpretation of the two coefficients in equation 4, the share of the daily production in which RAP is used was calculated (ton asphalt with RAP divided by total daily asphalt production) for this reduced dataset and a statistically significant (α<0.01), strong (P≤ 7.4E-5) correlation (correlation coefficient = 0.6) with the specific energy consumption is found. This means that the specific energy consumption (MJ/ton) increases if the share of mixtures with RAP increases.
The weighted average of the RAP content in the asphalt mixture for each production day is calculated (the total amount of RAP used on day X divided by the total asphalt production on day X). These data are taken from the continuous production registration (for COPRO). As supposed from Figure 26 and confirmed by statistical analyses with Pearson and Spearman correlation test, a statistically significant (α<0.01), strong (P≤ 8.8E-6) correlation (correlation coefficient = 0.7) is found. This means that the specific energy consumption (MJ/ton) increases if the RAP content in the mix increases. It is noted that this result is found without taking into account the moisture content in the aggregates.

In appendix 5, additional results are included from the analysis of this daily information for the period 2013, 2014, and 2015. A statistically significant difference in means is found between energy consumptions (m^3/ton asphalt) during asphalt production with and without RAP.

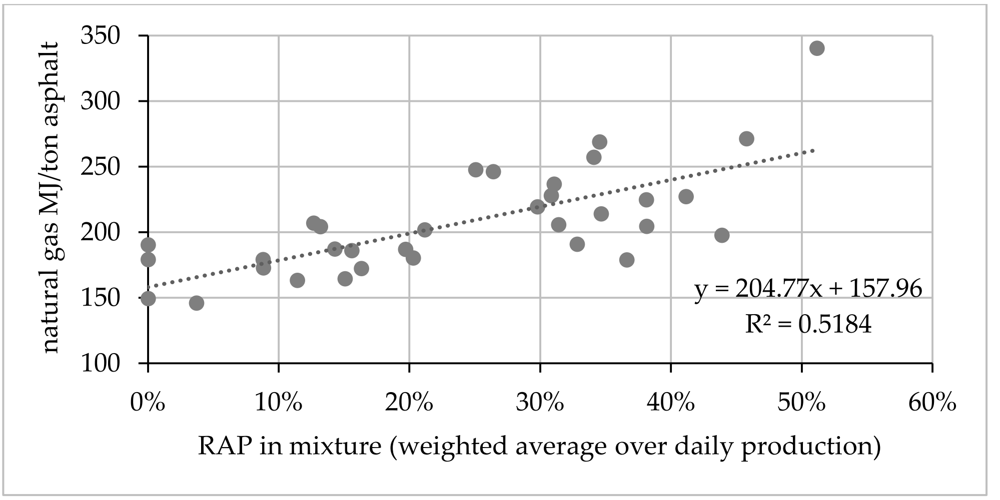


Figure 26: Specific energy as an effect of the weighted average RAP content in the asphalt mixture

5.3.2.2 Effect of number of interruptions in the asphalt production process on the energy consumption

Continuing with the dataset used in §5.3.2.1, the number of interruptions (of minimum 10 minutes) in the asphalt production process is counted. This might affect the energy consumption since the installation cools down during the break and more energy is necessary for reheating the drums to the desired temperature. Both interruptions in the production process and additional switches between production with and without RAP (interruptions in the operation of the parallel drum) are counted and presented in Figure 27. No statistical significant effect of the number of interruptions on the energy consumption at the asphalt plant was found in this analysis.

Contradictory results are found in literature, but might be influenced by the type of asphalt production plant, i.e. continuous or batch production system (Ang et al., 1993; Arbeider et al., 2016; Young, 2008). Young and Arbeider et al. stated that starts and stops during production increase the fuel consumption with 20 to 35% compared to steady production days; while Ang et al. found that the energy consumption would reduce by less than 1% if the daily average interruptions would decrease from 5 to 4. The average number of daily interruptions at the reference plant is only 1.4, for the current, specific analysis. Besides, Arbeider et al. found that the influence of changing recipes on the energy consumption is small.

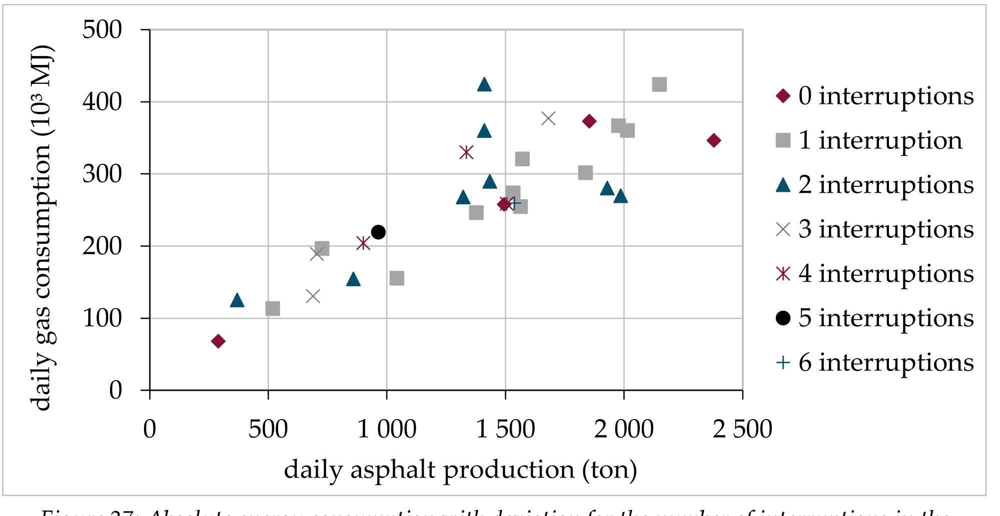


Figure 27: Absolute energy consumption with deviation for the number of interruptions in the asphalt production process

5.3.3 Verification of theoretical models for energy consumption for drying and heating aggregates

The total daily energy consumption of 16 production days is calculated with two different theoretical models and compared to the measured energy consumption for these specific days. Only production days with a minimum daily production of 1 000 ton and maximum two interruptions in the asphalt production process are selected for analysis. In this way, the influence of the start-up energy consumption is minimized. All production dates are selected from the dataset as used in §5.3.2.1, which are production days with exclusively HMA production. As can be seen in Table 14, the analysed production dates are in spring, summer and autumn, because of the production stop during winter months.

The primary aim of the results presented in Table 14 is not to compare the values for the different production days because it was found that there are statistically significant differences in the weather conditions on the different production days included in the analysis.

5.3.3.1 Energy calculation based on enthalpies

The first theoretical model to calculate the energy consumption for drying and heating aggregates is based on the enthalpies of aggregates and water (also described in the BRRC report (Belgian Road Research Centre, 2002)). This model is used to calculate the energy consumption for the LCA case studies in papers IV and V.

Equation 6 is used and comprises the energy needed for heating the dry aggregates, heating the moisture in the aggregates, evaporating the heated moisture, and heating the steam to the temperature of the flue gas.

$$E_{dry+heat} = M_a\, C_a\, (T - T_0) + M_a\, \frac{W}{100}\, \left[C_p(100 - T_0) + C_l + C_s\left(T_f - 100\right)\right] \qquad \textit{(Eq. 6)}$$

With: M_a = mass of aggregates (kg)

C_a = heat capacity of aggregates (kJ/kg.°C)

T = temperature of the aggregate mix after heating (°C)

T_0 = ambient temperature (°C)

W = aggregate moisture content (%)

C_p = specific heat capacity water (kJ/kg.°C)

100 °C = boiling temperature of water

C_l = latent heat capacity of water (kJ/kg)

C_s = specific heat capacity of steam (kJ/kg.°C)

T_f = temperature of flue gas (°C)

Similar equations to calculate energy consumption were found in literature (Ang et al., 1993; Grabowski et al., 2013; Spuziak, 1995). Ang et al. used an ambient temperature of 30 °C and an aggregate temperature of 160 °C while BRRC applied temperatures of respectively 10 °C and 160 °C. Ang et al. excluded the energy consumption for further heating the steam to the temperature of the flue gas. The results of a study by Spuziak (1995) were described by Grabowski et al. (2013) and included a similar equation, including the energy consumption for further heating the steam to the temperature of the fumes. Spuziak includes additional factors (i.e. coefficient of heating efficiency, price of heating oil, heating value of fuel) in order to calculate a monetized energy saving as a function of a reduced moisture content. However, the aim in the current research is to search for an equation that estimates the energy consumption at the asphalt plant, based on some parameters that can be measured in situ, at the asphalt plant, in order to obtain a practical tool to predict energy consumption. Therefore, a simplified version of the equation by Spuziak is used in the current research (equation 6).

The parameters that are necessary to make the calculation are described in the following paragraph and the data sources and calculation method are mentioned.
The material specifications needed for the calculations are presented in Table 13 and are constant for the different production days. Other parameters needed for the energy calculations are specific for the selected production days. The absolute value of the mass of dry aggregates is taken from the continuous production registration as the sum of the materials used in all batches. The heating temperature of the aggregates, both virgin and recycled, is also taken from the continuous production registration as the average over all batches from the temperature measurements of the materials when leaving the drum. The aggregate moisture content is estimated by the values presented in Table 11. The ambient temperature is used as starting temperature of the aggregates before heating. The KMI meteorological data, measured at a location close to the asphalt plant (±11 km), are used. The average temperature during the production hours of the 16 specific days is calculated and used. Finally, the temperature of the stack emissions is estimated based on a small number of measurements at the dust extraction for exit air and expert opinion (Van Damme et al., 2016). Two default values are used in the calculations: 110 °C for production without RAP, 140 °C for production with RAP. These values are estimated in consultation with the plant manager.

Table 13: Material specifications for theoretical energy calculation based on enthalpies

	material	value	unit	data source
specific heat capacity	Sandstone	0.92	J/kg.°C	CES EduPack
	Limestone	0.91	J/kg.°C	CES EduPack
	Porphyry	0.81	J/kg.°C	CES EduPack
	RAP	0.92	J/kg.°C	(van Atteveld et al., 2003)
	Water	4.18	J/kg.°C	(van Atteveld et al., 2003)
	Water vapour	2.0	J/kg.°C	(van Atteveld et al., 2003)
energy to evaporate	Water	2 260	J/kg	(van Atteveld et al., 2003)

The results are presented in Table 14. The deviation of the calculated energy consumption compared to the measured energy consumption is between 5% and 33%. For all analysed production days, the calculated energy consumption is higher compared to the measured result.

5.3.3.2 Energy calculation based on production mass with and without RAP

The second theoretical model to estimate the energy consumption for drying and heating aggregates in asphalt production is based on the linear regression equation 4 as described in subsection 5.3.2. This model is more user-friendly since fewer parameters are needed for the calculation.
It is noted that the 16 production days used in the current comparison are also included in the dataset that is used to develop the multiple linear regression model. However, in this way, the deviation of the theoretical model on the individual measurements is tested. The main goal of this comparison is to analyse the accuracy of both theoretical models. The results are presented in Table 14. The deviation between the new theoretical and the measured value is -4% to 28%.

With the new theoretical model, it is possible to better estimate the energy consumption at the asphalt plant compared to the theoretical model based on enthalpies. For only 2 of the 16 days, the deviation from the measured energy consumption is larger for the new model than for the enthalpies model. Taking into account the increased ease of use, due to less independent variables, the development of the model to estimate the energy consumption is a valuable improvement.

Table 14: Natural gas consumption at the plant: comparison of measured value with theoretical calculated estimations according to two different

	measurement in situ			estimation based on enthalpies (Equation 6)		estimation with linear regression (Equation 4)	
date	total daily production (ton)	daily production with RC (ton)	energy consumption natural gas (MJ)	energy consumption natural gas (MJ)	deviation between theoretic and measured	energy consumption natural gas (MJ)	deviation between theoretic and measured
30/04/2015	1 495	283	260 913	322 860	24%	285 584	9%
13/05/2015	1 359	645	283 883	298 784	5%	280 024	-1%
6/06/2015	2 150	2 148	428 828	523 271	22%	471 530	10%
7/06/2015	2 379	208	350 325	466 487	33%	422 125	20%
14/06/2015	1 043	0	157 172	201 530	28%	201 492	28%
19/06/2015	1 853	1 853	377 486	412 706	9%	411 637	9%
26/06/2015	1 564	385	257 620	315 626	23%	300 921	17%
2/07/2015	1 838	685	305 299	377 717	24%	357 613	17%
3/07/2015	2 015	0	364 296	412 063	13%	355 347	-2%
7/07/2015	1 930	1 062	364 172	446 621	23%	388 765	7%
10/07/2015	1 407	1 039	292 290	326 217	12%	304 989	4%
14/08/2015	1 434	1 247	270 911	299 094	10%	318 523	18%
11/09/2015	1 533	1 047	276 734	357 389	29%	325 365	18%
18/09/2015	1 322	1 103	272 721	291 960	7%	294 352	8%
2/11/2015	1 977	715	370 973	445 323	20%	380 879	3%
16/11/2015	1 986	1 343	429 173	478 628	12%	410 140	-4%

5.3.4 Electricity consumption at the plant

The dataset for the analysis of the electrical energy consumption is based on measurements on the same asphalt plant as used for measurements of natural gas consumption. It is described in §4.2.2.2 which components of the asphalt plant consume electrical energy.

The electricity consumption for 8 successive days (each day considered as a twenty-four hours period) in autumn 2015 is requested at the technical service of the reference plant. Since the plant uses smart meters, the historical data are saved. The electricity consumption includes all electricity consumption for each day, both related and not related to the asphalt production. In other words, it is all electricity consumption within twenty-four hours for asphalt production, heated storage of bitumen, offices, weighbridge, etc. Two weekend days, without any asphalt production, are included in the 8 successive analysed days. The average electricity consumption of these two days is considered as the electricity consumption of the plant in a standby mode, including heating bitumen, standby mode of desktops, heating, lighting, sensors etc. The difference between the electricity consumption on asphalt production days and the average electricity consumption on days without asphalt production is considered to be representative for the electricity consumption of most processes related to the asphalt production process i.e., operation of offices, weighbridge, conveyor belts, drum and mixer rotations, etc.

The bitumen tanks are assumed to be important electricity consumers. The installed electrical power for heating the five electrical bitumen tanks together is 100 kW, excluding the agitator mixer for PMB. However, the final electricity consumption by the tanks depends, amongst others, on the reservoir filling factor, ambient temperatures, and storage time. It is confirmed that the bitumen tanks are only heated during nights. Case specific measurements were carried out in the scope of the Carbon Free-Ways project. The average overnight electricity consumption (based on measurements over 3 nights) was found to be 42 kWh for one tank filled with pen-bitumen and 75 kWh for another tank filled with PMB. Based on these results, the estimated electricity consumption for heating bitumen is 45 kWh per night and for mixing PMB is 30 kWh per day and 30 kWh per night.

The average energy consumption is 4.80 kWh/ton asphalt (= 17.3 MJ/ton asphalt) when all electricity consumers for the six analysed production days are considered. The higher the daily asphalt production, the lower the electricity consumption per ton asphalt. Dividing the total annual electricity production by the total annual asphalt production at the reference plant in 2014, an average electricity consumption of 5.05 kWh/ton asphalt (=18.2 MJ/ton asphalt) is found.

Subtracting the stand-by consumption as measured during the weekend days without asphalt production, the average electricity consumption for the six analysed production days is 2.98 kWh/ton asphalt (=10.7 MJ/ton asphalt). The influence of the magnitude of the daily asphalt production is smaller for these results.

The installed electrical power of the installation is calculated for each of the six days by dividing the electricity consumption by the actual production period. The maximal calculated electrical power is 583.4 kW. However, it is recognised that the calculated power based on the consumption is different compared to the installed power since there is a shift by the efficiency of the plant and a margin for the maximal capacity that can be requested.

5.3.5 Comparison with literature

Values found in literature related to electricity consumption are presented in Table 15 and Table 16. The best available technique (BAT) study (Leyssens et al., 2013) gives the thermal and electrical power of the installation while the two other studies (Stripple, 2001; Wayman et al., 2012) give the energy consumption per ton asphalt.

An overview is made of the installed thermal power at the reference asphalt plant to validate the values found in literature (Leyssens et al., 2013). The burner in the drum for virgin raw materials has an installed power of 23 720 kW, delivered by the combustion of natural gas. The burner in the parallel drum (for heating RAP) has an installed power of 11 850 kW, delivered by the combustion of natural gas. The electrical power is calculated in subsection 5.3.4. The installed power of the installation for heating thermal oil is 880 kW, delivered by the combustion of natural gas and serving the two oldest bitumen tanks, heating of bitumen pipes, and wall heating for different components in the asphalt plant. Finally, the thermal power of the four newest bitumen tanks is 110 kW, delivered by the electrical heating installation.

The BAT study defines the thermal power for heating as the cumulative thermal power for the drums both for virgin and recycled aggregates. For the reference asphalt plant, this cumulative thermal power for both drums is larger, but in the same order of magnitude compared to the results presented in the BAT study. The higher thermal power for the drums is explained by the higher nominal production capacity compared to the average for Flanders (as explained in §4.2.2.3).
The thermal power for bitumen tanks in the BAT study includes the thermal power for non-electrical bitumen tanks. Even when the power for heating the electrical tanks is included, the installed power is beneath 1 000 kW and significantly smaller compared to the result in the BAT study. Therefore, it is supposed that a unit mistake

was made in the BAT study. In each case, the installed thermal power for both drums is higher compared to the thermal power for the bitumen tanks.
The electrical power of the asphalt plant is defined as all the power needed for driving all motors for dosing installations, conveyor belts, drums, fans, sieving installation, and also for the operation of the control room, and for the electrically heated bitumen tanks. The electrical power at the asphalt plant, as calculated in subsection 5.3.4 is of the same order of magnitude as the results presented in the BAT study.

Next, the results obtained in the current research are compared to the findings in literature for the energy consumption per ton asphalt produced (Table 16). For the current research, the energy consumption per ton asphalt was calculated as the average over all production days from 2013 to 2016 (see subsection 5.3.2). This means that all asphalt mixture types are included, i.e. HMA, WMA, mastic asphalt, cold asphalt, mixtures with RAP, mixtures without RAP etc. The results are lower compared to the findings in literature, but in the same order of magnitude.
For The Netherlands in 2010, the average energy consumption per ton asphalt is reported to be 320 MJ/ton and 290 MJ/ton for the most energy efficient plants (Roos, 2012), which is in the same order of magnitude as 285 to 315 MJ/ton as presented in Table 16 (Stripple, 2001; Wayman et al., 2012). However, it is not specified which energy consumers are included in the study by Roos. The energy consumption reported in the study of Wayman et al. is not adjusted for different mixtures with different recycling rates.

Table 15: Thermal and electrical power of an asphalt plant: own results compared to values found in literature

	own results	(Leyssens et al., 2013)
heating energy (kW_{th})	35 570	29 000
electrical energy (kW)	583	800
bitumen tanks (kW_{th})	880	530 000*

** A unit mistake in literature is assumed.*

Table 16: Energy consumption per ton asphalt: own results compared to values found in literature

	own results	(Stripple, 2001)	(Wayman et al., 2012)
heating energy (MJ/ton asphalt)	214	285	315
electrical energy (MJ/ton asphalt)	17.3	36	

5.3.6 Discussion and main conclusions

The covered storage of both RAP and virgin aggregates is defined to be a BAT from case to case (Leyssens et al., 2013). No effect from the covered storage of aggregates on the moisture content in RAP is found in the current study. Thus, the construction of a shelter is, based on the findings of this study, not assessed to be a BAT. However, it is noted that the standard deviation on the moisture content is relatively high (compared to the mean), since there is a large amount of variation in moisture content over seasons etc.

Besides, no significant difference in total moisture content in mixtures with and without RAP was found from the current analysis.

Based on the research in section 5.3, a user-friendly and accurate model to estimate the energy consumption at the asphalt plant is developed. The results calculated with this model, based on multiple linear regression, are closer to the measured energy consumption when compared with the theoretical model based on enthalpies. The developed statistical model is mainly useful for researchers to predict the energy consumption at the asphalt production site based on production mass with and without RAP. Environmental impacts can be calculated from the energy consumption based on existing databases and therefore the model is of high value for environmental assessment.

However, it is important to remark that the calculated natural gas consumption is not only applied for heating and drying aggregates. Based on the installed thermal power at the asphalt plant (see subsection 5.3.5), 2.5% of the consumed natural gas should be attributed to heating stored bitumen, walls, and pipelines in the plant.

Asphalt production with RAP consumes statistically significantly more energy compared to asphalt production with only virgin raw materials. The reason of the higher energy consumption is not known at this moment. This might be the result of a combination of different aspects: moisture content in virgin and recycled aggregates, lower efficiency of the heat transfer in the drum for virgin materials, or higher temperature of virgin materials when using RAP in the mixture. It was suspected from the data analysis and confirmed by expert (Van Damme et al., 2016) that the temperature of virgin aggregates is increased when RAP is used in the mixture. The default heating temperature of RAP is 120 °C and hence, heat transmission is required for reaching the desired mixing temperature of HMA, being 140 to 190 °C.

5.4 Holistic LCA study for Flanders

5.4.1 Introduction

As the final piece in the research on the environmental impact of the use of RAP in Flanders, an LCA study is established and the results are presented in this section. The Flemish situation as investigated in the thesis is the subject of the current LCA study. A cradle-to-gate life cycle with options (European Committee for Standardization, 2012) is modelled based on the real practice in Flanders.

The aim of the present LCA study is to avoid LCA results based on assumptions that are not verified with real practice in Flanders. The system boundaries of the study are selected with this aim in mind, and hence, due to missing information (i.e., related to the service life) some processes in the use phase are not included in this LCA study.

5.4.2 Outline of the case and used materials

As described in chapter 1, most Belgian road works are (structural) maintenance works instead of the construction of new roads at new locations. The present LCA study is based on this fact and applied on a secondary road. A realistic construction class for a secondary road is B4, with 8 to 16 million $ESAL_{100\,kN}$ over its service life, or about 1 000 to 2 000 $ESAL_{100\,kN}$ per day.

The geometry of the road section in the present study is determined to start from a certain mass of asphalt, selected within the 95% confidence interval of the dataset collected for Flemish road works (see Table 4, subsection 5.2.2), being 962 ton asphalt. Based on road works executed in practice in the past, a base course of 8 cm thick and a surface course of 4 cm thick are considered a realistic maintenance inlay intervention for secondary roads. It is noted that a second base course is used in Flanders in order to smooth away unevenness in the road foundation. The total thickness of the pavement on secondary roads can be up to 23 cm, as prescribed in the standard structures defined by ART. This second base course is not included in the current analysis. A density of 2.4 ton/m^3 asphalt and a paved width of 3.3 m per lane (Agentschap Wegen en Verkeer, 2012) are used to convert the asphalt tonnage to a road surface of 3 300 m^2, that equals a 1 000 m long single lane or a 250 m long 2x2 lanes road.

Due to insufficient knowledge on the service life of pavements in real practice in Flanders and the effect of RAP (see section 5.1), it is impossible to define a realistic service life of the surface and base course. Hence, the current analysis includes the replacement of the surface course (after x years after initial construction) and the end-of-life of the base course (including deconstruction of the surface course; after y years after initial construction). Since the processes in the use phase that are affected by the duration of the road operation (i.e. traffic, lighting, etc.) are excluded from the current analysis, the service life does not affect any process within the life cycle.

The asphalt mixture types are selected based on data from COPRO on the asphalt production in 2014 (COPRO, 2015a). The mixture type mostly used for base courses is APO (AC-20) and the asphalt mixture type mostly used for surface courses is AC (type 4). Data of COPRO 2014 showed that 96% of asphalt mixtures for base courses contain RAP. The average amount of RAP in asphalt mixtures for base courses with RAP is 44% and is calculated based on production information from three different asphalt plants, including the reference plant. A real mixture composition as used in practice is adapted for the APO mixture composition for the base course with 44% RAP. The bitumen content on the aggregate mixture remains the same for the mixture with RAP or without RAP, namely 4.6% on the aggregates, being the average for APO as calculated from the dataset (see subsection 5.1.1 and paper VI). The same dataset was used to determine a realistic %O/N when 44% RAP is included in the mixture. This is 59% O/N, calculated as the average value of four asphalt mixtures with RAP content varying from 42 to 47%. The asphalt mixture for the surface course includes only virgin raw materials, following the SB250. The mixture compositions from registered asphalt mixtures (according to SB 250 v2.2) are adapted if needed and used in the current study: AC-10 for the surface and APO-20 for the base course.

Following amounts of dense HMA mixtures are hence produced for initial road construction in the present study:

- 618 ton APO-20 with 44% RAP;
- 23.5 ton APO-20 without RAP;
- 321 ton AC-10 without RAP.

It is important to distinguish mixtures for the base layer with and without RAP since it affects the energy consumption (see equation 4). However, this scenario will not be the real practice within one road worksite. It is supposed that the 4% of mixtures for base layers without RAP are due to exhausted stocks or other practical constraints.

5.4.3 LCA framework

More information about the general life cycle assessment methodology is given in subsection 4.2.1. SimaPro 8.2 is the software used to conduct the analysis in this LCA study. The ecoinvent 3.1 database and the ReCiPe (endpoint v1.12 hierarchist average weighting) LCIA method are used. Indirect upstream processes are included in all the phases of this LCA study.

5.4.3.1 Goal and scope definition

Goal

An accurate environmental assessment of the Flemish asphalt sector does not exist at this moment. This work is specific for the Flemish situation and is elaborated for better understanding the major environmental impacts from bituminous road pavements, including the use of recycled material (RAP). Additional scenarios are generated for investigating the possible environmental savings when the transport distance between plant and road worksite is reduced, and when the durability of asphalt mixtures with RAP would be worse compared to virgin materials.

Functional unit

The functional unit (FU) of the present case study is a 250 m long pavement section on a secondary road (2x2 lanes). The paved width of each lane is 3.3 m and the thickness of the pavement is 12 cm for the baseline scenario. The analysis period is undefined, but includes an initial inlay construction and one time the replacement of the surface course.

System boundary

The following terms as defined in subsection 4.2.1 characterize the baseline scenario of the current LCA study:

- environmental assessment: social and economic assessments are necessary for a complete sustainable assessment, but not included in this chapter;
- cradle-to-gate with options: the study comes close to a cradle-to-grave life cycle, but operation time dependent processes in the use stage are excluded;
- project level: the study rather focuses on the choice for a specific design, however it approaches a corridor level since the possibilities to reduce environmental impact for the whole sector (e.g., optimised transport) are assessed as well;
- stand-alone (baseline): in order to identify the environmental hot spots of the current practice in Flanders.

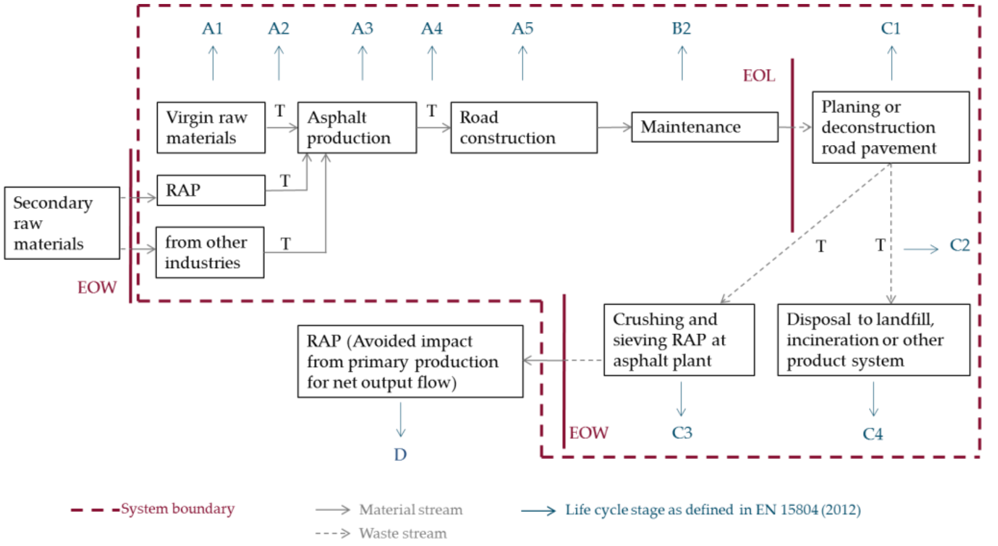


Figure 28: System boundaries of holistic LCA study

Figure 28 illustrates the life cycle stages as defined by EN 15804:2012 (European Committee for Standardization, 2012) that are included in the present LCA. Other life cycle stages are beyond the scope of this study:

- B1: use stage with environmental impact from e.g., road users;
- B3-B5: the replacement of the surface course is included in the maintenance stage (B2), other repair, replacement, or refurbishment are not applicable or not included;
- B6-B7: the operational energy (e.g., for lighting) and water use are not applicable or beyond the scope of the study;
- C4: no materials released at the end-of-life stage are disposed, because all materials are reused in different applications in another life cycle after a certain treatment.

It is recognized that the use stage is an important contributor to the cradle-to-grave life cycle environmental impact of road pavements, but this stage is however excluded from the study due to missing data. It is estimated from results in literature that the environmental impact of the traffic using the road construction over its service life is the major contributor to the life cycle impact, varying from 90 to 99.998% (Chappat and Bilal, 2003; Huang et al., 2009a; Kicak and Ménard, 2009; Milachowski et al., 2010; Stripple, 2001; Yu and Lu, 2012).

The focus of this thesis is on asphalt mixtures for base courses, where the use of RAP is allowed in accordance with the SB250 v3.1. Various aspects related to the environmental impact in the use phase are related to the surface course e.g., the influence of the rolling resistance of the pavement on the fuel consumption of vehicles. Environmental impacts of operation time dependent processes in the use

stage are therefore not investigated in the scope of the Flemish practice and hence omitted due to the absence of the appropriate data.
Some other processes are excluded, despite that they can be assigned to the life cycle stages within the system boundaries:

- preparation of the worksite (earthwork), construction of foundation and second base course, etc. are excluded since the FU includes only an inlay construction of surface and base course;
- pavement joints, bitumen strips, and construction equipment adjusted for the specific worksite;
- road marking is excluded;
- and overhead impact from plant operation e.g., paper used at offices etc.

Beside the baseline scenario, also other scenarios are generated:

- an LC similar to the baseline without the use of RAP for being able to define environmental benefit of the use of RAP;
- an LC similar to the baseline with a reduced transport distance between plant and road worksite, respecting the service areas as described in subsection 5.2.2;
- and an LC where the durability of asphalt with RAP is assumed to be lower and hence the same design service life is reached by the construction of a thicker base layer.

Assumptions

For modelling the life cycle of a bituminous road pavement in Flanders, some assumptions are made when proper information is lacking. Assumptions are described in the life cycle inventory section where appropriate.

5.4.3.2 Life cycle inventory

In general, foreground quantitative information (definition see 4.2.1) is collected in practice. Environmental information is taken from an existing database: ecoinvent v.3.1. The data used in the LCA is described per life cycle stage.
Data uncertainty analysis is included in this study. Information on the data distribution is included in the inventory for being able to conduct uncertainty analyses using Monte Carlo simulations, as integrated in SimaPro. In the unit process version in the ecoinvent database, almost all data records come with a specification of uncertainty. Four different data distribution types are included in SimaPro: lognormal, normal, triangular, and range. More information can be found in the report 'Introduction to LCA with SimaPro' (Goedkoop et al., 2016).
The distribution in the LCI data is determined by using statistical analysis. The analysis is executed in a strict order. First, data are checked for normal distribution by using the Z-value, and by using the results of the Kolmogorov-Smirnov and

Shapiro-Wilk Normality tests. If these analyses confirm a normal distribution, no further analysis occurs. For a normal distribution, the mean value is used as the "best guess" and the standard deviation is multiplied by 2 to characterize the distribution of the data. If the data are not normally distributed, a second step follows. The natural logarithm is calculated as a new variable, based on the original variable. The lognormal distribution of the original variable, is checked by controlling the normal distribution of the new, log-variable. For a lognormal distribution, the median value is used as the "best guess" and the standard deviation is squared to characterize the distribution of the data (Golsteijn, 2015). If the data are neither normally, nor lognormally distributed, the distribution of the data is analysed based on the shape of the histogram. Two options are left: a triangular distribution, or a range. In both cases, the mean value is used as the "best guess" and the minimum and maximum are used to characterize the distribution of the data.

An overview of the LCI of the different scenarios is included as an (interactive) Excel file in appendix 6. The rows are grouped in different levels, what also gives information on the way the different materials and processes are modelled. It is noted that the suffix "_BE" in the column 'ecoinvent record' means that the original ecoinvent record is adapted to better represent the Flemish situation. For example, the Swiss electricity mix is replaced by the Belgian electricity mix. The importance of these adaptations is described in paper VII.
The same column in appendix 6 shows that the system model 'allocation, recycled content' is chosen. More information on this choice is given in §4.2.1.2.

More information on the life cycle inventory in the different life cycle stages according to the system boundaries presented in Figure 28 is given in the next paragraphs.

A1 raw material supply

The quantity of raw materials is calculated based on the selected mixture compositions as described in subsection 5.4.2.
Since a real composition of filler is often protected and hence missing, a 100% limestone powder is used as filler in the LCI. Pure limestone powder is often used in Flemish practice as a type I filler and thus an acceptable simplification of the real practice.
RAP as a raw material is included in the product stage without an environmental burden, which is in accordance with the cut-off system model as defined by ecoinvent (ecoinvent Centre, 2014) and described in §4.2.1.2.

Fixed values are used for the quantities of raw materials, without information on the data distribution. Material processes from ecoinvent are used for the raw materials, except for bitumen and emulsion. Data for bitumen are taken from a life cycle inventory published by Eurobitume (Blomberg et al., 2012). More information on this LCI is given in paper IV.

A2 raw materials transport to plant

The dataset for the transport distances for the delivery of raw materials to the asphalt plant is taken from subsection 5.2.1. This dataset is subjected to the statistical analysis as described in §5.4.3.2. All transport distances for delivery of virgin raw materials are normally distributed, except for the distance of crushed aggregates that is lognormally distributed.

As a simplification, the transport distance for the delivery of RAP to the asphalt production plant is modelled as the transport distance between the road worksite and the plant. These data are discussed in subsection 5.2.2 and have a triangular distribution.

Emulsion is used for tack coating at the road worksite. As a simplification, it is assumed that the emulsion is always first delivered to the asphalt plant and is later transported from the plant to the road worksite with the appropriate equipment. Hence, the transport distance for the delivery of emulsion to the plant is the same as the transport distance for bitumen, i.e. from the port of Antwerp to the asphalt plant.

The amount of transport (tkm) as specified in the LCI ("best guess" value) is calculated by multiplying the average (for normally distributed data) or median (for lognormally distributed data) transport distance (km) in Table 3 or Table 4, by the mass (ton) of the material for this specific case. The deviation in the data was specified as follows:

- for normal distribution: [st. dev. (km) * mass (ton)]*2;
- for lognormal distribution: [st. dev. (km) * mass (ton)]^2;
- for triangular distribution: [MIN (km) * mass (ton)] and [MAX (km) * mass (ton)].

All transport processes of raw materials, asphalt mixture and waste are executed by truck. The trucks are assumed to be fully loaded with approximately 30 ton. The use of only trucks is a simplification. Due to the opportune location of some Flemish asphalt production plants, virgin raw materials are sometimes transported over inland water ways for the delivery to the plant. For the transportation of emulsion with the tack coating equipment and for the sweeping machine, a garbage truck was used as the best approximation.

The ecoinvent dataset lorry 16-32 metric ton with Euro 5 emission standard is used for all transport processes in the life cycle (see LCI in appendix 6). Euro 5 was implemented in October 2008 and Euro 6 was implemented in January 2013. However, it is recognized that lorries with Euro 4 or lower are still part of the current lorry fleet. Sensitivity analyses on the lorry size and emission standard of the truck are included in subsection 5.4.6.

"*The freight transport products describe the transport services in metric ton-kilometres with average load factors that include the average share of empty return trips.*" (Weidema et al., 2013) The (empty) return journeys are included in the selected ecoinvent dataset by the average load factor that is 5.79 ton for the lorry size class 16-32 ton. The average load factors in ecoinvent are taken from the European Tremove model v2.7b and the global EcoTransIT study. The mass of the transported material and the single way transport distance should be included for modelling the transport in ton-kilometre.

A3 asphalt production

The environmental impact from the asphalt production includes only energy consumption (natural gas and electricity) during the production process. The natural gas consumption is calculated based on the multiple linear regression equation 5 as presented in subsection 5.3.2. As specified in subsection 5.4.2, 618 ton asphalt contains RAP, being 64% of initial asphalt production in the baseline scenario.

The standard error on the different factors in equation 5 are known and so the standard deviation on the different factors and the overall standard deviation is calculated to characterize the data distribution.

The effect of production interruptions and switches between different mixtures on the energy consumption is not included in this case study. However, based on research results in §5.3.2.2 and based on literature both are assumed to have a minor influence (Arbeider et al., 2016).

The electricity consumption at the asphalt plant is calculated based on registration of electricity consumption at the plant during six asphalt production days as described in subsection 5.3.4. The data include all electricity consumption at the plant, including consumption from offices, bitumen tanks etc. The mean value and standard deviation are calculated and used as presented in appendix 6.

The accuracy of the Belgian electricity mix in ecoinvent is described in paper VII. The data for the Belgian electricity mix in ecoinvent v3.1, system model recycled content are a good estimation of the Belgian electricity mix in practice in 2015. Therefore, ecoinvent v3.1 is assessed to be a good LCI source for these data.

A4 transport from plant to road site

The transport distance between plant and road worksite has a triangular distribution. The total asphalt mass (962 ton) is multiplied by the mean, minimum and maximum transport distance and presented in appendix 6 as the transport of the asphalt mixture to the worksite. Besides, also the environmental impact from the transport of the road construction equipment to the worksite is included in the analysis.

The mass of the equipment used for the road construction is:

- finisher: 20.8 ton;
- rubber wheeled compactor: 15.8 ton;
- compactor: 10.1 ton;
- mini compactor: 3.2 ton.

These equipment are transported to the road worksite with a flatbed trailer. However, this is not included in the ecoinvent database, and hence, a regular lorry was selected, with a load capacity of 32 ton, sufficient to transport these equipment. Finally, the emulsion for tack coating is transported from the plant to the road worksite in the equipment used for the tack coating itself, represented by a garbage truck in this study.

A5 road construction

Energy consumption by machines for road construction is neither determined to be one of the major contributors to the total environmental impact nor significantly different for pavement construction with or without RAP. However, results of sections 5.1 to 5.3 indicate that it is important to verify data in literature to be representative for the current period and the specific region in the LCA analysis. Measurements on the energy consumption and pavement construction speed are executed in practice for comparison with the information as found in literature used in the preliminary LCA case studies (section 2.2).

WMA test sections are constructed at Scheldelaan in Antwerp, Flanders. The area of the road work is 1 km long and 6.8 m wide in the two directions (total surface of 136 000 m^2). The base course is 8 cm and the surface course is 4 cm thick. Eight different combinations of mixtures for base and surface course are applied.

Both the consumption of fuel, water, and/or gas oil of the machines and the construction speed are measured. The total consumption of the machines is measured for the construction of the whole road work and converted to a consumption per square meter. It is important to note that the activities related to road deconstruction (milling and sweeping) are mostly executed in one phase, over the whole thickness of the road pavement (including base and surface course).

Activities related to road construction (tack coating, finishing, and compacting), on the other hand, are executed in two different phases, separately for base course and surface course, and thus the processed surface is double.
The construction speed for milling, sweeping, tack coating, paving, and compacting is measured multiple times for a marked surface and the average is calculated. Tack coating is applied by a constant driving speed, depending on the emulsion dosage but independent from the coating width. The results are presented in Table 17 and compared to the findings in literature.

The measurements in situ reveal that the machines for the road construction have a lower construction speed and consume more fuel compared to the values reported by Stripple (Stripple, 2001). The reason for the difference between own measurements and values found in literature can be analysed in further research. Aspects that might induce differences in energy efficiency are the extent and the complexity (e.g. bend, intersections, etc.) of the road worksite.
The environmental impact calculated based on the measurements in situ will be higher compared to the values as found in literature (Stripple, 2001).

For the road construction, all road equipment (tack coating, finisher, and compactor) consume fuel. Water is consumed by the compactor and emulsion is consumed for the tack coat layer. Data, as described in Table 17, are used to quantify the consumption.

The amount of emulsion for tack coating is based on specifications in SB250 v3.1, being minimal 200 g/m^2 residual binder. Data for emulsion are taken from a life cycle inventory published by Eurobitume (Blomberg et al., 2012). The FU of the LCI for bitumen emulsion is 1 ton of residual bitumen and can hence directly be used for the minimal quantity as defined in SB250.

Table 17: Consumption of fuel, water, and gas oil of road construction machines and construction speed - measurements in situ compared to literature

		consumption litre/m²			construction speed				
		measurements	literature (Stripple, 2001)		unit	measurements		literature (Stripple, 2001)	
milling	fuel	0.18	0.0044		m²/h	1233	12,5 cm thick and 2,2 m width		
	water	2.9							
sweeping	fuel	0.022							
	gas oil	0.088							
	water	0.22							
tack coating	fuel	0.0040	0.00021	2.5 m width	km/h	5.82	0,3 kg/m²	5.7	0,2 kg/m²
			0.00013	4.0 m width				11.4	0,1 kg/m²
paving	fuel	0.033	0.020	5.0 m width	m²/h	875	8 cm thick and 3,4 m width	1000	5.0 m width
			0.017	6.5 m width	m²/h	934	4 cm thick and 3,4 m width	1300	6.5 m width
compacting	fuel	0.038	0.011	1.2 m width	m²/h	517	8 cm thick and 3,4 m width	425	1.2 m width
			0.023	1.7 m width	m²/h	685	4 cm thick and 6,9 m width	791	1.7 m width
	water	0.28							
total	fuel	0.27	0.048						
total	water	3.4							
total	gas oil	0.088							

** high accuracy of some data in this table needs a nuanced interpretation*

B2 surface course replacement

This life cycle stage includes the upstream life cycle stages related to the replacement surface course: raw materials, transport of raw materials to plant, energy consumption for asphalt production, transport of asphalt mixture from plant to worksite and road construction. Besides, also processes to deconstruct the surface course are included: milling the old pavement and sweeping the surface to remove small particles. This includes the transport of the milling machine (36.4 ton) and the sweeping machine from the asphalt plant to the road worksite and back.

The processes related to the transport and processing of the waste material released during surface course replacement are not included in this life cycle stage B2. These processes are included in life cycle stages C2 and C3 what deviates from the prescription in the standard EN 15804.

C1 road deconstruction

The surface and base course are milled at the end-of-life stage. It is assumed that only one passage of the milling machine is necessary to remove the surface and base course. Small particles are removed with a sweeping machine.

C2 transport of waste material

The different destinations of available RAP are described in Appendix 4, Table 19: 60.4% is reused in asphalt mixtures, 39.0% is reused in foundations, and 0.62% is mandatory exported for thermal cleansing (based on data for 2014). The data related to waste material treatment and transport are used to represent the average Flemish situation. The scenario in this case study differs from an actual scenario in practice, but is applied to take into account the different waste treatment scenarios found in real practice in Flanders. The transport of the waste material released during both surface course replacement and the end-of-life road deconstruction is included in this life cycle stage. The RAP for reuse in mixtures or foundations is transported to the asphalt plant. The asphalt that will be processed to remove tar is transported to REKO in The Netherlands. Since the transport distance between the road worksite and REKO is unknown, the transport distance between the asphalt plant and REKO is used. It is recognized that this is a distortion of the real practice. This life cycle stage also includes the transport of the machines for road deconstruction from the asphalt plant to the road worksite and back.

C3 waste processing

The final life cycle stage within the system boundaries is the waste processing. The life cycle under study generates in total 1 283 ton RAP (=321 ton from surface course replacement + 962 ton from end-of-life deconstruction). The RAP that will be reused in asphalt mixtures (775 ton = 1 283 ton * 0.604), is processed at the asphalt plant by crushing and sieving in a mobile crushing machine. It is estimated by an expert that this processing consumes 0.24 litre fuel per ton RAP (Van Damme et al., 2016). It is assumed that the RAP that will be reused in foundations (500 ton = 1 283 ton * 0.390) does not need any further treatment. Since a milling machine is used for the pavement deconstruction, the RAP is already fine enough for direct reuse in foundations. No process for the thermal cleansing of tar containing RAP (7.99 ton = 1 283 * 0.62) is included in ecoinvent and research on the environmental impact of these processes is not conducted in the scope of this research. Therefore, a similar process was searched in ecoinvent and the incineration of a waste bitumen sheet is selected as the best approximation. The process is adapted to better represent environmental impact related to the quantity of bitumen that is incinerated.

D benefits and loads beyond the system boundary

As recommended in EN 15804:2012, the benefits and loads beyond the system boundaries from reuse, recovery, and recycling potential are reported separately. It is important to note that these benefits and loads are calculated as net impacts and benefits. In module D of this study, the environmental benefits from the avoided consumption of virgin raw material due to the RAP generated by the system under study are described. It is important to note that only the net output of RAP from the product system under study that will avoid the consumption of virgin raw materials, is included in module D. A calculation example is given in literature (Leroy et al., 2012).

The life cycle under study generates in total 1 283 ton RAP, of which 774 ton will be reused in asphalt mixtures, 500 ton will be reused in foundations, and 7.98 ton will be reused in foundations after thermal cleansing.

But 260 ton RAP is used in the production process in the asphalt mixture for the base course. Hence, the product system under study is a net generator of 1 022 ton RAP, of which 515 ton will be reused in asphalt mixtures and replace a certain share of different raw materials, and 508 ton will be reused in foundations and replace crushed aggregates. Following information is used in order to exactly determine the quantity of replaced virgin raw materials in asphalt mixtures:

- the average recycling content in all types of asphalt mixtures (26%) was used ((COPRO, 2015a) and see paper VIII);
- the mixture has a binder content of 4.6% on the aggregates;
- 19.75% bitumen from RAP in the binder blend, calculated to be a realistic rate for 26% RAP in the mixture, based on the data used for paper VI;
- an APO-20 mixture composition, because APO is the mixture type mostly produced in 2014 by COPRO-certified plants.

In this way, the net generated RAP by the product system replaces:

- 508 ton crushed aggregates;
- 180 ton crushed limestone;
- 205 ton round gravel;
- 107 ton filler;
- 17.8 ton bitumen.

End-of-life modelling

The principles as described in paper VIII are applied regarding the EOL modelling. As described in §4.2.1.2, the cut-off system model or the 'allocation, recycled content' processes are chosen in ecoinvent.

The same system model was applied by different studies in literature and good explanations for justifying this choice are available in literature.

- *"When considering recycled materials in an attributional LCA, an allocation must be used to distribute environmental burdens between the primary and secondary/recycled materials. In this study, a cut-off criterion (also known as the recycled content method) is used to account for the production of recycled materials. According to this method, the current user of recycled materials receives the benefit as the recycled materials replaces virgin materials. Thus, recycled materials enter the system boundary without a burden and credit."* (Yang et al., 2015)
- *"To model the end-of-life of the pavement, it is assumed that all the materials of the pavement can be recycled and all the recycling processes and transport processes to the plant are attributed to the Impresa Bacchi S.r.l (the study was made in collaboration with this mid-size Italian asphalt plant). Because all the RAP is transported back to the plant and it will be used for other purposes (concrete granulates or asphalt granulates). As presented in literature* (Huang et al., 2012)*, LCA studies of road pavement tend to take the 'cut-off method': each product is assigned only the burdens directly associated with it. In other words, all benefits of recycling are given downstream to using the recycled material, with no indication of the actual rate of, or potential for, recycling."* (Giani et al., 2015)

5.4.4 LCA results

As an introduction, the single score environmental impact of 1 ton asphalt mixture for base layers and the impact from the different raw materials as used in 1 ton asphalt are presented in Figure 29. While bitumen is the smallest contributor in terms of mass percentage, namely 4.4% in the asphalt mixture (4.6% on the aggregate mixture), it is the major contributor to the environmental impact of 1 ton asphalt mixture for base layers, without RAP.

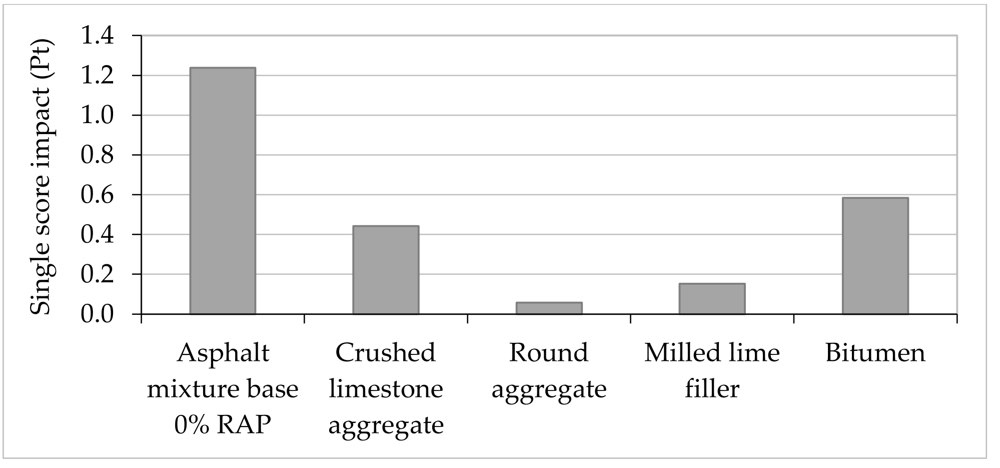


Figure 29: Single score impact of the raw materials for 1 ton asphalt mixture for base courses without RAP and the different raw materials separated according to their share in the mixture

In the following parts in this subsection, results of LCA calculations are presented. These calculations do not include uncertainties in the qualitative and environmental data. Only the 'best guess' value as described above is used for these calculations. However, these results are comparable to the results of the case specific LCA studies in the preliminary research where no uncertainties on data are included.

5.4.4.1 Baseline scenario

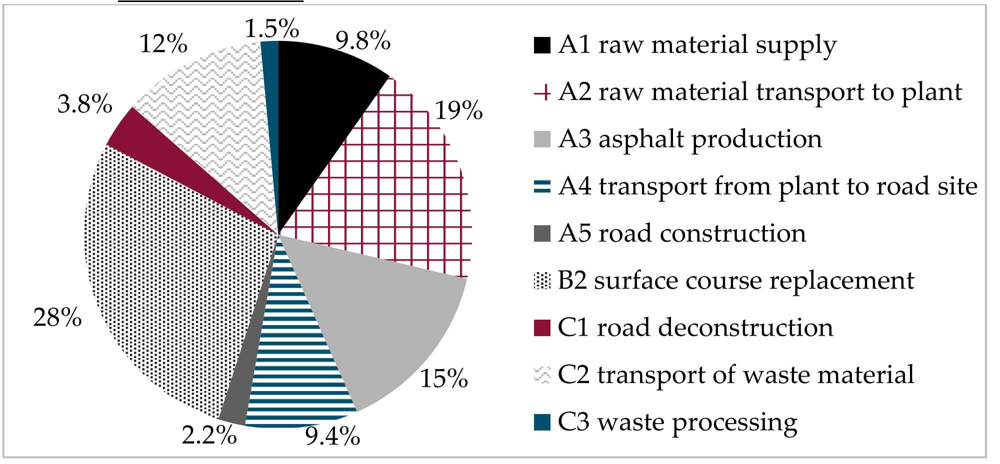


Figure 30: Contribution of different life cycle stages to the single score environmental impact of the baseline life cycle

The total single score environmental impact is 8 872 Pt for the investigated life cycle, taking into account all predefined burdens of the road pavement as outlined in subsections 5.4.2 and 5.4.3.

The results presented in Figure 30 show that the B2 life cycle stage is the main contributor to the life cycle environmental impact. The C3 waste processing life cycle stage has the smallest contribution to the life cycle single score impact. The A5 road construction and C1 road deconstruction life cycle stages also have a small contribution to the environmental impact. It is noted that the construction and deconstruction processes for the replacement of the surface course are included in B2 and not in A5 and C1. Life cycle stages related to transportation (A2 raw materials to the asphalt plant, A4 asphalt, equipment and emulsion to the worksite, and C2 transport of waste material) represent a large share of the total environmental impact. Besides, transport processes are also included in life cycle stage B2.

Figure 31 gives the contribution of different processes (including upstream processes) to the life cycle single score impact, disregarding the split up in different life cycle stages. The LCI in appendix 6 indicates where the different processes are used. It is seen from the results that 85% of the single score impact is caused by only four different processes. The transport process is the major contributor with 52%. The upstream processes includes the impact from road usage, lorry operation, lorry maintenance, diesel consumption, emissions to air, and waste from tyre wear. Other important contributors are the heat production from natural gas at the asphalt plant during asphalt production (17%), diesel burned in building machine (9.2%), and bitumen (excluding bitumen used for tack coating) raw material (7.2%).

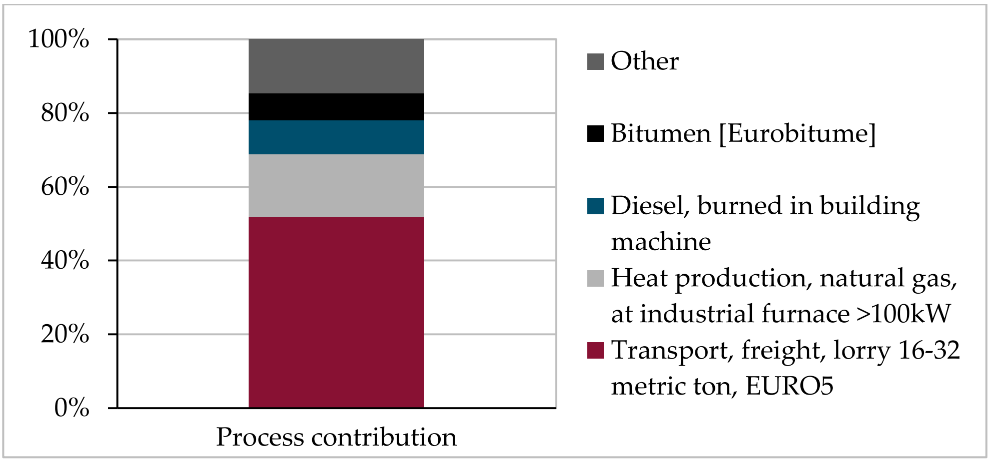


Figure 31: Contribution of different processes (including upstream processes) to the life cycle single score impact of the baseline scenario

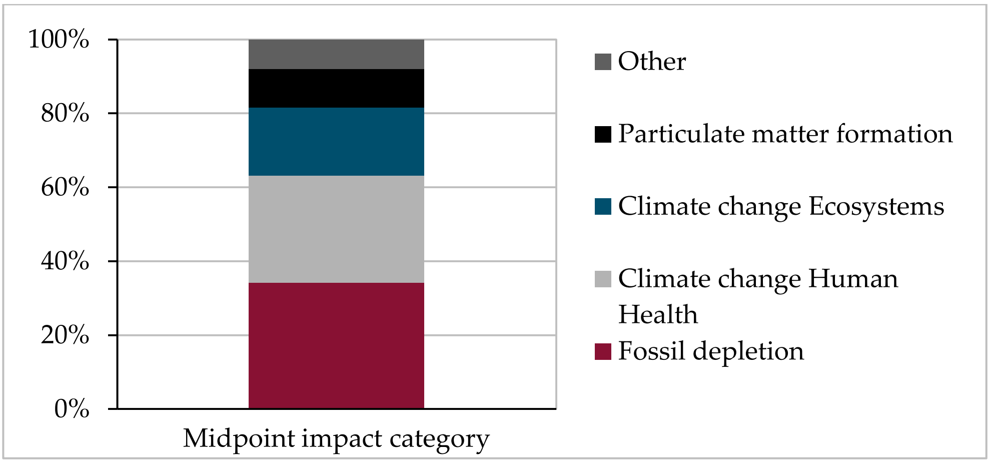


Figure 32: Contribution of different midpoint impact categories to the life cycle single score environmental impact in the baseline scenario

The contribution from the different impact categories to the life cycle single score impact are presented in Figure 32. The two impact categories related to climate change (human health and ecosystems) are together, with 47%, the main contributors to the single score impact. Transport by lorry (47%, including upstream processes) and heat generation (18%) mainly cause the climate change impact. Fossil depletion is with 34% another important contributor to the single score impact. The results revealed that transport by lorry contributes 56% and the heat generation from natural gas contributes 23% to the total fossil depletion impact. Particulate matter formation is the fourth important impact category, contribution for 10% to the total single score impact, with major contributions from freight transport (47%), diesel burned in building machine (17%) and asphalt mixtures for base course (17%) and surface course (15%).

Besides, as recommended by EN 15804:2012, the benefits and loads beyond the system boundary are described in module D. For this analysis, the environmental benefits related to the savings of primary materials, replaced by the net amount of RAP generated by the system under study, are included in module D. As described in §5.4.3.2, the consumption of a certain amount of crushed gravel, crushed limestone, round gravel and bitumen is avoided.

An environmental benefit of 1 052 Pt single score impact is reported in module D in the baseline scenario, mainly coming from the avoided amount of crushed gravel (383 Pt), the avoided amount of limestone powder (filler, 247 Pt) and the total amount of bitumen (237 Pt). Impact categories climate change human health (29%), particulate matter formation (19%) and fossil depletion (19%) are the main contributors to this environmental benefit.

5.4.4.2 Transport scenario

As discussed in subsection 5.2.2 of the thesis, the transport distance between the asphalt production plant and the road worksite often exceeds the maximal necessary transport distance. In this scenario, the same data as in the baseline scenario are used, but the transport distances outside the service area are subtracted from the transport distance between plant and road worksite for each road worksite. So the average transport distance between plant and worksite decreased from 43.3 km to 14.2 km. Hence, also the distance to transport RAP to the asphalt plant (in life cycle stage C2) is reduced.

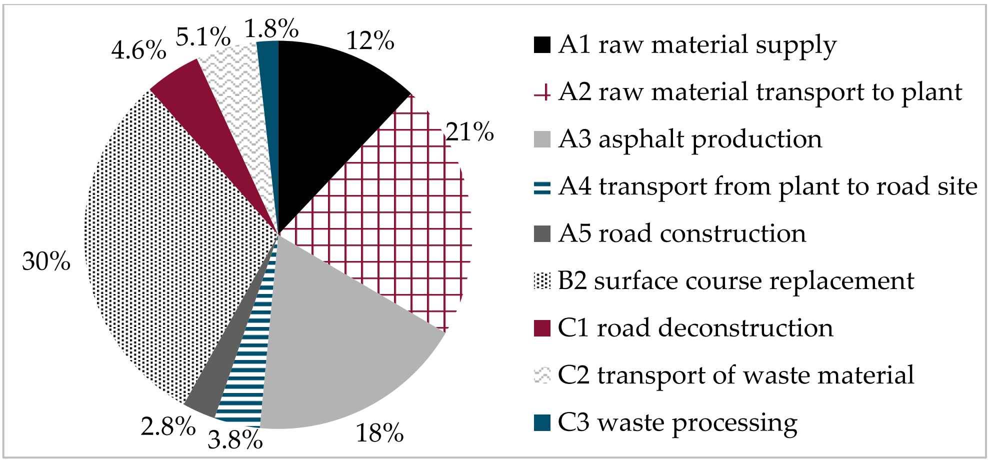


Figure 33: Contribution of different life cycle stages to the single score environmental impact of the life cycle in the scenario with reduced transport distance between plant and worksite

When considering the full life cycle, with adapted transport distance between plant and worksite, the total single score environmental impact is 7 202 Pt. The life cycle single score impact in the transport scenario is decreased by 19% in comparison to the baseline scenario. The life cycle stages related to transportation (A2, A4, and C2) together contributes for 30%, compared to 40% in the baseline scenario.
Compared to the baseline scenario, the absolute and relative impact of the transport process (including upstream processes) decreases from 52 to 41%. The absolute environmental impact of heat, diesel burned in building machine, and bitumen remain unchanged compared to the baseline, but the relative contribution to the environmental impact of these processes increases.

5.4.4.3 0% RAP scenario

For being able to quantify the environmental benefits from using RAP, the baseline scenario is adapted to a scenario where no RAP is used in the asphalt mixtures.
When considering the full life cycle, without the use of RAP, the total single score environmental impact is 9 440 Pt. The environmental impact is reduced by 6.0% when RAP is used according to the current Flemish practice if compared to a theoretical scenario where no RAP is used in bituminous mixtures.
Through the use of RAP in asphalt mixtures, the absolute environmental impact of transport and bitumen (and other virgin raw materials) decreases, while the environmental impact of heat production increases.

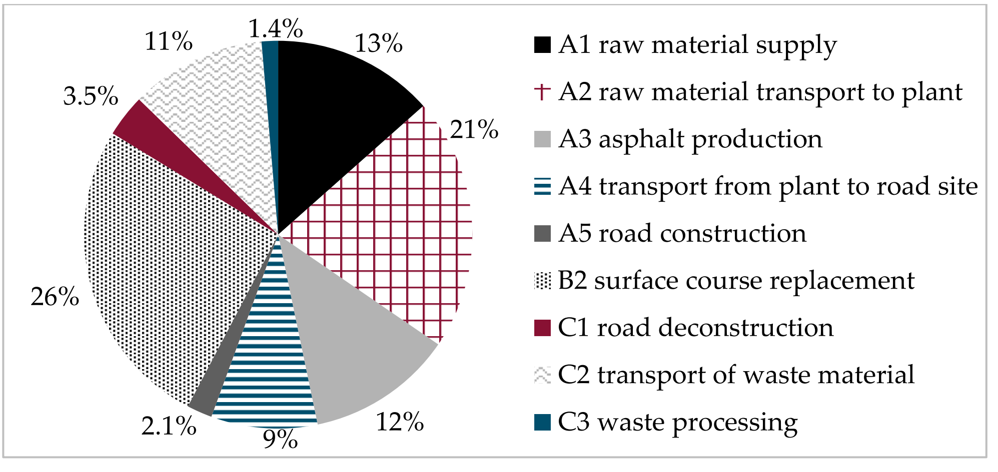


Figure 34: Contribution of different life cycle stages to the single score environmental impact of the life cycle in the 0% RAP scenario

5.4.4.4 Reduced durability

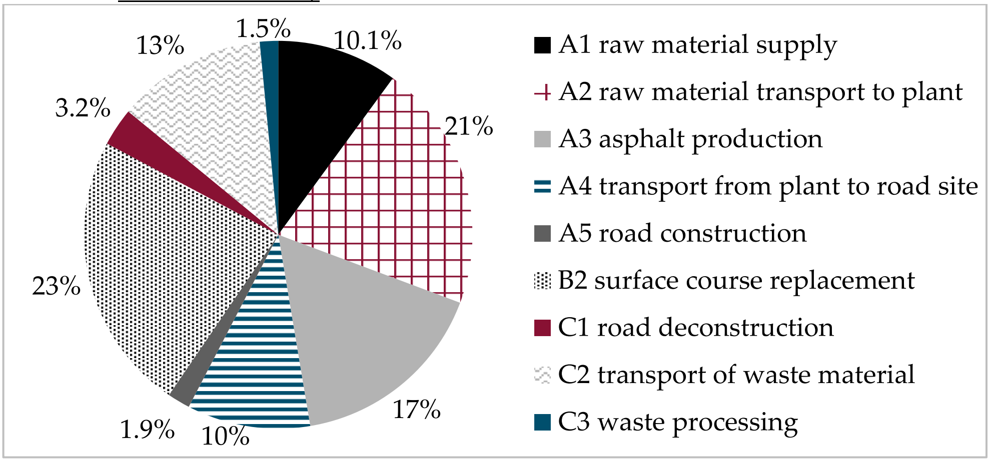


Figure 35: Contribution of different life cycle stages to the single score environmental impact of the life cycle in the scenario with reduced durability for mixtures with RAP

The last scenario involves a reduced durability of the base layer when RAP is used. The same design life is aimed for the scenario with a lower resistance to fatigue but a thicker base course. Based on the calculations described in §4.2.2.1, the base layer should be 4 cm thicker to reach the same pavement service life with a mixture using RAP when the resistance to fatigue is lower. Hence, the base course is 12 cm thick in this scenario instead of 8 cm in the baseline scenario.

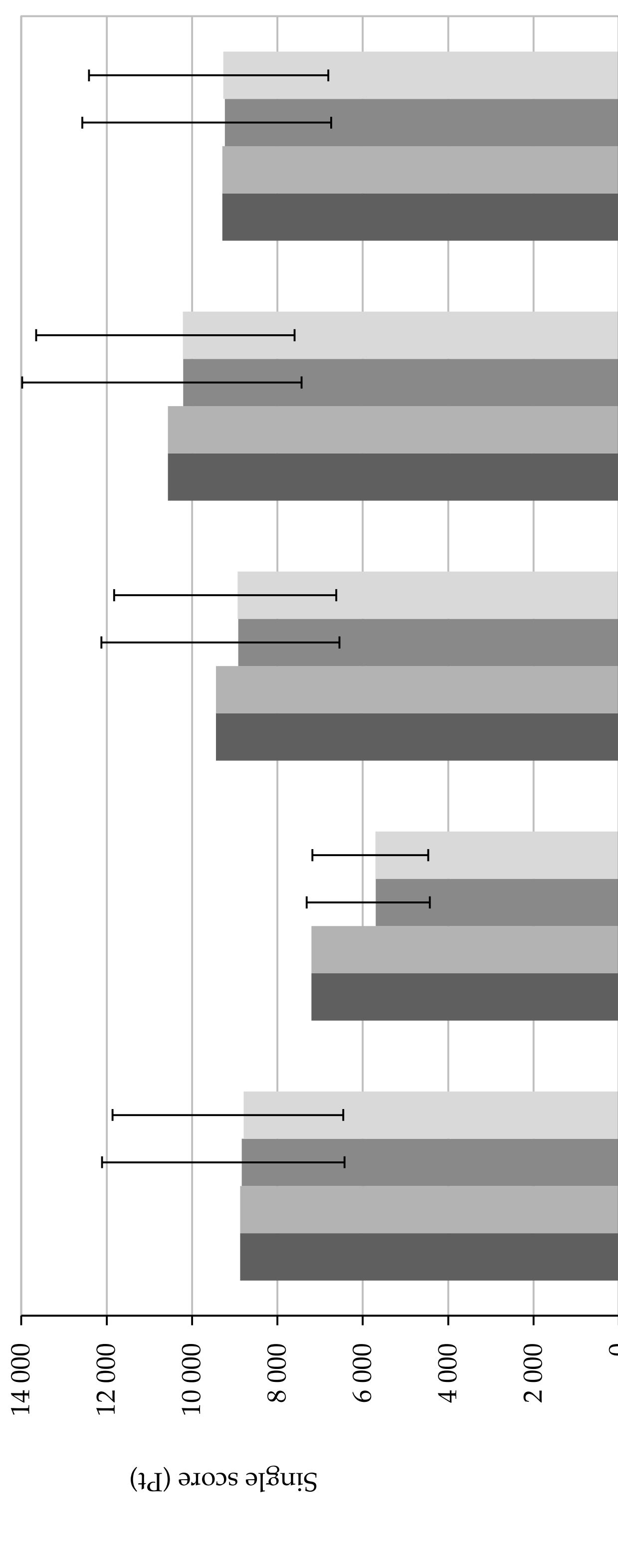
Due to the thicker base layer, the environmental impact increased by 19% compared to the baseline scenario. The environmental impact of this scenario with a thicker base course is 12% higher compared to the environmental impact of the scenario with only virgin raw materials. It is therefore very important to emphasize the importance of knowledge on the durability of asphalt mixtures with and without RAP since a reduced durability can importantly affect results. It is seen from these specific scenarios that the environmental benefit from using RAP is counteracted by the thicker layer as a result of the reduced durability.

5.4.5 Uncertainty results

Compared to the previous subsection reporting on the LCA results, the uncertainties on both the quantitative and environmental data are included in the results presented in this subsection. Uncertainty analyses are conducted in SimaPro. 5 000 Monte Carlo runs are performed.

For the same product or process, there are always two different types of data records in ecoinvent, for the three different system models (consequential, attributional recycled content, and attributional default), namely unit processes and system processes. "*A unit process version contains only emissions and resource inputs from one process step, plus references to input from other unit processes.*" (Goedkoop et al., 2016) A system process is an inventory result of a process or material, listing all emissions, but without links to other processes. The result of an LCA calculation (without uncertainties) with unit processes is the same as the results of an LCA calculation with system processes, as can be seen in Figure 36.

Only unit processes in ecoinvent contain uncertainty information. The uncertainty analysis based on the scenarios with unit processes, includes both uncertainties on the quantities as specified in the LCI and on the environmental data in ecoinvent.
The single score environmental impacts as the result of the LCA calculation (LCA, Unit) do fall within the 95% confidence intervals of the uncertainty analysis (Uncertainty, Unit) and are presented in Figure 36. However, the value for the transport scenario is close to the upper bound of the 95% interval.
It is important to note the difference in the single score in the LCA result and in the uncertainty result. The difference is large, especially in the transport scenario. When comparing the single score impact from two scenarios using the result of the uncertainty analysis, this yields different results compared to the results presented in subsection 5.4.4.



scenario	Baseline	Transport	0% RAP	Durability+4cm	Durability+1cm
LCA, Unit	8 872	7 202	9 440	10 564	9 294
LCA, System	8 872	7 202	9 440	10 564	9 294
Uncertainty, Unit	8 837	5 695	8 921	10 209	9 233
Uncertainty, System	8 795	5 708	8 933	10 214	9 268

Figure 36: LCA and uncertainty results using unit processes database and system processes database with indication of the 95% confidence interval for the five scenarios

It is found from the uncertainty results that:

- the single score in the transport scenario is decreased by 36% in comparison to the baseline;
- the single score in the baseline scenario is decreased by 0.9% in comparison to the 0%RAP scenario;
- the single score in the durability scenario (4 cm thicker) is increased by 16% in comparison with the baseline scenario;
- and the singe score in the durability scenario (4 cm thicker) is increased by 14% in comparison with the 0%RAP scenario.

These findings emphasize the importance of including the variation in the data and the uncertainty of the results.

The uncertainty analysis based on the scenarios with system processes, includes only the uncertainty on the quantitative data in the LCI. It is seen in Figure 36, that the results of the uncertainty analysis with unit processes and system processes slightly differ. It is seen from the error bars, representing the 95% confidence interval, that the deviation on the results, is slightly smaller when using the system processes. This means that the uncertainty in the quantitative data is the main contributor to the uncertainty on the life cycle environmental impact, because only the uncertainty on the environmental data is left out when system processes are used. The single score impact of the transport scenario (LCA, System) does not fall within the 95% confidence interval (Uncertainty, System), but the ranking of the single score impact of the four different scenarios remains the same for the different calculation methods.

Figure 37 illustrates the uncertainty on the results in the different impact categories. It is clear that the uncertainty slightly differs in the three scenarios, but the largest uncertainties are found in the same impact categories in all three scenarios, namely:

- ionising radiation;
- urban land occupation;
- freshwater eutrophication;
- and natural land transformation.

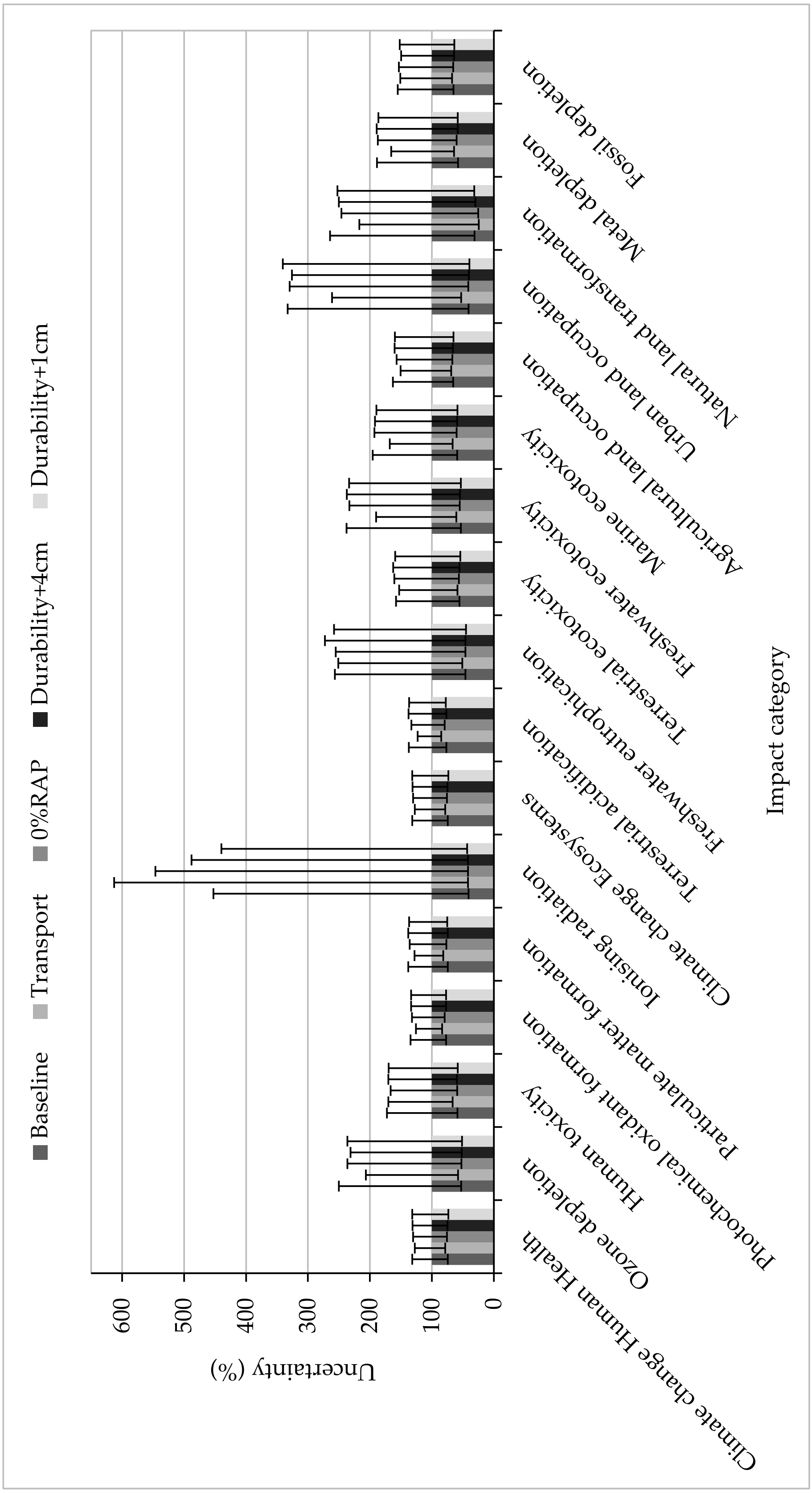


Figure 37: Relative uncertainty within the 95% confidence interval for the characterized results of the five life cycle scenarios

In Figure 38, the baseline scenario (A) is compared with the three alternative scenarios (B) and two alternative scenarios are compared with each other. It is noted that the full life cycles are compared, including all life cycle stages, also the stages that are identical for both compared scenarios.
The first bar demonstrates that within the 95% confidence interval, after 5 000 Monte Carlo runs, the single score environmental impact of the baseline scenario (with the use of RAP in asphalt mixture for the base course) is lower in 57% of the runs compared to the scenario without the use of RAP. This means that the chance that using RAP yields an environmental benefit is probable, but there is a high uncertainty related to the environmental benefit from the current use of RAP in asphalt mixtures in Flanders.
It is seen from the second bar that, within the 95% confidence interval, the single score environmental impact of the baseline scenario is higher compared to the transport scenario in 99.6% of the 5 000 Monte Carlo runs. This is the expected result for the environmental benefit from the reduced transport distance between the asphalt plant and the road worksite.
As expected and showed by the third bar, the environmental single score impact is higher when the base course is 4 cm thicker compared to the baseline scenario. This is found in 78% of the runs.
The lower bar indicates that for 76% of the runs within the 95% confidence interval, the environmental impact of the pavement life cycle without RAP is smaller, compared to the impact of the pavement with RAP in the mixture for the base course but with lower resistance to fatigue and therefore increased base layer thickness.

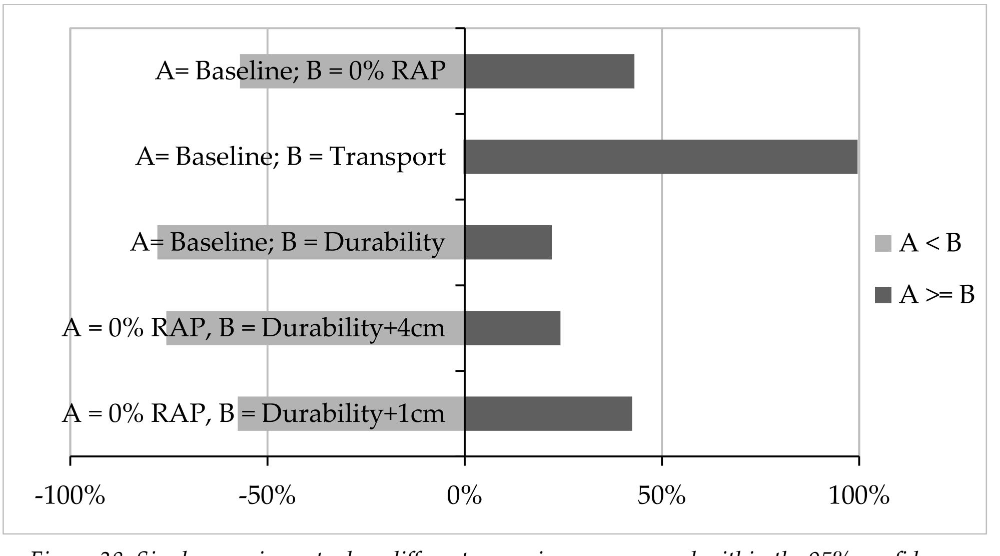


Figure 38: Single score impact when different scenarios are compared within the 95% confidence interval after 5 000 Monte Carlo runs in the uncertainty analysis

Additionally, the environmental impact is calculated in other scenarios with an increased base layer thickness of 2 cm and 1 cm and the environmental impact is compared with the scenario with only virgin raw materials (0%RAP). The single score from the uncertainty analysis in the scenario with 2 cm thicker base with RAP is 9% higher and the case with only virgin raw materials is favoured in 66% of the Monte Carlo runs. The single score in the scenario with 1 cm thicker base with RAP is 3% higher and the case with only virgin raw materials is favoured in 58% of the Monte Carlo runs.

Based on the LCA results, without the inclusion of uncertainties, the single score of 2 cm extra is 3% higher, but the single score of 1 cm extra is 2% lower compared to the 0%RAP scenario.

It is therefore expected, that for these specific scenarios, the turning point will be close to 1 cm additional layer thickness. This means that the environmental benefit from using RAP in asphalt mixtures as in the current Flemish practice will change into an additional environmental load if the use of RAP in the particular situation induces a reduced durability that is compensated by an increased layer thickness of 1 cm or more.

5.4.6 Sensitivity analyses

Since transport processes are determined to be the major contributors to the environmental impact, sensitivity analyses are performed for the main assumptions related to the transport. Transport by truck is represented by a lorry size class 16-32 ton with Euro 5 emission standard in all previous scenarios. First sensitivity analysis in this subsection concerns the European emission standard, the second sensitivity analysis compares two lorry size classes.

5.4.6.1 European emission standard for lorry

Euro 5 was selected as a default in previous scenarios, based on the date of implementation (see §5.4.3.2). No data on the European emission standard for the current fleet of lorries in Flanders or Belgium are publically available.

Production volumes for Europe are included in the datasets of market activities in ecoinvent v.3. These are data from 2011 extrapolated to 2014 for Euro 3, Euro 4, and Euro 5 and data from 2013 extrapolated to 2014 for Euro 6. The distribution as presented in Table 18 was found for lorry size class 16-32 ton in Europe.

In this sensitivity analysis, the environmental impact of the baseline scenario (see §5.4.4.1) with transport Euro 5 is compared to the transport Euro 4 and transport with the average European emission standards (Euro average, see Table 18).

Table 18: European emission standards for lorry and the share for the European fleet, calculated based on ecoinvent data

European emission standard for lorry	share (%)
Euro 3	47
Euro 4	38
Euro 5	13
Euro 6	2.3

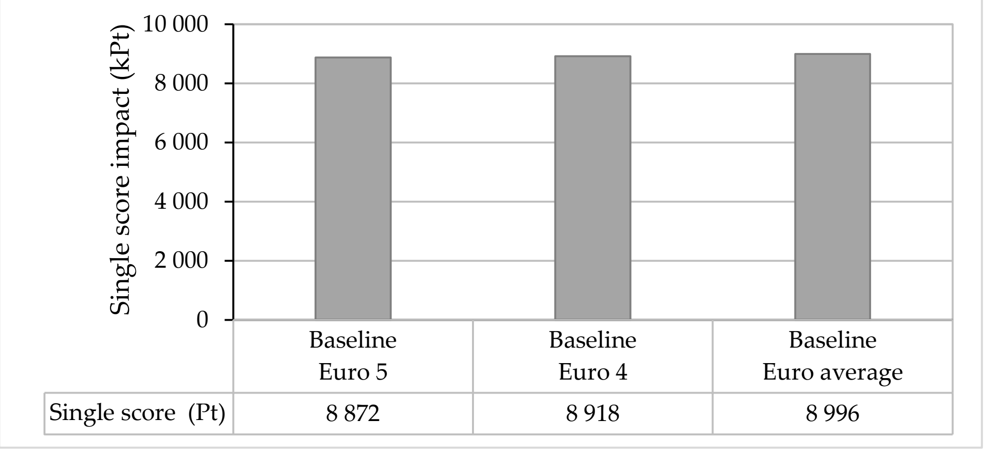


Figure 39: Environmental impact of baseline scenario with different European emission standards for lorry

The results presented in Figure 39 show that the effect of different European emission standards on the environmental impact of the baseline scenario is small. The scenario with the average emission standard has the highest environmental impact, but is only 1.4% higher when compared to the baseline scenario with Euro 5, used as default in previous scenarios. It is concluded that the emission class does not have a significant influence on the LCA results.

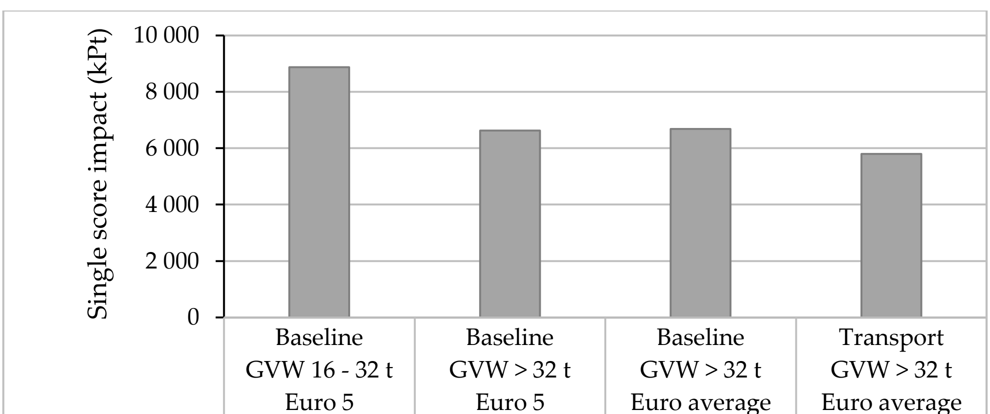
5.4.6.2 Lorry size class

Tipper trucks with a loading capacity of 16 m³ or ±30 ton are used in Flanders to transport the asphalt mixture from the plant to the worksite. As described in §5.4.3.2, the lorry size class 16-32 ton was selected for these transport processes and the delivery of virgin raw materials to the asphalt plant in the LCA and uncertainty calculations.

The average load factor in the transport dataset takes into account the return journey according to the average for Europe. It is known that the return journeys after delivery of asphalt mixture to the road worksite are often used to transport RAP from the worksite to the plant, or empty journeys are adjusted to transport raw materials from the quarry to the asphalt plant (Van Damme, 2015). An extensive

research on these return journeys is not included in the current research, but the average load factor in the ecoinvent dataset might be lower when compared to the real average load factor in the asphalt sector.
Additionally, it is found from the comments in the ecoinvent dataset, that the lorry size class determines the gross vehicle weight (GVW), which includes the mass of the vehicle itself and the transported materials. A Dutch study found that the average GVW for a tipper truck with 5 axles (2 tractor, 3 trailer) is 40.8 ton (Kuiper and Ligterink, 2013). This is not in accordance with the selected lorry size class.
In this sensitivity analysis, the environmental impact of the baseline scenario with different lorry size classes are compared.
The average emission standard instead of Euro 5 is included in the third case in Figure 40. The single score environmental impact of the baseline scenario with lorry size > 32 ton (for both the Euro 5 and average emission standard) is reduced with 25% compared to the original baseline scenario with lorry size class 16-32 ton.

The dataset that best approaches the real practice is with the average emission standard and the GVW higher than 32 ton. Using this dataset, LCA results show that the environmental impact of the scenario with reduced transport distances between plant and worksite is 13% lower compared to the baseline scenario (see two bars at the right in Figure 40). The reduction of 13% is smaller compared to the original results (19%, see §5.4.4.2). The comparative result of uncertainty analysis is very similar compared to results presented in Figure 38. In this sensitivity analysis with lorry > 32 ton and average emission standard, the scenario with reduced transport distance is preferred in 99.5% of the Monte Carlo runs, while this was 99.4% in the original calculation with lorry, 16-32 ton and Euro 5.



	Baseline GVW 16 - 32 t Euro 5	Baseline GVW > 32 t Euro 5	Baseline GVW > 32 t Euro average	Transport GVW > 32 t Euro average
Single score (Pt)	8 872	6 628	6 690	5 797

Figure 40: Environmental impact of baseline scenario with different lorry size class and European emission standards

It is concluded that the lorry size class has an important effect on the results. However similarly with original results, it is concluded that a reduced transport distance between asphalt production plant and road worksite significantly and robustly reduces the environmental impact.

5.4.7 Discussion

There are three main types of uncertainties in LCA studies: data uncertainties, uncertainties on the correctness of the model, and uncertainties caused by the incompleteness of the model. The data uncertainty is included in the study, by taking into account both uncertainty on the quantitative, foreground data and the uncertainty on the environmental data in ecoinvent by using unit processes and executing a Monte Carlo analysis. The two other types of uncertainties are not included in the current LCA study.

Uncertainties on the correctness of the model are for example related to the representability of data, allocation issues, and estimations on future events (e.g., service life). For this study, uncertainties on the correctness of the model may relate to the selected, best approximate processes for tack coat equipment (garbage truck), and thermal cleansing (waste bitumen sheet incineration), the allocation used in the LCI for bitumen (based on economic value and mass), and the transport of released RAP at the road worksite (represented by the transport distance between plant and worksite). Sensitivity analysis can be used to estimate the impact of the uncertainties on the correctness of the model on the results.

Uncertainties induced by an incomplete model can relate to unavoidable data gaps, resulting in specific system boundaries, or the inconsistency of the system boundaries. Exclusion of the use phase in the current research is an example. Another example in the current LCA study is including infrastructure in the bitumen LCI and ecoinvent processes (i.e. road and truck are included in transport processes) while excluding the asphalt production plant infrastructure (only energy consumption is taken into account to represent the asphalt production). It is difficult to handle these uncertainties.

Furthermore, data correlation in a process tree or within a process record may influence the uncertainty. More information related to the way this is handled in SimaPro can be found in literature (Goedkoop et al., 2016).

As opposed to the findings in paper III and IV, the results in Figure 32 of this LCA study show that the impact from climate change (both human health and ecosystems together) is the impact category with the largest contribution (47%) to the single score environmental impact. However, it is noted that the system boundaries and the scope of the studies differ. Moreover, the LCIA method ReCiPe V1.12 is used for the current analysis while the analyses in paper III and V are made with an older version, namely ReCiPe V1.06.

Nevertheless, it is emphasized to never make environmental conclusions based on only climate change results since, for this case, more than half of the impact is neglected. Detailed analysis of the LCA results of the current case study makes clear that the ranking of the different scenarios (baseline, transport 0%RAP, durability 4 cm, durability 2 cm, and durability 1 cm) changes when taking into account only the fossil depletion impact when compared to the ranking based on the single score. A similar shift was found in paper III when comparing the ranking for climate change impact with the ranking for single score impact.

5.4.8 Conclusions and recommendations

The transport processes in the baseline scenario have a major environmental impact. Transport for delivery of raw materials represents 52% of the life cycle single score impact. It is hence important to further investigate the possibility of the delivery of raw material to the asphalt plant with less impacting transport methods i.e., barge (see also chapter 1, Figure 1). The transport between plant and worksite (A4 and C2) contributed for 21% to the single score impact in the baseline scenario. Limiting the transport distance between plant and road to the maximal necessary transport distance, as calculated based on service areas, the environmental impact of the life cycle decreases with 36% (uncertainty analysis). The reduction of the environmental impact of the transport scenario compared to the baseline scenario is robust and not sensitive for data uncertainties.

When equal service life is assumed for pavements with RAP and without RAP, the environmental benefit from using RAP, as currently applied in Flanders, is 0.9% of the single score (uncertainty analysis). This result is sensitive to data uncertainty.

However, when the risk for reduced quality is set off by increased layer thickness to obtain the same service life, the environmental impact significantly increases. For only one extra centimetre, the single score uncertainty result increases with 4% compared to the baseline scenario and with 3% compared to 0%RAP scenario. In other words stated, taking into account uncertainties in the current scenario, there is a margin of less than 1 cm increased layer thickness to set off reduced durability characteristics of the material.

Reduced asphalt mixture quality can have different causes, but the results emphasize the importance of further research on the durability of pavements with RAP.

The incorporation of (data) uncertainty into life cycle assessment is crucial to the credibility of any conclusions, especially when comparing different scenarios.

6 CONCLUSIONS

The current research is new in the sense that the environmental impact of bituminous mixtures with RAP for road pavements, specific for Flanders was not extensively investigated before. Starting a new research subject is very interesting and enriching, but at the same time it involves difficulties, which are in the current research mainly related to data availability. Depending on the research topic, data were not available because there are no measurements, there is no registration of known or observable information, or there is no digital or central preservation of data and information. This is the main reason why it is not possible at this moment to quantify the service life of pavements with and without RAP (see RQ 1). As a consequence, it is also not possible to quantify the processes that depend on the operation time, like the traffic using the road, and energy consumption for light and traffic signs. Any inaccuracy in the estimation of the service life of the road pavement would significantly affect the impact from these processes. These processes in the use phase of the road pavement life cycle are therefore beyond the scope of the current study. However, these processes are mainly related to the surface course of the road (i.e. vehicle road interaction) while the current study primarily focusses on base courses since RAP is not allowed in surface courses. In other words stated, the use of RAP in asphalt mixtures according to the SB250 will not affect the environmental impact from vehicles using the road, or the energy consumption for road operation. Nevertheless, it is known that the environmental impact of the traffic over the service life of the road would surpass the environmental impact of the investigated life cycle (raw materials, transport, asphalt production, road construction, maintenance, and end-of-life). The results of the current research are however very important since different stakeholders are involved for these different research topics (i.e. innovation on engines and tires for fuel efficiency).

The LCA case study of WMA test sections in paper IV shows that using additives to produce WMA might counteract the environmental gain. Additives to produce WMA are hardly at all used in the Flemish sector. The production of WMA by foaming bitumen is seen as an innovative technique that might reduce the environmental impact. However, large scale experience in practice is lacking and prevents to assess the durability of these pavements and to make a robust environmental assessment. Moreover, based on findings in literature, it is expected that it is not possible to reduce the environmental impact by reducing the production temperature since the burners at the asphalt production plant are not designed for these lower temperatures.

Carbon Free-ways is a value pilot project in which the authorities encourage environmental friendly working methods. The processes that are the main contributors to the environmental impact (see RQ 4.2) in the current research are also included in the pilot project. However, the assessment of only CO_2-emissions is an incomplete assessment and can yield different results when compared to a life cycle assessment. Again, it is emphasized to never make an environmental assessment based on only one environmental impact. The results in paper III and section 5.4 show that climate change represents less than 50% of the total environmental impact. A single environmental impact can result in a different ranking of scenarios or alternatives when compared to a complete environmental assessment, which might induce unfavourable conclusions or (policy) decisions.
ART concluded that the methodology of the pilot project is not applicable as GPP due to (1) higher work load and costs, (2) increased environmental impacts behind the scope of the study due to the system boundaries, and (3) negative effect on the durability if only economic and environmental parameters are included.

Another important conclusion from the current research is the importance to take into account uncertainties on the quantitative data used in the LCA calculations and report the uncertainties on the LCA results. The LCA calculations use the 'best guess' value (average or median) for the quantitative data, while uncertainty assessment takes into account a range of possible values. The single score impact from LCA calculations can significantly differ from the single score impact from uncertainty analysis. It is therefore not possible to generalize the results of an environmental assessment of a specific case study for another situation or a whole sector, even if the particular case is representative for the sector.

The methodology as developed in this research, for data collection and environmental assessment by LCA can be used as a guide to make other environmental assessments for the effect of WMA, rejuvenators, PMB's, other special mixtures, etc.

Answers on the research questions are given in the following paragraphs. For most research topics, first the sub questions are answered since these may be part of the answer to the main research question for a particular topic.

RQ 1.1 *Are performance characteristics of asphalt influenced by the use of RAP?*
It is not possible to formulate robust conclusions based on the results of the current research. The analysis of the laboratory test results showed that the variation of the results for each performance characteristic investigated (rutting, stiffness, and resistance to fatigue) is very large for a specific amount of RAP. An important

conclusion, however, is that it is possible to design mixtures with high RAP content that have identical mechanical performances tested in the laboratory compared to asphalt mixtures produced with only virgin raw materials.

The analysis of the performance characteristics of pavements in practice (FWD and inventory of maintenance interventions) did not yield meaningful results within the goal and scope of this research, which is mainly due to a lack of sufficient measurements in situ and available information. The Flemish PMS does not register information on mixture composition and the use of RAP. The mixture composition of the pavement used on the road is only registered for test sections in research reports. However, the FWD test method is not suitable for short test sections unless the distance between measurements is short to obtain sufficient results for each test section.

The results reported in literature are found to be contradictory and hence no unambiguous conclusions can be drawn for the effect of RAP on properties of asphalt.

RQ 1.2 *Is the mixture composition (e.g. total bitumen content in the mix) adjusted when RAP is used?*

It is not possible to define significant differences in binder content or binder type in the asphalt mixture in relation to the recycling rate. Mixtures with and without RAP, with equal performance characteristics can hence not be distinguished based on mixture composition. Besides, the binder content and %O/N are not significantly correlated with the performance characteristics.

RQ 1 *What is the service life of pavements and the effect of using RAP in asphalt mixtures in base courses on the service life of pavements?*

The service life of bituminous pavements with and without RAP could not be quantified based on the current research. The service life of a road pavement is not measureable at a single moment in time, but requires an inventory of information related to initial construction, maintenance, end-of-life, and exposure to traffic and weather conditions. The collection of this information is currently not existing and therefore the quantification of the service life in the future is hindered as well.

RQ 2.1 *What are the transport distances for the delivery of virgin raw materials to the asphalt production plant?*

The road transport distances for the delivery of virgin raw materials to Flemish asphalt production plants are quantified. The average distance between Belgian quarries and the Flemish plants is 128 km (median 123 km) for crushed aggregates and 95 km for round aggregates. The average road transport distance for the delivery of filler from the four main suppliers in Belgium and The Netherlands is

124 km. The average road transport distance from the port of Antwerp to the Flemish asphalt plants is 61 km for the delivery of bitumen.

RQ 2.2 *What is the transport distance between the asphalt production plant and the road worksite?*
The average road transport distance between asphalt plant and road worksite is 43 km (minimum 0.5 km and maximum 182 km). The results also indicate that in general, large road works are located closer to the asphalt plant, while road works far away from the plant are rather small works.

RQ 2.3 *How is the real practice compared to the theoretical optimal situation for transport distance between plant and road worksite?*
The service area is a theoretical delineation of an area to assign all possible road worksites to the nearest asphalt production plant. The inventory of all worksites for one year of nine asphalt production plants shows that 79% of these worksites are located outside the theoretical service area for that particular plant. For the generated dataset, this means that 67% of all transport kilometres and 57% of all transport (tkm) are outside the service area. These results indicate that there is an important potential for reducing transport processes in the sector.
It is noted that the production capacity in 7 out of the 17 service areas, defined exclusively on shortest road transport distance, is not sufficient to provide all road works with the service area. However, based on the total Flemish road network and the total Flemish asphalt production capacity, the rearrangement of road worksites in adjusted service areas is possible in theory.
Implementation in practice of this kind of process optimisation will imply an extensive reorganization of the current way of public tender awarding.

RQ 2 *Are transport processes for the delivery of raw materials to the asphalt production plant influenced by the use of RAP? In other words: Is the transport distance for the delivery of RAP to the asphalt plant significantly different from the delivery of virgin raw materials?*
The road transport distance between the asphalt plant and the road worksite is shorter as compared to the road transport distance for the delivery of virgin raw materials. Therefore, less transport (tkm) for raw material delivery to the plant is needed if RAP is used in the asphalt mixture.

RQ 3.1 *Is the moisture content in aggregates affected when stock piled under a shelf?*
The average moisture content for RAP stored under a shelf is 4.09%m/m and higher compared to the average moisture content of 3.82%m/m for RAP stored outside. However, the difference in moisture content in RAP stored outside and stored under a shelf is not statistically significant.

The influence of the number of days the RAP is stored under the shelter on the moisture content is investigated. The longer the RAP is stored under the shelter, the lower the moisture content is. However, the correlation is weak and statistically insignificant.

RQ 3.2 *Is the moisture content in recycled aggregates higher compared to virgin aggregates?*
Without deviating grain size fractions, the moisture content in virgin aggregates is significantly lower compared to the moisture content in RAP, both stored covered and uncovered. However, when the different grain size fractions are separated for virgin aggregates, the average moisture content of 3.92%m/m in RAP (i.e. 0/20, no division for grain size fractions) is lower than the average moisture content of 7.39%m/m in sand (0/3), but higher than the average moisture content of 1.96%m/m in fraction 3/8, 1.3%m/m in fraction 8/16, and 0.73%m/m in fraction 16/40.
The total moisture content that should be evaporated from the aggregates is calculated for real mixture compositions, taking into account the average moisture content for the different virgin grain size fractions and RAP. It is concluded that the total moisture in the mixtures with RAP does not significantly differ from the total moisture in the mixtures with only virgin raw materials.
It is concluded from the current research that the grain size fraction has a greater influence on the moisture content than the aggregate type (virgin or recycled). The results are influenced by the fact that in Flanders virgin aggregates are washed to remove small particles.

RQ 3.3 *What is the effect of using RAP on the energy consumption for asphalt production?*
It is seen in the linear regression (see also RQ 3) that the coefficient for the independent variable 'mass asphalt production with RAP' is higher compared to the coefficient for the independent variable 'mass asphalt production without RAP'. This indicates that the energy consumption is higher when RAP is used in the mixture. Additionally, a statistical significant, strong, and positive correlation is found between the specific energy consumption (natural gas MJ/ton asphalt) and both the share of the daily production in which RAP is used and the share of RAP used in the mixture. The natural gas consumption during the asphalt production is hence significantly higher if RAP is used in the mixture. These results are generated based on energy measurements at one Flemish asphalt production plant, using a parallel drum to heat RAP before it is added to the mixture.

RQ 3 *What is the energy consumption for asphalt production at the plant?*
The total daily natural gas consumption, inventoried at the reference plant over four years, is used to develop a model to predict the natural gas consumption for asphalt production at a plant. Natural gas is consumed for drying and heating aggregates, for heating 2 (of the 6) bitumen tanks, and for heating walls and pipes at the reference plant. The average natural gas consumption over four years is 214 MJ/ton asphalt. Based on the installed thermal power at the asphalt plant, 2.5% of the consumed natural gas should be attributed to heating bitumen tanks, pipes, and walls at the plant. This means that the average energy consumption for drying and heating aggregates is 209 MJ/ton asphalt and the average energy consumption for heating tanks, pipes, and walls is 5.35 MJ/ton asphalt.
The linear regression model ($NG = 36\,488 + 202 * M_{RAP} + 158 * M_{0\%}$) predicts the natural gas consumption based on the mass of asphalt produced with RAP and the mass of asphalt produced without RAP in one production day.
The developed statistical model is compared to an existing, theoretical model to estimate the energy consumption based on enthalpies. While the model based on enthalpies only includes the energy for drying and heating aggregates, it overestimates the energy consumption measured at the plant. The predictive model devised during the current research is more accurate. The predicted consumption is mostly lower when compared to the method with enthalpies and better approaches the measured consumption. In addition, the new model is more user-friendly since only two independent variables are needed, which can be easily inventoried at the asphalt production plant, or are known from a project design.

RQ 4.1 *What is the appropriate approach for modelling the environmental analysis of bituminous road pavements with use of RAP?*
There is no prior environmental analysis of the current practice in the Flemish asphalt sector, so there is the need to do first a benchmark of this current practice. In the scope of the current research, an attributional LCA approach is selected as most appropriate since it focusses on describing the environmentally relevant flows within the chosen temporal window. The cut-off system model is selected because it is relevant in market situation where there is a surplus of recycled material available. Applying the cut-off approach, all non-waste by-products of a waste treatment are cut off. When applied for bituminous road pavements using RAP as recycled raw material, the waste treatment processes thermal cleansing or crushing and sieving – including the transport from the road worksite to the plant – are included in the life cycle, after which the end-of-waste stage is reached and the RAP is cut off and becomes burden free available to use as a raw material in a next life cycle.

RQ 4.2 *Which processes or materials are the main contributors to the environmental impact?*
The main contributors to the environmental impact (including upstream processes) are road transport processes by truck (41 to 53%, depending on the specific scenario), heat generation needed for asphalt production (14 to 21%), diesel burned in building machine (7.9 to 11%), and virgin raw material bitumen (6.8 to 9.0%).
Of all raw materials, bitumen – excluding bitumen used for tack coating – is the major contributor to the environmental impact, in spite of the small mass in the asphalt mixture.

RQ 4.3 *To what extent do transport processes contribute to the environmental impact?*
Total road transport by truck is the main contributor to the environmental impact. The absolute environmental impact of all road transport processes by truck – including upstream processes – in the scenario without RAP increases with 6.9% compared to the baseline scenario.
The analysis shows that the results are not sensitive for the selected European emission standard of the lorry. The single score environmental impact of the baseline scenario is only 1.4% higher when an average emission standard of the European fleet is applied for lorry transport compared to Euro 5 standard for lorry transport in the baseline scenario.
The selected lorry size class has an important effect on the results. The environmental impact of the baseline scenario reduces with 25% when lorry size class > 32 ton is selected instead of 16-32 ton. However, when using het > 32 ton lorry and comparing the baseline scenario with the transport scenario, the decrease in environmental impact remains significant.

RQ 4.4 *To what extent does energy consumption contribute to the environmental impact?*
The heat production from natural gas contributes 14 to 21% to the single score environmental impact, depending on the scenario. The energy consumption is hence an important contributor to the environmental impact. Moreover, the absolute environmental impact for heat production with natural gas reduced with 10% in the scenario without RAP when compared to the baseline scenario.

RQ 4.5 *To what extent is the environmental impact influenced by the service life of pavements?*
The scenario with a reduced durability of the asphalt mixture, resulting in a thicker pavement base layer in order to obtain the same design life is used to assess the influence of the service life. The environmental impact increases with 16% compared to the baseline scenario when the durability performance is assumed to be lower and the base layer should be 4 cm thicker to maintain the same service life.
For the specific scenarios in this study, the environmental benefit from using RAP will change into an environmental load if the use of RAP induces a reduction in the durability that should be compensated by an increased layer thickness of 1 cm or more.
The influence of the service life on the environmental impact is hence very important and can quickly counteract benefits from using RAP.

RQ 4.6 *Are there other techniques or processes besides using RAP, with a higher potential to decrease the environmental impact of bituminous road pavements?*
Based on the results of the uncertainty assessment, the decreased environmental impact in case of reduced transport distance between plant and worksite is very robust and not sensitive to the data uncertainties. Moreover, there is a realistic potential to reduce this transport distance when considering service areas and taking into account the production capacity of the existing Flemish plants.

RQ 4 *Is the current practice of using RAP having a beneficial effect on the environmental life cycle performance of bituminous pavements?*
Based on the uncertainty results, the use of RAP in the current Flemish practice reduces the environmental impact with 0.9% when equal service life is assumed. Uncertainties on the parameters yield results that are not robust. Within the 95% CI, 57% of the Monte Carlo runs are in favour of the use of RAP when comparing the baseline scenario with the scenario without RAP. Besides, important to note, no statistically significant effect of RAP on mechanical performances is found and hence the influence of RAP on the service life cannot be estimated specific for the Flemish practice. When the risk for quality loss (or shorter service life) is reduced by increasing the layer thickness by only one centimetre, the environmental gain of using RAP can already be counteracted by the need for extra materials, energy, transport etc. Therefore particular attention must be drawn to the performance characteristics of asphalt mixtures with RAP, where the quality of the RAP itself may be important as well.

7 RECOMMENDATIONS

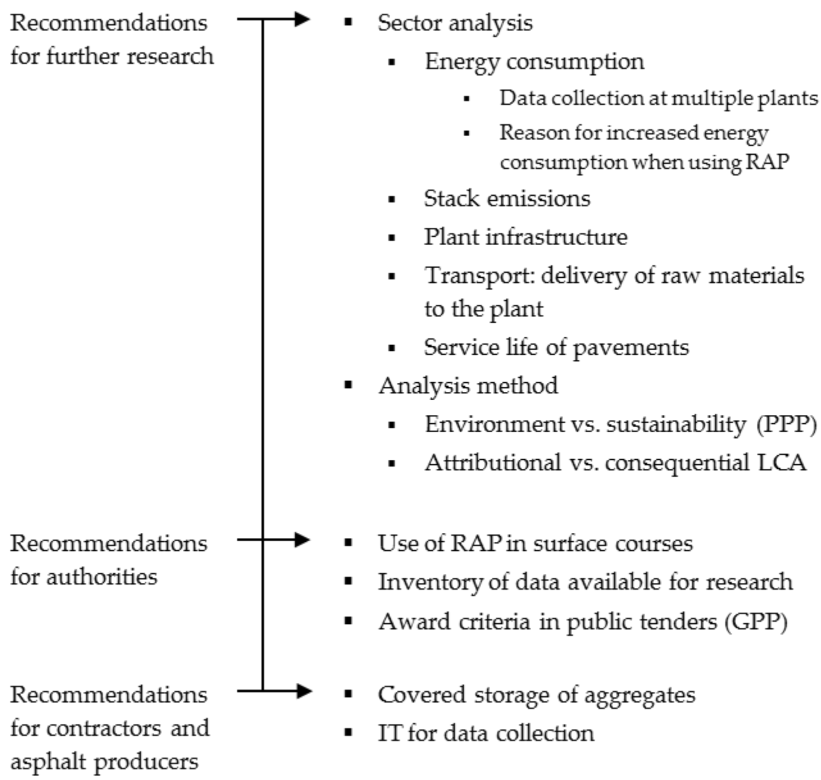


Figure 41: Overview of recommendations for further research, for authorities and for contractors

The results of the current study can be used by different actors. Analogously, the recommendations raised from the current research are addressed to three different stakeholders. An overview is presented in Figure 41. As can be seen in in the figure, most recommendations are possible research topics, but also recommendations for authorities and contractors or asphalt producers are discussed in this chapter.

7.1 Recommendations for further research

The environmental impact of bituminous mixtures for road pavements in Flanders and the effect of using RAP was not studied before. Many topics related to the environmental impact of using RAP in Flanders remain for further research. Some aspects in the asphalt sector must be further investigated to better understand several findings from this research or to create or extend a database, but also the use of other analysis methods may yield additional, interesting results related to sustainability.

The author recognizes that the strong cooperation with a single industrial partner for some of the data collection (including energy measurements at one plant with a specific infrastructure) is a weakness in the current research. The results of this research shall be generalised with caution. Both the translation from the one examined reference plant to the Flemish sector and the generalisation to an international context involve different contextual circumstances influencing the results. Therefore, it is recommended to collect similar data at other asphalt plants and analyse these to verify the robustness of the results. The energy measurements must be executed in the same period in different asphalt plants. An analysis period of at least one year is necessary for generating sufficient results that are applicable for all seasons.

A detailed study of the actual cause of the increased energy consumption for asphalt production with RAP (described in subsection 5.3.2) is missing in the current research. The causes of an increased energy consumption must be known to be able to efficiently reduce the energy consumption and thus the environmental impact. Therefore, it is recommended to investigate some aspects in more detail e.g., moisture content in materials, energy consumption for heating elements of the asphalt plant itself (i.e., the additional parallel drum used for asphalt production with RAP), and the influence of using RAP on the heating temperature of virgin aggregates.

The effect of start-up and interruptions in the asphalt production (and the associated cooling down of the installation) on the energy consumption should be investigated in more detail as well. No robust conclusions are found in §5.3.2.2. It is possible that the additional energy consumption caused by interruptions is not noticed in the obtained results because of the high overall energy consumption for a whole production day.

It is suggested to measure the energy (natural gas) consumption by both the burner in the drum for virgin materials and the burner in the parallel drum separately. This can be performed by using a clamp-on flow meter. In this way, the effect of the start-up, interruptions, use of the parallel drum etc. on the energy consumption can be analysed in time and the energy consumption (m^3 gas) can be compared to the amount of heated aggregates (ton).

The current research includes an analysis of the moisture content in aggregates. However, a bigger dataset might yield more robust conclusions. It is recommended to set up a measurement campaign at the plant itself, monitored by researchers. Laboratory assistants at the asphalt plant do not perform moisture content measurements on a regular basis. Results will be more meaningful if a researcher executes moisture content measurements from existing aggregate stockpiles while

making an inventory of data concerning the initial moisture content, duration of storage, grain size fraction, sheltered or not, weather conditions, moisture content before use, etc. The difference in the moisture content in different groups of aggregates (virgin or recycled, stored outside or covered) can be investigated in this way. Different results related to the effect of covered storage on the moisture content in aggregates are found in literature (see §5.3.1.1). The results of future research should be used to reassess if the construction of a shelter to prevent aggregates from moisture is a BAT (in the specific circumstances) or not.
The current study uses information on the weather conditions to validate certain results or as background information, but a direct link with energy consumption at the plant was not investigated.

Stack emissions are, amongst others, related to the energy consumption and the adjustment of the drums. Results of few emission measurements are discussed in the thesis (see section 2.1), but additional measurement campaigns in different Flemish asphalt plants are recommended during WMA and HMA asphalt production with and without RAP enabling a better understanding of the effect of reduced production temperature and the use of RAP on the emissions. Moreover, the concentration of multiple components should be measured since, for example, the environmental impact of SO_2 outweighs the impact of CO and CO_2.
Based on results of preliminary research, it is concluded that using WMA does not reduce the environmental impact for the current practice in Flanders. The burners at the asphalt plant need to be adjusted to be energy efficient at the lower production temperature before there is a chance that further development of the technique will result in environmental benefit. More research on this topic is needed to be able to assess the value of further implementation of this technique in the Flemish sector.
Besides, more research on the durability of pavements with WMA and on advantages of WMA compared to HMA that are described in literature (e.g. a faster turnover time) are essential for environmental assessment

The effect of using RAP on the asphalt plant infrastructure is not analysed in this research. For example, when using RAP, less virgin bitumen is used, but a soft bitumen B70/100 is only used in the mixtures with more than 40% RAP (in the analysis in paper VI, see Figure 79). This may influence the number of bitumen tanks needed on the plant, but is dependent on the specific infrastructure and organisation at the asphalt plant. Conducting a survey into the influence of RAP on the infrastructure of the Flemish asphalt plants may give more information on this issue.

Further research on the transport processes for the delivery of raw materials to the asphalt plant is recommended. In the current research, this analysis is simplified by only taking into account Belgian quarries, by neglecting import of virgin aggregates from abroad, by disregarding possible intermediate storage at the supplier sites, and by assuming that all materials are transported by lorry. In addition, also the interaction between transport of raw materials from quarry to plant, transport of asphalt from plant to worksite, and transport of RAP from worksite to plant should be investigated in real practice. This logistic situation in practice might significantly differ from the average load factor in ecoinvent and applied in the current study. More information should be collected in practice to be able to further elaborate on this topic.

The last, but very important recommendation for further research in the Flemish asphalt sector is related to the service life of pavements. It is an essential part of life cycle assessment studies, and on the other hand, it is also important information that could be used to estimate the mechanical performances of asphalt mixtures in situ. Following a learning process in time, this could yield better durability of asphalt mixtures on the long term.

The analysis in subsection 5.1.1 assesses three mechanical performance characteristics separately. However, road construction design is based on a combination of these characteristics. The layer thickness varies for different mechanical performances. It is hence important to investigate the effect of using RAP on the road construction design in its entirety.

The analysis in subsections 5.1.2 and 5.1.3 focuses on the durability of pavements in situ. For both the analysis of FWD measurements and the inventory of historical maintenance interventions, a lack of sufficient data hinders the research. Since no meaningful results were obtained by using the existing software and analysis methods for the FWD measurement results (RoSy, Qualidim, Alizé-LCPC, and graphical method), it is recommended to search for other analysis methods. A finite element method can therefore be used in further research.

Life cycle assessment is used for the analysis of the environmental impact. However, some issues related to sustainability are not included in this analysis. The current research focuses on the environmental impact, while the economic and social impacts are not considered in this thesis e.g., safety issues related to WMA compared to HMA and certain electricity generation types. These parameters might however be important for decision making. Hence it is important to always critically evaluate the results of LCA and even look further than these numerical values. In the future, a full LCC study and a social LCA might be relevant in order to generate results on the sustainability of bituminous road pavements.

Further, a different environmental modelling approach might yield different results or insights. In order to check the robustness of the results, it is recommended to use also other LCIA methods, i.e. a ReCiPe LCIA method with another timeframe (individualist or egalitarian) or an LCIA method developed by other researchers. Moreover, the current research only applies attributional LCA studies. However, results of a consequential life cycle assessment modelling approach are sometimes, depending on the research subject, more appropriate to be used for policy making. It is therefore recommended to compare the results of ALCA with the results of CLCA. An example of the comparison of the ALCA and the CLCA approach for the construction sector is found in literature (Buyle et al., 2016). A study applying system expansion was found in literature (Mladenovič et al., 2015), but a full consequential approach – with e.g. a life cycle inventory based on marginal suppliers[9] – for LCA in the road construction sector is one of the many frontiers of knowledge.

7.2 Recommendations for authorities

Based on the results of both mechanical performances and environmental impact, it is recommended to allow the use of RAP in surface courses. No negative effects are found in the current research. It is suggested to allow for example 20% RAP in asphalt mixture in surface courses because research results found in literature state that the mechanical properties are not significantly affected when recycling rates of maximum 20% are applied.

As described in the previous section, the main hindering in the research on the service life of pavements is the lack of data. More measurements in situ and a punctual inventory of the results are necessary.
Considering subsection 5.1.2, the evaluation of mechanical performances based on FWD measurements on test section in situ, it is impossible to analyse the evolution of the mechanical performances in time based on only two measurements (2006 and 2015 for the test sections at highway E19). Unfortunately, the road test section is not more intensively tested. It is therefore recommended to execute more frequently measurements on the road pavements in situ, on these particular test sections, but also on other road (test) sections to enlarge the available data that can be used for further research. Minimum 5 measurements are necessary for a valuable statistical analysis. With an estimated service life of surface layers of 14 years (Briessinck, 2013), an annual or maximum two-yearly frequency for executing tests on the pavements is required for collecting a sufficient set of data within the service life of the pavement course. Especially for short test sections, it is recommended to execute

[9] The marginal suppliers of a product are the suppliers that are able to and will change their production capacity in response to an accumulated change in demand for the product.

more measurements on each test section (for example every 5 m instead of every 50 m) in order to generate a larger results data set.

Based on the results of subsection 5.1.3, the government is encouraged to inventory more information, to save it, and to make it available for research e.g., date, mixture compositions, discharge temperatures, silo storage duration, compaction, etc. The LTPP program in the United States and Canada is a large scale project and a valuable example of the intended purpose. Since ART is responsible for the management of primary and secondary roads and hence decides on (structural) maintenance interventions, ART is the best organisation to be responsible for this central data collection. It is recommenced that ART obliges the Flemish contractors to collect all information and data related to the asphalt production, transport, and road construction processes and to transfer this information and data to ART after execution of a road work.

In the scope of the current research, especially the registration of the asphalt mixture compositions used for the different layers in the road pavement is crucial information for analysing the impact of using RAP on the mechanical performances and eventually extension on the service life of pavements.

A digital information registration gives opportunities for the inventory of these data and further analysis of it. It would be interesting for research purposes to associate the results of laboratory research for mixture registration according to SB250 with the results of routine pavement inspections. Both data sources are managed by ART and the scientific value of the data would increase when there is a connection.

It is noticed that the implementation of certain new techniques or procedures is most efficient if it is obliged by the contracting authorities. Adjustments in the next version of the road standard or an adjusted public procurement method are possibilities to implement parameters affecting the environmental impact. At this moment, the warranty period of the contractor for the construction of a road pavement is assessed to be too short to encourage the choice for durable materials and working methods. Besides, transport processes between plant and road worksite are not efficient. Results show that the implementation of service areas to assign road worksites to the plant located most nearby would significantly reduce the environmental impact. However, a whole new procurement system should be developed in order to be able to take into account the transport distance between the plant and the worksite, the production capacity of the production plants, and maintaining at the same time the positive competition between plants to increase the quality, encourage innovation, and guard for fair pricing. In this way, the procurement method will evolve towards GPP.

7.3 Recommendations for contractors

Further research on the moisture content in virgin and recycled aggregates is recommended, but only possible when laboratory test results on the moisture content in aggregates are detailed, inventoried, and available for research. As opposed to the results in the Flemish BAT study, no statistical significant reduction of the moisture content is found for covered storage of aggregates in the current research.

Since much more data on the production and construction processes is necessary, as described in the previous section, the collaboration of the Flemish road contractors is vital. The automatized inventory of data on the asphalt production process is already obliged for COPRO-certified asphalt production plants. It is noted that currently some additional information technology (IT) applications are integrated in the sector as a voluntary initiative of some road contractors. The implementation of IT applications for the inventory of data as described above (date, moisture content, mixture compositions, discharge temperatures, silo storage duration, transport distance, compaction, etc.) is strongly encouraged. The implementation of IT applications is an important opportunity to provide researchers with an extensive amount of data within a couple of years.

For the current research topic, the support from the industry is important to collect valuable data. On the other hand, it is expected that contractors benefit from this research since environmental gain often correlates with economic benefit. Results of similar research may in the long term induce sustainable optimisation of the sector.

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FIGURES AND TABLES

List of figures

List of tables

APPENDICES

Appendix 1

Additional information on statistical tests.
This appendix is added digitally.

Appendix 2

Contact information for questionnaire.
This appendix is added digitally.

Appendix 3

Map with Flemish asphalt plants, service areas, and road worksites.
This appendix is added digitally.

Appendix 4

Other applications of RAP in practice.

Besides RAP used in new asphalt mixtures, there is also a fraction of the RAP that is not allowed for reuse in new asphalt mixtures. In the next paragraph, more information is given on the different applications.
At this moment, ART is working on a stepwise implementation of the mandatory cleansing of tar containing RAP (COPRO, 2015b). According to SB250 v3.0 and older versions, tar containing RAP is allowed to be reused under strict conditions as described in 5.3.3.4 of VLAREMA (at least 1 500 m^3, inventory of the location by OVAM, and used in cold, hydraulic bound material). Since the implementation of SB250 v3.1, thermal cleansing is mandatory for small works where less than 2 000 ton tar containing RAP is released (COPRO, 2015b). This limit will be increased step by step until May 2019, when all released tar containing RAP must be thermally cleansed. The Flemish government designates an authorized company for this treatment, which is at this moment only the Dutch company Recycling Kombinatie REKO, thus currently, thermal cleansing of RAP is not applied by any Belgian company. The average transport distance from a Flemish asphalt plant to the Reko waste plant is 143 km (st. dev. = 34.5 km). Rijkswaterstaat is part of the Dutch Ministry of Infrastructure and the Environment and has an agreement with three Dutch companies for the thermal cleansing of tar containing RAP (Rijkswaterstaat Leefomgeving, 2015).

Table 19: Destination of released RAP in 2014

	scenario 2014		scenario 2019	
	ton	%	ton	%
RAP certified by COPRO for use in asphalt mixtures	970 000	60	970 000	60
RAP certified by COPRO for use in foundations	612 127	38	572 413	36
RAP certified by CERTIPRO for use in foundations	14 133	1	14 133	1
RAP exported for thermal cleansing	10 000	1	49 714	3
Total released RAP in 2014	1 606 260	100	1 606 260	100

References: (Lacaeyse, 2016; Zwijzen, 2016)

In this thesis, data from COPRO are mostly used to represent the Flemish asphalt sector. However, in Table 19 data from COPRO, Certipro and an estimation by ART are used for appointing the application of the released RAP. The table includes the situation as it was in 2014, and a prognosis for 2019. The scenario of 2019 is based on the data from 2014 where all RAP with tar is exported for thermal cleansing.

Appendix 5

Additional analyses of the data related to energy consumption to dry and heat aggregates in the asphalt plant are described in this appendix. The results are relevant and form the basis of some choices in subsection 5.3.2. The analysis and results described in subsection 5.3.2 are based on the absolute energy consumption, while this analysis uses the specific energy consumption.

The specific energy consumption – absolute natural gas consumption (m^3) divided by the total amount of asphalt produced (ton) – leads to a reduction of the variation in the data. Thereby, the distinctive power of a fit for a regression is penalized and only low R^2 values are found for linear regression. The difference between the distinctive powers of a fit for a linear regression can be seen in Figure 42 for the specific energy consumption and in Figure 43 for the absolute energy consumption. The data in both Figure 42 and Figure 43 are found to be heteroscedastic (Koenker test), but after adaption of the standard error, the correlation between the dependent and independent variable remains statistically significant with (α=0.01).

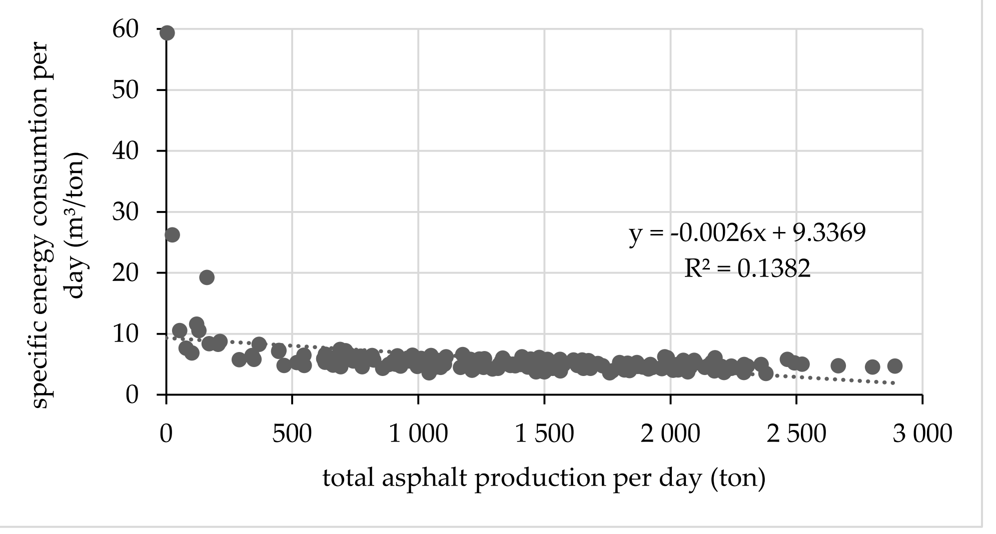

Figure 42: Data variation for specific energy consumption (m³/ton)

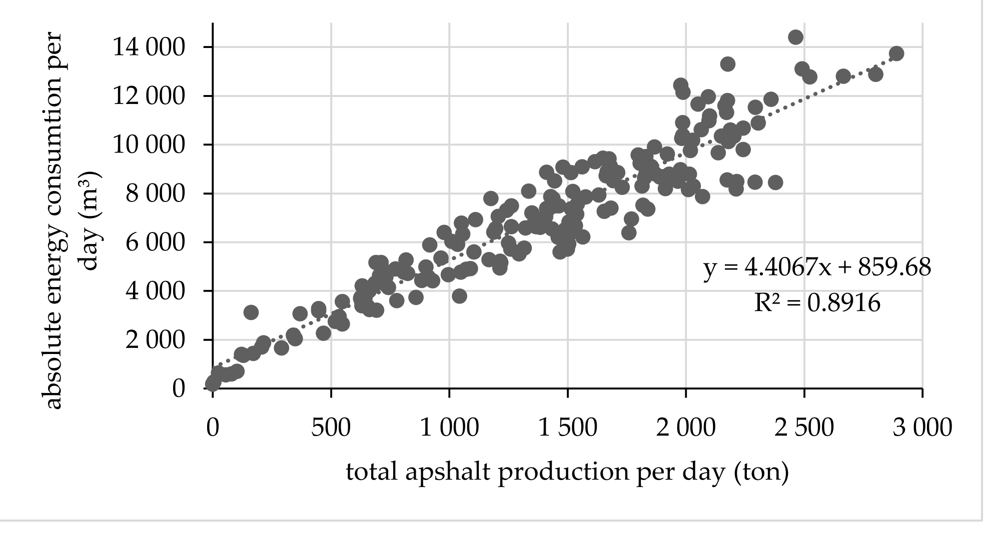

Figure 43: Data variation for absolute energy consumption (m³)

The daily production record includes the daily natural gas consumption and the daily total asphalt production. For the analysis of the energy consumption, we can only go back in time and include data up to and including 2013. In the winter between 2012 and 2013, the plant was adapted to use natural gas as energy source instead of fuel oil.

Days with exclusively HMA production with RAP or exclusively HMA production without RAP are searched in the available data (2013-2015). For these days, the produced amount of non-HMA asphalt (e.g., mastic asphalt or cold asphalt) is also registered. Production days with deviation less than 5%m/m on the percentage of RAP and the asphalt mixture type (AMT) are included in a data set for further analysis. For example, a maximal deviation of 5%m/m on the RAP content means that for the total production on a specific day, maximum 5%m/m of the produced mixtures includes RAP if the asphalt mixtures without RAP are investigated, or maximum 5%m/m of the produced mixtures does not contain RAP if the asphalt mixtures with RAP are investigated. The smaller the allowed deviation, the less results are available for analysis. The actual percentage of RAP in the mixtures is not taken into account in this analysis.
The goal is to investigate if there is a statistical significant increase in the energy (natural gas) consumption during the asphalt production with or without RAP.

The data used for analysis are presented in Table 20. The data in the different groups are not normally distributed. The non-parametric Mann-Witney test is used to search for statistical significant differences in the median energy consumption (m^3 natural gas/ton asphalt) for asphalt production with or without RAP. With a deviation of 2% on the RAP content and the mixture type, a statistical significant (α=0.01) difference in median energy consumption is found. The last row in the third column (2% deviation on AMT and %RAP) in the table shows that the specific energy consumption increases with 18% if asphalt mixtures with RAP are produced, compared to days where only mixtures without RAP are produced. However, when taking into account all results for 2013, 2014 and 2015, without a deviation on both RAP and AMT, no statistical significant difference in median was found (see last column in Table 20).

Table 20: Specific energy consumption (m^3 natural gas/ton asphalt) for selected production days in 2013, 2014 and 2015

deviation (%)	≤ 5		≤ 2		0 AMT, ≤ 2 RAP		0 RAP, ≤ 2 AMT		0	
RAP (%)	0	100	0	100	0	100	0	100	0	100
energy	10,33	5,41	10,33	5,43	10,33	5,43	10,33	5,62	10,33	5,62
consumption	5,09	6,40	5,09	5,62	3,70	5,62	5,09	5,77	3,70	5,77
(m^3/ton)	3,70	5,43	3,70	5,29	4,18	5,29	3,70	4,92	4,18	4,92
	3,96	5,62	3,96	5,77	3,98	5,77	3,96	4,82	3,98	4,82
	4,38	5,29	3,98	5,22	3,82	4,39	3,98		3,82	
	3,98	5,20	4,18	4,39	4,19	4,92	4,18		4,19	
	4,18	5,77	3,98	5,16	4,45	4,82	3,98		4,45	
	3,87	5,04	3,82	4,80	4,96	8,33	3,82		4,96	
	5,63	5,22	4,19	4,75	4,95		4,19		4,95	
	3,98	4,39	4,45	4,92	4,48		4,45		4,48	
	3,82	5,16	4,96	4,82	4,95		4,96		4,95	
	4,19	4,80	4,95	5,85	4,55		4,95		4,55	
	4,45	4,75	4,48	8,33	6,01		4,48		6,01	
	4,96	4,92	4,95		4,80		4,95		4,80	
	4,95	4,82	4,54		4,31		4,54		4,31	
	4,48	5,85	4,55		7,46		4,55		7,46	
	4,95	8,33	6,01		4,65		6,01		4,65	
	4,54		3,72		4,36		3,72		4,36	
	4,55		4,42		3,64		4,42		3,64	
	4,45		4,80				4,80			
	6,01		4,31				4,31			
	3,72		4,10				4,10			
	4,42		7,46				7,46			
	4,80		4,65				4,65			
	4,31		4,40				4,40			
	4,10		4,25				4,25			
	7,46		4,36				4,36			
	4,65		3,64				3,64			
	4,54		3,83				3,83			
	4,30		4,52				4,52			
	4,40		4,78				4,78			
	4,57									
	4,57									
	3,82									
	4,25									
	4,36									
	3,64									
	3,83									
	4,52									
	4,78									
median	4,43	5,22	4,42	5,22	4,48	5,36	4,42	5,27	4,48	5,27
P-value	α=0,01		α=0,01		α=0,05		α=0,05		none	
ratio	118%		118%		120%		119%		118%	

Some data based on small daily production amounts are included in the analysis. For small daily productions, the energy to heat the different components of the asphalt plant itself may be dominant and affect the specific energy consumption per ton asphalt. For analysing this effect, the specific energy consumption for all production days in 2015 (including days with non-HMA mixtures) towards the total daily asphalt production is depicted in Figure 44. Outliers (very high specific energy consumption) are seen in the graph for small production quantities. After trying different values for the minimal daily production amount, the strongest linear correlation (R^2=0.2978) is found when only the days with a minimal production of 170 ton/day are included in the graph (see Figure 45).

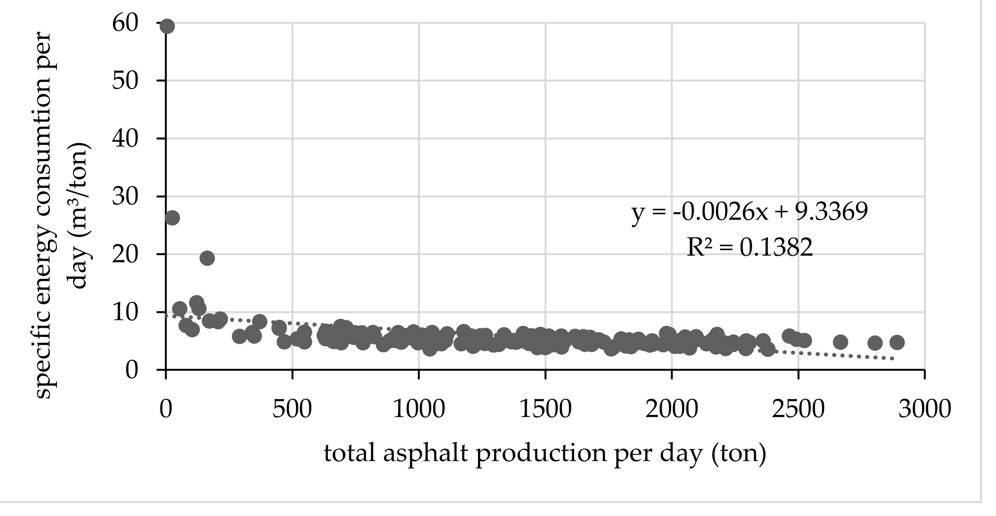

Figure 44: Specific energy consumption towards the total daily asphalt production for all asphalt production days in 2015

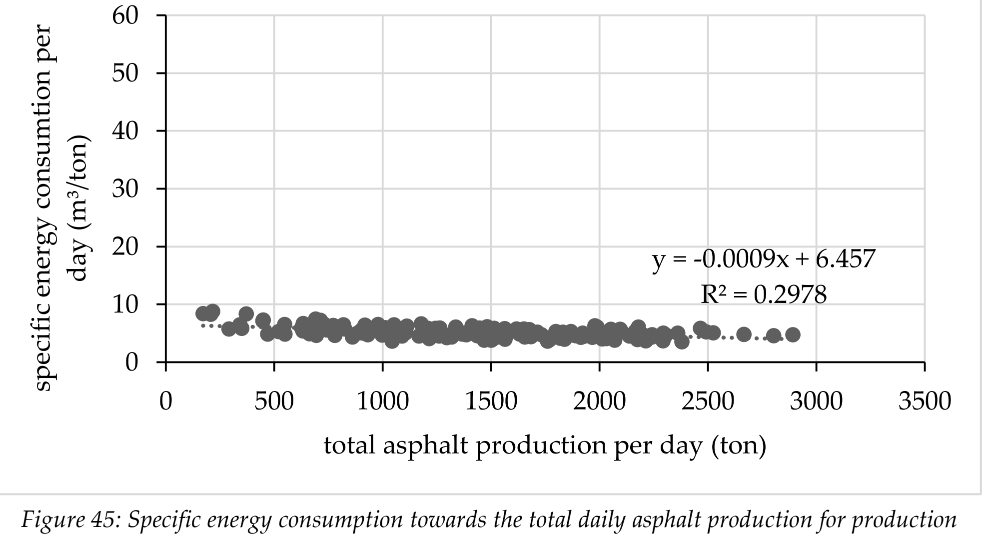

Figure 45: Specific energy consumption towards the total daily asphalt production for production days in 2015 with a production of minimal 170 ton/day

The statistical analysis (difference in median) is repeated on the truncated data sample, taking into account only asphalt productions of minimal 170 ton/day.

Table 21: Specific energy consumption (m³ natural gas/ton asphalt) for selected production days in 2013, 2014 and 2015, with a minimal production of 170 ton asphalt per day

deviation (%)	≤ 5		≤ 2		0 AMT, ≤ 2 RAP		0 RAP, ≤ 2 AMT		0	
RAP (%)	0	100	0	100	0	100	0	100	0	100
energy	5,09	5,41	5,09	5,43	3,70	5,43	5,09	5,62	3,70	5,62
consumption	3,70	6,40	3,70	5,62	4,18	5,62	3,70	5,77	4,18	5,77
(m^3/ton)	3,96	5,43	3,96	5,29	3,98	5,29	3,96	4,92	3,98	4,92
	4,38	5,62	3,98	5,77	3,82	5,77	3,98	4,82	3,82	4,82
	3,98	5,29	4,18	5,22	4,19	4,39	4,18		4,19	
	4,18	5,20	3,98	4,39	4,45	4,92	3,98		4,45	
	3,87	5,77	3,82	5,16	4,96	4,82	3,82		4,96	
	5,63	5,04	4,19	4,80	4,95	8,33	4,19		4,95	
	3,98	5,22	4,45	4,75	4,48		4,45		4,48	
	3,82	4,39	4,96	4,92	4,95		4,96		4,95	
	4,19	5,16	4,95	4,82	4,55		4,95		4,55	
	4,45	4,80	4,48	5,85	6,01		4,48		6,01	
	4,96	4,75	4,95	8,33	4,80		4,95		4,80	
	4,95	4,92	4,54		4,31		4,54		4,31	
	4,48	4,82	4,55		4,65		4,55		4,65	
	4,95	5,85	6,01		4,36		6,01		4,36	
	4,54	8,33	3,72		3,64		3,72		3,64	
	4,55		4,42				4,42			
	4,45		4,80				4,80			
	6,01		4,31				4,31			
	3,72		4,10				4,10			
	4,42		4,65				4,65			
	4,80		4,40				4,40			
	4,31		4,25				4,25			
	4,10		4,36				4,36			
	4,65		3,64				3,64			
	4,54		3,83				3,83			
	4,30		4,52				4,52			
	4,40		4,78				4,78			
	4,57									
	4,57									
	3,82									
	4,25									
	4,36									
	3,64									
	3,83									
	4,52									
	4,78									
median	4,41	5,22	4,40	5,22	4,45	5,36	4,40	5,27	4,45	5,27
P-value	α=0,01		α=0,01		α=0,01		α=0,05		α=0,05	
ratio	118%		118%		120%		120%		118%	

A statistically significant (α=0.05) difference in median was found between asphalt production with RAP and asphalt production without RAP when no deviation on the asphalt mixture type and RAP is allowed. It is remarked that there is an overlap of the values for productions with and without RAP. However, the median for the specific energy consumption for asphalt production with RAP is 18% higher compared to the median of the specific energy consumption for asphalt production without RAP.

This result is in accordance with the results in literature (van den Berk, 2004). Van den Berk found that the energy consumption increases with 14% if 15 to 30% RAP is included in the asphalt mixtures, and that the energy consumption increases with 17% if more than 45% RAP is included in the asphalt mixture. The difference with the findings in literature and the findings in this thesis is the way RAP is included. The analysis in this thesis takes into account the ratio of asphalt mixtures that includes RAP in the asphalt mixture, while the percentage of RAP in the mixtures is unknown. Van den Berk deviates the results for different percentages of RAP in the mixtures.

Appendix 6

Life cycle inventory for holistic LCA study for Flanders as presented in section 5.4. This appendix is added digitally.

PART II: PUBLICATIONS

Only small layout and linguistic adjustments were made in the papers in order to maintain consistency in the whole thesis text. For example, any spelling, typing or styling mistakes are corrected and figures and tables are numbered consecutively in order to be able to make unambiguous cross-references.

PAPER I: REVIEW AND ENVIRONMENTAL IMPACT ASSESSMENT OF GREEN TECHNOLOGIES FOR BASE COURSES IN BITUMINOUS PAVEMENTS

Authors: Joke Anthonissen, Wim Van den bergh, Johan Braet

Abstract: This paper provides a critical review of different approaches applied in the Belgian asphalt sector in order to reduce the environmental impact of bituminous road construction works. The focus is on (1) reusing reclaimed asphalt pavement; (2) reducing the asphalt production temperature; and (3) prolonging the service life of the pavement. Environmental impact assessment of these methods is necessary to be able to compare these approaches and understand better the ability to reduce the environmental impact during the life cycle of the road pavement. Attention should be drawn to the possible shift in environmental impact between various life cycle stages e.g., raw material production, asphalt production or waste treatment. Life cycle assessment is necessary to adequately assess the environmental impact of these approaches over the entire service life of the bituminous pavement. The three approaches and their implementation in the road sector in Flanders (region in Belgium) are described and the main findings from life cycle assessment studies on these subjects are discussed. It was found from the review that using reclaimed asphalt pavement in new bituminous mixtures might yield significant environmental gains. The environmental impact of the application of warm mix asphalt technologies, on the other hand, depends on the technique used.

Keywords: bituminous pavement, life cycle assessment (LCA), reclaimed asphalt pavement (RAP), warm mix asphalt (WMA), half-warm mix asphalt (HWMA), Flanders

Abbreviations:

AADT	Average annual daily traffic	HWMA	Half-warm mix asphalt
AADTT	Average annual daily truck traffic	IBA	Incinerator bottom ash
ADT	Average daily traffic	LCA	Life cycle assessment
AP	Acidification potential	LCCA	Life cycle cost analysis
CED	Cumulative energy demand	LCIA	Life cycle impact assessment
CMA	Cold mix asphalt	NRD	Natural resource depletion
CSOL	Crack, seat, and overlay	PAH	Polycyclic aromatic hydrocarbon
EE	Energy equivalent	PCC	Portland cement concrete
EI	Eutrophication index	PCR	Product category rules

EP	Ecotoxic potential	POPC	Photochemical ozone creation potential
EPD	Environmental product declaration	RAP	Reclaimed asphalt pavement
EU ETS	European Union emission trading system	SMA	Stone mastic asphalt
GWP	Global warming potential	TP	Toxic potential (human)
HMA	Hot mix asphalt	VOC	Volatile organic compounds
HMB	High modulus bituminous	WMA	Warm mix asphalt

1 INTRODUCTION

1.1 Framework and problem

On the occasion of the Kyoto Protocol, adopted and signed in 1997 and setting binding obligations on industrialized countries in order to reduce emissions of greenhouse gases, the European Union emissions trading system (EU ETS) was initiated in 2005 for energy-intensive industrial installations and the electricity sector. The EU ETS works based on the 'cap and trade' principle (Departement Leefmilieu Natuur en Energie, 2014; European Union, 2013). The overall volume of greenhouse gases that can be emitted each year by the companies covered by the system is subject to a cap set at EU level. Within this Europe-wide cap, companies receive or buy emission allowances they can trade if wanted. All companies subjected to the EU ETS have to monitor and report on their CO_2 emissions. Each year, the companies have to hand in emission allowances in accordance with the emitted quantity.
In Flanders, about 220 companies were subjected to the EU ETS in 2014 altogether responsible for 40% of the CO_2 emissions in Flanders. These 220 companies emitted together 31.6 million tons of CO_2 equivalents in 2014. Since 2013, all installations with a net heat excess of 20 MW or more are subjected to the Kyoto Protocol, including 13 of the 18 Flemish asphalt plants. These 13 asphalt plants are responsible for 0.13% of all Flemish CO_2 emissions registered according to EU ETS (Departement Leefmilieu Natuur en Energie, 2014). The EU ETS regulations induced some innovative technologies in order to reduce the greenhouse gas emissions.

Besides, triggered by economic benefits, some new technologies were introduced in the bituminous road pavement sector earlier, which are nowadays considered to have also a beneficial impact on the environment. These techniques, which are considered to be "green", need to be analysed in detail in order to be able to make an informed decision on the environmental impact. The environmental impact of a certain product is dependent on various preconditions e.g. local aspects, valid regulations, and application and performance in practice.

1.2 Objective and scope

The objective of the current study is to evaluate the possibilities for the industry to reduce the life cycle environmental impact of bituminous pavements in Flanders.

Kluts & Miliutenko (2012) and Stripple & Erlandsson (2004) presented three decision stages in the road infrastructure planning: (1) network level: choice of transport modality at the national level; (2) corridor level: choice of localization and construction type of a specific project; (3) project level: choice of specific design. Kluts & Miliutenko (2012) mention that it is likely to use one single environmental impact assessment process to evaluate both the second and third decision level. Based on this idea, Butt et al. (2015) suggested a framework which includes two complexity levels (network and project level) and two decision situations (early planning and late planning/design).

The current study focuses on the possible reductions of environmental impact which might be realized by efforts of the industry. Hence, according to the framework suggested by Butt et al. (2015), the current study concerns decisions at the project level in the late planning and design stage. This includes questions as "Which road or material alternative to select?" and "What specific design alternative to choose?".

It is important to note that Belgium is divided in three different regions (Flanders, the Walloon Region, and Brussels) where road infrastructure is subjected to the regional regulations. The Flemish road standard SB250 v3.1 prescribes all rules and conditions for asphalt mixtures to be used for public road construction. The current version of this standard does not allow the use of reclaimed asphalt pavement (RAP) in surface courses of road pavements. In order to allow comparison between the use of RAP and other green techniques, the current contribution focuses on base layers. This justifies the exclusion of some important components in road infrastructure as described by Araújo et al. (2014), AzariJafari et al. (2016), Muench (2010), and Santero et al. (2011b). As base courses do not affect the noise from pavement tire interaction, lighting requirements, albedo effect, carbonation, etc., these components are excluded from the scope of the current literature review. Although the deformation of base courses affects the international roughness index of the pavement and consequently the vehicle fuel consumption, the use phase in general is beyond the scope of this study. Nevertheless, the authors recognize the importance of these aspects and the use phase impacts in environmental impact assessment studies within another research scope.

1.3 Research approach

Three groups of techniques are investigated: (1) reducing the demand for virgin materials e.g., by recycling recuperated materials into new asphalt mixtures i.e., reclaimed asphalt pavement (RAP); (2) reducing the energy consumption e.g., by decreasing the production temperature of asphalt mixtures; and (3) lengthening the service life of the pavements by optimizing the mechanical properties of asphalt mixtures. Other aspects affecting the environmental impact are considered as well e.g., transport distances, moisture content in aggregates, energy consumption in the asphalt plant, etc.

Life cycle assessment (LCA) is seen as the appropriate method to assess the environmental impact of bituminous road pavements. It allows including different life cycle stages and multiple environmental issues. The framework of Butt et al. (2015) for the implementation of LCA in road infrastructure indicates that stand-alone LCA studies and attributional LCA studies are suitable methodologies to answer the defined research questions in the current study.

A literature review focusing on the current practices in Flanders is conducted. Various literature reviews of pavement LCA are published (AzariJafari et al., 2016; Muench, 2010; Santero et al., 2011c), but the current one is different because of the different, specific scope and area of applications. Both regional (Flanders and Belgium) and international (Europe and worldwide) literature have been consulted for this review. First, the techniques that are supposed to reduce the environmental impact are described e.g., the influence on the mechanical properties, the required adaptation of the asphalt plant or the implementation of the techniques in the Flemish road sector. Subsequently, a review of selected life cycle assessment (LCA) studies on road pavement is given in order to discuss the environmental impact of these techniques. Note that the aim of the study is not to compare framework gaps and inconsistencies in LCA studies. The findings of this study can be used by bench makers in order to decide for investments or funding and by the asphalt sector to optimize the environmental performance.

2 APPROACHES IN ORDER TO ADDRESS SUSTAINABILITY AND THEIR USE IN FLANDERS

In general, it can be stated that efforts are made in order to make the bituminous road sector in Flanders more environmentally friendly. The Flemish road agency recently implemented a pilot project, assigning a public tender for repaving a road section based on two criteria: economic cost and CO_2 emissions of the project (Anthonissen et al., 2015b).

2.1 Use of reclaimed asphalt pavement

Among the various materials (steel slag, fly ashes, cast iron sand, dredging spoil, glass, crumb rubber, roofing waste and bio base bitumen) mentioned in the Best Available Techniques study (Leyssens et al., 2013), reclaimed asphalt pavement (RAP) is the most used material to replace virgin raw materials in asphalt mixtures in Flanders. Reclaimed asphalt pavement is released during maintenance interventions. It is a high quality material that contains valuable constituents (inert material and bituminous binder). The reuse and the recycling of RAP are encouraged by some economic benefits and started more than 30 years ago, and nowadays, it has become common practice in many European countries (EAPA, 2008).

The Flemish Road Standard (for public road works) SB250 defines criteria for mixture compositions (empirical method) or the required minimum performances (fundamental method). The current version SB250 v.3.1 (Vlaamse Overheid, 2014) prohibits the use of RAP in asphalt mixtures for surface courses. On the other hand, some mixtures for base courses are defined based on the fundamental method without a limit on the percentage of RAP.

Before the RAP is reused, it is screened for contaminations (tar, organic material, etc.) and pre-treated (breaking, sieving) in order to control its homogeneity. Thereafter, it can be used in new asphalt mixtures reducing the need (and costs) for virgin inert materials and virgin bitumen. This type of recycling is called closed loop recycling. This means that the output of the product system (the end of service life of a road pavement) is used as its input again (material produced in order to repave the road).

In practice, different ways are applied in order to use RAP in asphalt mixtures. The RAP can be added cold in the mixer together with the overheated virgin materials or the RAP can be preheated (e.g., by parallel drum) before it is added to the asphalt mixture. Cold recycling is quite easy and only few additions to the asphalt plant are required to enable, but the main disadvantages are the required higher temperature

of the virgin materials and a longer mixing time at high recycling rates. Following the Flemish Road Standard SB250 v.3.1, maximum 20% of the bitumen in the asphalt mixture may come from RAP when applying cold recycling. The implementation of a parallel drum demands extensive adaptations of the asphalt plant with higher investments, but is a more efficient approach for recycling. Most Flemish asphalt plants are equipped with a parallel drum. The use of a parallel drum allows a better control of the moisture content in RAP. It was found in literature (Vidal et al., 2013; Wayman et al., 2012) that the moisture content in RAP is higher compared to virgin aggregates since water is used for milling the old pavement. In Flanders, virgin aggregates are washed and might therefore be very wet as well. Remaining moisture in asphalt mixtures will influence the performances and hence the service life in a negative way, and more moisture requires more energy for drying the aggregates during the asphalt production process. Depending on the circumstances, the moisture in RAP may offset the environmental benefits from using RAP instead of virgin materials.
In general, no additives for the production of asphalt mixtures with RAP are used in the Flemish asphalt sector.

In 2014, 38 asphalt plants are located in Belgium, of which 18 in Flanders, 19 in the Walloon Region and 1 in Brussels (Belgian Road Research Centre, 2014). COPRO [10] publishes the results of measurements on certified asphalt mixtures and certified asphalt plants. 17 Flemish and 4 Walloon asphalt production plants are COPRO certified (meaning 1 Flemish, 15 Walloon and 1 Brussels asphalt plants are not and thus excluded from this COPRO data collection) (COPRO, 2015). All COPRO-certified asphalt plants are able to produce asphalt mixtures with RAP.
The data from the publications COPRO (2015, 2014, 2013) and European Asphalt Pavement Association (2015, 2014, 2013) – discussing some figures on asphalt production and the use of RAP – are compared in Table 22. The data from EAPA are an estimation of the national industry sector, made by the Belgian association of asphalt producers. Hence the scope of the data sources is different (see number of production sites). This is reflected in the annual asphalt production, which is reported to be higher in EAPA figures compared to COPRO. The available amount of RAP, on the other hand, is higher in the COPRO report. These figures account all COPRO-certified RAP which can be used in new asphalt mixtures or in unbound base material. Also, the percentages on the use of RAP differ for both data sources. In general, it is assumed that the COPRO data are more accurate in its specific scope.

[10] COPRO is the abbreviation for "COntrol of PROducts". COPRO is an independent Belgian organization and implements controls of quality on construction products as on their integration on sites.

Table 22: Figures of asphalt production in Belgium in 2012, 2013 and 2014

	2012		2013		2014	
	EAPA	COPRO	EAPA	COPRO	EAPA	COPRO
Number of production sites	38	21	38	21	38	22
HMA and WMA production (million tons)	5.6	3.7	5.3	3.3	5.2	3.3
Available amount of RAP (million tons)	1.5	1.9	1.5	2.0	1.5	1.6
Available RAP used in asphalt (%)	61	50	61	43		61
Mixtures containing RAP (%)	49	58	51	58		61
RAP content in mixtures with RAP (%)		39		45		43

The proportion of residual binder from RAP and virgin binder in asphalt mixtures is expected to affect mixture volumetric and mechanical properties. Contradiction is found in literature concerning the percentage of actual blending occurring between RAP and virgin binders. Some studies assume that aged and virgin binder approaches complete mixing (Al-Qadi et al., 2009; Lopes et al., 2015; Shen et al., 2007), while others assume partial blending (Apeagyei et al., 2011; Huang and Bird, 2007) and Huang et al. (2005) found that mechanical blending affects only a small portion of aged asphalt binder in RAP.

Li et al. (2008), Lopes et al. (2015) and Swamy et al. (2011) found that asphalt mixtures containing RAP have higher dynamic modulus values and hence become stiffer than the same mixtures containing no RAP. Colbert & You (2012), on the other hand, notice a decrease of the dynamic modulus and the resilient modulus as RAP percentage increased. Several investigations (Al-Qadi et al., 2009; Li et al., 2008; Mogawer et al., 2012; Tapsoba et al., 2012; Zhao et al., 2013) have shown that mixtures with RAP have a lower thermal cracking resistance. Colbert & You (2012), Lopes et al. (2015) and Zhao et al. (2013) found that the addition of RAP increases the rutting resistance; while Apeagyei et al. (2011) found similar rutting performances for a mixture without RAP and a similar mixture with 25% RAP. Finally, Zhao et al. (2013) found that adding RAP decreases the fatigue resistance, while Lopes et al. (2015) found that the presence of RAP improves the fatigue life of hot mix asphalt.

Mogawer et al. (2012) found that some production parameters at the plant i.e., discharge temperature and silo storage may have an impact on the relative degree of blending between the RAP and virgin binders and hence affect the mixture stiffness and cracking properties.

2.2 Warm mix asphalt

The annual emitted CO_2 equivalents in the scope of the EU ETS (as described in chapter 1) are calculated based on the fuel consumption of an installation. In this scope, techniques are implemented in order to reduce the asphalt production temperature.

Leyssens et al. (2013) define four main categories of asphalt processing techniques in relation to the temperature: (1) cold mix asphalt (CMA) manufactured at temperature lower than 40 °C; (2) half-warm mix asphalt (HWMA) manufactured at temperatures of 60 to 95 °C; (3) warm mix asphalt (WMA) manufactured at temperatures of 100 to 150 °C; and (4) hot mix asphalt (HMA) manufactured at temperatures higher than 150°C. Currently, WMA is the best of those alternatives to replace HMA due to similar performances. In general, three main groups of techniques for the production of WMA can be distinguished (Rubio et al., 2012): (1) organic additives, (2) chemical additives, and (3) water-based foaming processes. The effect of the different techniques is equal: reducing the viscosity of bitumen in order to improve the workability of the asphalt mixture at lower temperature.

WMA production using organic or chemical additives is rarely applied in Flanders. The WMA production based on foaming techniques does not require the addition of additives at the asphalt plant. The implementation of a foam-unit in an asphalt plant requires only small adjustments. A number of asphalt plants in Belgium are provided with a foam-unit. Nevertheless, this technique is not yet used in order to produce WMA on a large scale. In Flanders, WMA mixtures are currently only produced in the scope of research and pilot projects. SB250 v.3.1 includes specifications for WMA e.g., the production temperature is defined to be 105 to 160 °C compared to 140 to 210 °C for HMA. After acceptance of a validation dossier for a specific asphalt mixture produced at decreased temperatures, this mixture can be used for public road works. In this way, the Flemish Road Agency encourages the industry to use the WMA technology. The use of the WMA mixtures in practice on a large scale is necessary to build up experience and confidence.

Regarding the mechanical performances, Hill (2011) and Zhao et al. (2013) found that WMA is less resistant to rutting than a corresponding HMA, while Zhang (2010) concludes that WMA generally presents better rut resistance than their HMA counterparts. Hill (2011), Zhang (2010) and Zhao et al. (2013) indicate that WMA mixtures are more susceptible to moisture compared with their HMA equivalents.

Furthermore, the studies by Hill (2011), Hurley et al. (2009) and Zhang (2010) investigate the impact of different WMA additives on the mechanical performances of the WMA mixture. The Fischer Tropsch wax positively affects the rut resistance

(Hill, 2011; Zhang, 2010) while an emulsion additive increases the rut depths (Hill, 2011; Hurley et al., 2009).

It is recommended to not decrease the heating temperature of the virgin and recycled materials beneath 100 °C for WMA because the drying process would not be complete and the remaining moisture could affect negatively the pavement durability (van Bochove et al., 2012).

The feasibility of applying high percentages of RAP (75% to 100%) in WMA is proved by studies of D'Angelo et al. (2008) and Mallick et al. (2008). In a laboratory research environment, different researchers found an improvement of WMA performances by adding RAP: higher rut resistance (Hill, 2011; Zhao et al., 2012), better moisture damage resistance (Hill, 2011; Shu et al., 2012; Zhao et al., 2012), and better fatigue performance (Zhao et al., 2012). Performance evaluation, however, needs to be conducted in situ on the road in order to investigate its capability to resist pavement distresses during service life (Zhao et al., 2013).

2.3 Longer lasting roads

The longer the service life of material on the road, the fewer maintenance interventions are necessary, implying less material and energy consumption, less transport, less emissions etc. Therefore, research was conducted in order to develop more sustainable materials.

A well-known binder type is polymer-modified bitumen. Studies indicate that the properties of polymer-modified bitumen are significantly improved compared to penetration bitumen e.g., higher elastic recovery, a higher softening point, higher viscosity, larger cohesive strength or greater ductility (Yildirim, 2007), resulting in an improved resistance to rutting, to fatigue and to thermal cracking and an extended service live of the road pavement (Buncher and Rosenberger, 2005; Glanzman, 2005).

The addition of fibres is another technique to improve the mechanical properties of an asphalt mixture and thereby the service life of a pavement. A field and laboratory study by Kaloush et al. (2010) of bituminous mixtures with polypropylene and aramid fibres indicated that an improvement was found in permanent deformation, fatigue cracking and thermal cracking compared with a control mix with no fibres.

A Flemish laboratory study by Anthonissen and Boonen (2012) investigated the impact of aramid, polyester and glass fibres on the performances of asphalt and bitumen and compared the results to a reference without fibres. Both asphalt mixtures with aramid and polyester fibres have an increased rutting resistance. The results of the Bending Beam Rheometer (BBR) reveal a higher minimal user temperature for the aramid fibre, which might yield thermal cracks at higher

temperatures. The force ductility test showed a very high force but a small prolongation for the aramid fibres. A first test section on a Belgian road was constructed in 2013 using fibres in the mixture for the surface course in order to absorb the high tensile strains in the pavement.
Using fibres is an interesting possibility to improve the mechanical properties of the asphalt mixture and lengthen the service life of the pavement, but needs more research. An important research topic is the recyclability of road pavements with fibres at the end of the service life.

Another innovative concept is the use of old bituminous roofing felt waste in hot mix asphalt. A mixture was developed, composed of 3% reduced bituminous roofing waste, 45 to 55% reclaimed asphalt pavement, 40 to 50% new granulates and only 1% new bituminous binder, called i-aB³ (improved aged-Bitumen Bound Base) (Van den bergh and Stoop, 2009; Van den bergh et al., 2008). This mixture, preliminary designed for asphalt base courses, is currently described as bitumen grave in SB250 v3.1 and can be used as a bound base material. When using this mixture in the construction of a flexible road pavement, the thickness of the structure can be reduced, while at the same time the service life and the durability of the pavement are increased. Three different test sections were constructed in Flanders in 2001, 2006 and 2010 and the evaluation (i.e. falling weight deflection measurements) of these test sections shows – still – promising results (Van den bergh et al., 2013).

The standard value for the design life of road structures with an asphalt concrete pavement is set at 20 years in Flanders. The default service life is 14 years for the wearing course and 24 years for the base course [reference: interview with senior adviser at Agency for Roads and Traffic]. In the Netherlands, the default service life of the bituminous road structure is defined to be 20 years and the surface course has a service life of 10 to 12 years (Van Gelder, 2012).
Generally, it is difficult to predict the prolongation of the roads service life when improved asphalt mixtures are used. Many contextual parameters influence the service life of a road pavement: conscientious execution of the works (asphalt production and road construction), (extreme) weather conditions, traffic load, performances of other courses in the road construction, etc. Besides, the necessary maintenance interventions are often not executed based on mechanical failure of the road pavement, but in practice these are scheduled based on the financial policy of the responsible authorities.

3 LIFE CYCLE ASSESSMENT OF PAVEMENTS

An extensive analysis about the environmental impact of the techniques discussed (chapter 2) is necessary in order to evaluate the impact over the lifetime of the road pavement. Life cycle assessment is an appropriate technique for this environmental analysis. Buyle et al. (2013) clearly describe the theoretical frame and the four steps of a life cycle assessment according to ISO 14040 series (ISO 14040, 2006; ISO 14044, 2006).

Table 23 presents more information on the LCA studies that are discussed in this chapter. The only LCA studies included in the table are those who contribute relevant information to the study objective. In this way, the results of the study can be described in text and other background information of the study might be looked up in this table to see the conclusions in a broader context.

Table 23: Overview of relevant LCA studies

No.	Reference & country	Objective of environmental LCA study
1	Ventura et al. 2008 France	compare binding courses of pavement sections made of RAP using various recycling rates (0, 10, 20 and 30%) in a hot mix process
2	Ventura et al. 2009 France	assess a half-warm mix process by means of measurements at the plant as well as during actual road works
3	Leng & Al-Qadi 2011 Illinois, USA	compare the life cycle environmental and economic performances of WMA SMA and HMA SMA binder courses as part of an overlay project
4	Nicuţă, 2011 Romania	evaluate and compare two asphalt mixtures (0% or 75% RAP) and conclude on the advantages or disadvantages of one road structure type
5	Santero et al. 2011 California, USA	evaluate the environmental effectiveness of long-life pavements
6	Tatari et al. 2012 USA	develop a hybrid Eco-LCA model to evaluate pavements: WMA with different additives and HMA
7	Wayman et al. 2012 Europe	identify product level parameters that have a significant impact on the environmental performance of RAP
8	Yu & Lu 2012 Florida, USA	develop an LCA model with six modules and use it to explore three overlay options: PCC, HMA and CSOL
9	Gschösser & Wallbaum 2013 Switzerland	analyze typical Swiss asphalt, concrete, and composite road pavements for national roads (highways) by performing LCA combined with LCCA
10	Rubio et al. 2013 Spain	compare HWMA and HMA in order to obtain field data (emission measurements)
11	Vidal et al. 2013 Spain	calculate the impacts of different road pavements: HMA and zeolite-based WMA, both with and without RAP
12	Anthonissen et al. 2014 Flanders, Belgium	compare the production of a HMA, a WMA with foamed bitumen technology and a HMA with 50% RAP
13	Blankendaal et al. 2014 North-Western Europe	gain insight in and improve upon the environmental impact of concrete and asphalt
14	Gschösser et al. 2014 Switzerland	determine the impacts for the new construction and maintenance of typical asphalt, concrete and composite road constructions
15	Anthonissen et al. 2015 Flanders, Belgium	compare different bituminous binders or manufacturing methods for road pavement construction
16	Giani et al. 2015 Italy	quantify the environmental savings producing asphalt pavements with a major percentage of RAP and using WMA

Table 23: Overview of relevant LCA studies (continued)

No.	Functional Unit	Layers: surface	binder	base	sub-base	Lifespan/ analysis period (years)
1	road section (±350 m x 3,8 m wide x 7 cm thick) corresponding to one hour of mixing plant output (±100 tons)		x			/
2	surface area of 3750 m², 6 cm thick (=560 ton)	x				/
3	one lane-mile (3,6 m width; 4,45 cm thick) with AADT=60120 vehicles north bound and 35920 vehicles south bound		x			/
4	1 km road pavement, 7 m width	x	x	x		15
5	3 different roads (different AADTT) with 3 different structures (layer thickness) in order to reach the design life	x		x	x	20, 40, 100
6	1 km two-lane (7,2 m width) highway, AADTT=2000 vehicles/day, 50% trucks	x		x		30
7	1 m² single lane highway with ADT = 450 vehicles (across all classes) in 1 direction with 1% growth	x	x	x	x	60
8	1 km, 2 x 2 lanes, AADT=70000 with 8% trucks, 4% growth a year	x	x			40
9	10 km four-lane (20,5 m width) highway, traffic load class T6	x	x	x	x	75
10	*(does not apply)*	x				/
11	1 km long, 13 m with, 8 cm thick with ADT=1000 vehicles/day with 8% of heavy vehicles	x				40
12	1 ton asphalt mixture			x		/
13	1 m³ asphalt				?	?
14	4 lanes (20,5 m width), 10 km length (traffic load class T6); and 2 lanes (7,5 m width), 0,5 km long (traffic load class T5 or T4)	x		x	x	?
15	section of 300 m length and 6 m width	x				48
16	1 km suburban road 2x2 lanes, 15 m width and 25 cm thick	x	x	x		15

Table 23: Overview of relevant LCA studies (continued)

	Life cycle stages									Environmental indicators / LCIA method												
No.	Materials extraction	Production	Earth works	Pavement construction	Maintenance	Traffic congestion during works	Use	End-of-life	Sensitivity analyses	EE / CED	Bitumen feedstock energy	GWP	Ecological scarcity / NRD	Fossil (fuel) depletion	POPC / smog	EP	TP	ODP	EI	AP	AD	relevant to LCA of roads:
1	x	x		x						x		x	x		x	x	x		x	x		RAP
2	x	x		x						x		x			x				x	x		WMA
3	x	x		x								x		x	x							WMA
										+ criteria air pollutants												
4	x	x		x								x										RAP
										aSPECT software												
5	x	x		x	x			x	x	x		x										general
										EIO-LCA												
6	x	x		x					x	x			x									WMA
										+ atmospheric emissions												
7	x	x		x	x			x	x			x			x	x	x	x	x	x	x	general
										CML2000 Midpoint impact categories (10)												RAP
8	x	x		x	x	x	x	x		x	x	x										general
9	x	x		x	x		x	x	x	x	x	x	x									general
10		x		x																		WMA
										Channeled and diffuse emissions												
11	x	x		x	x		x	x		x		x		x	x	x	x	x	x	x	x	RAP
										ReCiPe Midpoint (18) & Endpoint (3) categories, Hierarchist perspective + CED												WMA
12	x	x							x			x		x	x	x	x	x	x	x	x	WMA
										ReCiPe Midpoint (17), Endpoint (3) and single score impact, Hierarhist perspective + other LCIA methods												
13	x	x		x			x	x				x		x	x	x	x	x	x	x	x	WMA
										ReCiPe single score impact, Individualist, Hierarchist and Egalitarian perspectives												
14	x	x		x	x				x	x		x	x									general
										(CED non-renewable)												
15	x	x		x	x				x			x		x	x	x	x	x	x	x	x	WMA
										ReCiPe Midpoint (18) and single score impact, Hierarchist perspective + other LCIA methods												
16	x	x		x	x			x		x	x	x		x	x	x	x	x	x	x	x	RAP
										ReCiPe Midpoint (17), Endpoint (3), Hierarchist perspective + selected LCI results, Water Consumption												

3.1 LCA of roads: general

Wayman et al. (2012) conducted a cradle-to-grave study and divided the life cycle in different stages. Asphalt production (incorporating raw material acquisition and processing, raw material transport, raw material storage and asphalt production at plant), transport of asphalt to the worksite, laying and compaction of the road, in situ (including leaching from the in situ road pavement and dust from wear of the surface layer), and end-of-life (including milling of surface, binder and base layer after 60 year service life and transport of these materials to a stockpile). Asphalt production, transport to site and laying and compaction includes the initial construction and all maintenance interventions (three times inlay of surface layer and one time inlay of binding layer). The contribution of the different life cycle stages to the environmental impact over the life cycle depends on the impact category. Asphalt production represents 45 to 95% of the environmental impact, transport to site 1 to 8%, laying and compaction 1 to 12%, in situ 0 to 1% and end-of-life 0 to 40%. Within the asphalt production, the bitumen production (56 to 67%), the transport for supplying raw materials to the plant (13 to 16%) and the energy to dry and heat raw materials (11 to 25%) are found to be the main impacting processes.

Similarly, Giani et al. (2015), Gschösser and Wallbauw (2013), and Gschösser et al. (2014) found that extraction and material production have the biggest environmental impact during the life cycle, while the pavement construction and deconstruction processes have a marginal impact on the analysed environmental indicators.

When analysing the environmental impact of the asphalt production process, it is important not to confuse energy resources used for processing (process energy) and energy resources used as raw material (feedstock energy e.g., in bitumen). The first is mostly included in LCA studies. The feedstock energy, however, is not a direct energy consumption because the bitumen is not burned when it is used for road materials and hence the energy is not released. Moreover, at the end of the service life of the pavement, the bitumen can be used again as raw material binder without losing the feedstock energy. The feedstock energy of bitumen is rarely mentioned in LCA studies because it is rather complex to model.

Nevertheless, the inclusion or exclusion of it may be a decisive parameter when comparing the environmental impact of different materials e.g., asphalt and concrete (Yu and Lu, 2012). Including feedstock energy is less important when comparing different types of asphalt. The best practice is to include the feedstock energy (as stated in ISO 14040 (2006)) but present (the impact of) it separately in LCA results. Butt et al. (2014) describe a method to calculate the feedstock energy in bitumen.

Another factor with a major influence on the environmental impact during the life cycle of the road pavement is the intermediate maintenance period. Wayman et al. (2012) found a reduction of the environmental impact of minimum 10% in each impact category when the intermediate maintenance period of a surface course is prolonged from 10 to 14 years. Gschösser and Wallbauw (2013) found a reduction of the global warming potential of 25% when the intermediate maintenance periods are prolonged from 7.5 to 12.5 years for the surface course and from 15 to 25 years for the base course. Hence, the definition of the service life of a road pavement is an important subject of the definition of the functional unit of an LCA, but difficult to predict as described in section 2.3. For LCA calculations, the service life of the pavement is chosen based on experiences of local transportation administration or based on rehabilitation program and life design of the road (AzariJafari et al., 2016). Santero et al. (2011a) investigated the environmental impact of a road structure with a 20, 40 and 100 year design life. The structural design is a doweled Portland cement concrete pavement with an asphalt concrete base and a granular sub-base. The layer thicknesses vary in function of the design life. In spite of the fact that concrete pavements are behind the scope of the current literature review, some interesting conclusions were formulated, which are applicable to asphalt layers as well. When comparing the 20- and 40-year design, Santero et al. (2011a) found a crossover point of 29 to 45 years. This means that after a maximum of 45 years, the life cycle global warming potential (GWP) and energy consumption of the 20-year design exceeds the GWP and energy consumption of the 40-year design. Comparing the 40- and 100-year design, the authors found a minimum crossover point of 93 years and a maximum of more than 100 years. If the analysis period in an LCA study is shorter than the period before crossover, then the environmental benefits will not be realized in time. Furthermore, Santero et al. (2011a) stated that the rigidity of longer-life pavements makes them more susceptible to unforeseen shifts in their functionality and serviceability expectations.

The extra environmental impact caused by traffic disturbance during maintenance interventions is another important issue. Huang et al. (2009) found that reducing the duration of the roadwork by three days for a full reconstruction (base, binder and surface course) results in an important amount of avoided emissions and avoided energy consumption by the disturbed traffic. The amount of avoided carbon oxide (CO) and particulate matter (PM) emissions are almost equal to those caused by the roadwork itself. This indicates the importance of limiting the disturbance of the traffic during road works.

Similarly, it was found in literature (Carlson, 2011) that the energy consumption and emissions of the traffic using a road over its service life exceeds the energy consumptions and emissions from the other stages in the life cycle by 2 to 500 times, depending e.g. on the analysis period, the traffic intensity and the road construction alternative. The impact from vehicles using the road might be reduced by increased car energy efficiency and by optimizing the surface structure of the pavement.

Furthermore, it is found in literature that the results of LCA studies are not directly comparable since the specific contextual characteristics, environmental data sources and system boundaries differ considerably (Carlson, 2011; Santero et al., 2010; Ventura and Jullien, 2009). This finding emphasizes the importance of a specific framework for LCA studies on bituminous pavements. Butt et al. (2015) introduced a framework for pavement LCA studies with a distinction in the components which should be included in the study depending on the decision level (network or project) and decision stage (early planning or late planning/design). The International EPD® System, on the other hand, intends the development of Product Category Rules (PCR). A PCR is defined in ISO 14025 (ISO 14025, 2006) as a set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories. It defines the type of data that should be collected, measured and reported in a life cycle analysis. At this moment, the most appropriate PCR related to the current research topic is "Highways (except elevated highways), streets and roads" (EPD International, n.d.).

3.2 LCA of asphalt mixtures containing RAP

The environmental impact of using RAP in new hot or warm asphalt mixtures is affected by factors, such as moisture content (National Technology Development, 2009; Wayman et al., 2012), hot mix asphalt discharge temperature (National Technology Development, 2009), RAP content (National Technology Development, 2009), transport process (Ventura et al., 2008) and the quality of RAP (homogeneity, bitumen content, tar, etc.).

A study by Wayman et al. (2012) found that recycling of asphalt to bound courses is favoured compared with recycling asphalt to unbound applications (sub-base or fill) and waste management alternatives (landfill or incineration). These benefits mainly stem from the avoided extraction and refining of virgin bitumen that comes with a significant environmental impact (see section 3.1). Furthermore, Wayman et al. (2012) indicate that recycling RAP from surface courses and use it again in surface courses (recycling surface-to-surface) might realise some additional benefit if high specification aggregates are (re)used in order to optimize the surface characteristics. Recycling surface-to-surface is particularly pertinent if the high specification aggregate sources are widely dispersed or if road transport is the only available transport mode between quarry and plant.

Giani et al. (2015) found that the environmental impact reduces when adding 10% and 20% RAP in the HMA mixtures for surface and binder course respectively. The percentage of reduction is 6.8% for greenhouse gasses (ton CO_2eq) and 6.4% for the single score endpoint impact over a lifetime of 15 years.
Vidal et al. (2013) found that all endpoint impacts (human health, ecosystem diversity, resource availability), as well as midpoint impacts (climate change and fossil depletion) and the total cumulative energy demand were decreased by 13 to 14% when adding 15% RAP to HMA or WMA. Only a very small increase of the two midpoint impact categories were reported when considering only the asphalt production, which includes the asphalt plant (land use, infrastructure and machinery) and the electricity and fuel consumption for the asphalt production process (screening, drying, mixing and storing).
In the specific context of the study, Ventura et al. (2008) found a trend of decreasing potential environmental impacts with an increasing recycling rate except for the (eco)toxicity. The (eco)toxicity impact is mainly due to emission of PAH during roadwork (paving and rolling) and shows an increase with recycling rate.
Nicuţă (2011) found a reduction of the CO_2e emissions by 40% if 75% RAP is used in a cradle-to-laid environmental analysis of a road structure.

A disadvantage of using RAP is the increased energy costs during asphalt production due to the use of an additional burner in the parallel drum (van den Berk, 2004). A parallel drum is used in order to preheat the RAP before it is added to the mixer. The energy consumption is assumed to rise up to 14% when using 15 to 30% RAP and up to 17% if more than 45% RAP is used in new asphalt mixtures.

Another important environmental issue related to the use of RAP is the possible contamination of the subsoil and groundwater through leaching. It was stated in a study by EAPA (2008) that the leaching behaviour of asphalt containing RAP is not different from asphalt produced with virgin materials. Asphalt with or without RAP does meet the most onerous requirements in Europe with regard to leaching. Legret et al. (2005) show that pollutant leaching from stockpiles is rather weak and generally remained below EC limit values for drinking water. Nevertheless, the comparison between new conventional asphalt and RAP seemed to indicate that concentrations of total hydrocarbons and some PAHs were higher in leachate from RAP. The grain size of the material and the percolation water flow rate were found to be factors influencing the results. A study by Enell et al. (2012) remarks that the use of RAP within bound pavement mixtures results in no increase in environmental risk related to leaching of contaminants. On the other hand, appreciable levels of leaching associated with water infiltrating stockpiles of RAP are observed. The risk associated with storing RAP (with high levels of contaminants) outdoors appears high. Furthermore, tar-contaminated RAP is associated with the highest leaching levels and with highest emissions. Hence, no alarming amounts of leaching values for asphalt and (not-contaminated) RAP were found in literature. The findings are supporting the practice of restricting the use of tar containing RAP in road construction and encourages the storage of RAP under a shelf, particularly when it is contaminated.

Besides, Enell et al. (2012) conclude that the total emission of asphalt fumes during plant hot recycling does not change substantially due to addition of uncontaminated RAP. Jullien et al. (2006), on the other hand, investigate the release of airborne emissions related to asphalt laying among various recycling rates. This study found that some gaseous emissions (VOC, PAH) increase with the recycling rate while odours decrease.

3.3 LCA of WMA and HWMA

A reduced production temperature is generally associated with a reduced energy consumption and consequently less emissions. Nevertheless, it is important to investigate in detail the used technology in order to enable a lower production temperature.

Ventura et al. (2009) found that for the asphalt mix processes, there is an energy (natural gas, gasoil and electricity) saving for HWMA when compared to HMA. The study also reports that the amount of most airborne emissions (measured in the stack) reduces, except for CO and CH_4, which are correlated with the burner adjustments and natural gas combustion reactions. Rubio et al. (2013) conducted similar measurements in the stack of the plant and did found a reduction of CO (and other) emissions for HWMA compared to HMA. The main difference with the study of Ventura et al. (2009) is the fact that the HWMA was produced at a plant, with a burner specially designed to heat aggregate at temperatures of 65 to 130 °C.

For the airborne emissions during road works, it was found by Ventura et al. (2009) that the amount of non-methanic gaseous organic compounds decreases while the amount of CO_2, N_2O, SO_2 and particles increases, which is explained by the longer compaction process of the HWMA pavement compared to HMA. Within the scope of the experiment, the HWMA has been found to reduce all environmental indicators. Note that the study by Ventura et al. (2009) does not include information on both the production processes and transport of the chemical additive.

The environmental burden from the production of additives might counteract the environmental gain at the asphalt plant by lowering the production temperature. Three WMA mixtures with different additives (a synthetic zeolite, a Fischer Tropsch wax and an emulsion) are compared with a conventional HMA in a cradle-to-laid study (Tatari et al., 2012). Overall, the WMA do not appear to perform better than HMA. The environmental impact of the WMA with zeolite and wax is highly dependent on the additive production, while that of the mixture with emulsion is dependent on the energy consumption during mixing. Anthonissen et al. (2015a) and Vidal et al. (2013) conclude similarly that the reduction of the impacts of WMA due to lowering the manufacturing temperature is offset by the greater impacts of the synthetic zeolites production.

These results indicate that including the supply chain (material production and transportation) is very important in order to get a comprehensive environmental assessment of asphalt production or a road pavement.

Furthermore, some research was carried out on WMA mixtures containing RAP. It is important to note that the savings of airborne emissions expressed in terms of CO_2 equivalent achieved by recycling RAP far outweigh those that may be achieved by reducing the production temperature (Anthonissen et al., 2014, 2013; van Bochove et al., 2012; Wayman et al., 2012). Likewise, the results of studies by Vidal et al. (2013) and Wayman et al. (2012) indicate that the environmental benefits in most impact categories of WMA are inferior to those achieved by a low recycling rate of 15%. Blankendaal et al. (2014), on the other hand, found that WMA compared to HMA can reduce the single score environmental impact with 26 to 39% while adding (extra) 20% RAP to a HMA mixture reduces this environmental impact by only 10 to 13%. Note that it is not clearly described which WMA technique is used, which processes are included, and what analysis period is applied in the LCA analysis of Blankendaal et al. (2014).

Some studies by van Bochove et al. (2012), D'Angelo et al. (2008), Leng & Al-Qadi (2011) and Vidal et al. (2013) indicate the potentially larger use of RAP as a key advantage of WMA.

An important advantage of WMA compared to HMA is the lower diffusion emissions during road construction, which is clearly visible to the naked eye (Finset, 2012; Ventura et al., 2009). This is associated with higher safety for the road workers who work day after day in the fumes of the hot or warm materials. Nevertheless, the advantages of WMA for the human health of the road workers do not show up in the results of the LCA calculations. This is due to the fact that the environmental impact of the production of bitumen or the energy for drying and heating the aggregates is very large and therefore the relative reduction of the diffusion emissions due to the warm mix technology is invisible. Furthermore, some aspects are not included (i.e. increased safety), because at this moment, it is not possible to model it in LCA. Hence it is important to always critically evaluate the results from LCA and even look further than these numerical values.

4 CONCLUSIONS

Even though the aim of the study is not to compare the methodology of LCA studies, it is obvious that the results of the studies discussed are difficult to compare since the specific contextual characteristics differ considerably, as seen in Table 23. For instance, they include different stages in the life cycle (e.g., including or excluding use phase, end-of-life, etc.) and different aspects of the environmental impacts (e.g., analysis of greenhouse gases or energy consumption opposed to a broad environmental assessment with multiple impact categories). Besides, each road section is unique due to various geotechnical conditions, traffic intensity, etc. Therefore, only the rough trends found in different studies can be compared. As discussed, a specific framework for LCA studies on pavements might reduce such varieties and is therefore important.

The use of RAP in new asphalt mixtures yields significant environmental advantages due to virgin material savings and reduced transport distances. Therefore, it would be beneficial to allow the use of RAP in surface courses of public works, by lifting this ban in the next version of the Flemish Road Standard SB250. Nevertheless, the contamination with tar leads to a significant environmental burden and therefore tar containing RAP should be avoided by removing it from the cycle.

The use of additives in WMA technologies is a determining factor considering the environmental impact. The shift of the environmental impact from the asphalt plant to the producer of additives should be avoided because it might lead to increased life cycle environmental impact. WMA techniques without (impacting) additives are favoured i.e., foam techniques. It is also concludes that the production of asphalt at reduced temperatures (HWMA and WMA) is only environmentally beneficial (reduced energy and emissions) when these mixtures are produced in asphalt plants with adjusted burners.

In general, independent of the asphalt mixture used, the durability of the asphalt pavement is a parameter with a significant effect on the total environmental impact. The service life and hence the intermediate maintenance interval have to be increased if possible. It is therefore recommended to further investigate the service life in practice of asphalt pavements with RAP or produced with various WMA techniques and it is necessary to incorporate this in LCA studies.

Furthermore, it is important to note that the EU ETS only accounts for the emissions due to fuel consumption in particular companies, while it is seen from the current literature review that other interventions might yield more significant reductions of the environmental impact i.e., recycling. A certain asphalt plant may gain beneficial grades in the EU ETS when producing WMA with scarce aggregates and impacting additives. On a life cycle point of view, the environmental impact of such asphalt mixture would be pernicious. Therefore, it might be wondered if there is a need for other regulations in order to encourage environmentally friendly road infrastructure.

It is seen that some Flemish asphalt plants invest in the construction of a shelter in order to protect raw material from rain during storage. In this way, the moisture content of virgin and recycled aggregates might decrease during storage and hence the energy consumption to dry the raw materials might decrease as well. Remaining moisture content in asphalt mixtures negatively affect the mechanical properties of asphalt mixtures and hence the service life of a road pavement. The moisture content of RAP and virgin aggregates should be investigated in practice since it is mandatory in Flanders to use washed virgin aggregates. Consequently, both virgin and recycled aggregates could be very wet when delivered at the asphalt plant. For HWMA and WMA, on the other hand, the risk for remaining moisture in the mixture is due to the lower temperatures and an incomplete evaporation of the water. Other advantage of the sheltered materials are the lower energy consumption for drying and heating aggregates with a lower moisture content and reduced leaching from RAP stockpiles.

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PAPER II: USING CARBON DIOXIDE EMISSIONS AS A CRITERION TO AWARD ROAD CONSTRUCTION PROJECTS: A PILOT CASE IN FLANDERS

Authors: Joke Anthonissen, Dirk Van Troyen, Johan Braet, Wim Van den bergh

Abstract: In the last decade, innovative technologies with regard to improved energy and material efficiency of asphalt pavement construction have been implemented by road industries. Two technologies are currently advocated: warm mix asphalt technologies and the increased use of reclaimed asphalt pavement. Unfortunately, these technologies were evaluated only by their technical and economic benefits and in most cases without an environmental impact study for the overall process. For encouraging the endeavour of the industry to implement newer – greener – technologies with focus to environmental benefit, the procuring authorities made an effort to enforce a sustainable approach for road works by the Project Carbon Free-ways. This pilot project included basic environmental parameters in the award criteria for public tenders on road works in Flanders. For this project two calculation tools, called Carbon Counter and Traffic Tool, were developed by the Flemish Agency for Roads and Traffic in order to estimate the carbon dioxide emissions of respectively the construction process and the traffic disturbance caused by the construction. The subject of this first public tender – with an evaluation of both tools – was the reconstruction of an asphalt road pavement in Kontich (Belgium). In this contribution the preliminary study on the methods of the tools and the main conclusions of the project are reported and discussed. The study illustrated that the current tendering process and the tools used, do have some limitations and drawbacks: the tools do not cover the total environmental impact as e.g. LCA do, the data concerning recycling or specific plant-related processes are outdated or missing and the data collection for back calculation of the total emission required too much manual efforts and shortcomings. Nevertheless, this pilot project proved to be a valued attempt to achieve more innovative and sustainable public procurement – as a first step, giving an unambiguous signal to the industry that this type of selection will be part of future tenders.

Keywords: green public procurement; greenhouse gas emissions; asphalt pavement; road engineering; carbon footprint; traffic

1 INTRODUCTION

The compulsory targets to reduce the greenhouse gases, initiated by the Kyoto protocol encouraged a search for innovative techniques. Various technologies have been developed by the road pavement industry in order to reduce the environmental impact: the use of reclaimed asphalt pavement; reducing the asphalt production temperatures; and concepts that prolong the service life of a pavement. According to the annual report Asphalt in Figures (European Asphalt Pavement Association, 2014) the total production of hot mix asphalt (HMA) and warm mix asphalt (WMA) in Belgium in 2013 was 5.3 million tons of which 51% contain reclaimed asphalt. In this way, 61% of 1.5 million tons available reclaimed asphalt were used in HMA and WMA. According to the Flemish guidelines on best available techniques for asphalt plants (Leyssens, Verstappen, & Huybrechts, 2013), recycling reclaimed asphalt in asphalt is seen as the best solution in Flanders (a region within Belgium) to decrease waste disposal and use of natural materials.

The contracting pavement administrator has an important role by encouraging a more sustainable road infrastructure. Green public procurement (GPP) can be understood as "a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured" (European Commission, 2008). The European Commission (European Commission, 2014) stated that the criteria for GPP used by Member States should be equal to avoid distortion of the market and reduction of EU-wide competition; and to reduce the administrative burden. The EU GPP criteria for road construction (currently under revision) are formulated as guidelines rather than specific quantitative criteria (European Commission, 2010). Three core award criteria for GPP were defined: i) the use of secondary aggregates and recycled materials, ii) the durability and performance characteristics, and iii) the reduction of energy consumption through the life cycle. These three criteria are supplemented with four other, comprehensive GPP award criteria.

A Swedish investigation (Varnäs et al., 2009) found that both public and private clients in the construction industry take environmental impacts into consideration in their procurements, however, environmental criteria in tender evaluation are less common and seldom affect the award decisions. This trend is currently also been observed in Belgium, where until 2014 no environmental criterion was implemented in public tenders for road construction. As summarized by (Testa et al., 2014), the main obstacles limiting the uptake of GPP, are the lack of organizational resources for political support, the limited information on the real environmental impact of the products, the difficulties in preparing calls for tenders and purchasing, the absence of guidelines from general authorities and a non-coordination between authorities.

The Dutch Department of Public Works within the Ministry of Infrastructure and the Environment, Rijkswaterstaat (RWS), implements monetised environmental award criteria in their public procurement for road construction by using two different tools (van Geldermalsen, 2013, 2014). DuboCalc converts life cycle environmental impacts in 11 areas (using a life cycle assessment (LCA) database), into an environmental cost indicator (ECI) value. The CO_2 performance ladder is used to assess the efforts of a company to reduce carbon dioxide (CO_2) emissions caused by the project. The supplier chooses a level of ambition, with each level yielding a 1% reduction of the submission price. The project is awarded to the supplier with the lowest adjusted quoted price.

The Flemish Agency for Roads and Traffic (ART), in collaboration with the Dutch and British Highways Agencies, considered methods that can reduce CO_2 emissions from road works. These agencies agreed on three evaluation criteria for road construction: procurement, street lighting and construction of the road. The Flemish ART started a pilot project called Carbon Free-Ways, where the reduction of CO_2 emission of the road work was an award criterion for the public tender, together with the price.

Since 2013, the European Union Emission Trading System (European Union, 2013a) covers all installations with a net heat excess of 20 MW. For Flanders (Departement Leefmilieu Natuur en Energie, 2014), 220 installations were subjected to the emission trading system in 2013, together emitting approximately 40% of the greenhouse gas emissions. For the asphalt production sector, 13 of the 19 plants are subjected to this system, representing 43 269 tons CO_2 equivalent or 0.13% of the registered CO_2 equivalent emissions in Flanders.

2 PILOT PROJECT CARBON FREE-WAYS: OBJECTIVE AND APPROACH

The objective of the pilot project Carbon Free-Ways was to stimulate CO_2 efficient working methods for road construction. The authors want to emphasize that taking into account only CO_2 emissions, will lead to a significant underestimation of the full environmental impact by excluding impact categories such as fossil depletion, land use, human and ecotoxicity, ionising radiation, eutrophication, particulate matter, etc. . The public tender for this road work, executed in May 2014, included: milling and repaving a test section on a Flemish primary road (N171 in Kontich); applying road markings; providing traffic management; and the maintenance of the work during the three year warranty period. The test section was 1 km long, consisting two lanes and a paved emergency lane in each direction. The work, monitored in the context of the pilot study, included repaving the base (7 cm) and top (3 cm) layer of the test section.

2.1 Framework and problem

Presently, for all public works, the tender price is the standard (sole) award criterion. In this pilot project the tender was evaluated by price for 50% and by CO_2 emissions for the other 50%. The score for the price (maximum 50 points) was calculated with equation 7.

$$score\ price = 50 - 25\ \times \left(\frac{P - P_{min}}{P_m - P_{min}}\right) \qquad (Eq.\ 7)$$

With: *P: project price of the contractor in euro;*
P_{min}: lowest price of all applicants;
P_m: arithmetical average of the prices from all applicants.

Two different tools were developed by the Flemish ART in order to calculate the theoretical CO_2 emissions based on measurable data. All contractors, applying for the public tender, were forced to use these two tools to calculate the emissions. The Carbon Counter (original Dutch name: '*Koolstofteller*'), accounting for a weight of 30% in the judgment, was used to calculate the emissions from the asphalt production, the transport of materials and the production of the raw components of the asphalt mixture. The score for the Carbon Counter (maximum 30 points) was calculated with equation 8.

$$score\ Carbon\ Counter = 15 + \frac{15}{0.25} \times \left(1 - \frac{CO_{2,kt}}{CO_{2,kt,m}}\right) \qquad (Eq.\ 8)$$

With: *$CO_{2,kt}$: tons of CO_2 produced (the Carbon Counter result);*
$CO_{2,kt,m}$: arithmetical average of the Carbon Counter results from all applicants in ton

The Traffic Tool, which counted for 20%, was used to calculate the extra emissions due to the disturbance of the traffic. The score for the Traffic Tool (maximum 20 points) was calculated with equation 9.

$$score\ Traffic\ Tool = 10 + \frac{10}{0.25} \times \left(1 - \frac{CO_{2,tt}}{CO_{2,tt,m}}\right) \qquad (Eq.\ 9)$$

With: *$CO_{2,tt}$: tons of CO_2 produced by disturbed traffic (the Traffic Tool result);*
$CO_{2,tt,m}$: arithmetical average of the Traffic Tool results from all applicants in ton.

$$total\ score = score\ price\ + score\ Carbon\ Counter + score\ Traffic\ Tool \qquad (Eq.\ 10)$$

The contractor was selected based on the application with the highest total score (equation 10).
Measurable and verifiable parameters were reported and used by the contactor as input data for the assessment of the CO_2 emissions: amount of raw materials; transport distances and methods; the energy type and consumption on the asphalt plant; and the working period and traffic management scenario.
The objective of these tools was to compare different execution methods and to select the most CO_2 efficient candidate based on the calculated values rather than accurately estimating the total CO_2 emitted for this work.

After completion of the work, ART used both tools to calculate the emissions based on the verified data, collected during the construction. A positive or negative difference with the emissions declared by the applicant larger than 5% would lead to respectively a penalty or bonus.
Furthermore, after the construction, the longitudinal evenness of the pavement is measured. Unevenness or roughness creates vibrations in tires and suspension (Jackson, Willis, Arnold, & Palmer, 2011). Energy is lost in these vibrations because the shock absorbers absorb this energy and hence the fuel consumption is influenced. Shortwave unevenness is seen as the most important factor in determining fuel consumption. It can cause up to 10% changes in fuel consumption. If the measured unevenness is less than 75% of the maximum allowed unevenness as described by the Flemish road standard SB250 ($VC2.5_{i,max}$ = 40 000 mm^2/hm for this test section), this will be rewarded with a financial bonus.

2.2 Carbon Counter

The Carbon Counter, worked out in an Excel® sheet, was developed in order to estimate the emissions from the production and transport of raw materials and asphalt. Table 24 illustrates the layout of the tool, based on a very simple, hypothetical case of 300 ton asphalt mixture.

Table 24: Overview of the Layout of the Carbon Counter for a simple, hypothetical case of 300 ton asphalt

RAW MATERIALS

1. Aggregates	Quantity (m^3)	Density (t/m^3)	Mass (ton)	Emission factor (tCO_2/t)	CO_2 (t)
Coarse aggregates (virgin)	84,00	1,600	134,40	0,00520	0,699
Coarse aggregates (recycled)	38,00	1,600	60,80	0,00260	0,158
Sand (virgin)	28,00	1,600	44,80	0,00510	0,228
Sand (recycled)	26,00	1,600	41,60	0,00255	0,106

2. Binder	Quantity (m^3)	Density (t/m^3)	Mass (ton)	Emission factor (tCO_2/t)	CO_2 (t)
Bitumen (virgin)	11,00	1,030	11,33	0,48000	5,438
Bitumen (recycled)	8,00	1,030	8,24	0,24000	1,978
				Total CO_2 (t)	8,608

TRANSPORT

1. Raw material from source to plant	Number of journeys	Distance (km/journey)	Conveyance	Emission (g/km)	Share-factor	Utilisation-coefficient (full = 1,5; empty =	CO_2 (t)
	10	75	Trailer (25-30 ton)	822,87	0,75	1,5	0,694

2. Transport asphalt mixture to site and return	Number of journeys	Distance (km/journey)	Conveyance	Emission (g/km)	Share-factor	Utilisation-coefficient (full = 1,5; empty =	CO_2 (t)
	20	50	Trailer (25-30 ton)	822,87	1,00	1,5	1,234

3. Transport reclaimed pavement	Number of journeys	Distance (km/journey)	Conveyance	Emission (g/km)	Share-factor	Utilisation-coefficient (full = 1,5; empty =	CO_2 (t)
	10	50	Trailer (25-30 ton)	822,87	1,00	1,5	0,617
						Total CO_2 (t)	2,546

Conveyance	Emission-factor
4-axled truck (16-20 ton)	638,05
Trailer (25-30 ton)	822,87
Barge (per 30 ton)	261,21
Sea-vessel (per 30 ton)	206,52
Train (per railroad car)	633,60

ASPHALT PRODUCTION

	Energy source	Quantity (kWh for electricity or m^3 for other)	CO_2 (t)
Drying aggregates	Diesel	0	0,00
	Refinery gas	1500	3,05
Warming bitumen	Electricity	30	0,02
	Refinery gas	0	0,00
		Total CO_2 (ton)	3,06

Energy source	Emission factor	Unit
Diesel	3,162661	tCO_2/m^3
Fuel oil	2,90	tCO_2/m^3
Heavy fuel oil	3,1411	tCO_2/m^3
Lignite	2,04	tCO_2/m^3
Refinery gas	0,002031	tCO_2/m^3
Electricity	0,0005	$tCO_2/kWhe$

The emissions from the production of raw materials (Table 24) are determined by multiplying the mass with a default emission conversion factor in ton CO_2 per ton material, derived from the Inventory of Carbon & Energy (ICE) version 2.0 . Only the main components of an asphalt mixture are included: coarse aggregates, sand and bitumen. A recycled variant for each material can be selected and is associated with a 50% reduced emission factor. This is a stimulus for the applicant to use recycled materials.

In Flanders, using additives in asphalt is not a common practice and currently no standard emission factors could be found for filler materials. Therefore, emissions from filler and additives are not included in the tool. Nevertheless, different types of filler are on the market, from pure lime stone to biomass filler, and, moreover, the use of both industrial filler and baghouse dust is allowed. One should consider in future the impact of the type of filler in the calculation.

The transport part in Table 24 contains three trajectories: the transport of raw materials to the asphalt plant (supply single way); the transport of the asphalt mixture from the plant to the worksite (including the return empty state); and the transport of the milled, old pavement from the worksite to the asphalt plant (the return of the empty truck to site). The user of the tool must select the appropriate means of transport for the three trajectories: truck, barge, sea ship or train. Similar to the materials, each transport method has a fixed emission factor in gram per kilometre, derived from ICE v.2.0 . For each trajectory, the distance in kilometres, the share factor[11], the utilisation coefficient[12] and the number of identical journeys must be specified in the Carbon Counter. The multiplication of all these factors, added up for all different trajectories is the total CO_2 emission related to transport.

The asphalt production part (Table 24) accounts for the energy consumption for drying and heating aggregates and for the hot storage of the binder in the tank. Likewise the other parts, the six energy types available in the tool have a fixed emission factor in t CO_2/m^3 for diesel, fuel oil, lignite and gas or in t CO_2/kWh for electricity, derived from ICE v.2.0 . The quantity of each energy type is multiplied by its emission factor. The use of warm mix asphalt, the insulation of the bitumen tanks and the dry storage of granulates result in reduced fuel consumption and are hence encouraged in this part of the tool.

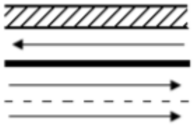
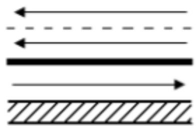
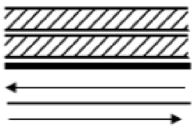
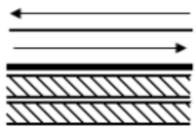
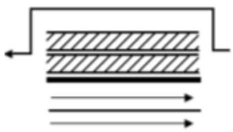
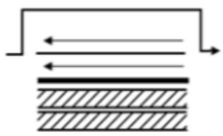
2.3 Traffic Tool

The Traffic Tool, worked out in Excel®, calculates the additional amount of CO_2 emitted by road users of the considered road section and traffic diversions during road works. Three different traffic management scenarios (see Table 25) have been specified for this particular case. The user of the tool must choose one scenario for the total project period.

[11] The share factor charges the percentage of the haulage that could be assigned to the investigated project e.g., if a fully loaded barge supplies 350 ton virgin aggregates to the asphalt plant, but only 70 ton is used in the project under research, the share factor for this supply is 0.2.

[12] The utilization coefficient charges the load of the conveyance i.e., value 1 if empty or 1.5 if fully loaded conveyance.

Table 25: Three traffic management scenarios in the Traffic Tool

		working direction		explanation
		←	→	
scenario	1			Alternately one lane is closed in the working direction to repave, while two lanes in the opposite direction remain open
	2			Both lanes in the working direction are closed to repave, while each lane of the other site of the road is used by the traffic in a different direction.
	3			Both lanes in the working direction are closed. The traffic in this direction is redirected with a detour. Both lanes in th eopposite direction remain open.

	0h-1h	1h-2h	2h-3h	3h-4h	4h-5h	5h-6h	6h-7h	7h-8h	8h-9h	9h-10h	10h-11h	11h-12h	12h-13h	13h-14h	14h-15h	15h-16h	16h-17h	17h-18h	18h-19h	19h-20h	20h-21h	21h-22h	22h-23h	23h-24h
Mo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tu	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
We	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Th	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Fr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0
Sa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Su	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mo	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Tu	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
We	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Th	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Fr	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Sa	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Su	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tu	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
We	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Th	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Su	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tu	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
We	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Th	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Su	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 46: Completed Traffic Tool for traffic management scenario 2 with the indication of the periods with road works

The Traffic Tool associated with a particular scenario looks like a time schedule with 1 h intervals (see Figure 46). Every time slot has a corresponding CO_2 emission value, depending on the scenario chosen, the day of the week and the hour of the day. These emission factors have been determined by the Agency on beforehand by simulating the influence of the measures on traffic congestion for the different scenarios.

Based on traffic counts during 10 days in September 2010 on the specific field track in Kontich, average intensities per day of the week and per hour of the day were calculated.

The theoretical capacity of the road depends on the width of the road and the design speed (90 km/h). The maximum capacity per day per lane is 20 000 passenger car equivalents (pce) in the original situation (Agency for Roads and Traffic n.d.) or 833 pce per hour per lane. In the direction of the road works the speed limit is reduced to 50 km/h, associated with a maximum capacity of 10 000 pce per day per lane (Agency for Roads and Traffic n.d.) or 417 pce per hour per lane. In this specific road work situation, correction factors are included to reflect the reduced capacity due to turning traffic at the T-junction at one end of the field case. These correction factors are 0.85 and 0.95 respectively for right and left turning traffic (CROW kennisplatform, 2014). Therefore, the corrected theoretical capacity is calculated by multiplying 417 pce per hour per lane with both correction factors resulting in 337 pce per hour per lane during the road works. In scenario 3, an additional correction factor of 0.93 should be applied in order to take into account the lane width of the detour track (CROW kennisplatform, 2014) resulting in a theoretical capacity of 313 pce per hour per lane.

If the actual traffic volume is lower than the theoretical capacity, free flowing traffic is assumed corresponding to an emission factor of 152 g CO_2/km (den Boer et al., 2008). However, if the traffic volume is higher than the capacity, congested traffic is supposed with an emission factor of 228 g CO_2/km (den Boer et al., 2008). In this model, there is no situation between both extremes.

The emission schedule of the original situation was calculated by multiplying the intensity per hour by the CO_2 emission factor for free flowing traffic (152 g CO_2/km) and the length of the test section for each time slot (see example equation 11). Free flowing traffic was assumed because no traffic congestion was observed during the traffic counts (before the road works).

$$32\ \frac{pce}{h} \times 152\ \frac{g\ CO_2}{pce\ \times\ km} \times 1\ km\ = 4\ 864\ \frac{g\ CO_2}{h}\ = 5\ \frac{kg\ CO_2}{h} \qquad \textit{(Eq. 11)}$$

Equation 12 is the calculation of the corrected theoretical capacity in one direction of the detour scenario 3 (313 pce/h lane) and a comparison with the measured intensity in this direction for a specific time slot (626 pce/h). Equation 13 is the calculation of the emissions for that time slot in that direction (analogue to equation 11). These calculations were repeated for the three scenarios and for each working direction (see Table 25) using the corresponding intensities, capacities, emission factor (free flowing or congested traffic), correction factors and section length which resulted in a schedule with the CO_2 emissions per hour.

$$10\ 000\,\frac{pce}{day \times lane} \times \frac{1}{24}\frac{day}{h} \times 0.85 \times 0.95 \times 0.93 = 313\,\frac{pce}{h \times lane} < 626\,\frac{pce}{h}$$

(Eq. 12)

$$626\ \frac{pce}{h} \times 228\ \frac{g\ CO_2}{pce\ \times km} \times 1.6\ km\ = 228\ 365\ \frac{g\ CO_2}{h}\ = 228\ \frac{kg\ CO_2}{h}$$

(Eq. 13)

As the additional emissions from traffic as a consequence of the road works are searched, the next step included the calculation of the difference of the emissions in the three scenarios compared to the emissions in the basic situation. These differences are the basis for the final calculations with the Traffic Tool.

The user of the Traffic Tool has to specify the time intervals when the road works will take place by entering a "1-value". A "0-value" is placed in the time slots when there is no road work activity. The sum of the emission factors in the time slots with a "1-value" gives the final result of the Traffic Tool (expressed in kg CO_2).
It can be seen from the tool (see Figure 46) that working on a Monday morning from 7:00 a.m. till 8:00 a.m. will yield higher emissions than working from 7:00 a.m. till 8:00 a.m. on a Saturday morning. Hence, the contractor is stimulated to minimise the working period and traffic disturbances.

An important note for this Traffic Tool is that the effect on the surrounding roads was not taken into account because it was assumed that only a small number of vehicles would use other routes. Furthermore, it is clear that if this tool should be used for other road projects, the method can be used, but specific traffic counts, speed limits and correction factors will be necessary.

After the construction, ART will fill out the Traffic Tool again and re-calculate the total CO_2 emission, based upon the actual working times.

3 VERIFICATIONS DURING THE EXECUTION OF THE WORK

In Belgium, COPRO (an impartial institute for control and testing) performs quality and conformity controls on construction products and on its on-site integration. During the pilot project in Kontich, COPRO performed a large number of measurements and verifications of the asphalt plant and road works. At the asphalt plant, COPRO verified i) the delivery of raw materials: the weight of the materials, the transport distance and method from the suppliers to the asphalt plant, and the origin of the materials; ii) the energy consumption for the hot storage of bitumen and for drying and heating aggregates in both the white and parallel drums; iii) various temperatures: external temperature, bitumen tank, and asphalt in the mixer; and iv) the moisture content of the aggregates in the stockpile was measured.

Furthermore, all transport between the plant and the worksite was monitored for truck load, origin and destination.
At the worksite, COPRO examined the asphalt mixture temperatures (before and after compaction).
In addition the Belgian Road Research Centre has performed tests on the compaction (gamma probe and cores) and ART measured the evenness of the road pavement.

Lastly, researchers from the research group EMIB from the Faculty of Applied Engineering at the University of Antwerp monitored the project to collect data for environmental assessment with the inclusion of various LCA impact categories.

4 WINNING TENDER

In this section, the approach chosen by the selected candidate is discussed based on the two tools. Compared to other contractors, the selected candidate had better scores for price as well as carbon counter and traffic tool. Due to confidentially, the proposed approaches of other contractors cannot be discussed.

4.1 Carbon Counter

The tender specified the use of split mastic asphalt for the wearing course and an asphalt concrete with performance requirements for the base course. According to the Flemish road standard (SB250 v2.2) the use of reclaimed asphalt is not allowed in surface layers. For the base layer, 50% reclaimed asphalt was added in the mixture, yielding a significant CO_2 reduction due to material use. For base layers with a mixture with performance requirements, the SB250 v2.2 does not limit the percentage of reclaimed asphalt.
In order to reduce the emissions from the transport, the delivery of all raw materials to the asphalt plant was done by ship.
To reduce the impact from asphalt production, both produced asphalt mixtures were chosen to be WMA based on foaming technology. According to the tender, a WMA has a temperature between 100 and 130 °C after the mixing process. The asphalt plant is equipped with a natural gas burner emitting less CO_2 than e.g., fuel oil.

4.2 Traffic Tool

The emissions from the disrupted traffic have been limited by choosing the scenario with the lowest emissions, scenario 1 (see Table 25) and to working the weekends instead of the week.

4.3 Environment versus costs

Some of the measures to reduce the environmental impact, might induce extra costs e.g., the supply of raw materials to the asphalt plant by ship and working during weekends. The contractor is free to decide whether he bears those cost himself or to charge those to the procuring authorities. The contractor with the highest total score (see section 2.1) is awarded the contract and hence each contractor might try to find an optimal balance between costs and impact on environment.

5 RESULTS AND DISCUSSION

It was seen during the construction that, compared to standard procedures, some specific adjustments were implemented by the contractor in order to reduce the environmental impact associated with the pilot project. Some examples are listed in Table 26.

Table 26: Measures during the execution of the works in order to reduce CO_2 emissions

Raw materials
using RAP-mixtures with high coarse aggregates and bitumen content
Transport
delivering raw materials to the asphalt plant by barge
avoiding empty journeys between plant and worksite
Asphalt production
using most energy efficient bitumen tanks
delivering of bitumen to the asphalt plant shortly before asphalt production

Interviewing workers at the road worksite, told us that the mechanical compaction of the WMA pavement seemed visually as good as a HMA pavement. Nevertheless, imperfections after the paver were difficult to correct e.g., little bumps, wells or footprints in the paved material. Hence, a conscientious manufacturing process is recommended while using WMA. Results of the gamma probe showed a good compaction of the base layer. The compaction of the split mastic asphalt in the wearing course is difficult to assess. The evenness of the road surface was remarkably good. This work also showed the good workability of WMA.

However, the additional work for the contracting authority due to the pilot project was considered: development of both calculation tools (reusable for other projects) and execution of traffic counts. An intensive follow up on the asphalt plant and the road worksite during the execution of the works was also required. Most of this surveillance was accomplished by COPRO, while the costs were incurred by the contracting authority. This surveillance in practice is time consuming and it would not be feasible to do this for all future public road works.

It can be argued that the warranty for 3 years is too short in order to encourage the contractor to construct a durable pavement and hence avoid costs and environmental impact from maintenance interventions. Decisions were made in favour of the environmental impact yielding suboptimal results to the performances and the durability of the pavement. In this case the width of the road in each direction was divided in two and paved during two consecutive days. Therefore, the joint between the two sections could not be compacted when both materials were warm. The working method was chosen in order to avoid higher emissions from the disrupted traffic, but the quality of the road pavement might have decreased because of this.

Analyzing the approach for the public procurement, it is seen that the Carbon Free-Ways takes into account the three proposed core award criteria as described by the European Commission (see chapter 1): the use of secondary or recycled materials, the reduction of the energy consumption throughout the life cycle (raw material production to paving) and the durability and performance characteristics of materials. The latter was taken into account by the fact that all bituminous mixtures used for public road works should comply with the Flemish road standard SB250. Additionally, one out of four comprehensive GPP criteria was included by assessing the evenness after the pavement construction: reduce fuel consumption of vehicles travelling on the road and hence reduce emissions to the environment during the use phase of the road.

As described before, this study examined only CO_2 emissions, which is an incomplete environmental assessment. (European Commission, 2010) stated that the greatest environmental impact from road construction is from the combustion of fossil fuels, specifically the emission of CO_2 and nitrogen dioxides (NO_2) by normal traffic. Hence, despite the incomplete environmental assessment, one of the key environmental impacts is covered in the pilot project.
The European Commission recommends for GPP a contribution of all environmental award criteria together for at least 10 to 15% of the total points. The Flemish pilot project uses a 50% rate for both the environmental part and the acceptation price. This ratio was applied to maximise the effect of the CO_2 emissions and not in the light of a general application in the future.
Since the inclusion of environmental parameters in the public procurement was a novelty, some points for improvement were found. Some processes were excluded from the assessment e.g., filler production and transport, transport of machines to

worksite, machines operation on site, etc. This is due to the lack of appropriate data and the extent of the project. Besides, it is remarked that data source (den Boer et al., 2008) is slightly outdated with regard to the significant difference in emission caused by new and old vehicles. This is due to the fact that the project was initiated and the tools were developed in 2010 while the execution of the works was in May 2014. Hence, for future projects, the tools used should be updated. Another point of discussion related to the data sources is the default reduction of 50% for emission factors for recycled materials.

Finally, expanding such analyses from single project based to continuous plant based assessment might be interesting in order to encourage continuous environmentally friendly asphalt production as part of the optimisation of projects.

6 CONCLUSIONS

The inclusion of environmental award criteria in a public tender is new for Flanders. In spite of the obstacles which make the application of GPP for road works difficult, the pilot project is a good first attempt to detect significant and insignificant parameters and data. Furthermore, with the elaboration of the methods and the development of the tools, the basis is laid for GPP in this sector.

There are limitations in the pilot project to keep the tool workable in this first attempt: the number of parameters (and hence, verifications) used in the Carbon Counter and the Traffic Tool are limited by applying a number of assumptions. As a result, the emissions from a number of processes are left out and only one environmental issue (global warming potential) is analysed, which results in a very incomplete environmental impact assessment.

In a future phase, the calculation tools might be extended in order to include more processes (e.g. production and transport of filler and additives, transport and use of equipment on the worksite, etc.) and various environmental impacts. In addition, focusing both on the sustainability and on the durability of the road pavement is recommended.

At least ART gave an unambiguous signal to the road industry that neglecting the environmental impact from road works is no longer an option for public works and it might become a fixed selection criterion for tender in the long run.

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PAPER III: CLIMATE CHANGE IMPACT COMPARED TO LIFE CYCLE ASSESSMENT RESULTS: A PILOT CASE IN FLANDERS

Authors: Joke Anthonissen, Wim Van den bergh, Johan Braet

Abstract: In 2013, a pilot project 'Carbon Free-Ways' was elaborated in which the Flemish government included both price and CO_2 emissions as award criterion in a public tender for the reconstruction of a field case in Kontich (Belgium). The road works include the construction of a base course with 50% reclaimed asphalt pavement and a surface course with 100% virgin split mastic asphalt, both are warm asphalt mixtures. Data were measured during the execution of the works for raw materials, transport and asphalt production. This real live data are used for all calculations. The approach used in the pilot project (Carbon Counter tool) to assess the emissions from the road construction is compared to a comprehensive environmental analysis following the life cycle assessment methodology. This paper aims to answer the following four main research questions. What is the difference between the results from the Carbon Counter and the life cycle assessment calculation? What is the contribution of climate change impact to the total single score environmental impact? Which materials or processes have the highest environmental impact? What is the environmental impact of processes which are beyond the scope of the pilot project? It was found from the current study that CO_2 emissions or climate change impact is for sure not the only important environmental impact. Fossil depletion was found to majorly contribute to the total single score impact and transport by lorry and the raw material bitumen are processes and materials with an important contribution to the environmental impact.

Keywords: climate change, green procurement, life cycle assessment, warm asphalt mixture

1 INTRODUCTION

Since all installations with a net heat excess of 20 MW or more are subjected to the Kyoto Protocol and hence the European Union Emissions Trading System, 13 of the 18 Flemish asphalt plants have to monitor and report on their CO_2 emissions. This system only accounts for the emissions due to fuel consumption by a particular company. Hereby the reduction of the asphalt production temperature is encouraged.

The last decade, the warm mix asphalt (WMA) technology for Belgian plants was illustrated mainly in its characteristics of performance (Bogaert, 2010; De Visscher et al., 2009). There were few studies carried out about the environmental impact of WMA in Flanders (Gonda, 2011).
In 2011, the University of Antwerp in co-operation with the Flemish asphalt pavement sector and authorities started a preliminary study focusing on the CO_2 emissions of Flemish asphalt producers. In this study, several CO_2 software are used for different cases of asphalt production, e.g. using reclaimed asphalt (RAP) in wet and dry condition, the effect of different energy resources and transport methods. These results were published (Anthonissen et al., 2013).
However, there was a need for a more detailed investigation of the environmental impact of WMA in Flanders. The environmental analysis should be based on practical data, measured in situ and with broadened system boundaries to be able to include multiple environmental parameters and as much as possible processes of the life cycle of the pavement.

The Flemish Agency for Roads and Traffic together with the Dutch and British highway agencies jointly investigated in which ways they can contribute to the reduction of CO_2 emissions from road works. The project is called Carbon Free Ways. One of the opportunities to stimulate contractors for CO_2 efficient road works was found to be the inclusion of a parameter related to the emissions in the public tender. In Flanders, this approach was implemented for the first time in a pilot study, which contains the construction of a field case.

The current paper briefly describes the methodology used in the pilot project Carbon Free Ways. The main goal of this contribution is the comparison of the results to a more comprehensive environmental life cycle assessment (LCA) study. Chapter 2 describes the field case which was the subject of the pilot and which is the subject of the current case study. Some environmental issues which were investigated in the preliminary study (Anthonissen et al., 2013) or found in other literature were compared to the execution of the field case. In chapter 3, the life cycle assessment methodology which is applied for the analysis of the case study is clarified. Some results of the LCA analysis are discussed in chapter 4. Finally, conclusions and recommendations are formulated.

2 FLEMISH FIELD CASE

In 2013 the Flemish Road Agency initiated a call for a public tender for the maintenance works of a road pavement in which carbon dioxide emissions are included as an award criterion. The tender was evaluated by price for 50% and by CO_2 emissions for the other 50%. Two software tools were introduced to estimate the CO_2 emissions of the project: the Carbon Counter (original Dutch name: *Koolstofteller*) and the Traffic Tool. Both tools are Excel® workbooks and calculate a theoretical amount of emissions based on measurable and controllable input data. This Flemish pilot project and both calculation tools are described in (Anthonissen et al., 2015b).

The Carbon Counter tool uses the emission factors from the Inventory of Carbon & Energy version 2.0 (Hammond and Jones, 2011). The result is weighted for 30% for the public tender. The analysis includes three different aspects i.e.:

- Emissions from raw materials mining and production;
- Emissions from transport of raw materials supply to the asphalt plant and transport of asphalt mixture and reclaimed asphalt pavement (RA) between asphalt plant and worksite; and
- Emissions from energy consumption for asphalt production at the asphalt plant.

The result from the Traffic Tool is weighted for 20% for the public tender. The tool calculates the additional amount of CO_2 emitted by road users of the considered road section and traffic diversions during road works. These results are not discussed in the current contribution.

The field case under the pilot project is situated on a Flemish primary road (N171 in Kontich), is 1.15 km in length and consists of two lanes and a paved emergency lane in each direction. The work, monitored in the context of the pilot study, includes repaving the base (7 cm) and surface (3 cm) layers.

Figure 47: Localization of the studied field case

2.1 Materials and transport

For the surface course, split mastic asphalt (SMA) was used with polymer modified bitumen, without reclaimed asphalt (RAP). An asphalt concrete with performance requirements (APO), defined according to the fundamental method was used for the base course. The APO mixture contained a paving grade bitumen and 50% RAP. Both mixtures are warm mix asphalt (WMA), with a production temperature between 100 °C and 130 °C. The foaming technology is used in order to reduce the viscosity of the binder by injecting water in the hot bitumen before it is added to the mixture.

In order to further reduce the CO_2 emissions from the project, the contractor optimized the transport processes. All aggregates (virgin raw materials) are supplied to the asphalt plant by ship (sea ship and/or barge). The transport of the asphalt mixture to the worksite and the transport of the RAP from the worksite to the asphalt plant were geared to one another in order to reduce the number of empty journeys by truck between the asphalt plant and the worksite.

2.2 Asphalt production at plant

Various studies (Anthonissen et al., 2013; National Technology Development, 2009; Wayman et al., 2012) describe the effect of moisture in aggregates (virgin and recycled) on the fuel consumption for the asphalt production. The moisture in the aggregates has a major influence on the energy consumption compared to the production temperature. Additional moisture content is sometimes speculated as a factor to be associated with RAP because water is used when breaking up old pavement. In Flanders, the difference between the moisture content in RAP and in virgin aggregates is small because most of the virgin aggregates are washed at the quarry. Therefore, both virgin and reclaimed aggregates are wet when they arrive to the asphalt plant. The asphalt plant has two big sheds in order to store aggregates (mostly reclaimed asphalt) to shield them from rain.

Figure 48: Shed to store aggregates in order to reduce the moisture content

In Flanders, all asphalt plants are batch plants and use a parallel drum in order to dry and heat RAP before it is added to the mixture. A Dutch study (van den Berk, 2004) found that the energy consumption per ton asphalt mixture increases for mixtures with RAP due to the use of the additional parallel drum. An increase in energy consumption of 14 to 17% is pretended, however the temperature in the parallel drum is lower compared to the white drum. This finding was not confirmed by the current case study, where the average gas consumption per ton SMA (without RA) was higher compared to the energy consumption per ton APO (with 50% RA). This observation might be caused by the significant higher production temperature of SMA (137.8 ± 2.4 °C) compared to the production temperature of APO (121.8 ± 3.5 °C). Hence, the production temperature of the SMA mixture was not within the temperature range for WMA as defined by the contracting authority. Anyhow, the production temperature of SMA was decreased compared to the production temperature of conventional hot mix asphalt (HMA). No requirements on the production temperature were imposed in the tender, but the measured energy consumption is used to calculate the related CO_2 emissions.

Various studies (Gasthauer et al., 2008; Olsen et al., 2012; Read and Whiteoak, 2003) state a reduction of the emissions if the asphalt production temperature is reduced. Nevertheless, previous measurements of stack emissions in a Flemish asphalt plant during HMA and WMA production did not reveal a decrease of the concentration of pollutants. Moreover, an increase of the CO concentration in the stack emissions was measured, which could be attributed to an incomplete combustion of gases. No measurements of emissions were accomplished during the asphalt production for the field case investigated, and hence this assertion could not be verified.

3 LIFE CYCLE ASSESSMENT METHODOLOGY

Life cycle assessment methodology was used in order to investigate the environmental impact of the current field case. In this section, the applied LCA methodology is described following the different steps as defined by ISO 14040:2006. Chapter 4 describes the LCA results.

3.1 Goal and scope

The goal of the LCA part in this research was to analyse, on the basis of the field case described, whether the used method (CO_2 emissions calculated with the Carbon Counter) is representative for the assessment of the environmental impact. Therefore, the results of the pilot project were compared to the results of an LCA study.

The functional unit used for this investigation was a 1.15 km long dual carriageway with two lanes and an emergency lane in each direction. The road structure investigated includes a base course of 7 cm and a surface course of 3 cm.

The system boundaries of the LCA are presented in Figure 49 and are based on the system boundaries of the Carbon Counter. Not the full life cycle of the materials was considered. Several processes are excluded from the assessment e.g., filler and additives production and transport, empty return journey from raw material delivery to the asphalt plant, emissions from equipment on site (milling of the old pavement, compaction of the new pavement), etc.

The research questions can be summarized as follows:

- What is the difference between CO_2 calculations in Carbon Counter and an LCA calculation (only including climate change) when using the same system boundaries?
- What is the contribution of the calculated climate change impact to the single score environmental impact (including various environmental issues)?
- Which materials or processes have the highest environmental impact?
- What is the share of the environmental impact from processes which are beyond the scope of the pilot project?

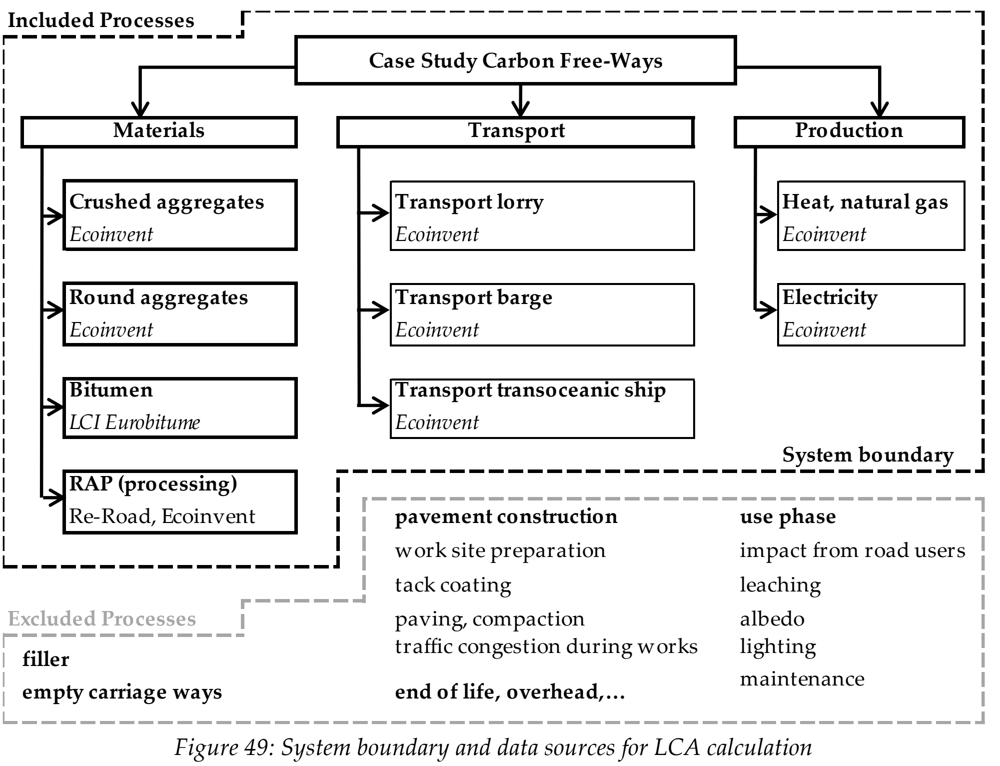

Figure 49: System boundary and data sources for LCA calculation

3.2 Life cycle inventory

All data needed, related to the quantity of materials, energy consumption, transport distance, transport method, etc. was information verified or measured in practice. For the environmental data (e.g. environmental impact of transport, gas combustion, raw material extraction etc.) the ecoinvent database was mostly used, excepted for the raw material bitumen and polymer modified bitumen (see Figure 49). The life cycle inventory from Eurobitume (Blomberg et al., 2012a) was used for the environmental data for the bituminous binders because these data are specific for the geographical area Amsterdam, Rotterdam, Antwerp and were more recent compared to the ecoinvent data.

3.3 Methodology and life cycle impact assessment

The SimaPro software, developed by Pré-consultants BV, was used for the LCA calculations. SimaPro includes the ecoinvent database and multiple life cycle impact assessment (LCIA) methods. Environmental impacts and used resources are quantified based on the inventory analysis in the LCIA step in order to understand the environmental relevance of all the inputs and outputs. The selected LCIA-method is ReCiPe, created by RIVM, CML, PRé Consultants, Radboud Universiteit, and CML-IA. This method, implements both midpoints (problem-oriented approach; impact categories) and endpoints (damage-oriented approach; damage categories) (Buyle et al., 2015a). The three endpoint categories (damage to human health, ecosystems, and resource availability) are normalized, weighted, and aggregated into a single score. The hierarchist perspective is applied since it is based on the most common policy principles with regards to time-frame and other issues and therefore considered as the default model. Furthermore, the European normalization set and the average weighting set were used. More information about the LCIA-method can be found in literature (Goedkoop et al., 2013; Sleeswijk et al., 2008).

4 LIFE CYCLE ASSESSMENT RESULTS AND DISCUSSION

As a rule, it is important to keep in mind that the commonly accepted precisions of LCA calculations are between 10 and 20% for single score results and about 10% for characterized results. Hence, some of the results discussed below might fall outside the validity range of the ReCiPe method. Besides, most of the quantitative input parameters are measured in situ and hence case specific. Thus we need to be careful with the interpretation and firm conclusions are not always allowed.

4.1 Comparison of results from Carbon Counter and SimaPro

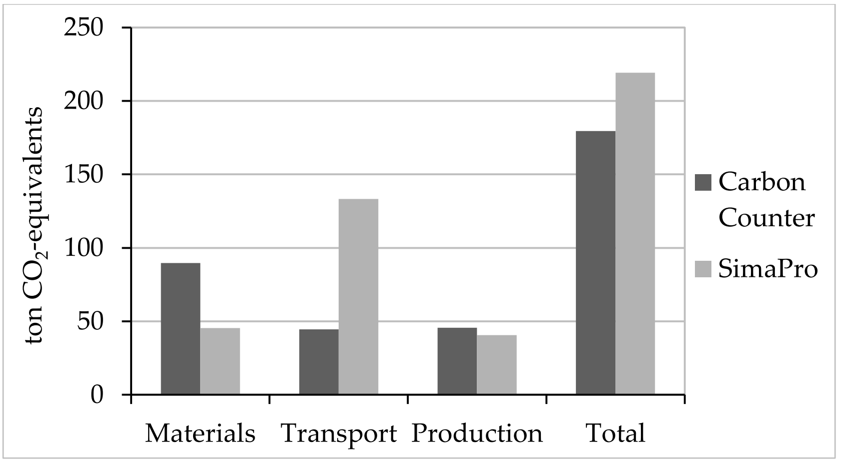

Figure 50: CO_2-emissions calculated with Carbon Counter and SimaPro

In a first comparison, results on climate change impact from the Carbon Counter are compared with the results from SimaPro, using the LCA methodology as described above.

Results from both tools are presented in Figure 50. It is seen that there are significant differences in each category. Detailed analysis revealed that for the materials part the emission factors (in kg CO_2e/ton material) are higher in the Carbon Counter (using the ICE version 2.0 (Hammond and Jones, 2011)) for all constituents. Besides, the inclusion of RAP in the calculations is different in both tools. The Carbon Counter uses a default reduction of the emissions by 50% compared to the virgin aggregates and bitumen. In SimaPro, only the emissions are included from processing (breaking and sieving) the reclaimed material in order to make the waste material suitable for reuse. Other burdens from RAP have not been included because this material is declared as waste and therefore has no direct burdens associated to it (Vidal et al., 2013).

4.2 Contribution to the single score environmental impact

In this section, the share of the CO_2 emissions or the climate change impact to the single score environmental impact is expound, based on results from SimaPro. The single score impact of different (groups of) processes is also discussed in this section. Figure 51 is a legend applicable for Figures 52-54. The methodology used for the calculations with SimaPro is specified in section 3.3.

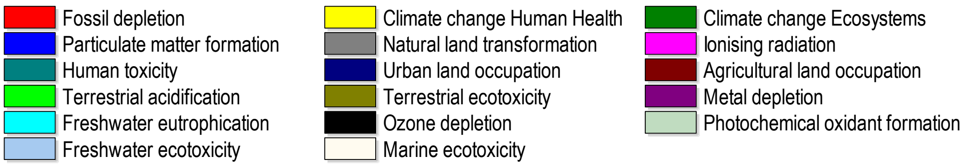

Figure 51: Legend of SimaPro results (Figure 52 - Figure 54)

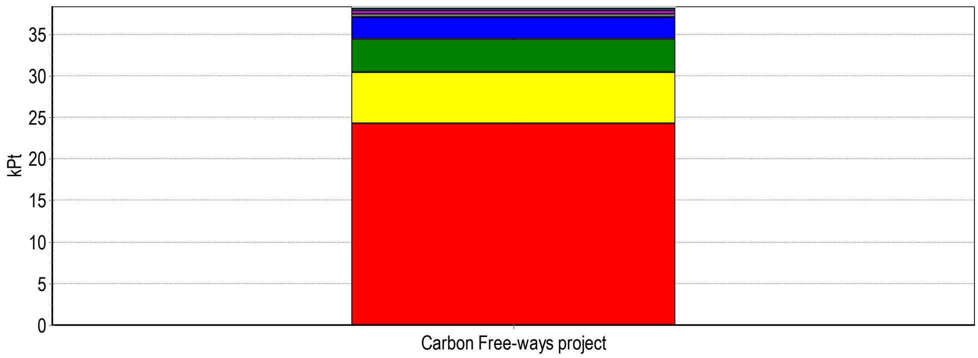

Figure 52: Contribution of climate change (yellow and green) to the environmental impact of the case study

Figure 52 illustrates the contribution of various impact categories to the single score impact.
The single score impact in ReCiPe includes 17 different impact categories (see Figure 51), of which two are related to climate change i.e., climate change human health and climate change ecosystems (respectively yellow and green). It is apparent from this figure that not climate change (human health and ecosystems together), but fossil depletion is the major contributor to the environmental impact. 63% of the single score impact is caused by the impact from fossil depletion. The main contributors to fossil depletion are the raw material bitumen and all transport by lorry (supply of raw materials to asphalt plant and transport of RAP and asphalt mixture between plant and worksite). Climate change represents 26% of the single score impact and is mainly caused by all transport by lorry, natural gas for heat production and the raw material bitumen. The next significant environmental impact category is particulate matter formation (7%), mainly coming from transport by lorry, transoceanic freight ship and the raw material bitumen. Finally, the last environmental impact category with a contribution to the single score of more than 1% is natural land transformation (1%). This impact majorly comes from transport by lorry, crushed gravel, transport by barge and natural gas for heat.
These results reveal the importance of integrating more environmental issues in an analysis. It is also seen from the results that transport processes and the raw material bitumen importantly contribute to most of the four discussed impact categories.

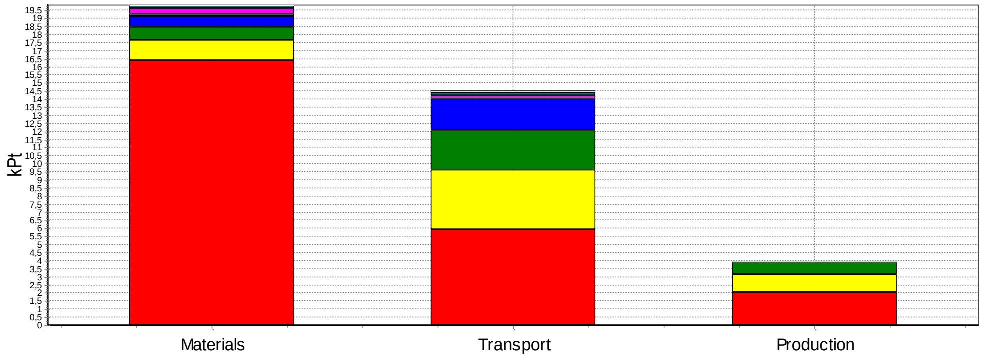

Figure 53: Single score impact of groups similar as in the Carbon Counter

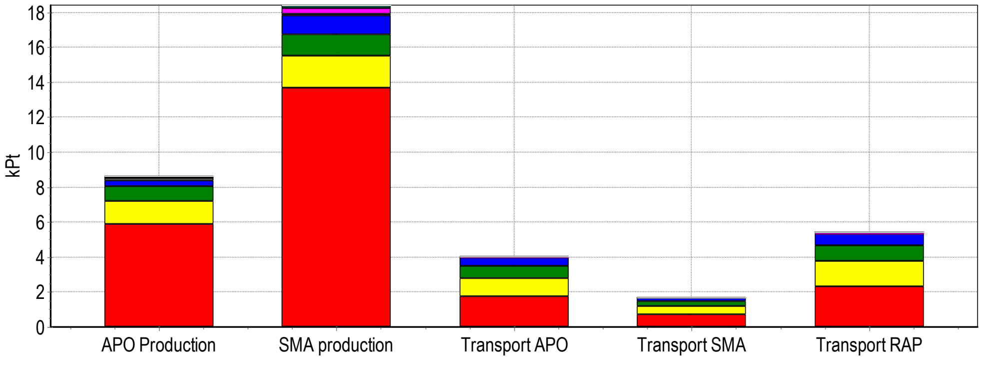

Figure 54: Single score impact of groups based on the chronological execution of the works

Figure 53 includes three groups analogue to the breakdown in the Carbon Counter. It is seen that the ranking of the three groups is different compared to the analysis of the CO_2 emissions. The materials part has the largest single score impact while the transport had the largest climate change impact (see section 4.1, Figure 54 results from SimaPro). The impact from fossil depletion was the largest in each group, followed by climate change and particulate matter formation.

Figure 54 provides an overview of five groups of processes, based on the chronological execution of the works.
The APO production and SMA production includes the raw materials, the transport of the raw materials to the asphalt plant and the energy consumption for the asphalt production. It is seen from the figure that the impact from the SMA production is more than double the impact from the APO production, despite the thicker base layer (7 cm) compared to the surface layer (3 cm). This higher impact is due to the higher virgin bitumen consumption in SMA because no RAP is used. It is also seen from the figure that the transport between asphalt plant and worksite (sum of the three transport groups) yields a higher single score environmental impact compared

to the production of APO. It should be noticed that the distance between asphalt plant and worksite (68 km) in this pilot project is rather high compared to the average in Flanders.

4.3 Environmental impact of processes beyond the scope of the pilot project

Some processes are not included in the analyses with the Carbon Counter because they are behind the scope of the pilot project i.e., filler production and transport to the asphalt plant; and empty carriage ways. In this section, the CO_2 emissions from these processes and the contribution to the single score impact are examined.

In the LCA calculation with SimaPro, the filler is represented by a limestone powder because the specific composition of fillers in asphalt mixtures is unknown due to confidential business information. It was found that including the filler production, and the transport from the production plant to the asphalt plant and including empty transports by lorry between asphalt plant and worksite increases the impact on climate change (CO_2 equivalent) by 15% and the single score impact by 9%.

It is important to note that even with the inclusion of the filler and the empty transport between the asphalt plant and the worksite, not all environmental impact caused during the pilot project is covered. During the asphalt production, some batches reached not the desired quality. Therefore these batches were not used for the road construction. Hence all impacts from raw materials, energy consumption and transport, related to those wasted batches are not taken into account. The return journeys after the delivery of raw materials to the asphalt plant are excluded as well, because it is unknown if this journey is empty or could be assigned to another project. Furthermore, the environmental impact from the road construction itself (tack coating, paving, compacting, etc.) is not included.

5 CONCLUSIONS AND RECOMMENDATIONS

The public tender describing the construction of the field case in the scope of the pilot project Carbon Free-Ways was a first for the Flemish government due to the inclusion of CO_2 emission as an award criterion.

It was seen that there are significant differences between the results from Carbon Counter and SimaPro. These differences are mainly due to different emission factors (e.g., ton CO_2/km or ton CO_2/m^3 energy source) which confirm the importance of the selected data source, in relation to the goal and scope of the research. Another important conclusion from the current study is the fact that climate change is not the dominant impact factor in bituminous pavement LCA. It is seen in this case study that fossil depletion has a major contribution to the single score impact. It is also concluded that the distance between the asphalt plant and the worksite is an important factor considering the environmental impact of a work. It is suggested to limit this. Finally it was found that, at first sight negligible processes, like filler production and transport and empty journeys, might have a remarkable environmental impact.

In the literature, some parameters with an effect on the environmental impact of asphalt production are described, but not all of them could be verified during the current case study. Therefore, additional research with field cases is required on e.g., the relation between the use of the parallel drum and the fuel consumption, and the stack emissions during WMA production.

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PAPER IV: LIFE CYCLE ASSESSMENT OF BITUMINOUS PAVEMENTS PRODUCED AT VARIOUS TEMPERATURES IN THE BELGIUM CONTEXT

Authors: Joke Anthonissen, Johan Braet, Wim Van den bergh

Abstract: Bituminous mixture is the premier material for road construction in Belgium. Innovative technologies to improve energy efficiency of pavement constructions are necessary. Warm mix asphalt may provide significant energy savings to the asphalt industry, but the environmental impact of the total life cycle has to be investigated. The use of additives may counteract the reduced environmental impact due to energy savings. This paper presents the results of an environmental impact assessment of four wearing course test sections. Using life cycle assessment, hot mix asphalt is compared to a cold asphalt mix with emulsion and warm mix asphalt with two types of additives: a synthetic zeolite and an organic Fischer-Tropsch wax. Neither hot nor warm mix asphalt could be preferred based on the results of this study, because the additive has a major influence on the environmental results. It was seen that the production of bitumen, the transport and energy in order to generate heat mainly contribute to the total environmental impact. The results from the sensitivity analyses show that the total environmental impact of the life of the pavement can vary significantly based on the choice of the specific data source and service life.

Keywords: life cycle assessment (LCA); warm mix asphalt (WMA); hot mix asphalt (HMA); additives; sensitivity analysis; contribution analysis

1 INTRODUCTION

Infrastructure plays a vital role in the society in order to move people and goods. Roads in particular offer service without fixed departure times or limited service offers and is therefore experienced as freedom. Furthermore roads are the crucial connection between e.g., other transport services (airports, railway stations, bus stops), services, health facilities etc. (International Road Research Board, 2013).
Since all installations with a net heat excess of 20 MW or more are subjected to the Kyoto Protocol and hence the European Union emissions trading system (EU ETS), 13 of the 20 Flemish asphalt plants have to monitor and report on their CO_2-emissions. Each year these companies have to hand in emission allowances in accordance with the emitted quantity (Departement Leefmilieu Natuur en Energie,

2014; European Union, 2013a). It is important to note that the EU ETS only accounts for the emissions due to fuel consumption by particular companies. Hereby the reduction of the asphalt production temperature is encouraged by the EU ETS.
In various recent developments, researchers succeeded to reduce the production temperature of asphalt mixtures from 150 °C - 190 °C for hot mix asphalt (HMA) to 100 °C - 150 °C for warm mix asphalt (WMA) (Leyssens et al., 2013). As described by (Rubio et al., 2012), roughly three technologies to produce warm mix asphalt could be distinguished: i) adding organic additives (e.g., Fischer-Tropsch wax); ii) adding chemical additives (e.g., emulsifiers); iii) adding small amounts of water, either by water-containing technologies (e.g., a synthetic zeolite additive) or by water-based technologies (e.g., directly injecting water into the hot binder).
For the bitumen and asphalt industry, additional key drivers to decrease the production temperature of asphalt are related to less fumes and emissions, which lead to better working conditions and safer working situations.
Cold asphalt is another technique sometimes used in Flanders, mainly for maintenance projects. A bitumen emulsion (fluid at ambient temperature) is the binder of the cold asphalt mixture.

Despite these promising ideas, an assessment of the environmental impact of these technologies applied in practice is necessary. The aim of the presented study was to perform a life cycle assessment (LCA) of bituminous road pavements with asphalt mixtures produced at various temperatures. This paper focused on the methodology, difficulties and challenges of conducting an LCA study on bituminous pavements. The main results and findings are discussed as well.

In the following chapter, the applied methodology is elaborated including the different stages of an LCA as defined in the LCA standard (ISO 14040, 2006): goal, scope, life cycle inventory and life cycle impact assessment. In the next section, the results will be presented, including a comparison of four different cases, contribution analysis and sensitivity analysis. In the final section, the conclusions and recommendations are described.

2 METHODOLOGICAL FRAMEWORK

The LCA methodology was chosen as the most adapted method for the current case study that takes the entire life cycle into account, from resource extraction, maintenance operations and including end-of-life of the pavement.
A full, in depth life cycle assessment was chosen as the most appropriate LCA methodology. This type of analysis offers the possibility to express the contribution to the environmental impact in terms of percentage for various processes and

materials i.e., the contribution of the warm mix to the environmental impact of the total life cycle. This is not possible in a comparative LCA, where identical processes are omitted from analysis and only the differences are to be compared.

Difficulties in bituminous pavement life cycle assessment are related to the complexity of the asphalt sector and the variability in numerous related parameters. In Belgium, as in most other countries, multiple types of asphalt mixtures are applied, with differences in public and private works, differences in different layers etc. Furthermore there is a significant variability in raw material resources, in transport method (ship, truck, and train) and distance, energy type, manufacturing principles etc. Differences are observed from one asphalt work to the other, from one asphalt plant to the other, and from one country to another. This results in a large variability in calculated and measured data, and makes it difficult to apply average data. The deviation from possible "generic" or "average" data will be large. Hence, in the current case study, most quantitative data are case specific and therefore the results from LCA-calculations are only representative for the current situation.

A number of software tools have been developed to analyse the environmental impact of road pavements. Some of these tools are based on the life cycle assessment method and allow including processes from different phases in the life cycle of a road pavement, e.g. asphalt production, road construction, maintenance and end-of-life. On the other hand, the simplified tools to assess the environmental impact of road pavements are often limited to a single impact (i.e. global warming potential). These single issue LCA approaches may take a life cycle perspective but focus on one impact category only.

It is recognized internationally (European Union, 2013b), that the assessment of CO_2-equivalents or in general any single metric (e.g. carbon footprint, water footprint) is limited and does not reveal the full picture of the effect on the environment. The LCA approach applied in this study includes multiple environmental issues.

The SimaPro software version 8.0, developed by PRé-consultants BV in the Netherlands, was used to elaborate the analysis.

2.1 Goal and scope definition

A common pitfall when trying to implement an LCA is the lack of a clear purpose and intended application of an LCA (Goedkoop et al., 2016). Furthermore, in order to perform an LCA, a product, service, or system life cycle has to be modelled. It is important to realize that a model is a simplification of a complex reality and as with all simplifications this means that the reality will be distorted in some way. The challenge is to develop the model in such a way that the simplifications and distortions do not influence the results too much. The best way to deal with both problems is to carefully define the goal and scope of the LCA study.

2.1.1 Goal

Defining the goal includes a description of both the application and intended audiences and the reasons for carrying out the study (Goedkoop et al., 2016; ISO 14040, 2006).

The goal of this research was to analyse, on the basis of a specific example, the differences in environmental impact when different bituminous binders or manufacturing methods are used for road pavement construction. The focus is on the environmental impact of a reduction in asphalt production temperatures. Besides, the aim of this study is to determine the processes which significantly contribute to the environmental impact and to evaluate the influence of the most important assumptions on the results. A second goal is to evaluate a more complete environmental impact instead of limiting the study to CO_2 footprint.

The intended audiences are other researchers but also road engineers and the road agency which might yield to the implementation of the main findings into their policy.

2.1.2 Scope

The scope of the study consists of the most important methodological choices, assumptions and limitations; e.g. functional unit and reference flow, system boundaries, thresholds for inclusion of inputs and outputs and type of allocation (Goedkoop et al., 2016; ISO 14040, 2006).

Product system

The environmental impact of four wearing courses of pavement sections made of hot mix asphalt (HMA), warm mix asphalt (WMA) and cold asphalt are compared in the current case study. The HMA is a dense grade mixture and serves as the control or reference pavement. The WMA is based on the recipe of the reference mixture. Two different types of additives are used to facilitate warm mixing: Fischer-Tropsch wax and a synthetic zeolite. An emulsion is used for the cold asphalt. All materials used for the asphalt production are virgin, non-recycled materials because recycling in wearing courses is not allowed according to the Flemish road standard SB250 version 3.1. The case study is based on a real construction case, except for the cold mix asphalt, which is added to the study as a theoretical case, with a maximum temperature reduction. The field case is located in Assenede in Belgium on a single carriageway with one lane for each direction (a two-lane road). It is a quiet road with sometimes heavy agricultural traffic and a speed limit of 70 km/h.

Functional unit

(Jullien et al., 2014) mentioned that the functional unit can be described in four various ways in the road LCA practice. The preferred way for the current study is the definition of the functional unit by their geometry, service life, and levels of traffic supported (also stated by (Vidal et al., 2013)). (Araújo et al., 2014) clarified that the length and width of the road should be the same for all alternatives in order to be able to compare them. (Araújo et al., 2014) also stated: "The pavement thickness can vary and is determined (by conventional pavement design methods) so that all analysed solutions are capable of carrying the same design traffic in a similar service life".

The functional unit used for this study is a wearing course section of 300 m in length and 6 m in width over a 48 years' service life. The functional unit represents pavement structures of the same length and width and hence meet the same performance requirements; and the functional unit represents pavement structures on the same road with the same traffic intensity (which is unknown for this road) and hence meets equal technical requirements.

WMA is recently introduced in the Flemish road industry. The quality of the mixture and therefore the service life and rolling resistance of the pavement are not yet investigated in practice. At the design stage, the same thickness was applied to all test sections.

System boundary

The system boundaries for the baseline scenario for the four cases (reference, wax, zeolites and emulsion) are described in this section.

This work primarily focuses on the analysis of the material production, road construction and maintenance phases considering the selection of green construction techniques at the design stage (analogue to study (Celauro et al., 2015)). The period of analysis includes the entire life cycle of the pavement material from raw material extraction to final disposal, thus a "cradle-to-grave" life cycle analysis is considered. The system boundaries include all the significant life cycle phases covering the production and transportation of materials, their placement in the road structure, the maintenance of the construction and the situation after the use of the construction.

Following processes are beyond the scope of the study:

- preparation of the worksite (including earthwork etc.);
- construction of sub base, base and binder courses;
- leaching, lighting of the road, impact from traffic, albedo, etc.;
- land use impact due to the presence of the road;
- overhead impacts e.g. from offices;
- traffic congestion during road works.

The importance of the users phase for pavement life cycle assessment is known (Araújo et al., 2014), but not included in this study. The decision to omit the users phase arises from the consideration that user phase impacts (due to e.g., rolling resistance or retroflection) are assumed to be the same, due to lack of research in practice.

Hence, only a few differences among the four cases were investigated.

- The mixture composition of the reference mixture is adapted for the other mixtures. In the WMA mixtures a fraction of bitumen is replaced by the wax additive, or a fraction of filler is replaced by the zeolite additive. In the cold asphalt mixture an emulsion is used instead of bitumen.
- The target production temperature is 160 °C for the HMA control mixture; and 130 °C for the WMA mixtures. In case of the emulsion, only the bitumen, before emulsification, was heated.
- The roller passes for the compaction of the pavement were measured in practice. 14 roller passes were needed for the pavement with the wax mixture compared to 9 roller passes for all other mixtures.

The life cycle assessment in this case study takes ecological aspects into account. The social and economic factors are important as well for decision-making in civil engineering, but are beyond the scope of the current study.

Assumptions

Besides the observations in practice, some assumptions have been made for the LCA calculations of the baseline scenario to deal with the lack of proper information. The assumptions are varied in sensitivity analyses, to compare alternative scenarios with the baseline scenario.

- It was assumed that the pavement (all bound courses) would remain in service for 48 years, what is the analysis period. The unbound layers of pavement structures usually remain in situ at the end of the structural pavement life.
- The default service life is 14 years for the wearing course and 24 years for the base course. This yields 3 maintenance interventions for the wearing course during the analysis period of 48 years. [reference: interview with senior adviser at Agency for Roads and Traffic]
- Based on internal laboratory test results for rut resistance and similar conclusions in literature (Hill, 2011; Zhang, 2010), it was assumed that the service life of the wearing course with FT wax is prolonged with 5 years. Hereby 3 maintenance interventions would be needed during 60 years, what is converted to 2.5 maintenance interventions during the analysis period of 48 years.
- In this case study, the wearing course is milled at end-of-life and the released materials are transported to a stockpile for reuse or deposited to a landfill. Based on figures from EATA (European Asphalt Pavement Association, 2013) for the Belgian situation, a 60% reuse and 40% landfill rate was applied.
- The landfill scenario takes into account the transport of the material from worksite to sanitary landfill (a distance of 100 km was assumed) and the environmental impact related to the deposited asphalt material (predefined in ecoinvent).
- The reuse scenario takes into account the transport of the material from the worksite to the stockpile on the asphalt plant (a distance of 35 km in this case) and the impact associated with processing the material from waste to material ready for reuse (breaking, sieving).

2.2 Life cycle inventory

Both quantitative and environmental data are necessary to develop a life cycle inventory. The inventory for this case study was built up by combining information from literature or existing databases (generic data) and specific data for the investigated case. The three test sections were constructed in actual practice in 2009 and some useful quantitative information was collected in a case description. This includes the following information useful for the LCA:

- origin and moisture content of the raw materials,
- recipe of the three asphalt mixtures,
- fuel type for heating the drum in the asphalt plant,
- mixing temperatures,
- transport distance asphalt plant to worksite and
- number of roller passes for the compaction of the pavement.

Table 27: Data sources for the quantification of parameters in the case study

Process	Source
Energy consumption for the storage of bitumen	(Wayman et al., 2012)
Electrical energy consumption for engines at the asphalt plant (sieving, dosing, conveyor belt,…)	(Leyssens et al., 2013)
Fuel consumption for processing of reclaimed asphalt pavement	(Wayman et al., 2012)
Fuel consumption for milling existing pavement	(Wayman et al., 2012)
Fuel consumption for tack coating, paving, compaction	(Stripple, 2001)
Bitumen consumption for tack coating	(Stripple, 2001; Vlaamse overheid, n.d.)
Rate of laying asphalt courses	(ECRPD, 2010)
Emissions VOC and PAH during road construction	(Finset, 2012; Jullien et al., 2006)

Table 27 illustrates the data sources for the quantification of processes which are not specified in the case description. The fuel consumption for drying and heating aggregates was calculated based on the moisture content and the temperature of aggregates, the production temperature, the flue gas temperature and the specific heat capacities as defined by (OCW, 2002).
Information on diffuse emissions during road construction for HMA were taken from study (Jullien et al., 2006) and reduced by 30% for WMA, based on findings from (Finset, 2012). It is important to note that other values were found in other sources in the literature. Study (Read and Whiteoak, 2003) states: "the amount of fume generated doubles for each 10 to 12 °C".

Environmental data were taken from the Swiss ecoinvent database version 2.2 for all raw materials and processes, except for the bitumen and the Fischer-Tropsch wax. The ecoinvent database is widely accepted as one of the most complete and consistent databases; it is especially representative for the Western European context and is updated regularly.
Data for bitumen were taken from a life cycle inventory (LCI) published by Eurobitume (Eurobitume, 2012) which is in compliance with ISO 14040 and ISO 14044. The LCI is specific for the Amsterdam-Rotterdam-Antwerp area and is more recently dated compared to the data for bitumen in ecoinvent (respectively published in 2012 and 2007). The allocation between bitumen and other co-products made from crude oil is based on mass balances at the crude oil extraction and the transport stages; while at the refining level, the allocation is based on relative economic values. Within the LCI, no quantitative uncertainty assessment was

provided since the standard deviation for each input and output of the process is not available. The LCI is less accurate for analysing toxicity and eco-toxicity indicators.

Environmental data for the additive Fischer-Tropsch (FT) wax are not included in the ecoinvent database. Information on the production process and the global warming potential of FT wax was found in the cradle-to-gate study (Allen et al., 2010). The primary resource for the wax additive is natural gas. The carbon monoxide, gained from the natural gas is reacted over catalysts together with hydrogen to form syngas, which are the desired hydrocarbon molecules. The reaction product, a mix of n-alkenes over a large c-number distribution is then distilled into fractions of different molecular weight. The wax additive is the heaviest fraction, with a chain length from C40 to more than C115. Mass allocation was applied to divide the global warming potential and the consumption of natural gas among the different products. It is important to notice that the data for the wax additive are only dealing with global warming and fossil depletion because of a lack of more complete data in literature.
No feedstock energy, which is the energy potentially released by ignition, was considered for the studied materials.

2.3 Life cycle impact assessment

The first step in the impact assessment is selecting appropriate impact categories (see Figure 55). Once the impact categories are defined and the LCI results are assigned to these impact categories (classification), it is necessary to define characterisation factors. This is the last obligated step in an LCA study according to the standards. Characterisation factors reflect the relative contribution of an LCI result to the impact category. For example, on a time scale of 100 years the contribution of 1 kg CH_4 to global warming is 25 times as high as the emission of 1 kg CO_2. This means that if the characterisation factor of CO_2 is 1, the characterisation factor of CH_4 is 25. Multiplying the inventory result by the characterisation factor gives the impact category indicator. Characterization uses science-based conversion factors, many of them were found through European research (Scientific Applications International Corporation (SAIC), 2006). The characterized results are thus based on scientific findings.
An optional step to generate midpoint results is the use of normalisation. This is a procedure needed to show to what extent an impact category has a significant contribution to the overall environmental problem in a defined region (e.g. Europe). Sensitivity analysis is performed by dividing the impact category indicators by a “normal” value. The most common procedure to define the “normal” value is the determination of the impact category indicators for a region during a year and, if

desired, divided by the number of inhabitants in that area. Normalization is used to express the data in a way that can be compared among impact categories.
Another optional step to facilitate interpretation of the results is to group and rank the impact category indicators. Impact category indicators that have some common features may be presented as a group. Ranking refers to a procedure, where impact categories are sorted by a panel in a descending order of significance. Weighting is the most controversial and most difficult step in life cycle impact assessment.

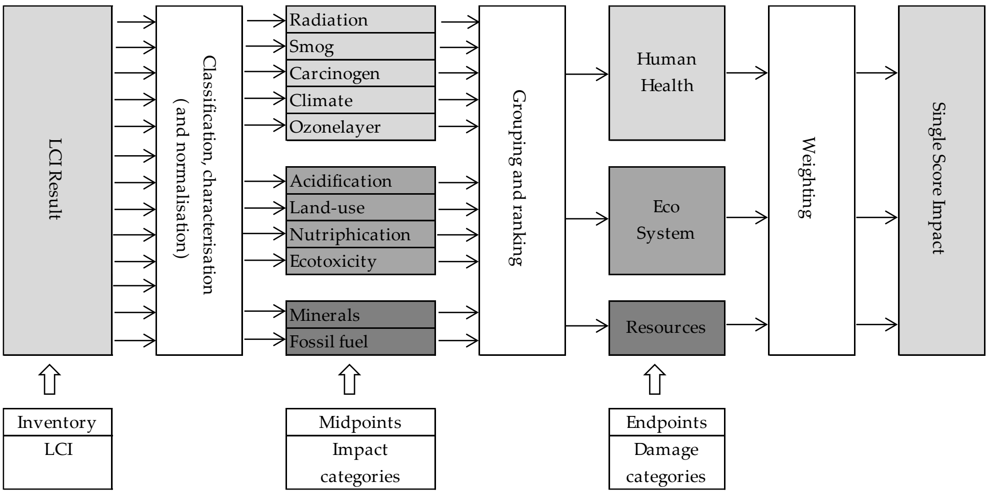

Figure 55: Methodology - Inventory, Midpoints (non-exhaustive), Endpoints & Single score impact

In connection with the selection of an appropriate life cycle impact assessment (LCIA) method for the current case study, it was obvious from the goal and scope that multiple environmental impacts have to be included in the analysis. Furthermore, ISO 14044 does not allow weighting of the impact categories for calculation of a single score impact for public comparisons between products, however, weighting is explicitly allowed for other applications (Goedkoop et al., 2016).
ReCiPe is chosen as life cycle impact assessment method (LCIA-method) because it implements both midpoint (impact categories) and endpoint (damage categories) impact categories. Furthermore, ReCiPe Endpoint contains a set of weighting factors with regard to calculating a single score impact from the three damage categories, used for the internal interpretation of the results. The default perspective is the hierarchist, which is based on the most common policy principles with regards to time-frame and other issues. Besides the hierarchist perspective, ReCiPe has an individualist and an egalitarian variant that respectively assume a short time frame and a long term perspective. The hierarchist ReCiPe version with European normalization and average weighting set was chosen. More information about the

chosen LCIA-method can be found in the literature (Goedkoop et al., 2013; PRé, 2013; Sleeswijk et al., 2008).

3 RESULTS OF THE CASE STUDY

It is important to keep in mind that the commonly accepted precisions of LCA-calculations may vary between 10 and 20% for single score results and about 10% for characterized results.

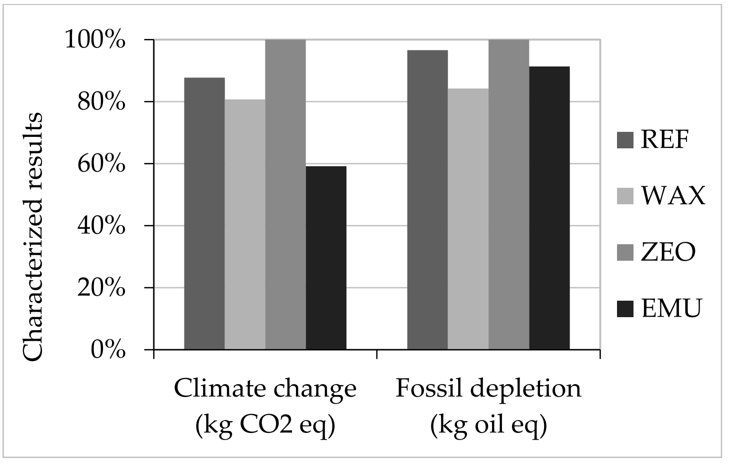

Figure 56: Results of comparison after characterization

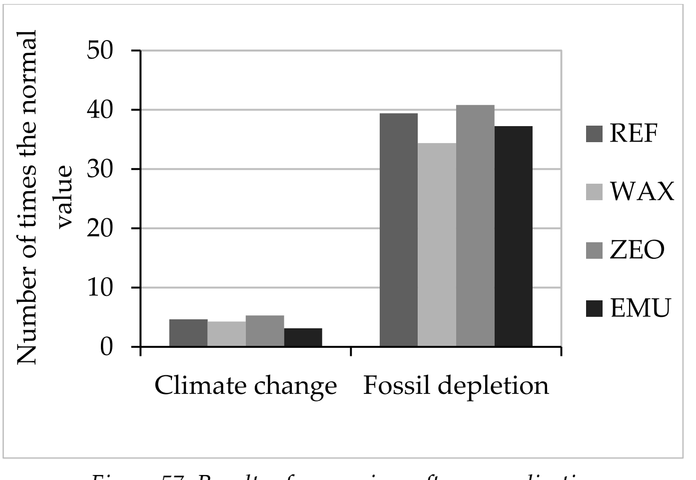

Figure 57: Results of comparison after normalization

Figure 56 and Figure 57 respectively illustrate the characterized and normalized results of the comparison of the cradle-to-grave life cycle of the four road pavement test sections. It must be taken into account that, due to a lack of appropriate data, the environmental data for the production of the FT wax additive is only based on the emission of CO_2eq and a consumption of natural gas resource. Therefore, only the associated impact categories of the ReCiPe LCIA-method were used in these two figures, namely climate change and fossil depletion. In all following figures and results, discussed in this paper, all 18 impact categories included in the ReCiPe method are taken into account.

The results presented in Figure 56 show a significant reduction (> 40%) of the impact on climate change for the pavement with emulsion compared to the reference pavement. The reduction is due to the absolute reduction of the impact from the production of emulsion compared to the production of bitumen and the reduction of the impact from heat demand.
The reduction of the impact for the emulsion case compared to the reference case is less pronounced in the category of fossil depletion (± 9%)[13]. The main contributors to this impact category are the production of the binder (bitumen or emulsion) and the transport. Because the impact of the production of two different binders on fossil depletion is similar in absolute value, and because the heat has an inferior impact on fossil depletion, the difference between reference and emulsion is less distinct for the impact on fossil depletion compared to the major difference in the climate change impact category.
The increased impact of the zeolite case compared to the reference case is due to the production of the zeolite additive. The absolute impact on climate change from the zeolite production is equivalent to the impact of the energy for heat in the same case. Similar, in the category fossil depletion, the increased impact in the zeolite case comes from the additive. The reduced impact of the wax case, compared to the reference, is mainly due to the longer service life and therefore the reduced amount of maintenance interventions.

In Figure 57, the normalised results are given for the two impact categories and the four life cycles. The impact category indicators (presented in Figure 56) are divided by a normal value. In ReCiPe, with European normalisation factors, the normal value is the total environmental impact of whole Europe during one year, divided by the number of European inhabitants. Put in another way, the normal value is the

[13] This small value or difference falls outside the validity range of the ReCiPe method as described in chapter 4 and so we need to be careful with the interpretation and firm conclusions are not allowed based on this result.

impact in the certain impact category of an average European citizen during one year.
It can be seen that the normalized impact on fossil depletion is very high (34 to 41 times the impact of an average European citizen per year) compared to the normalized climate change impact (namely 3 to 6 times the normal value). Hence, the fossil depletion impact of the pavement in this case contributes significantly to the total fossil depletion related environmental problem. The contribution of the road sections to the European environmental problem on climate change is less pronounced. This does not mean that the impact from the road sections on climate change is negligible, but it imputes that the yearly impact on climate change of a European person is large when compared to the yearly impact on fossil depletion of a European person.

The single score impact (including all 18 impact categories) of the pavement with wax, differs less than 1% compared to the single score impact of the pavement with emulsion (see Figure 58)[i]. It is important to take into account that the life cycle of the pavement with wax includes only 2.5 maintenance interventions compared to 3 maintenance interventions for all other life cycles. The extended life time for the pavement with wax is an assumption based on performance characteristics tested in the laboratory (i.e., rut resistance).

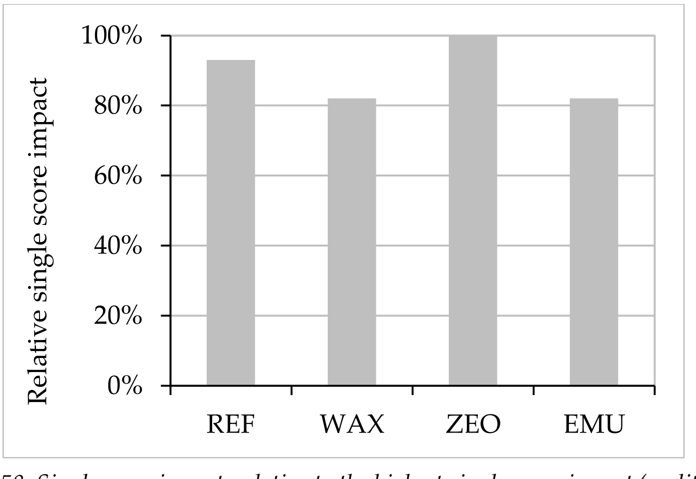

Figure 58: Single score impact, relative to the highest single score impact (zeolite case)

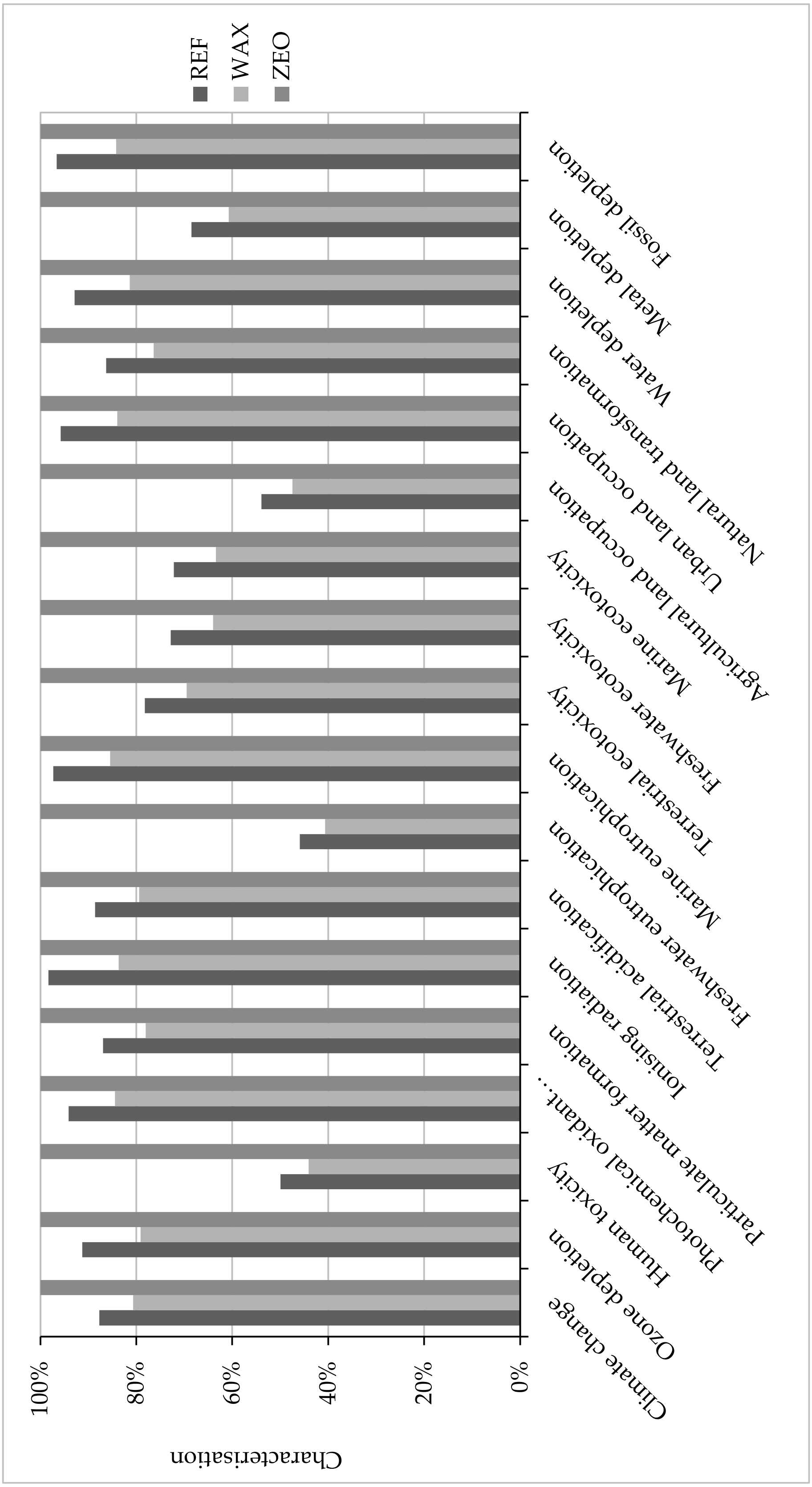

Figure 59: Characterisation results of life cycles reference, wax and zeolite

Neglecting the emulsion pavement, the ranking of the characterized results of the three other pavements (baseline scenario) is the same in all 18 impact categories (see Figure 59). This means that no weighting to a single score is actually needed to find the most favourable case. The results obtained based on sciences (characterisation) point to the wax pavement as the best choice (when excluding the emulsion pavement). The environmental impact during the life cycle of the zeolite pavement is the highest. Including the emulsion pavement, the ranking of the four cases is not the same in the different impact categories (wax and emulsion mutually exchange), and therefore weighting is necessary to prefer a certain case.
All results are based on the data that were available (which might be incomplete i.e., data for wax). The determination of the reliability of those published data are beyond the scope of the project. Changing the data source might have influenced the results (see 3.2).

An analysis showed that the environmental impact (single score) from 1 kg wax is higher when compared to 1 kg bitumen. Analogous, it is found that the single score impact of the filler is small compared to the impact of the same mass of zeolite.
The analysis of the environmental impact of the asphalt mixture production (cradle-to-gate) includes the acquisition and production of raw materials; transport of raw materials to asphalt plant; energy to heat and dry aggregates and store bitumen; and electrical energy for engines. The impact of 1 ton reference mixture is almost equal to the impact of 1 ton mixture with wax additive (note the limited data for wax). The impact of the mixture with zeolite is, on the other hand, 10% larger compared to the reference and the impact of the mixture with emulsion is 15% smaller compared to the reference[i].

3.1 Contribution analyses

The processes that have a significant part in the results can be determined by a contribution analysis. This is an impact analysis breakdown. It is often found in contribution analysis that 95 to 99% of the results are determined by just a few processes (Goedkoop et al., 2016). With this information, it is possible to focus the attention on these processes and analyse if these processes are sufficiently representative, complete, and if there are important assumptions within these processes. Furthermore, researchers might focus on these processes in order to optimize the environmental impact of the product system and apply measures.

Figure 60 illustrates that, among important processes, the binder (bitumen or emulsion) is the major contributor to the total single score impact (all 18 impact categories in ReCiPe are included) for all cases of the baseline scenario, with 55% to 62% depending on the case. Furthermore all transport of materials and equipment (excluding transport of waste, that is assigned to the waste treatment) represents 18% to 21% of the total single score[i]. The natural gas used to generate heat is responsible for 7% to 9% of the total single score impact, respectively for the WMA cases and for the HMA case[i]. The impact of heat from natural gas represents less than 0.1% in the life cycle of the cold pavement with emulsion[i].

The contribution to the single score impact of the fuel consumption by equipment for road construction (paver, roller) ranges from 18 to 21%[i]. The contribution of the production of the additive to the total single score impact is small for the wax (2.8%) but larger for the zeolite (7.8%), which explains the variation in the contribution of the impact from raw materials (ranging from 4 to 12%)[i]. Finally the 'other' processes including the waste treatment from maintenance and end-of-life; the electricity consumption and the installation emissions represent ±6% of the total single score impact[i].

The interpretation of these percentages is important. A smaller percentage of contribution does not indicate a smaller absolute impact of a certain process or material. Nevertheless the percentage of the contribution gives an indicative idea of the main contributors.

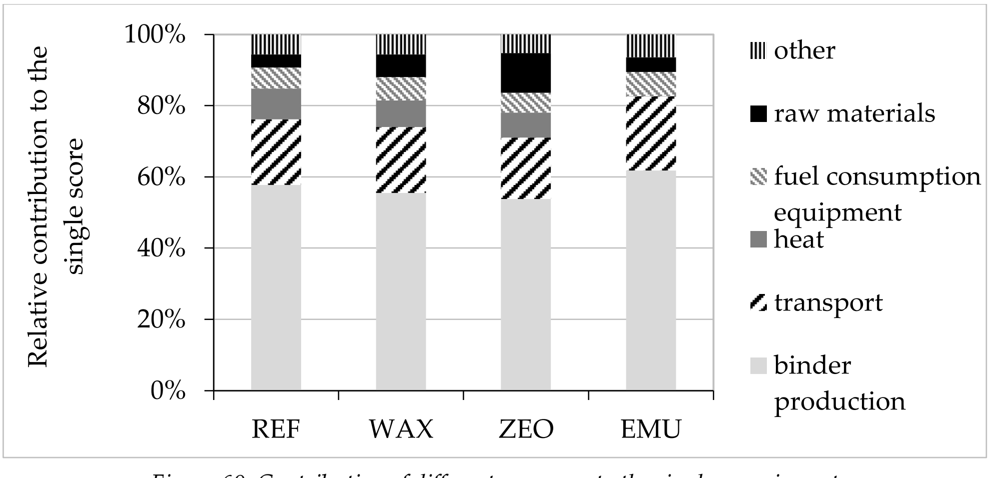

Figure 60: Contribution of different processes to the single score impact

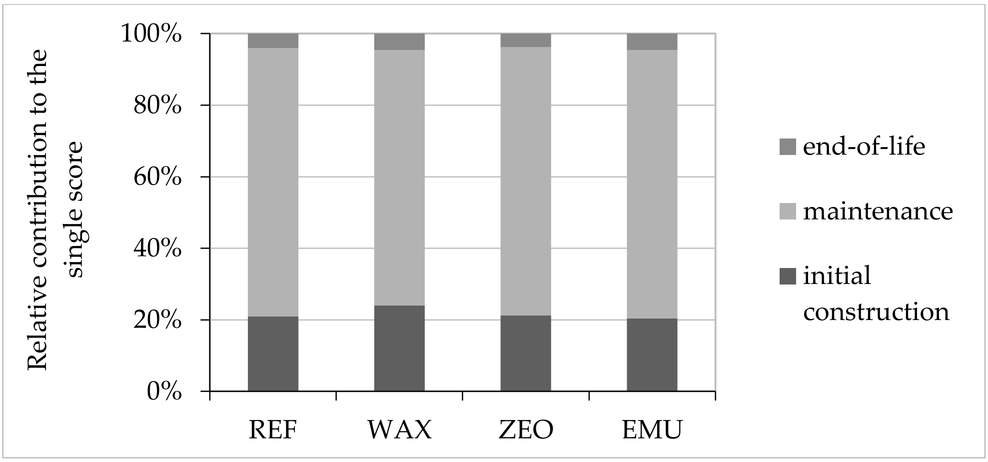

Figure 61: Contribution of different life cycle processes to the single score impact

The division of the total single score impact between the three main life cycle stages is illustrated in Figure 61. The impact of the initial construction contributes 20 to 24% to the total single score impact. The maintenance stage represents 71% in the wax life cycle and 75% in the three other life cycles. The decrease of the relative impact during the maintenance stage (due to the longer service life for the wax pavement) leads to a relative increase of the impact in the construction and end-of-life stage. At last, the end-of-life stage is responsible for 4 to 5% of the total single score impact[i].

3.2 Sensitivity analyses

In this chapter, the influences of some assumptions on the LCA-results were analysed. Sensitivity analyses are carried out in order to investigate the influence of some alternatives for a certain assumption e.g., data from different data sources, haulage of a lorry, transport type, fuel type, etc. Among others, the most important contributors to the single score impact are investigated by sensitivity analyses: bitumen (data source), transport (method) and heat (fuel type). The variant of these parameters, used in the baseline scenario is indicated by 'default'.

It can be seen from Figure 63 and Figure 64 that the effect, respectively of the transport method (±5%) and the fuel type (±3%), is rather small[i]. On the other hand, the total environmental impact of the life of the pavement can vary more significantly based on the choice of data source of bitumen (±10%) (Figure 62)[i].

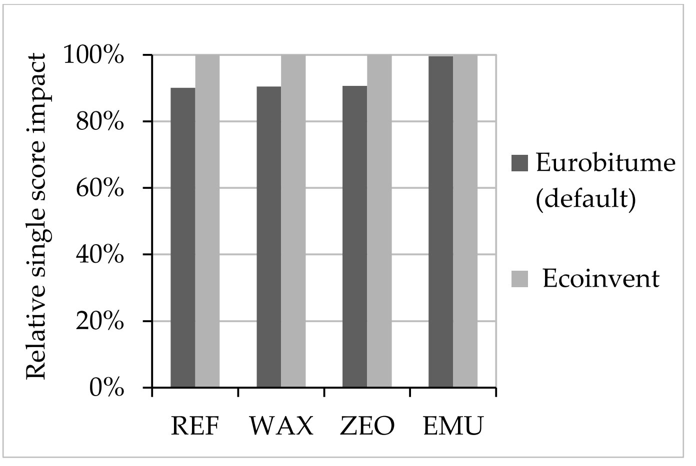

Figure 62: Sensitivity analysis data source bitumen

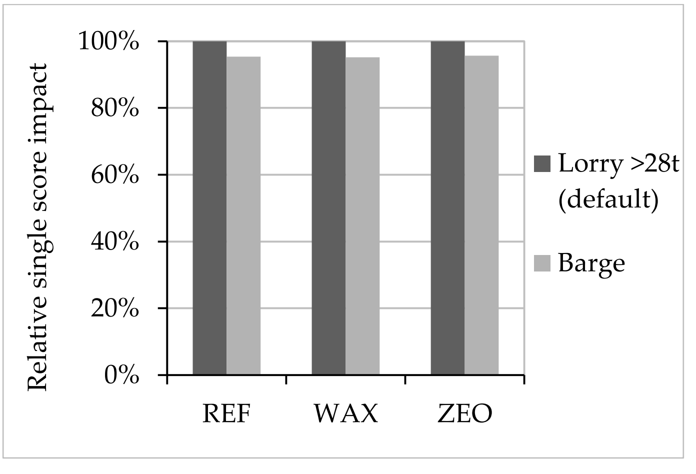

Figure 63: Sensitivity analysis transport method for supplying raw materials to the asphalt plant

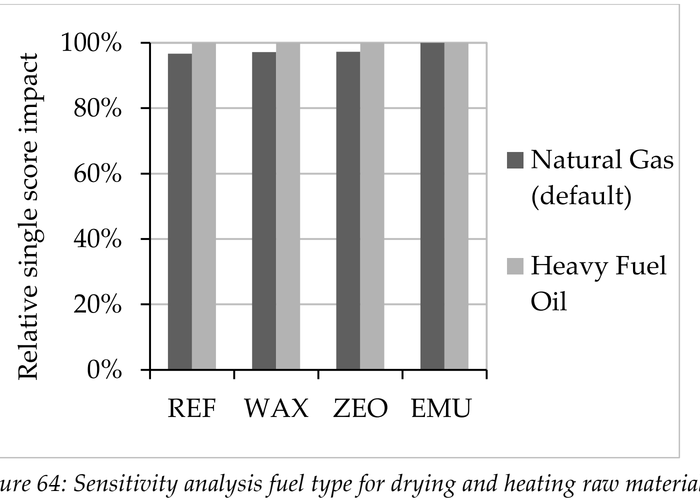

Figure 64: Sensitivity analysis fuel type for drying and heating raw materials

Furthermore, the ranking of the single score impact of the four cases investigated may change when changing the service life or the LCIA-method.

The emulsion case is only added as a theoretical calculation, and the pavement life as for the reference case is assumed. In practice, it is not sure if this pavement can be constructed and certainly not sure what pavement life may be achieved. Therefore, the sensitivity of this assumption is analysed. The service life of the road pavement and hence the number of maintenance interventions during the analysis period is varied in Figure 65. The baseline scenario of 19 years of service life (2.5 maintenance interventions) for the wax pavement and 14 years of service life (3 maintenance interventions) for the other pavements is changed to an equal service life for all four pavements (14 years, or 3 maintenance interventions) and is changed to 10 years (4 maintenance interventions) for the cold pavement and an equal service life of 14 years for the other top layers. Changing the expected pavement life from 19 to 14 years or from 14 to 10 years, is enough to change the rankings of the various construction modes. This indicates that service life, and techniques for enhancing service life, are very important when developing sustainable pavements.

Detailed results showed that the ranking of the cases was not the same in all impact categories for both sensitivity analyses. Hence, no absolute ranking can be presented without weighting.

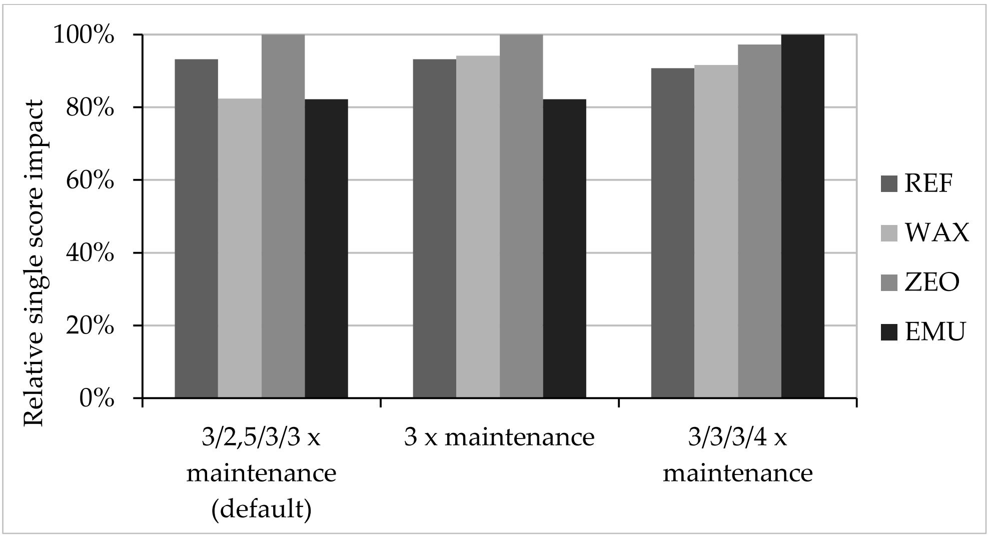

Figure 65: Sensitivity analysis service life top layer pavement

Table 28: Sensitivity analysis LCIA-method (single score impact relative to the reference)

LCIA-method	REF	WAX	ZEO	EMU
ReCiPe Endpoint (E) V1.06 / Europe ReCiPe E/A	1,00	0,88	1,15	0,90
ReCiPe Endpoint (H) V1.06 / Europe ReCiPe H/A	1,00	0,88	1,07	0,88
ReCiPe Endpoint (I) V1.06 / Europe ReCiPe I/A	1,00	0,88	1,06	0,89
Eco-indicator 99 (E) V2.08 / Europe EI 99 E/A	1,00	0,88	1,10	0,92
Eco-indicator 99 (H) V2.08 / Europe EI 99 H/A	1,00	0,88	1,08	0,93
Eco-indicator 99 (I) V2.08 / Europe EI 99 I/A	1,00	0,90	1,77	0,85
ReCiPe Endpoint (H) V1.06 / World ReCiPe H/A	1,00	0,88	1,07	0,89
EPS 2000 V2.06 / EPS	1,00	0,89	1,16	0,89
Ecological Scarcity 2006 V1.06 / Ecological scarcity 2006	1,00	0,88	1,03	0,90
EDIP 2003 V1.03 / Default	1,00	0,88	1,09	0,98
IMPACT 2002+ V2.10 / IMPACT 2002+	1,00	0,89	1,08	0,90

Table 28 presents the single score impact (relative to the reference case) of the four baseline cases (note the longer service life for the wax pavement), calculated with different LCIA-methods. The results in Table 28 indicate that the ranking of the single score impact of the different pavements is influenced by the LCIA-method. The wax and emulsion pavement swapped places. The ranking of the four cases with Europe ReCiPe H/A (default) and Europe EI 99 I/A is different compared to the ranking obtained with all the other methods.

The trend is similar for the different LCIA-methods: 10 to 12% reduction for the wax case, 3 to 16% increase for the zeolite case and a decrease of 2 to 12% for the emulsion pavement compared to the reference (in the baseline scenario)[i]. One exception is found for the LCIA-method Europe EI 99 I/A, where an increase of 77% of the single score is noticed for the zeolite pavement compared to the reference. This is due to a large impact in the minerals impact category (4.5 times the impact of the reference in the same category), which stems from the zeolite powder production.

4 CONCLUSIONS AND RECOMMENDATIONS

The objective of this paper was to compare sustainability aspects of four wearing courses of pavement sections made of hot mix asphalt, warm mix asphalt and cold asphalt; to determine the processes that play a significant role in the results and to evaluate the influence of the most important assumptions on the results. The focus was not laid on the results only but also on the methodology, difficulties and challenges of conducting an LCA study on bituminous pavements.

Analysis of the baseline scenario highlighted that the impact of the life cycle of the pavement is dependent on the type of additive and the expected service life. From the results of this analysis, no preference could be given to either HMA or WMA. Based on science, and excluding the emulsion mixture, the three cases in the baseline scenario are ranked from most to less impacting as follows: zeolite, reference, wax. It is important to keep in mind that at this moment we still assume a longer service life for the pavement with the wax additive. A study by (Vidal et al. 2013) concluded the same: 'The reduction in the impacts of WMA resulting from the lowering of the manufacturing temperature was offset by the greater impacts of the materials used, especially the impacts of the synthetic zeolites'.

Other and broader studies are required in order to compare the total environmental impact of HMA and WMA with different additives and production techniques. Uncertainties, however, remain on these additives (i.e. wax) for which full life cycle inventories were not found. Furthermore, uncertainties in the actual service life of the pavement materials remain. More information about the intrinsic inaccuracy of LCIA-methods is needed to draw firm conclusions.

From the contribution analysis of the baseline scenario, it was seen that mainly the combination of production of bitumen, all transport and energy for generating heat, contributes to the total environmental impact. Furthermore the impact of the additive might be significant, even though a very small quantity of the material is used in the asphalt mixture.

The results from the sensitivity analyses show that the total environmental impact of the life of the pavement can vary significantly based on the choice of data under analysis, service life and LCIA-method.

An important advantage of WMA compared to HMA is the lower diffusion emissions during road construction, which is clearly visible to the naked eye. This is associated with higher safety for the road workers who work day after day in the fumes of the hot or warm material. Nevertheless, the advantages of WMA for the human health of the road workers do not show up in the results of the calculations. This is due to the fact that the environmental impact from e.g., the production of bitumen, and the energy for drying and heating the aggregates is very large and therefore the relative reduction of the emissions from the diffusion emissions due to the warm mix technology is invisible. Furthermore, some aspects are not included (e.g., increased safety), because at this moment, it is not possible to model it in LCA. Hence it is important to always critically evaluate the results from LCA and even look further than these numerical values.

In terms of future development, more information on the life time of different asphalt pavements would be extremely useful. As is the case with many life cycle based studies of construction products, the rate of replacement of materials is very significant in environmental terms. In Belgium, WMA is not frequently used. The evaluation of the service life takes some time and more (test) sections are needed to allow for robust conclusions on this parameter.

Furthermore some environmental data on some specific products like the wax additive in this case are still missing. Companies should be encouraged to register and monitor the production process of their products for generating environmental data, available for research.

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PAPER V: CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF RECYCLING AND IMPACT OF REDUCED PRODUCTION TEMPERATURE FOR THE ASPHALT SECTOR IN BELGIUM

Authors: Joke Anthonissen, Wim Van den bergh, Johan Braet

Abstract: Bituminous mixture is the premier material for road construction in Belgium. Innovative technologies with regard to improve energy and material efficiency of pavement construction are necessary. Warm mix asphalt (WMA) may provide significant energy savings to the asphalt industry. Also, the use of reclaimed asphalt pavement (RAP) into new bituminous mixtures may diminishes the extraction and processing of minerals and binders. Using life cycle assessment, the environmental impact of the production of WMA is compared with hot mix asphalt (HMA) containing reclaimed asphalt pavement and with conventional hot mix asphalt as a reference. Contribution analyses were performed in order to determine which processes are significant for the results and sensitivity analyses were conducted in order to take into account the influence of the most important assumptions in the process on the results.

It was found from the results in the current study that a greater reduction of the environmental impact is obtained by using RAP in asphalt mixtures compared to reducing the mixture temperature. It was seen from the contribution analyses that mainly the production of bitumen, the transport of raw materials from the quarry or production site to the asphalt plant and the energy in order to generate heat, contribute to the total environmental impact. The results of the sensitivity analyses show that the total environmental impact of the asphalt mixtures varies mostly on the choice of the data source and the transport method.

Keywords: life cycle assessment (LCA), warm mix asphalt (WMA), hot mix asphalt (HMA), reclaimed asphalt pavement (RAP), contribution analysis, sensitivity analysis

1 INTRODUCTION

In recent years, more environmental awareness and increasing energy costs have encouraged industries to consider research on environmentally friendly technologies. For the bituminous pavement sector, this culminates the development of technologies designed in order to reduce energy consumption and increase recycling, this latter in order to decrease the virgin material extraction.

A number of software tools have been developed with regard to analyze the environmental impact of road pavements. Some of these tools are based on the life cycle assessment method and allow including processes from different phases in the life cycle of a road pavement, e.g. asphalt production, road construction, maintenance and end-of-life. On the other hand, simplified tools are used to assess in a more general way the environmental impact of road pavements and are often limited to a single impact (i.e. global warming potential).
However, it is recognized internationally (European Union, 2013b) that the assessment of CO_2-equivalents or in general any single metric (e.g. carbon footprint, water footprint) is too limited to assess a correct and significant environmental impact. An evaluation by only CO_2-equivalents does not reveal the full picture of the effect on the environment. The life cycle assessment (LCA) approach includes multiple environmental issues. These life cycle impacts are being used increasingly as a selection criterion for products and materials since a more accurate impact is provided.

In this study the LCA methodology was chosen as the most adapted method for the current comparative cradle-to-gate assessment. The study takes into account the asphalt production and all upstream processes including resource extraction, material production, transport etc. Otherwise stated, the analysis includes all processes involved in asphalt production until the asphalt mixture reaches the gate of the asphalt plant i.e., excluding the transport to the consumer or worksite.
The SimaPro software version 8.0 was used to elaborate the analysis. This software was developed by the Dutch company Pré. Depending on the license type and duration, the charge is between €1 800 ($2 466) and €21 000 ($28 770).

This paper set forth the method and results from the LCA case study. In a first section, the applied methodology is illustrated including the different stages of an LCA as defined in the LCA standard (ISO 14040, 2006): goal, scope, life cycle inventory and life cycle impact assessment. In the second section, the results of these LCA calculations are presented, including a comparison of three different cases, a contribution analysis and sensitivity analysis. In the last section, the conclusions and recommendations are described.

2 LITERATURE

The objective of this life cycle assessment is to compare the environmental impact of two different technologies, implemented in order to reduce the environmental impact of asphalt production. The comparative study is done for the foamed-bitumen process for WMA production and HMA with and without recycling.

2.1 Warm mix asphalt

Decreasing the production temperature of asphalt mixtures is seen as the most important way to reduce the energy consumption of asphalt production. In Belgium it is assumed that HMA is manufactured between 140 °C till 190 °C while the production of WMA is situated between 70 °C and 140 °C (VITO (BBT-kenniscentrum), 2012). It is assumed that the production of WMA will have an average reduction in energy consumption of 20% compared to the conventional HMA production (VITO (BBT-kenniscentrum), 2012). The fundamental idea while developing warm mix asphalt (WMA) is to reach equal or better performance characteristics compared with the conventional hot mix asphalt (HMA). This is mainly reached by reducing bitumen viscosity, which in turn improves mix workability, produces fewer emissions, and generally yields better working conditions (Rubio et al., 2012).
Initially, German research focused on adding additives to the asphalt mixture in order to facilitate the production and processing of WMA; while in Norway the WMA-foam process was developed (VITO (BBT-kenniscentrum), 2012). The various technologies which have been developed in order to produce WMA can be classified in the following three groups: organic additives, chemical additives, and water-based or water-containing foaming processes.

Several studies have investigated the environmental impact of WMA, of which some compared WMA to the impact of a conventional HMA mixture. Study (Anthonissen et al., 2014a; Vidal et al., 2013) found that the reduction in the impact of WMA resulting from decreasing the manufacturing temperature was countered by the impacts of the materials used, specifically the impacts of additives e.g., synthetic zeolites.

Study (Hill, 2011) investigates the WMA production with foamed bitumen technology and describes the Double Barrel Green technology which uses multiple nozzles to inject directly cold water into the hot binder flow. The production technique requires 0.45 liters of water per ton asphalt mixture and provides 20 to 30 °C production temperature reduction. No additive is required in order to apply this technique.

Nevertheless, an advantage of WMA compared to HMA is the potentially higher use of RAP. A decrease of production temperature leads to less ageing of the binder, thus counteracting the stiffer RAP binder (Rubio et al., 2012). Analogous, an improved moisture sensitivity and rutting resistance were obtained by including up to 50% RAP in the WMA mixture compared with the virgin WMA (Hill, 2011).
In the same way, study (Zhao et al., 2013) ranked mixtures from worse to better rutting and moisture resistance as follows: WMA mixtures with low RAP content, WMA mixtures with high RAP content, and HMA mixtures with high RAP content.

In Belgium, the applicability of WMA is a current research item. A few pilot projects are finished in order to investigate the applicability and performance of WMA techniques. Some of the projects have led to promising results but until now, the projects in which these techniques are used are rather small-scale. Moreover, in 2014, no mixtures based on specific technologies in order to facilitate WMA are defined in the Flemish standard SB250 v.2.2., the 'Standaard Bestek SB250' that defines the rules for public tenders in Flanders.

2.2 Reclaimed asphalt pavement

Recycling asphalt pavements is the current valuable approach for technical, economic and environmental reasons. The use of RAP in new asphalt mixtures is mainly encouraged by the increasing cost of bitumen and the scarcity of quality aggregates. The international regulations in order to decrease polluting emissions and preserve the environment force industries to move towards extensive recycling. From an environmental point of view, the use of RAP in new bituminous mixtures avoids the need to mine virgin raw materials, the need to process bitumen, and the need to dispose of the released asphalt to landfill (Vidal et al., 2013). On the other hand, some screening is necessary in order to detect and eliminate tar containing RAP. Preliminary to the reuse, the RAP is processed by sieving and crushing in order to provide proper material for new high quality asphalt mixtures.

The environmental impact of using RAP is affected by a few factors, such as moisture content (National Technology Development, 2009; Wayman et al., 2012), hot mix asphalt discharge temperature (National Technology Development, 2009), RAP content (National Technology Development, 2009) and transport process (Ventura et al., 2008). Furthermore, study (Wayman et al., 2012) found that recycling of asphalt to bound courses (in particular surface-to-surface) is favoured compared with recycling asphalt to unbound applications (sub-base or fill) or waste management alternatives (landfill or incineration).

All asphalt production plants in Flanders are batch types and about 80% of them are provided with a parallel drum to preheat the RAP before addition to the mixer (Leyssens et al., 2013). The SB250 defined a minimum preheating temperature for RAP of 110 °C. In practice, the temperature of the RAP is limited to 140 °C in order to minimize binder oxidation and explosion risk.
It was noticed (van den Berk, 2004) that the energy consumption of the asphalt plant for drying and heating aggregates increases with 14 to 17% when this second, parallel drum is used. Despite the lower temperature for RAP (±130 °C) compared to virgin aggregates for HMA (±160 °C), an elevated energy demand is observed caused by the additional drum.

In the current versions of the SB250 (v.2.2 and v.3.0), it is still prohibited to use RAP in new asphalt mixtures for top layers. For binder layers, this SB250 defines asphalt mixtures based on either mixture composition or on the performance requirements. The first method allows a maximum of 20% (cold addition) and 50% (warm addition by parallel drum) of the bitumen content from RAP. The second method does not define a maximum quantity of bitumen content from RAP in the asphalt mixture. Based on figures from the certified asphalt plants in Flanders *(unpublished data – interview expert at COPRO)*, the minimum quantity of RAP is assessed to be 40%, the maximum 75% and the average ±55% RAP in new asphalt mixtures.
The use of tar containing RAP is prohibited in Belgian asphalt mixtures.

3 GOAL, SCOPE AND METHODOLOGY

This paper presents the comparative life cycle assessment (LCA) for the production of three different asphalt mixtures. Therefore, only the asphalt production is included because other parameters are (assumed to be) the same. The pavement construction, including site preparation, tack coating, paving and compaction is independent of the asphalt mixture. Furthermore, the asphalt mixture used in the binder layer does not affect the use phase (e.g., rolling resistance and associated fuel consumption). The service life of the pavement layers constructed with the three different asphalt mixtures is assumed to be equal and therefore no difference in maintenance should occur. Finally the recyclability and waste treatment is assumed to be similar for these bituminous mixtures.

3.1 Goal

The aim of the current study is to compare the environmental impact of the production of three different asphalt mixtures: a conventional reference hot mix asphalt (referred to as REF); a warm mix asphalt produced with foamed bitumen technology (referred to as WMA); and a hot mix asphalt including reclaimed asphalt pavement (referred to as RAP). The goal of the paper is to study the difference of these three asphalt mixtures which to achieve by using LCA and sensitivity analyses. The three asphalt mixtures investigated are dense grade mixtures for binder layers with the same composition. The foaming process for the WMA relies on the capability of hot bitumen to foam when cold water is directly added to the hot binder flow with special nozzles. The third asphalt mixture contains 50% RAP. Both virgin aggregate and virgin binder are replaced for 50% with RAP.

The current study is in this stage only a theoretical study; it is aimed to use this strategy in upcoming cases in practice. The aim of the current study is to compare the two different techniques (warm mix asphalt and recycling) in general with a conventional asphalt mixture. Data were used which is representative for the specific techniques and for the Flemish situation.

Besides comparing the three asphalt mixtures, the aim of this study was also to determine the processes which are playing a significant role in the results and to evaluate the influence of the most important assumptions on the results. Therefore some contribution and sensitivity analyses were performed.

3.2 Scope

In this section, the system boundaries and assumptions for the baseline scenario for the three mixtures (reference, WMA and RAP) are described.

The functional unit used is the production of 1 ton asphalt mixture. In order to guarantee equal functionality, the mechanical performance of the three asphalt mixtures is assumed to be the same. This assumption is based on findings in literature of equal performance between HMA with and without RAP (Al-Qadi et al., 2007; Hong et al., 2010; Kandhal et al., 1995; National Center for Asphalt Technology, 2009; Paul, 1995; Sullivan, 1996; Zaghloul and Holland, 2008) and between HMA and WMA (Chowdhury and Button, 2008; D'Angelo et al., 2008). In this way, a surface with equal dimensions and equal technical requirements can be paved with the three mixtures investigated.

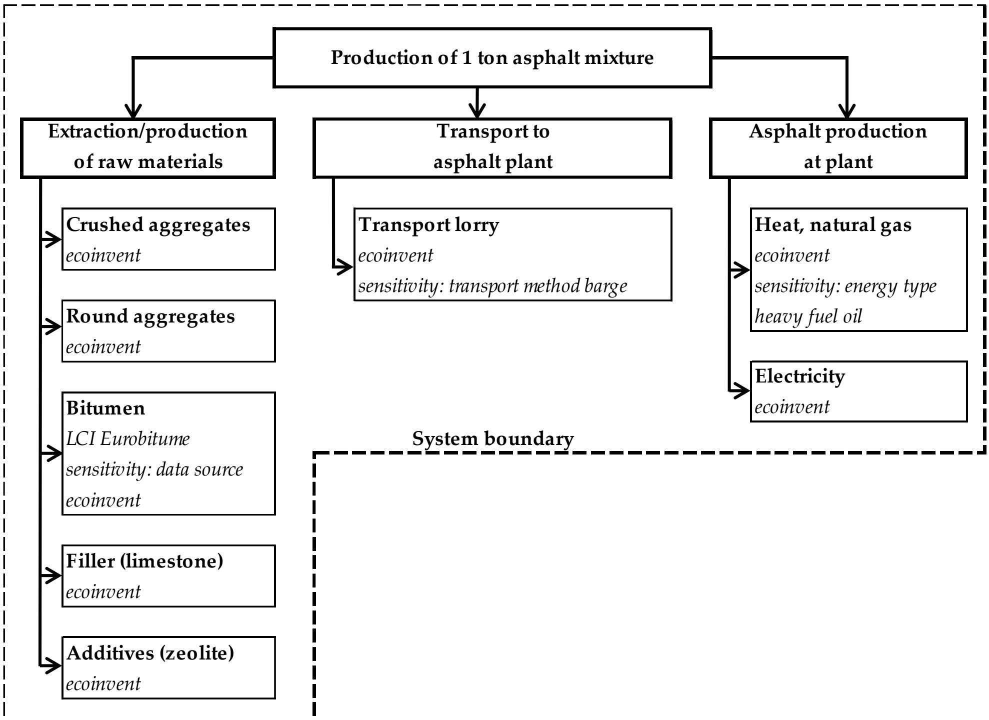

Figure 66: System boundary, data sources and sensitivity analyses

The analysis includes all direct and indirect processes related to the production of asphalt and thus a “cradle-to-gate” life cycle was considered (see Figure 66).
Following processes are beyond the scope of the study:

- Additives (in order to improve the performance of the asphalt mixture);
- Overhead (energy and material consumption for the construction of the asphalt plant and for the operation of the asphalt plant, offices etc.).

The life cycle assessment in this case study takes only ecological aspects into account, not the social and economic factors which must be considered as well for decision-making in civil engineering.
There are only few differences between the three mixtures investigated. The production temperature for the HMA control mixture is 160 °C while the production temperature for the WMA mixture is 130 °C; the RAP is preheated in a parallel drum up to 130 °C. In order to foam the bitumen for the WMA, a quantity of 4.5% (mass of the binder fraction) of cold water is added to the hot bitumen.
Some assumptions have been made for the calculations in order to deal with the lack of case specific information. The default assumptions for the baseline scenario are explained and the influence on the results of some of them is investigated with sensitivity analyses in chapter 4.3.

- All raw materials are supplied to the asphalt plant with a lorry;
- The temperature of the aggregates before heating is 10 °C;
- The moisture content before heating is 2% for coarse aggregates and 5% for sand;
- The fuel type for drying and heating aggregates in the asphalt plant is natural gas;
- The flue gas temperature of the white drum (virgin aggregates) is 140 °C and the flue gas temperature for the parallel drum (RAP) and during the production of WMA is 110 °C;
- The theoretically calculated energy consumption for the HMA case to dry and heat aggregates is multiplied by 1.16 for the RAP case in order to take into account the extra fuel consumption in practice by the second drum (see section 2.2).

3.3 Life cycle inventory

The inventory was drawn up by combining data from the ecoinvent database, international literature and average, but specific data for the Belgium area.

Representative transport distances for the raw material supply to the Flemish asphalt plant have been calculated. It was found that the average distance between a random asphalt plant and a random quarry is 114 km. The average distance specific for the crushed aggregates is 122 km and the average distance specific for round aggregates is 98 km. In the same way, the average distance from the port of Antwerp to a Flemish asphalt plant was calculated to be 57 km, what is used for the supply of bitumen.

Data from the ecoinvent database version 2.2 were used for all raw materials and processes, except for bitumen and RAP (see Figure 66). Data for bitumen were taken from a life cycle inventory (LCI) published by Eurobitume (Blomberg et al., 2012b) because this LCI is more recent compared to the data for bitumen in ecoinvent (respectively published in 2012 and 2007) and the LCI from Eurobitume is specific for the Amsterdam-Rotterdam-Antwerp territory. The energy consumption for the heated storage of the bitumen was found in study (Wayman et al., 2012). Burdens from RAP have not been included because this material is declared as waste and therefore has no direct burdens associated to it (Vidal et al., 2013). Finally, the electrical energy consumption for engines at the asphalt plant (sieving, dosing, conveyor belt, etc.) was taken from study (Leyssens et al., 2013).

3.4 Life cycle impact assessment

ReCiPe is chosen as life cycle impact assessment method (LCIA-method) because it implements both midpoint (impact categories) and endpoint (damage categories) categories. Furthermore, ReCiPe Endpoint contains a set of weighting factors with regard to calculating a single score impact from the three damage categories. The default perspective is the hierarchist, which is based on the most common policy principles with regards to time-frame and other issues. Furthermore, the ReCiPe version with European normalization and average weighting set was chosen. More information about the chosen LCIA-method can be found in the literature (Goedkoop et al., 2013; PRé, 2013; Sleeswijk et al., 2008).

4 RESULTS AND DISCUSSION

The life cycle assessment results are discussed in this section. The comparison of the three mixtures and the contribution analysis only includes results from the baseline scenario as described above. This baseline scenario is adapted for the sensitivity analyses.
It is important to note that the accuracy and precision of the LCA-calculations based on the used data might be about 10% and therefore conclusions have to be refined accordingly.

4.1 Comparison of the three asphalt mixtures

Figure 67 illustrates the single score impact per damage category for the three different mixtures: REF, WMA and RAP. The reference asphalt mixture holds the largest impact factor.

The single score impacts of the WMA mixture and the mixture with RAP have decreased with respectively 2% and 41% compared with REF. The damage category "resources" represents more than 70% of the total single score impact for the three mixtures.

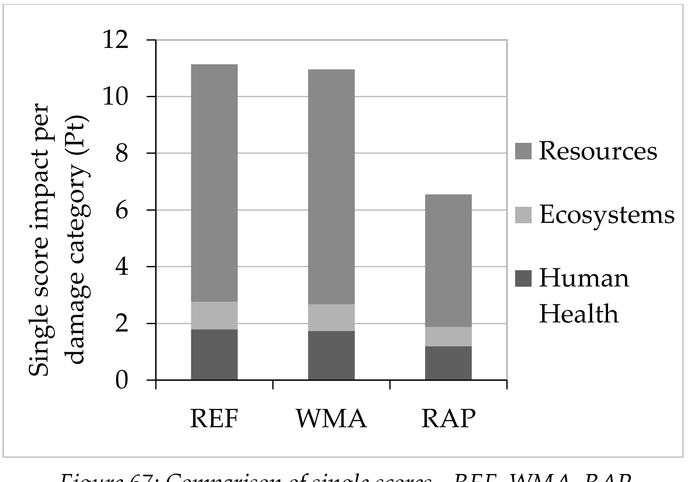

Figure 67: Comparison of single scores - REF, WMA, RAP

For the three mixtures, the comparisons for each impact category are presented in Table 29. It can be seen from the table that the ranking of the different mixtures is equal in each impact category assessed with the selected LCIA-method. Therefore, no weighting to a single score was actually needed to indicate a favourable mixture. The results obtained based on natural sciences (characterization) do clearly favour the RAP mixture. The single score is only used to simplify the presentation of the results.

The impact categories are ranked from highest to least impacting for the reference mixture. It can be seen from Table 29 that this ranking is the same for the WMA and the RAP mixture. The four main impacting categories for all mixtures are fossil depletion, climate change human health, climate change ecosystems and particulate matter formation.

Table 29: Characterization results per impact and damage category - REF, WMA, RAP

Impact category	Unit	REF	WMA	%	RAP	%
Total	mPt	11137,564	10953,813	-2%	6554,656	-41%
Fossil depletion	mPt	8371,037	8277,348	-1%	4680,881	-44%
Climate change Human Health	mPt	1319,470	1267,152	-4%	941,191	-29%
Climate change Ecosystems	mPt	862,902	828,688	-4%	615,515	-29%
Particulate matter formation	mPt	407,172	404,989	-1%	218,030	-46%
Natural land transformation	mPt	77,624	76,744	-1%	43,441	-44%
Human toxicity	mPt	60,768	60,403	-1%	34,929	-43%
Urban land occupation	mPt	25,449	25,418	0%	12,988	-49%
Agricultural land occupation	mPt	4,477	4,461	0%	2,547	-43%
Ionising radiation	mPt	3,214	3,207	0%	2,082	-35%
Terrestrial acidification	mPt	2,672	2,654	-1%	1,448	-46%
Metal depletion	mPt	1,013	1,009	0%	0,532	-48%
Terrestrial ecotoxicity	mPt	0,849	0,839	-1%	0,490	-42%
Freshwater eutrophication	mPt	0,375	0,372	-1%	0,224	-40%
Ozone depletion	mPt	0,276	0,262	-5%	0,212	-23%
Photochemical oxidant formation	mPt	0,213	0,212	-1%	0,114	-46%
Freshwater ecotoxicity	mPt	0,054	0,054	-1%	0,031	-43%
Marine ecotoxicity	mPt	1,80E-04	1,78E-04	-1%	1,05E-04	-41%
Damage category	**Unit**	**REF**	**WMA**	**%**	**RAP**	**%**
Total	mPt	11137,564	10953,813	-2%	6554,656	-41%
Human Health	mPt	1791,113	1736,226	-3%	1196,559	-33%
Ecosystems	mPt	974,401	939,230	-4%	676,684	-31%
Resources	mPt	8372,050	8278,357	-1%	4681,412	-44%

The reduction of the single score impact from the WMA mixture compared with the reference mixture is steadily spread in the different impact categories and counts 0 to 5% per impact category. The major difference is the ozone depletion impact category, which is in this study dominated by the transport of natural gas in an on-shore pipeline. The reduction of the production temperature causes a reduction of natural gas demand for heating the aggregates; therefore less natural gas has to be transported.

The difference between the RAP mixture and the reference pavement is spread in the different impact categories as well and ranges from 23 to 49% reduction for the RAP mixture. The main differences are found in the urban land occupation (49%) and metal depletion (48%). The category urban land occupation is for this study dominated by the mining and processing of the gravel. A reduction of the impact with ±50% is noticed for this process because 50% less virgin gravel has to be mined in order to produce the asphalt mixture. The category metal depletion is in this study dominated by the mining of iron ore which is associated to the transport process and the production of crushed gravel. The demand for crushed gravel and transport to supply raw materials to the asphalt plant is halved and thus the impact related to iron ore is almost halved as well.

4.2 Contribution analyses

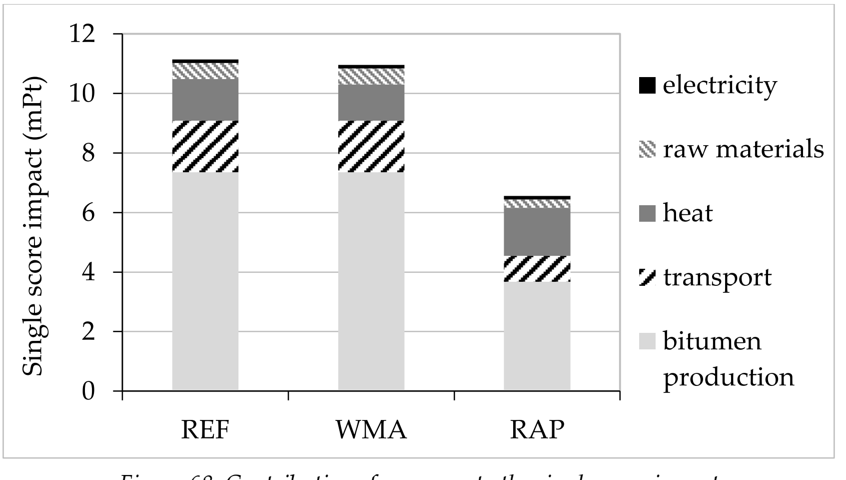

Figure 68: Contribution of processes to the single score impact

From the process network in SimaPro, the relative contributions of the processes to the single score impact can be calculated. The contribution of the most impacting processes is depicted in Figure 68. Among all processes, it is observed that bitumen is the major contributor to the total single score impact for all mixtures of the baseline scenario, with 56% to 67%. Furthermore all transport of raw materials represents 13% to 16% of the total single score. The natural gas used to generate heat is responsible for 11 to 25% of the total single score impact. The difference between the

HMA (12.6%) and WMA (11.1%) is small. The high impact in the RAP mixture is due to the increase of the energy consumption with 16% compared with HMA.

The interpretation of these percentages is important. A smaller percentage of contribution does not always indicate a smaller absolute impact of a certain process or material. Nevertheless the percentage of the contribution gives for a single cradle-to-gate life cycle an idea of the main contributors.

Besides the contribution of different processes, the contribution of elementary flows to the total environmental impact can be analysed.

The five most impacting elementary flows are the same for the three life cycles investigated: crude oil, fossil carbon dioxide, natural gas, carbon dioxide and nitrogen oxides.

The impact from 'oil, crude, in ground' comes for ±90% from the bitumen and for ±9% from transport in all life cycles. The impact from 'carbon dioxide, fossil' is diffuse and comes from different processes e.g., transport by lorry and heat from natural gas. About 72% (REF and WMA) or 85% (RAP) of the total impact due to 'gas, natural, in ground' comes from the heat used to dry and heat aggregates and to store bitumen. The impact from 'carbon dioxide' derives for 100% from the production of bitumen for the three mixtures investigated. Finally, the impact from 'Nitrogen oxides' originates for 56 to 60% from transport and for ±25% from the production of bitumen.

4.3 Sensitivity analyses

Sensitivity analyses are carried out in order to investigate the influence of some alternatives for a certain assumption, e.g. data from different data sources, haulage of a lorry, transport type, fuel type, etc. Only one parameter of the baseline scenario is changed in each sensitivity analysis.

In a first analysis, the environmental impact for the production of bitumen from ecoinvent and from Eurobitume (Blomberg et al., 2012b) is compared. The 'short LCI for bitumen with infrastructures' (Blomberg et al., 2012b) was used in the baseline scenario. Figure 69 shows that the single score impact increases (9 to 11%) if ecoinvent data are used for the production of bitumen. However, the ranking of the single score impact from the different cases does not change when the data source for bitumen is changed.

In the baseline scenario, all raw materials are supplied to the asphalt plant by lorry. Nevertheless, the supply of raw materials (aggregates, bitumen and filler) is likewise possible by inland ship transport (Figure 70). The transport distance is kept constant in order to investigate only the influence of the transport method (lorry or barge) on the results. The single score impact decreases (11% to 9%) when the raw materials are supplied by barge instead of a lorry >28 ton. The ranking of the three cases does not change with an alternative transport method.

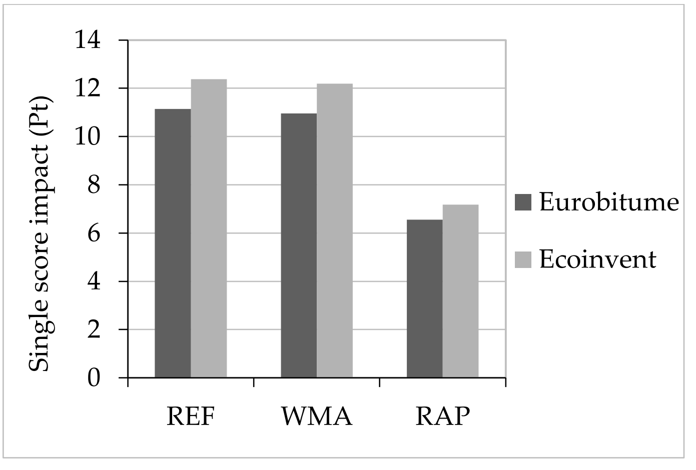

Figure 69: Sensitivity data source bitumen

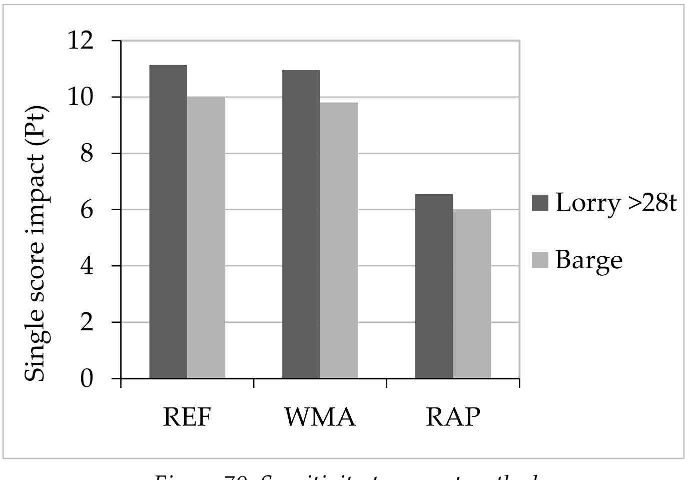

Figure 70: Sensitivity transport method

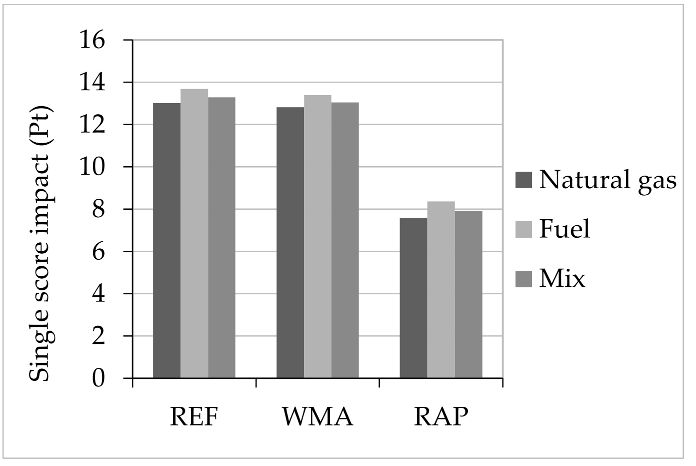

Figure 71: Sensitivity fuel type

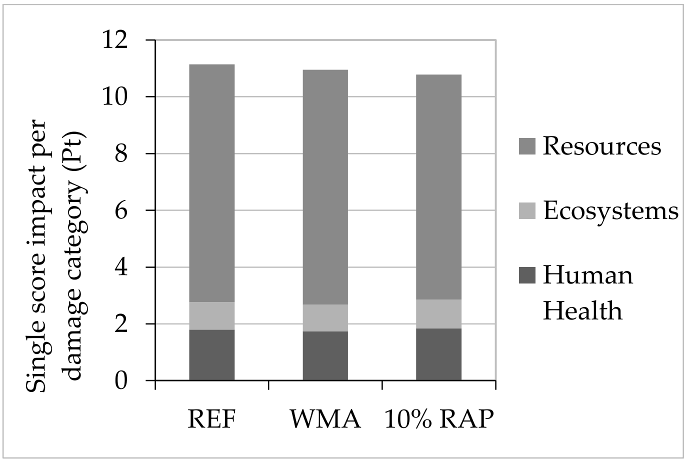

Figure 72: Sensitivity %RAP

In the baseline scenario, natural gas is used for drying and heating the aggregates and the heated storage of bitumen. In general, 60% of the asphalt plants in Belgium uses natural gas as energy source for drying and heating. Nevertheless, 40% uses different energy types. In the sensitivity analysis the use of natural gas, heavy fuel oil and a mix (60% natural gas and 40% heavy fuel oil) is compared. It can be seen from Figure 71 that the difference between the different scenarios is rather small (2 to 10%) and the ranking of the three cases is unchanged.

Another parameter investigated in this sensitivity analysis is the amount of RAP. It can be seen from Figure 72 that even with a small amount of 10% RAP, this mixture is less impacting compared to the WMA and the reference. The single score impact of the mixture with 10% RAP is decreased with 3% compared with the reference and with 1% compared with the WMA. The total single score impact increases with 38% if 40% less RAP is added to the mixture.

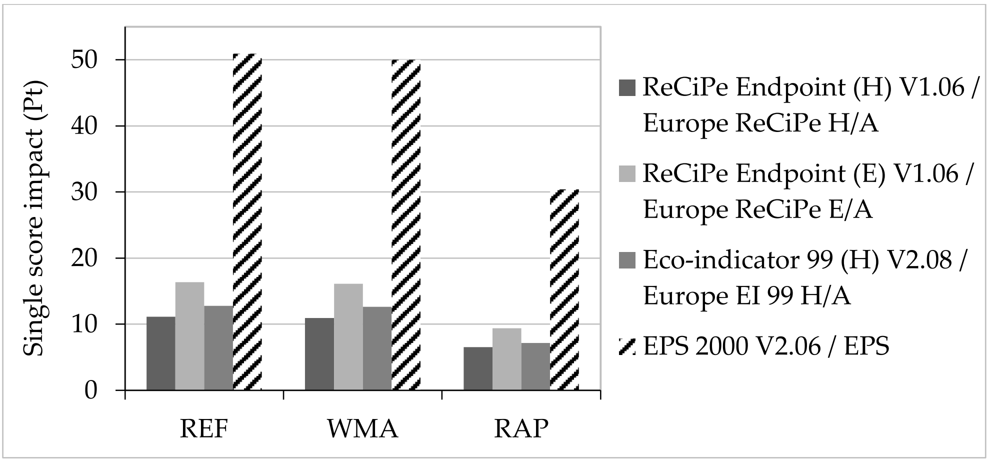

Figure 73: Sensitivity LCIA-method

Table 30: Single score impact relative to the reference

Life cycle impact assessment method	REF	WMA	RAP
ReCiPe Endpoint (H) V1.06 / Europe ReCiPe H/A	1.00	0.98	0.59
ReCiPe Endpoint (E) V1.06 / Europe ReCiPe E/A	1.00	0.99	0.57
Eco-indicator 99 (H) V2.08 / Europe EI 99 H/A	1.00	0.99	0.56
EPS 2000 V2.06 / EPS	1.00	0.98	0.60
IMPACT 2002+ V2.10 / IMPACT 2002+	1.00	0.99	0.58
Ecological Scarcity 2006 V1.06 / Ecological scarcity 2006	1.00	0.99	0.57
EDIP 2003 V1.03 / Default	1.00	0.98	0.61

Another choice made for the analysis of the baseline scenario was the life cycle impact assessment method (LCIA-method). The single score impact results obtained with other LCIA-methods are illustrated in Figure 73. It can be seen that the ranking of the three cases does not change significantly by LCIA-method. Although the results from the different LCIA-methods are depicted on the same figure, it is not possible to compare the results from different LCIA-methods with each other. All results are expressed in points (Pt), but are calculated in a different way.

Besides the LCIA-methods analyzed in Figure 73, three more methods are analyzed. The single score results (in points) generated with LCIA-methods IMPACT 2002+ V2.10 and EDIP 2003 V1.03 are too small to depict on the same figure. On the other hand, the single score impact (in points) generated with LCIA-method Ecological Scarcity 2006 V1.06 is too high to depict on the same figure. Table 30 presents the single score impact of the three baseline mixtures, calculated with different life cycle impact assessment methods and relative to the single score impact of the reference case. The three undermost LCIA-methods were excluded from Figure 73. It can be seen from Table 30 that the ranking of the three cases is independent of the

LCIA-method selected and the trend observed is similar for the different LCIA-methods: 1 to 2% reduction for the WMA and 39 to 44% decrease for the mixture with RAP.

Figure 73 and Table 30 demonstrate that results from different (case) studies in the literature may not be compared based on the absolute values (in points) if another LCIA-method was used for the calculations. The ranking of different subcases within a study may be compared with the ranking of subcases within another study, but the LCIA-method will, nevertheless, have an influence on the results and even on the ranking of different sub-cases in other studies.

It can be seen from the sensitivity analyses that the conclusion on the ranking of the three mixtures is robust because the ranking is not changed with the alternative scenarios investigated in the sensitivity analyses. Nevertheless, these alternative scenarios resulting from altering assumptions may have a significant influence on the single score impact of each individual mixture, e.g. an increase of the single score with ±10% if the data source for bitumen or the transport method changes; and an increase of 38% if 40% less RAP is added to the HMA.

Equal performance of REF, WMA and RAP is assumed in the baseline scenario, based on research findings (see section 3.2). Nevertheless, it is important to note that a conscientious execution of the works (asphalt production and road construction) is necessary in order to reach the same quality with WMA and RAP mixtures compared to traditionally used HMA mixtures. Furthermore, extreme weather conditions, traffic load, performances of other layers in the road construction, etc. may influence the service life of a layer in the road construction.
Therefore, the last sensitivity analysis is related to the performance of the asphalt mixtures. If a service life of 25 years of the binder layer is assumed in the baseline scenario, this is reduced to 20 years for WMA and RAP in the sensitivity analysis. This means that over an analysis period of 25 years 1 ton REF, 1.25 ton WMA and 1.25 ton RAP is needed in order to meet the same performance. It is seen from Figure 74 that the environmental impact of WMA exceeds (23%) the environmental impact of REF, while the environmental impact of RAP is still lower (26%) compared with REF. The service life of a binder layer with RAP should decrease to 14 years in order to exceed the environmental impact of REF in this case study.

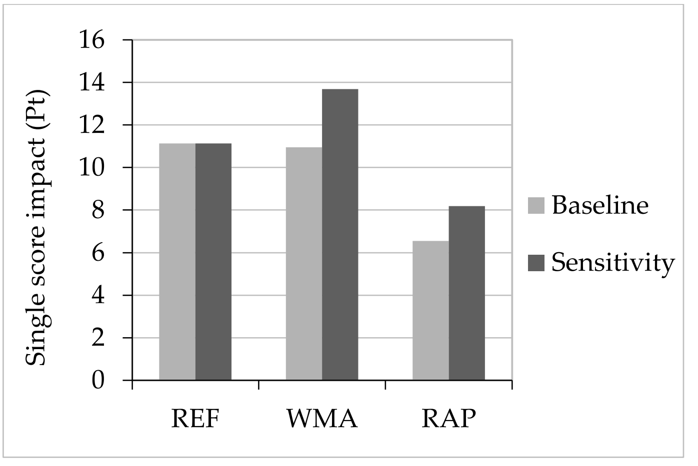

Figure 74: Sensitivity service life

5 CONCLUSIONS AND RECOMMENDATIONS

The objective of this paper was to compare by LCA methodology the environmental impact of two different technologies, implemented in the asphalt production process: WMA and recycling. Both technologies are expected to reduce the environmental impact of asphalt production and are compared with a reference conventional asphalt mixture. A second objective was to determine the processes which are significant for the LCA results and to evaluate the influence of the most important assumptions on the results.

Cradle-to-gate analysis of the baseline scenario has highlighted that the mixture with RAP is significantly less impacting compared to both other mixtures.

The environmental impact of the WMA mixture is close to the impact of the conventional HMA. The comparative study demonstrates clearly that the reduction of the mixture temperature by 30 °C leads to a very small reduction of the total single score impact. This might be caused by the major contribution of the moisture content in the aggregate to the fuel consumption for drying and heating. This indicates that reducing the moisture content might have a more distinct effect on the environmental impact in the asphalt production. Solutions might be to protect aggregates from moisture by storing it under a shelf or dried continuously by the chimney heat flow. It is important to note that the aggregates used for asphalt production in Belgium are washed and thus supplied to the asphalt plant in a wet condition.

If the relative difference between two single score impacts is less than 20%, it is often considered in LCA to be impossible to draw robust conclusions based on this relative difference. Therefore, other and broader studies are required in order to compare the total environmental impact of HMA compared to WMA. In terms of future enhancement, other WMA techniques may be investigated as well, for example with various additives. It is important to note that several advantages of WMA are not included in the current cradle-to-gate study. Diffuse emissions during production and road construction with WMA might be significantly reduced compared to HMA which is in favour of the health of the workers. Furthermore it is suggested by other studies that WMA might allow higher percentages of RAP in the mixture, which might reduce the environmental impact of WMA compared with HMA as well. These kinds of issues need further investigation and a cradle-to-grave analysis is appropriate in order to formulate more conclusions.

From the contribution analysis of the baseline scenario, it was demonstrated that mainly the production of bitumen and the transport of raw materials to the asphalt plant contribute to the total environmental impact of the reference and the WMA mixture. For the HMA mixture with RAP, the production of bitumen and the energy in order to dry and heat aggregates are the main contributors to the total single score impact.

The results from the sensitivity analyses show that the total environmental impact can vary significantly based on the choice of data source and transport method. Nevertheless, the ranking of the three mixtures is robust in this study and does not change with different assumptions. On the other hand, this finding is an important note to consider when developing Product Category Rules to ensure a robust Environmental Product Declaration program.

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PAPER VI: EFFECT OF RAP ON THE MECHANICAL PROPERTIES OF REGISTERED ASPHALT MIXTURES IN FLANDERS

Authors: Joke Anthonissen, Wim Van den bergh, Johan Braet

Abstract: A short service life of bituminous road pavements can counteract the environmental gain of using reclaimed asphalt pavement (RAP) instead of virgin raw materials. Numerous case-related laboratory researches investigated the influence of RAP on mechanical performances of asphalt mixtures. In the scope of life cycle environmental assessment it is essential to know the performances of asphalt mixtures that are used on the road in practice. Due to the lack of real service life of pavements in Flanders, the current investigation analyses the effect of RAP on the performance characteristics (rutting, stiffness and resistance to fatigue) of a large number of bituminous mixtures in order to better estimate the effect of RAP on the service life of road pavements. 65 different hot asphalt mixtures for base layers that are registered and accepted for public road works in Flanders are analysed. The RAP content in these mixtures ranges from 0 to 63%.

1 INTRODUCTION

The longer the materials on the road preserve a minimal acceptable quality, the longer the service life of the pavement and the fewer structural maintenance interventions are necessary, implying less material and energy consumption, less traffic congestion etc. It was found in literature that a short service life could counteract environmental gains (e.g., from reduced production temperature, or the use of secondary material) over the life cycle of a road pavement.

Wayman et al. (2012) investigated the environmental impact of 1 m² of single lane highway over a 60 year service life. Some upper and lower bounds of durability for split mastic asphalt were used for modelling in order to analyse the changes in environmental impact over the lifetime of the road pavement. For the particular case, it was found that decreasing the service life of the surface course from 20 to 14 years, results in an increased characterized environmental impact with 12.1 to 13.6% depending on the environmental impact category. An increase of the service life of the surface course from 20 to 25 years decreases the impact with 5.7 to 6.5% depending on the impact category.

It was found by Anthonissen et al. (2014) that the assumption of the service life of different asphalt mixtures for the base layer in road pavements (a reference hot mix asphalt, a warm mix asphalt produced with foamed bitumen technology and a hot mix asphalt with 50% reclaimed asphalt pavement (RAP)) can change the ranking of the environmentally beneficial material. In the baseline scenario, with a service life of 25 years for all base layers, the reference hot mix asphalt has the highest environmental impact. If the service life of the warm mix asphalt and the hot mix with 50% RAP is reduced to 20 years, the environmental impact of the base layer with warm mix asphalt exceeds the environmental impact of the reference.

Although difficult to determine, the definition of the service life of a road pavement is an important subject of the definition of the functional unit of an life cycle assessment (LCA) study. Therefore, the current investigation analyses the effect of RAP on the performance characteristics of bituminous mixtures in order to better estimate the effect of RAP on the service life of road pavements.

Reclaimed asphalt pavement is released during maintenance interventions. It is a high quality material that contains valuable constituents (inert material and bituminous binder) that can be recycled for almost 100%. The reuse and the recycling of RAP is encouraged by some economic benefits and started more than 30 years ago and nowadays it has become common practice in many European countries (EAPA 2008, European Asphalt Pavement Association 2014).

2 LITERATURE REVIEW

Some research has been conducted in order to understand the effect of adding RAP on the mechanical properties of a new asphalt mixture.

The proportion of residual binder and virgin binder in asphalt mixtures is expected to affect mixture volumetric and mechanical properties. Contradiction is found in literature concerning the percentage of actual blending occurring between RAP and virgin binders. As described by Shen et al. (2007), three situations were proposed: i) black rock: absolutely no mixing between the RAP binder and virgin binder; ii) total blending: the two binders completely and uniformly mix; and iii) real practice. The Illinois Department of Transportation (Al-Qadi et al. 2009) and Lopes et al. (2015) assume a 100% contribution of binder from RAP for the residual binder. Shen et al. (2007) found that the actual situation approaches complete mixing, depending on the amount of RAP. Apeagyei et al. (2011) found that the amount of effective binder content decreases with increasing RAP content. Huang & Bird (2007), on the other hand, assume that 50% of the old binder is recovered in the new asphalt and 50% is acting like black rock, while the research of Huang et al. (2005) found that mechanical blending affects only a small portion of aged asphalt binder in RAP.

The bituminous binder in RAP has been aged, resulting in an increase of the stiffness modulus. Mogawer et al. (2012) state that stiff asphalt mixtures may experience low temperature cracking and may crack prematurely for pavements experiencing higher deflections; while soft asphalt mixtures, on the other hand, could be more susceptible to rutting.

The use of a soft, new binder to counteract the stiffness of the aged binder from RAP is frequently discussed in literature (Al-Qadi et al. 2009, Mogawer et al. 2012, Shah et al. 2007). Al-Qadi et al. (2009) state that a change in binder grade is not necessary up to a RAP content of 20% in the mixture. The authors also showed that the stiff binder effect could be offset by modification of the binder grade for dynamic modulus, but the use of a soft binder does not affect the thermal cracking resistance. Shah et al. (2007), on the other hand, mention that the addition of 40% RAP did not alter the mix properties (complex dynamic modulus, low temperature creep compliance and indirect tensile strength) dramatically in their experiment. The authors suggest that the use of a softer bitumen for mixtures with up to 40% RAP is not necessary. Swamy et al. (2011) found that RAP percentages up to 15% cause a negligible change in volumetric properties.

Li et al. (2008), Lopes et al. (2015) and Swamy et al. (2011) found that asphalt mixtures containing RAP have higher dynamic modulus values and hence become stiffer than the same mixtures containing no RAP. Colbert & You (2012), on the other hand, notice a decrease of the dynamic modulus and the resilient modulus as RAP percentage increased. Several investigations (Al-Qadi et al. 2009, Li et al. 2008, Mogawer et al. 2012, Tapsoba et al. 2012, Zhao et al. 2013) have shown that mixtures with RAP have a lower thermal cracking resistance. Colbert & You (2012), Lopes et al. (2015) and Zhao et al. (2013) found that the addition of RAP increases the rutting resistance; while Apeagyei et al. (2011) found similar rutting performances for a similar mixture with 25% RAP and without RAP. Finally, Zhao et al. (2013) found that adding RAP decreases the fatigue resistance, while Lopes et al. (2015) found that the presence of RAP improves the fatigue life of hot mix asphalt.

Mogawer et al. (2012) found that some production parameters at the plant i.e., discharge temperature and silo storage may have an impact on the relative degree of blending between the RAP and virgin binders and hence affect the mixture stiffness and cracking properties.

3 RESEARCH DESIGN

All bituminous mixtures used for public road works should comply with the Flemish road standard SB250. As described by Van den bergh et al. (2016), this standard is revised every four year by the Flemish Agency for Roads and Traffic. In 2015 the SB250 v2.2 was revised to a newer version SB250 v3.1 (Vlaamse Overheid 2014), the current version. The use of reclaimed asphalt pavement in asphalt mixtures for surface layers is still not allowed in Flanders but for the base course some items changed. Only asphalt mixtures designed for base courses with the fundamental method according to EN 13108-1 (as firstly introduced in SB250 v2.2) are now allowed. This involves mainly two types of asphalt mixtures for base courses i.e., “APO” and “AVS”, which respectively stands for (translated from Dutch) asphalt mixtures with performance characteristics for base courses and asphalt mixtures with increased stiffness. Besides, only homogenous RAP can be used. If the RAP is added with preheating (minimum 110 °C), the amount of RAP-binder is unlimited in “APO” and limited to 20% in “AVS”. If the RAP is added to the mixture without preheating, the amount of RAP binder is restricted to 20%.

As opposed to the empirical method, the fundamental method includes fewer requirements on materials and mixture composition, but defines requirements on the most important performances. Asphalt mixtures for base courses designed with the fundamental method are subjected to a series of lab tests (i.e., air voids content, water sensitivity, rutting resistance, stiffness and fatigue) prior to acceptance for use on public roads in Flanders, according to SB250 v2.2 and following versions.

In the current research, the results of these tests are used for the analysis of the effect of RAP on rutting, stiffness and fatigue. The mechanical properties of 65 different hot mix asphalt mixtures were analyzed with RAP content ranging from 0 up to 63% and with a mixture composition that is already optimized in order to counteract effects of the RAP. Unlike numerous case related laboratory researches, the current research investigates the performances of asphalt mixtures in compliance with the identical composition on the road.

For each mixture, the average of two measures of the rutting depth after 30.000 cycles was used to calculate Pi, the rut depth calculated as a proportion of the thickness of the test specimen, according to EN 12697-22+A1. The stiffness E* (MPa) was measured according to EN 12697-26 as the average of the result on 2 to 22 trapezoidal cores with the two point bending test at 15 °C and 10 Hz. The test was carried out in ‘constant displacement mode’ at an imposed strain of 50 μm/m. The resistance to fatigue (ε_6) was measured according to EN 12697-24 at 15 °C and 10 Hz. ε6 is the maximal strain that should be imposed so that the material is able to resist one million of load repetitions.

Firstly, the available data from laboratory tests were subjected to a statistical analysis in order to search for a relation between the use of RAP in the mixtures and the three mechanical performance characteristics. In this way, it is investigated if mixtures with and without RAP can reach the same quality, as is required according to SB250. Finally, it was investigated how the mixture composition is adapted if RAP is included. In the latter part, the research mainly focuses on the binder type and binder content of the asphalt mixture.

Table 31: Spearman's rho correlation between different mixture properties

		Needle penetration *EN 1426*	Ring and Ball *EN 1427*	% Stones *EN 12697-2*	% Sand *EN 12697-2*	% Filler *EN 12697-2*	Air voids content (V_m) *EN 12697-8*
Rutting	r_s	0.50	-0.50	-0.31	0.34	/	/
	p	0.00	0.00	0.02	0.01		
Stiffness	r_s	-0.37	0.30	0.29	-0.32	0.28	/
	p	0.00	0.03	0.02	0.01	0.02	
Fatigue resistance	r_s	-0.58	0.59	0.50	-0.48	/	-0.45
	p	0.00	0.00	0.00	0.00		0.00

Table 32: Independent samples T-test for mixtures with and without RAP

		%RAP = 0	%RAP > 0	ES_r p	Interpretation (Lipsey and Wilson, 2001)
Rutting P_i (%)	Mean	4.9	3.4	0.50	Large ES
	Std. Dev.	1.3	1.2	0.00	Significant
Stiffness E* (MPa)	Mean	1.3E+04	1.4E+04	0.15	Small to medium ES
	Std. Dev.	2.0E+03	2.4E+04	0.22	Not significant
Fatigue resistance ε_6 (μm/m)	Mean	98	1.2E+02	0.38	Medium to large ES
	Std. Dev.	23	25	0.00	Significant

4 ANALYSIS AND DISCUSSION

4.1 Mechanical properties vs. %RAP

Statistical analyses were performed in two different ways.

Initially the independent parameters ("%RAP" in the mixture and "%O/N" old vs. new bitumen) were seen as continuous, non-normal distributed datasets and the depending parameters (rutting, stiffness and fatigue) were assessed to be continuous, normal distributed datasets. Hence, a two tailed correlation between the different parameters was sought by carrying out the Spearman's rho test. The Spearman's rho correlation coefficient (r_s) indicates how much one variable tends to change based on a linear relation-ship when the other one does. Besides, the two tailed significance level (p) of the correlation is given. A statistically significant correlation was found between %RAP and rutting (r_s = -0.307; p = 0.015), %O/N and rutting (r_s = -0.295; p = 0.020) and %O/N and stiffness (r_s = 0.251; p = 0.046). Although these correlations are statistically significant with $\alpha = 0.05$, these correlations are not considered to be strong correlations. A negative correlation was found for rutting, meaning that the rutting depth reduces if the amount of RAP in the mix increases. A positive correlation was found for stiffness, meaning that the stiffness of the mixture increases if the amount of RAP in the mix increases. The Spearman's rho correlation test was also applied to search for correlations between the three performance characteristics and other mixture properties. Statistically significant correlations (α=0.05) are indicated in Table 31. Because of the statistically significant correlation between %RAP and rutting, the correlation between %RAP and needle penetration, ring and ball, % stones, % sand and % filler are investigated, but no significant correlation exists. It is seen from Table 31 that stiffness and fatigue have similar correlation direction with needle penetration, ring and ball, % stones and % sand, and opposed correlation compared to rutting.

Secondly, the independent parameter %RAP was considered as a non-continuous variable and was divided into two categories (dichotomized): %RAP = 0 and %RAP > 0. There are at least 11 values in each group and the groups are independent (not paired) since each value represents a characteristic of another asphalt mixture. The values in all groups are normally distributed. The Levene's test was used to check the equality of the variances. Equality of variances can be assumed for analysis of the three performance characteristics. The parametric 'independent samples T-test' was used to search for a statistically significant difference in means between the two categories (mixtures with and without RAP) for the three performance characteristics (rutting, stiffness and fatigue resistance).

The tests indicated that there are statistically significant (α=0.01) differences in means between mixtures with and without RAP for the performance characteristic rutting and fatigue. It is seen from Table 32 that the rutting parameter (Pi) is higher for asphalt mixtures without RAP. This means that the mixtures with RAP have a higher resistance to rutting. These results confirm the findings by Colbert & You (2012), Lopes et al. (2015) and Zhao et al. (2013).

It is seen from Table 32 that the mean fatigue value (ε_6) for mixtures with RAP is higher compared to the fatigue value in mixtures without RAP. This means that mixtures with RAP can resist a higher strain (μm/m) without failure after one million of load repetitions. These results are similar to the findings of Lopes et al. (2015) but in contradiction with the findings of Zhao et al. (2013).

The mixtures with RAP have an increased resistance to rutting and an increased resistance to fatigue compared to mixtures without RAP. Besides these findings, Table 32 presents the correlation effect size (ES_r) and the two tailed significance (p), which are both parameters of the statistical analyses. The correlation effect size is calculated with Equation 14 where t is the test variable from the independent t-test and df are the degrees of freedom. The correlation effect size is defined to be small if $ES_r \leq 0.10$; medium if $ES_r = 0.25$; or large if $ES_r \geq 0.40$ (Lipsey & Wilson 2001).

$$ES_r = \sqrt{\frac{t^2}{t^2 + df}} \tag{Eq. 14}$$

The non-parametric test '2 independent samples test' was used as a control and yields the same results.

Finally, the performance characteristics are reconsidered in a graphical manner and compared to the findings of the dichotomous analysis. It is seen on Figures 75-77 that the variance of the results is very large. For the same percentage of RAP, the results for rutting, stiffness and fatigue may vary for one mixture to another. This means that there are other parameters, besides RAP that have an effect on the performance characteristics (e.g., granulometry and binder characteristics), as stated in Table 31. Furthermore, it is not possible to draw a regression line on Figures 75-77 since the regression type (linear, logarithmic, exponential,…) for these performance characteristics as a function of the percentage of RAP in the mixture is unknown.

Based on the large variance in the results, one should be very careful making conclusions. Nevertheless, analysis of the test results does not reveal any adverse influence on the mechanical properties from RAP. No strong or robust correlation was found between %RAP and the mechanical properties. In order to be able to make robust conclusions, the influence of RAP on the service life of bituminous base courses should be investigated in practice.

The results from the current investigation demonstrate that including RAP does not influence the quality of the asphalt mixture, if the mixture composition is adapted.

The following section investigates how these mixtures were adapted in order to counteract the effect of RAP in the mixture.

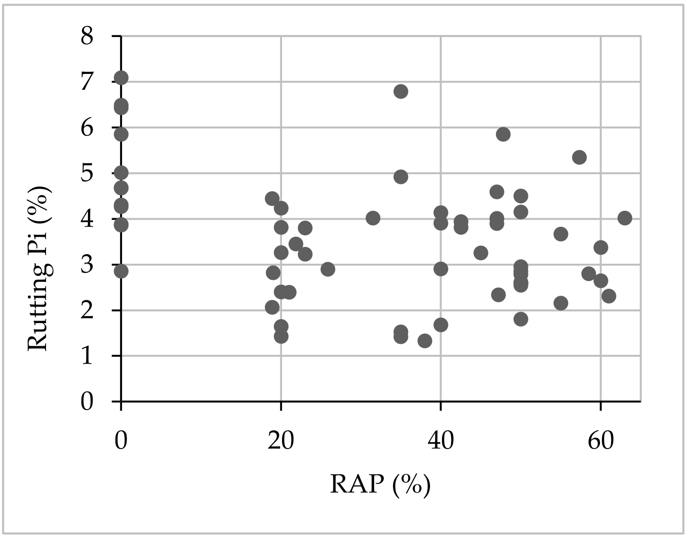

Figure 75: Graphical analysis of test results for rutting

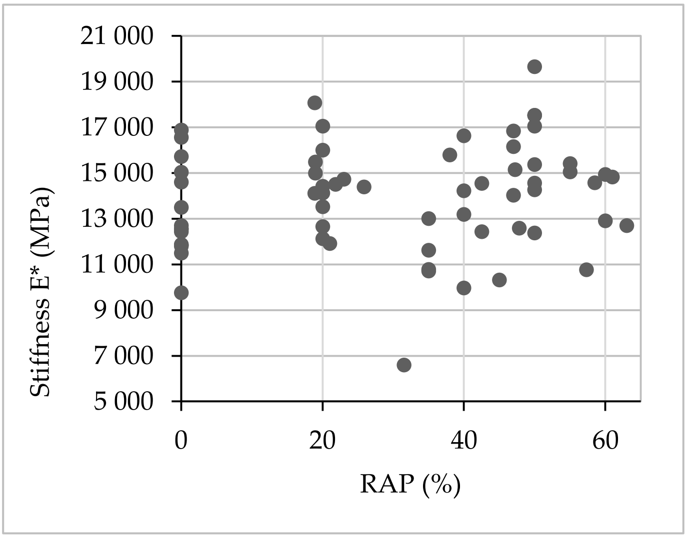

Figure 76: Graphical analysis of test results for stiffness

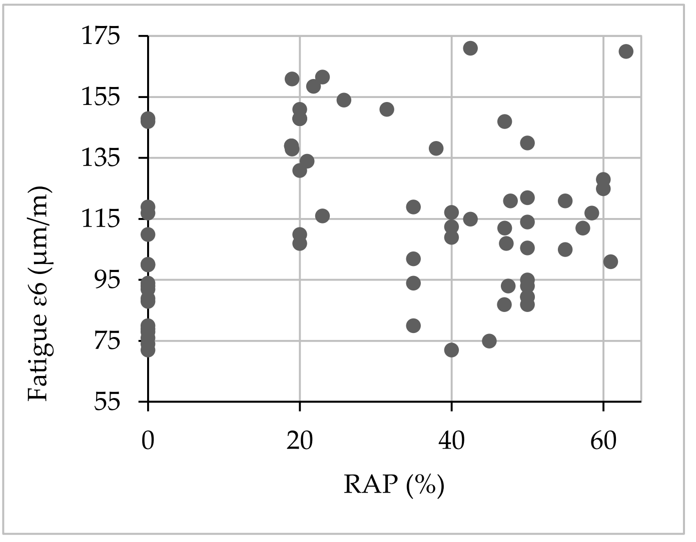

Figure 77: Graphical analysis of test results for resistance to fatigue

4.2 Adapted mixture composition with RAP

The current section focuses on the %O/N (that is the percentage of the total amount of binder that comes from RAP) rather than on the %RAP. Depending on the binder content in the RAP, there can be a shift between both parameters.

Firstly, the relation between %O/N and %Bit-on (what is the amount of bitumen (old and new together) on the mass of aggregates, which account for 100%) was investigated based on Figure 78. Three different groups of asphalt mixtures are distinguished: APO-A (with maximal aggregate size D=20), APO-B (D=14) and AVS-B (D=14). As defined in chapter 3, %O/N for AVS is maximum 20%. As can be seen on Figure 78, the total binder content on the aggregate mixture is higher for AVS compared to the APO mixtures in order to reach the same fatigue performance with a stiffer binder. For the APO mixtures, no statistically significant difference in mean or median in the bitumen content of mixtures with RAP compared to mixtures without RAP was found, nor a statistically significant correlation between %Bit-on and %O/N.

Figure 79 shows the %O/N in relation to the %Bit-on, with a distinction for the different bitumen types. As described in chapter 2, the use of a soft, new binder to counteract the stiffness of the aged binder from RAP, is discussed in literature. It is seen from Figure 79 that the most soft binder (B70/100) is only used in combination with high recycling rates (≥48%O/N). Besides, another certain bitumen type is not strictly associated with a certain mixture type or a specific recycling rate. It is seen that the binder type B50/70 is used for both mixtures without RAP and with high recycling rates (up to 75%O/N).

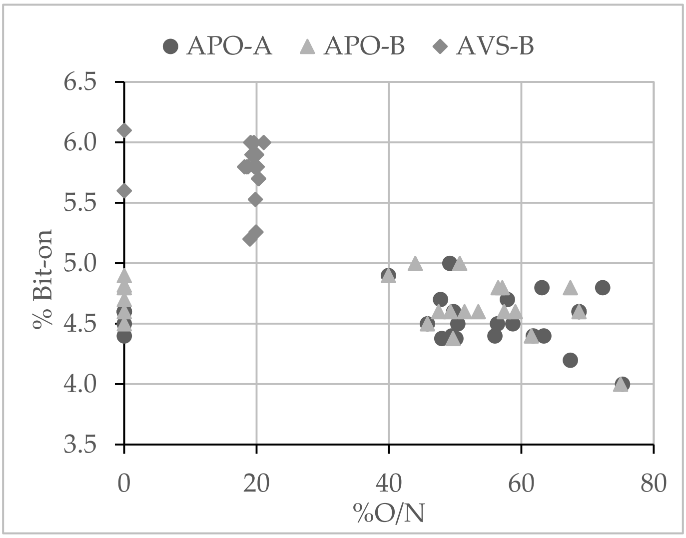

Figure 78: Adaption of mixture composition - bitumen content

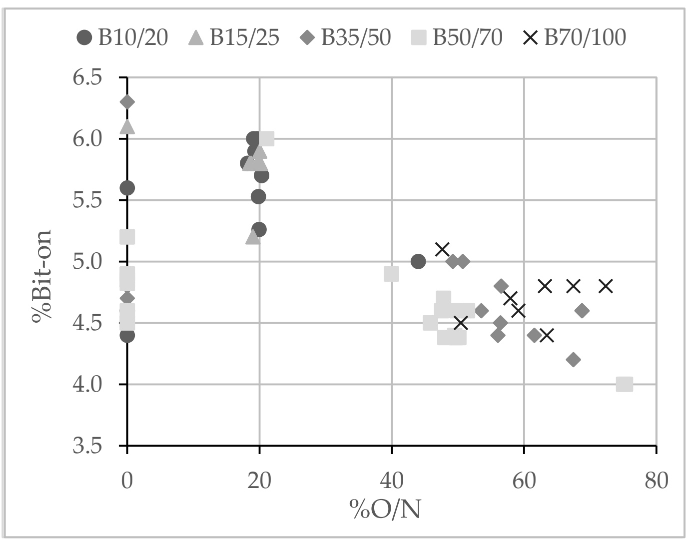

Figure 79: Adaption of mixture composition - bitumen type

5 SERVICE LIFE VERSUS ENVIRONMENTAL IMPACT

The findings as described in section 4.1 justify the assumption of equal service life for bituminous base courses without RAP and with RAP in LCA studies.
The environmental impact from cradle-to-laid was modelled for the construction of two identical base course test sections of 1 km long, 8 cm thick and consisting one lane (width 3.45 m) for a mixture without RAP and a mixture with 20% RAP. The scope of the LCA study includes: raw material extraction and/or production, transport of raw materials to asphalt plant, asphalt production (electricity and gas

consumption), transport of asphalt mixtures from asphalt plant to worksite, energy consumption by machines at road worksite (milling old pavement, cleaning the surface, tack coating, asphalt spreading and compacting) and the transport of the old pavement to the asphalt plant. The LCA study is based on practical data, collected during the construction of a field case at Scheldelaan in Flanders. The ecoinvent v.2.2 database was used for the life cycle inventory. The ReCiPe life cycle environmental impact assessment method was used, with hierarchist perspective and the average European weighting factors. More information on the methodology of LCA case studies can be found in the study of Anthonissen et al. (2015) and more information on the impact assessment method ReCiPe can be found in the manual from PRé (2013).

The default service life is assumed to be 14 years for the surface course and 24 years for the base course [reference: interview with senior adviser at Flemish Agency for Roads and Traffic].

It is seen on Figures 80-81 that the environmental impact for the 24 years pavement service life for the mixture with 0% RAP (1.40 MPt) is 52% higher compared to the mixture with 20% RAP (0.92 MPt) for this case study.

An equal cradle-to-laid environmental impact is searched in Figures 80-81 by changing the assumption on the service life for the base course with and without RAP.

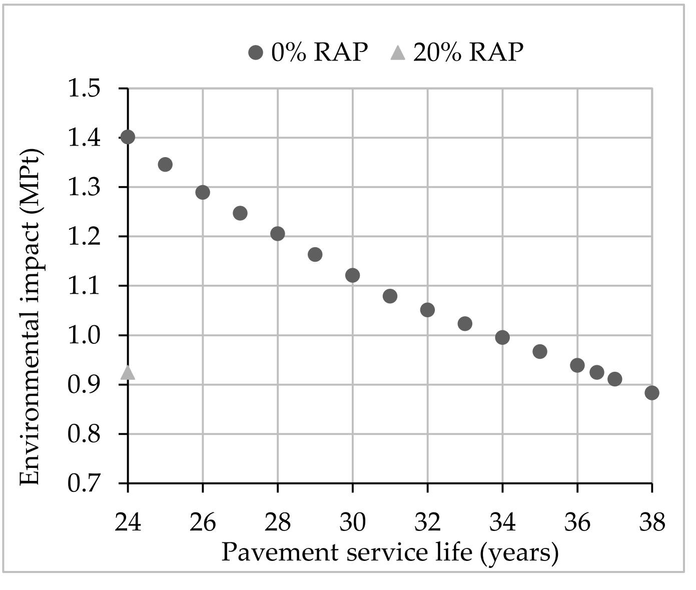

Figure 80: Environmental impact of base course (i) with 20% RAP and (ii) without RAP and varying service life

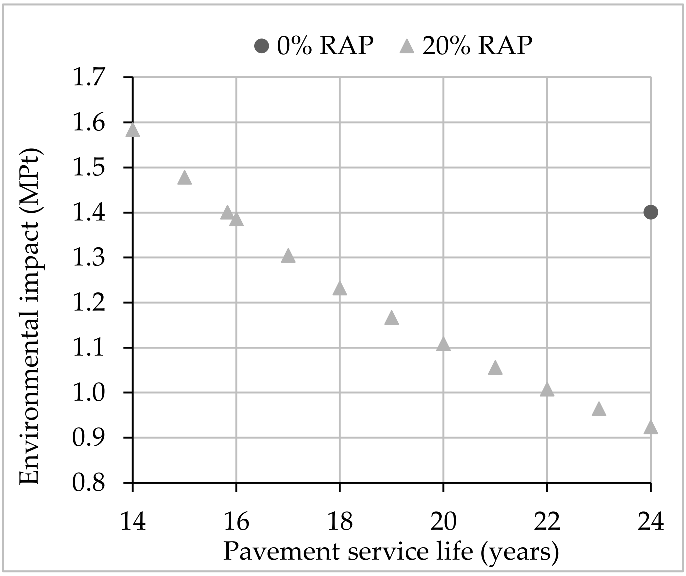

Figure 81: Environmental impact of base courses (i) with 20% RAP and various service life and (ii) without RAP

It was found for this LCA case study, that the environmental benefit of adding 20% RAP to an asphalt mixture, is equal to the increase of the service life with 12.5 years for an asphalt mixture without RAP. On the other hand, it is seen that the service life of the base course with 20% RAP should decrease with at least 8.2 years before the environmental impact of the base course with RAP is higher compared to the base course without RAP.

6 CONCLUSIONS AND RECOMMENDATIONS

In this study, a relation was searched between the RAP content and the mechanical performances of the asphalt mixtures in order to better understand the effect of RAP on the service life of bituminous road pavements. It is not possible to formulate robust conclusions based on the current analysis since the variance of the results is very large.

The variance is due to the effect of other mixture properties (like granulometry and binder characteristics) on the investigated performance characteristics. Important to conclude is that it is possible to design mixtures with high RAP content with equal mechanical performances (rutting, stiffness and resistance to fatigue). Hence, these mixtures comply with the requirements in the SB250 and are allowed for public road construction. Nevertheless it was not possible within the current analysis to define significant differences in binder content or binder type in relation to the recycling rate.

From the analysis of the environmental impact, it was seen that the service life of mixtures with RAP should strongly be decreased before counteracting the environmental gain of using RAP. Based on the findings in the current research, such a large difference in service life for mixtures with and without RAP is unlikely. It is concluded from the current study that the use of RAP in asphalt mixtures for base courses is beneficial for the life cycle environmental impact.

Based on the results from this study, there is still a missing link between mechanical performance characteristics as tested in laboratory and the actual performance in situ. Additional research in the field is recommended in order to be able to formulate robust conclusions. Nevertheless, the actual service life of a road pavement depends on multiple factors besides the mechanical performance characteristics of the bituminous mixture itself e.g., weather conditions, traffic load, quality of pavement construction works.

On the other hand, investigation of the service life of road pavements in situ is difficult since not all information is inventoried. Furthermore, since RAP is not allowed to be used in surface courses, it is only used in base courses. Due to the economic advantage of using RAP, almost every base course includes RAP, which makes it very difficult to compare the service life in situ of pavements with and without RAP.

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PAPER VII: ANALYSIS OF THE BELGIAN ELECTRICITY MIX USED IN ENVIRONMENTAL LIFE CYCLE ASSESSMENT STUDIES: HOW RELIABLE IS THE ECOINVENT 3 MIX?

Authors: Joke Anthonissen, Matthias Buyle, Wim Van den bergh, Johan Braet, Amaryllis Audenaert

Abstract: The current contribution gives insight into the Belgian low voltage electricity mix, used in environmental life cycle assessment studies and modelled following the attributional and consequential approach. Is the electricity mix for Belgium, as available in the life cycle inventory database ecoinvent 3.1, representative for the current electricity mix and the future developments? Studies on this research topic are missing in the literature, especially for this particular geographical and time frame. In this study, data from the European Network of Transmission System Operators for Electricity and the Federal Planning Bureau have been used to model the historical and future Belgian low voltage electricity mix. The environmental impact is analysed for different scenarios: attributional and consequential modelling, historic and outlook data, the domestic electricity mix and the extended mix with import from other countries. The life cycle inventory database ecoinvent 3.1 and the life cycle impact assessment method ReCiPe version 1.12 are used. It was found that the historical attributional mixes are well represented by the ecoinvent 3.1 mix. All other scenario mixes significantly differs from the mixes in ecoinvent 3.1.

Keywords: Belgium, low voltage electricity mix, life cycle assessment, attributional, consequential

1 INTRODUCTION

Life cycle assessment (LCA) according to ISO 14040:2006 is an accepted tool for the assessment of the environmental impact of a product or service, from cradle to grave. All aspects considering natural environment, human health and resource depletion are taken into account and together with the life cycle perspective, LCA avoids problem-shifting between different life cycle stages, between regions and between environmental problems (Buyle et al., 2013). Although LCA is an accepted method and useful in support of making (policy) decisions, it was found in literature that several studies on similar products, processes or services yield different results (e.g., the environmental impact of concrete pavements compared to asphalt pavements (Athena Institute, 2006; Kicak and Ménard, 2009) or renewable (wood)

versus non-renewable materials (masonry, concrete, steel) in the construction sector (Cole and Kernan, 1996; Gerilla et al., 2007; Mithraratne and Vale, 2004)).
The regional, electricity production mix plays an important part in many LCA studies but is amongst others one of the aspects that can significantly deviate from one study to another. The electricity sector is strongly influenced by governments and consequently developments take place differently compared to other sectors. Environmental and social targets may have an influence on historic and future developments e.g., decreasing the emissions from energy production processes, increasing the share of renewable energy production, safety issues and electricity self-sufficiency. Another aspect of complexity in the electricity sector is the increasing liberalization of the market and thereby the growing interconnection between regions. Especially for the current Belgian electricity market, the sector is subject to technical problems at the nuclear power plants and a short-term policy that is inconsistent with long-term goals for example related to the planned nuclear phase-out in 2025.

Various LCA studies emphasize the importance of the selection of the electricity mix and its influence on the results. (Braet, 2011) includes a sensitivity analysis for an alternative electricity mix in an LCA case study. The Belgian electricity mix was compared to the continental mix, solely nuclear energy, wind energy, coal energy and natural gas energy. It was found that the preference based on environmental assessment for a specific transport concept in the Antwerp Harbour might turn over from pipeline to road depending on the electricity mix. Also (Buyle et al., 2015b) performed a sensitivity analysis to investigate the influence of the electricity mix on the life cycle assessment results. It was found that the electricity mix has a significant influence on the LCA results. Methodological choices affect the results as well. The composition of a regional mix can change radically when only technologies are included that can react to a change in demand (consequential LCA) instead of the average of the total production volume (attributional LCA) (Lund et al., 2010; Soimakallio et al., 2011).

However, most of these studies use the electricity mixes as defined by existing life cycle inventory (LCI) databases, without examining the composition of this mix for compatibility with the real situation or affected suppliers. Ecoinvent is one of the most important LCI databases and accepted as the default LCI database in Europe (Martínez-Rocamora et al., 2016). Ecoinvent contains electricity mixes for 71 different non-overlapping regions. Three different system models are available in ecoinvent v3.1: allocation at the point of substitution (=default) and cut-off (=recycled content) for attributional LCA and one for consequential LCA. The choice for a specific system model depends on LCA modelling choices (allocation or substitution, average or marginal suppliers, how assessing by-product treatments etc.).

This paper aims to answer the following main research questions:

- Does the data record in ecoinvent v3.1 correctly represent the Belgian low voltage electricity mixes for the different system models?
- To what extend differs the environmental impact of ecoinvent mix compared to the mixes of this study?

Only the Belgian electricity mix is analysed in the current contribution, but the methodology can be used for other regions as well. The study is scientifically relevant for all LCA practitioners because verifying life cycle inventory data are essential in order to obtain robust LCA results.

2 METHODOLOGY

2.1 General

The approaches to calculate environmental impacts can be subdivided into two types: attributional and consequential LCA. Attributional LCA is defined by its focus on describing the environmentally relevant flows within the chosen temporal window, while consequential LCA aims to describe how environmentally relevant flows will change in response to possible decisions (Buyle et al., 2013). The specific methodologies for the two LCA types are discussed in the sections 2.2 and 2.3.
Aspects discussed in this section are generally valid over this whole study. The functional unit for the environmental impact assessment is 1 kWh electricity low voltage as available on the Belgian grid. Transmission, distribution and conversion losses are included. The used life cycle impact assessment method is ReCiPe. ReCiPe implements both midpoint (impact) and endpoint (damage) categories and contains a set of weighting factors to calculate a single score impact. The single score indicator is used in this study for the interpretation of the results. The default perspective is the hierarchist, which is based on the most common policy principles with regards to time-frame and other issues. The hierarchist ReCiPe version with European normalization and average weighting set was chosen. More information about the chosen LCIA-method can be found in literature (Goedkoop et al., 2013; PRé, 2013; Sleeswijk et al., 2008).

Data collection was split in two parts: historical data for the period 2006-2015 and data predictions for 2030. Historical data were taken from a statistical database, available on the website of the European Network of Transmission System Operators for Electricity (ENTSO-E). The Belgian figures on the ENTSO-E web pages are related to the Belgian territory and reflect the national figures (including all voltage levels). These figures represent the hourly average of real measurements and estimates. Elia is the Belgian transmission system operator and forwards the relevant information of the Belgian electricity system to ENTSO-E ("Elia Web Page," n.d.). Figures of total load (definition see Figure 82) are used for the composition of the mixes. Total load is calculated from the net generation and accounts for the import and exports according to model 2 of the report by Frischknecht (2012) as presented in Figure 83 (Itten et al., 2012). ecoinvent uses the same model for calculating import and export of electricity in the mix.

There are some gaps in the data from ENTSO-E until 2013. The total electricity production from fossil fuels is not the same as the sum of the different contributors (coal, oil, gas, lignite). This is corrected by respecting the ratio between coal, oil and gas but by applying the total amount of electricity production by fossil fuels. Since 2008, a part of the hydropower was specified as renewable (run of river) and the data for renewable electricity production by solar are included in the ENTSO-E data. The amount of hydropower run of river was kept and all other hydropower was assumed to be 'other' (pump storage) since this is the generation type with the highest environmental impact and hence a worst case scenario is created. Similar, the amount of electricity production from solar and wind was retained while all other renewable electricity was assigned to biomass. Electricity production from biomass is included since 2014. The solar, wind and biomass electricity generation are mixes of different generation processes. The solar electricity is generated by two types of photovoltaic panels (monocrystalline and multi-crystalline silicon solar panels). Wind energy is divided in four different types of installations, depending on the power and location (onshore or offshore) of the installation. Electricity produced from biomass includes five different feedstock materials: biogas, wood chips, blast furnace gas, coal gas and municipal waste. The ratio for the different generation types is taken from Ecoivent 3.1.

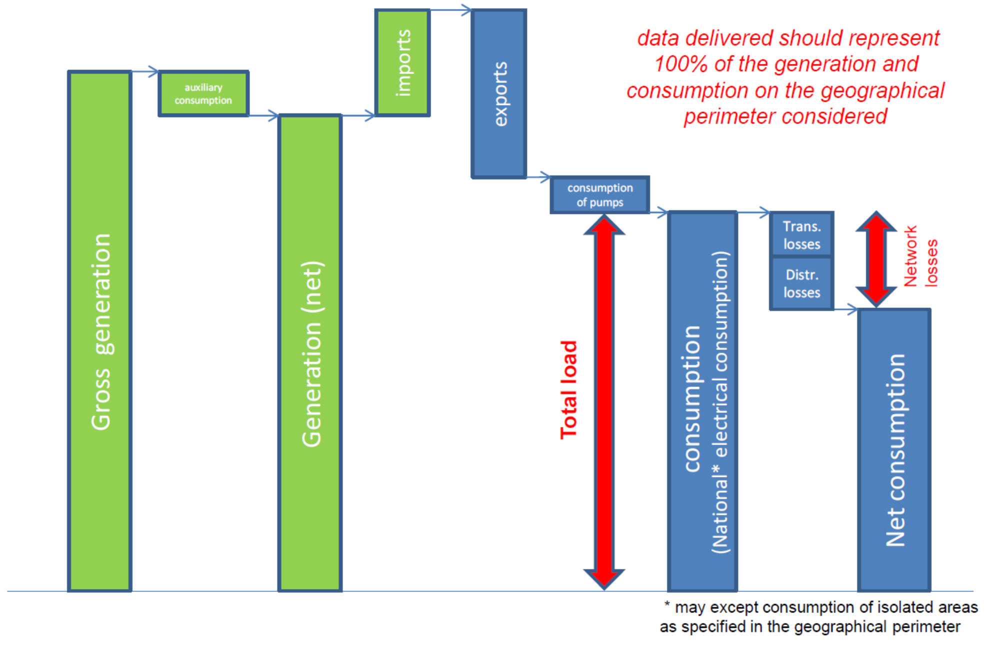

Figure 82: Definition of generation, consumption and load (Data Expert Group ENTSO-E, 2015)

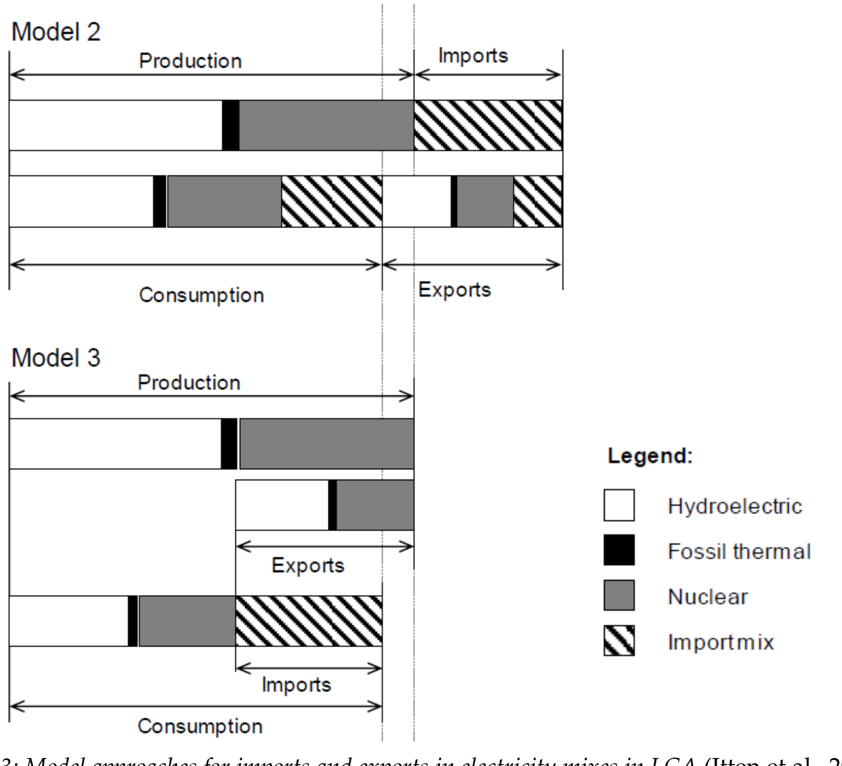

Figure 83: Model approaches for imports and exports in electricity mixes in LCA (Itten et al., 2012)

Outlook data for the electricity mix in 2030 were taken from the Federal Planning Bureau (Federal Planning Bureau, 2015, 2014). The composition of the mix is calculated based on the gross generation and the exchange balance (= import – export). As can be seen on Figure 82, this differs from the calculation setup used for the historical data but was applied since absolute values of import and export are missing in the report of the Federal Planning Bureau. Besides, the classification of various electricity generation methods slightly differs for the data from the Federal Planning Bureau compared to ENTSO-E. For the outlook data there is no detailed deviation for electricity production by biomass and waste over different feedstock materials. It is assumed that the electricity production from industrial (blast furnace gas and coal gas) and municipal waste is constrained since it is dependent on the amount of waste generation (Kuppens et al., 2013). Hence, the absolute electricity production (in GWh) of these types is kept equal in comparison to the data of 2015. The additional electricity production by biomass for 2030 compared to 2015 is associated to the electricity production by biogas and wood chips while keeping the ratio between these two constant.

For each generation method, a relevant process is available in the ecoinvent database, for both attributional and consequential LCA modelling. All electricity datasets in ecoinvent 3.1 were calculated for the reference year 2008 and if applicable extrapolated to the year 2014. Technological evolutions in the generation processes are beyond the scope of the current study and therefore not taken into account. The environmental impacts from the transmission network itself, the transmission and distribution losses, the conversion between different voltage levels and emissions from the electro-magnetic field are not analysed. These impacts are included by applying the values from the ecoinvent database. The full LCI can be found in the attached supplementary information (SI).

The included scenarios are listed in Table 33 and briefly described below, for more details see (Federal Planning Bureau, 2015, 2014). Only one scenario per model approach is included for the historical scenarios, while the future predictions include more scenarios. The ACLA scenarios (ALCA [H+] and ALCA [F+ ref]) represent the national average supply, including trade, thus no scenario for domestic production only is included. For the consequential scenarios, on the other hand, these scenarios (CLCA [H-] and CLCA [F- ref]) are included because this is the default assumption of ecoinvent 3.1 as well (Weidema et al., 2013). The included future predictions are:

- Ref.: evolution of the Belgian energy system under current trends and adopted policies in the field of climate, energy and transport while integrating the 2020 Climate/Energy binding objectives.
- Scenario v1: focuses exclusively on the 2030 and 2050 greenhouse gas (GHG) emission reduction targets and is driven by the application of carbon prices and carbon values

- Scenario v2: adds ambitious energy efficiency (EE) policies and measures to scenario v1
- Scenario v3: complements scenario v2 with a binding EU renewables (RES) target of 30% in 2030

Table 33: Included scenarios. Minus and plus signs refer to small and large market respectively. "H" refers to "Historical", "F" refers to "Future"

Data type	Domestic market	Domestic market + import
Historical data	CLCA [H-]	ALCA [H+]
Outlook data	CLCA [F- ref]	ALCA [F+ ref] CLCA [F+ ref] CLCA [F+ v1] CLCA [F+ v2] CLCA [F+ v3]

2.2 ALCA

Ecoinvent 3.1 includes two system models ('allocation, default' and 'allocation, recycled content') that can be used for attributional LCA modelling. Both system models use the average supply of products. This means that all electricity generation types with a contribution to Belgium low voltage grid mix are included. Both system models apply allocation to convert multi-product datasets to single-product datasets. The allocation, default system model allocates at the point of substitution, based on the market value of the products (economically). The allocation, recycled content system model makes a cut-off. This means that the secondary (recycled) materials bear only the impacts of the recycling processes. The allocation, recycled content system model is used in the current contribution because this system model is easier to understand and it is aligned to ecoinvent 1 and 2 modelling.

2.3 CLCA

The concept and methodology of consequential LCA have been described extensively by Ekvall and Weidema in terms of system boundaries, allocation and data selection and by Weidema related to the identification of marginal technologies (Ekvall and Weidema, 2004; Weidema et al., 1999). The presented five-step procedure of Weidema is the most common approach of identifying a marginal technology, taking into account scale and time horizon of the research, market delimitation, market trend, potential to increase capacity and competitiveness (Weidema, 2003). Previous research applying this procedure can be categorized by whether the simple or dynamic marginal technology was identified (Mathiesen et al., 2009). The first category is the marginal technology without taking into account the possibility to react to an increased demand at any time e.g., wind turbines. The second category takes only the technologies into account who always can react at an increase in demand e.g., conventional thermal power plants. In reality however, the (short-term) marginal technology can change on an hourly basis, depending on time of the day, season and climate conditions. Additionally, an increased production volume of one technology might affect the production volume of other technologies as well, since they are all connected to the regulated grid. Thus instead of focusing on a single marginal technology, a third approach is defining the complex marginal technology, which consists of a mix of technologies (Mathiesen et al., 2009). Such a mix is described by Lund et al. as "*the long-term yearly average marginal (YAM) technology takes into account the fact that a change in capacity has to be adjusted to the existing energy system*" (Lund et al., 2010). The advantages of working with a YAM technology mix are, among others, (1) that not only the installed capacity is taken into account but also how this is used and interact with existing capacity, (2) short-term changes in marginal supply are included, and (3) also non-flexible technologies can contribute if their capacity is increased.

The Belgian consequential mix in this study is modelled according to the principles described in the previous section, working with YAM technology mixes. Since the identification of future developments is per definition uncertain, multiple scenarios are developed. An important conclusion of the outlook studies with regard to the 5-step procedure is related to the market delimitation. After the phase-out of the nuclear plants, there will be a structural deficit in production capacity which is covered by imports. On the long-term (2050) however, the share of imported electricity is expected to decrease. The latter results in two scenarios for the market delimitation: (1) domestic production only, and (2) expanding the market by taking into account import and export. To define the boundaries of the expanded market, the ratio of a trade flow compared to the total production volume of the market is applied as main criteria. The criteria to define the countries included in this market is based on the size of individual cross border trade flows compared to the total production volume of the market. If a trade flow is smaller than 3% of the total production volume of the market, it is assumed that the trade connection is not significant and the country is excluded from the market. On the other hand, if a flow is above the threshold of 3%, the market boundaries are extended by including the country into the market. This procedure has to be repeated until all individual cross boundary trade flows are identified as insignificant and the final market size can be determined.

A second parameter in the scenarios relates to the selection of marginal technologies. The simplest way is to assume current trends represent future developments, of course taking (future) constraints into account as well. The contribution to the marginal mix can be calculated as the share of the increment in production volume of a technology over certain period of time compared to the total increase in production volume of the market. In this research as a simplification no cost data are included. It is assumed that the increased production volume is an empirical proof of competitiveness. The slope of the linear regression of historical data are used as indicator for the increment (Schmidt and Thrane, 2009). Such scenarios are of course only relevant if no fundamental changes in the market structure occur. A more complex way is to model outlook scenarios to identify the changes in production volume. Similar to the historical data, the share of a technology in the marginal mix is the proportion of the change of this technology in comparison with the total change. As pointed out by Mathiesen et al. it is relevant to model multiple possible futures (Mathiesen et al., 2009). Due to the relative small contribution of trade compared to domestic production, only one scenario is included per neighbouring country, based on the European forecasts up to 2030 (Capros et al., 2013).

3 RESULTS

Table 34 presents the historical electricity production and Table 35 presents the forecast of future electricity production. The composition of the market mixes for both ALCA and CLCA modelling were calculated based on these data. If a generation type does not contribute to the electricity mix and hence the value is zero, the field is left empty in Table 34, Table 35, Table 36 and Table 37.

Table 34: Historical electricity production and import (ENTSO-E, n.d.)

	ENTSO-E									
	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Net generation (GWh)										
Coal	1 854	1 225	3 770	3 669	2 796	2 191	2 411	2 555	3 763	3 628
Gas	27 141	28 852	24 933	26 416	28 235	22 665	23 711	21 706	17 171	19 942
Oil	183	102	92	160	50	11	8		34	50
Nuclear	39 704	40 902	39 661	39 105	38 654	39 402	34 891	36 622	30 057	23 421
Hydro	1 445	1 493								
hydro renewable r.o.r.			370	282	250	166	402	322	249	269
hydro pumped storage			1 225	1 235	1 142	1 041	1 110	1 185	1 092	1 017
Wind	322	438	576	859	1 088	1 960	2 611	3 211	4 155	5 100
Solar			40	141	468	1 075	1 477	2 185	2 654	2 963
Biomass	2 725	2 894	3 775	4 260	4 603	4 923	2 887	2 831	4 216	5 409
Import (GWh)										
France	9 655	7 579	6 742	1 401	3 203	7 341	6 732	7 898	10 217	9 355
Luxembourg	2 251	1 892	1 507	1 531	1 941	1 581	1 271	641	1 316	462
The Netherlands	5 082	4 784	7 514	4 746	7 768	4 663	7 345	7 084	8 803	12 787
Total Load (GWh)	90 362	90 160	90 205	83 805	90 199	87 020	84 857	86 239	83 728	84 403

** 10^{-5} accuracy needs a nuanced interpretation*

Table 35: Forecast of future electricity production in different scenarios (with respect to base level 2010) (Federal Planning Bureau, 2015, 2014)

	Federal Planning Bureau				
	2010	2030			
		[F+ ref]	[F+ v1]	[F+ v2]	[F+ v3]
Gross generation (GWh)					
Coal	4 190	1 882	1 882	1 882	1 882
Gas	31 420	36 567	32 550	36 436	30 504
Petroleum production & derived gases	2 164	1 562	722	742	742
Nuclear	47 944				
Hydro renewable r.o.r.	312	395	395	395	395
Wind	1 292	19 926	22 448	20 864	25 313
Solar	560	5 122	5 131	5 291	5 291
Biomass	3 994	6 722	6 686	6 204	7 687
Waste	1 888	2 053	2 053	2 053	2 053
Geothermal		289	289	289	289
Import (GWh)					
France	2 921	10 217	10 063	10 111	10 111
Luxembourg	2 574	5 400	5 318	5 344	5 344
The Netherlands	898	5 000	4 924	4 948	4 948
United Kingdom		400	394	396	396
Total (GWh)	94 315	95 535	92 855	94 956	94 956

* 10^{-5} *accuracy needs a nuanced interpretation*

3.1 Composition market mixes - ALCA

For attributional LCA modelling, all electricity generation types are included, even when they are a by-product from another production process e.g., the heat and power co-generation from biogas or constrained e.g., nuclear power. The data presented in Table 34 are converted to the electricity mix composition in terms of percentage (for 1 kWh) as presented in Table 36 as the composition of the ALCA scenarios. The electricity mix by country of France, Luxembourg, The Netherlands and United Kingdom from ecoinvent is used to represent the import from other countries. For the single score impact per generation type in Table 36, the weighted average for 2015 was taken if more technologies are available (wind, solar, biomass). For 2015, the domestic annual production according to ENTSO-E is rather low compared to 2008, the reference year in ecoinvent: a reduction of 6.4% (see Table 34). It can be concluded that the decrease in annual Belgian electricity production is mainly due to the decrease in production by nuclear reaction and gas combustion. The decrease in nuclear electricity production might be explained by (1) problems of little cracks in the steel walls of the reactor vessels (Doel 3 and Tihange 2) since 2012; and (2) the first phase of the nuclear power phase-out originally scheduled for 2015. Regarding the latter, the current Belgian government postponed the closures of the first phase to 2025. The decrease in electricity production by gas plants is due to the closure of multiple units in Belgium during the last decade as a consequence of economic and political decisions.

The contribution of renewable electricity production to the mix is increasing during the last decade. It is important to note that the energy generation by "other hydro" (pump storage) is smaller compared to the energy consumption by the pumps used for this energy production. Hence hydropower generation by pump storage plants has some efficiency loss [Reference: e-mail contact with Dries Couckuyt, Belgian correspondent for the ENTSO-E data and market analyst at Elia (Extra High Voltage System Development)]. When the electricity demand is low, energy is consumed to pump water from a lower reservoir to an upper reservoir. When the energy demand is high, the water flows through pressure pipes into turbines, generating electricity. Hydropower production by pumped storage is considered as non-renewable electricity.

A part of the electrical production by fossil fuels still comes from coal and oil with an installed generation capacity of 470 MW and 190 MW respectively in 2015 (ENTSO-E, n.d.). It was seen from (ENTSO-E, n.d.) that the power plants Langerlo 1 and Langerlo 2 use hard coal in combination with biomass and natural gas. Fossil oil is mainly used in small electrical power plants for the production during peak hours. Belgium has several turbojet plants using kerosene.

Belgium exchanges electricity with three neighbouring countries: France, Luxembourg and The Netherlands. The electricity import increased with 43% in 2015 compared to 2008. This trend is especially strong for 2014 and 2015.

The most important differences between the attributional mix for 2015 and the mix for 2030 based on the outlook data of the Federal Planning Bureau are the termination of nuclear production and production by hydro pumped and an increase in electricity production by wind power.

In general, it was seen that there is a strong agreement between the Belgian Electricity mix as defined in the database 'ecoinvent 3.1, Allocation, Recycled content' and the electricity mix generated based on the ENTSO-E data. For both mixes, the same electricity generation techniques contribute to the composition and the shares of the different techniques are in the same order of magnitude. The ecoinvent 3.1 electricity mix includes the import of electricity from the same countries as defined by the ENTSO-E data.

3.2 Composition market mixes - CLCA

The composition of the market mixes for the different consequential scenarios is calculated according to five-step procedure, based on data presented in Table 34 and Table 35. The first step is to define the scale and time horizon of the study. A long-term and large scale is assumed. The latter is in particular true for the future scenarios as fundamental changes in development of the electricity sector are taken into account. The second step is defining the market boundaries. Both the domestic market and an expanded market are taken into account. In this particular case, Belgium is assumed to import significantly from the Netherlands, France and Luxembourg. According to a study of the International Energy Agency (IEA) Luxembourg is a net importer and not planning to increase its capacity. Therefore it is assumed Luxembourg is only a transit country for German electricity, since it has only a grid connection with Belgium and Germany (International Energy Agency, 2014). Hence the included countries in the expanded market are Belgium, the Netherlands, France and Germany. If a smaller threshold is desired, the UK grid could be included. In this case, all trade flows to regions outside the cluster are below 1.5% of the clusters' production volume. Since Belgium has no direct connection with the UK, this would affect the final results only to a small extent. Third, the market trend was determined. The historical data have a stable to slightly decreasing trend, while the outlook data take a stable situation into account. Since no sharp decreasing trend is observed, it is assumed the marginal suppliers should be the most competitive ones. Fourth, the constrained suppliers should be excluded as potential marginal suppliers. Multiple types of constraints occur in this situation:

political, natural and by-product constraints. Nuclear generation is the most obvious example of a political constraint due to the planned phase-out, together with the ban on new coal-based power plants. Hydro power has a natural constraint in the Belgian context, no new spots are left to expand capacity. The last group of constraints are the non-determining by-products. Only an increase in demand for the determining product will result in a growing production volume. Energy recuperation at municipal waste incineration plants and other industrial processes are typical examples of technologies that cannot contribute to the marginal mixes. The final step is to identify which of the unconstrained suppliers are the most sensitive to a change in demand. Technologies with a decreasing trend are excluded in the mix (e.g. oil), the others contribute to the mix. In Table 37 all mixes are presented, as well as the ecoinvent 3.1 mix for Belgium.

The variation in the composition of the mixes is noticeable, but a general observation is the dominant share of technologies based on renewable energy sources (RES) both for the historical as the future scenarios. To date, these technologies are growing fast, but they represent only a small part of the total mix. The scenarios indicate however that the trend is expected to continue, resulting in a significant contribution to the market share. The situation of gas plants is less clear, appearing only in some of the mixes. Gas plants in Belgium produce electricity at a high cost compared to other domestic technologies and imported electricity. This resulted in the last years in a reduced working load of gas plant and even in some closures. However in future scenarios, gas plants play an important role as they are able to supply a constant base-load in contrast to most RES technologies. Geothermal production is an expected new technology in the future scenarios. Despite it has only a small contribution in the mixes, it still points out the growing attention for renewable energy sources.

Compared to the presented scenarios, the composition of the ecoinvent 3.1 mix is completely the opposite. Nuclear, coal and hydro account for almost 99% of the mix, while in this research these technologies are considered to be constrained. On the other hand, technologies based on RES are barely represented in this mix.

Table 36: ALCA scenarios - Composition market mixes and life cycle impact

	Single score impact (mPt/kWh)	Composition ALCA scenarios (%)											
		[H+]										[F+ ref]	ecoinvent 3.1
		2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2030	
Generation													
Coal	90.5	2.05%	1.36%	4.18%	4.38%	3.10%	2.52%	2.84%	2.96%	4.49%	4.30%	1.97%	5.23%
Gas	46.8	30.0%	32.0%	27.6%	31.5%	31.3%	26.0%	27.9%	25.2%	20.5%	23.6%	38.3%	23.2%
Oil	87.9	0.20%	0.11%	0.10%	0.19%	0.06%	0.01%	0.01%		0.04%	0.06%	1.64%	0.38%
Nuclear	2.60	43.9%	45.4%	44.0%	46.7%	42.9%	45.3%	41.1%	42.5%	35.9%	27.7%		44.8%
Hydro r.o.r.	0.56	0.37%	0.38%	0.41%	0.34%	0.28%	0.19%	0.47%	0.37%	0.30%	0.32%	0.41%	0.43%
Hydro pumped	41.1	1.23%	1.27%	1.36%	1.47%	1.27%	1.20%	1.31%	1.37%	1.30%	1.20%		1.40%
Wind (mix)	3.35	0.36%	0.49%	0.64%	1.03%	1.21%	2.25%	3.08%	3.72%	4.96%	6.04%	20.9%	0.66%
Solar (mix)	14.4			0.04%	0.17%	0.52%	1.23%	1.74%	2.53%	3.17%	3.51%	5.36%	0.07%
Biomass (mix)	24.1	3.02%	3.21%	4.18%	5.08%	5.10%	5.66%	3.40%	3.28%	5.04%	6.41%	9.19%	5.85%
Geothermal	9.27											0.30%	
Import													
FR	10.5	10.7%	8.41%	7.47%	1.67%	3.55%	8.44%	7.93%	9.16%	12.2%	11.1%	10.7%	7.75%
LU	57.6	2.49%	2.10%	1.67%	1.83%	2.15%	1.82%	1.50%	0.74%	1.57%	0.55%	5.65%	1.70%
NL	56.9	5.62%	5.31%	8.33%	5.66%	8.61%	5.36%	8.66%	8.21%	10.5%	15.1%	5.23%	8.49%
UK	56.9											0.42%	
total impact per scenario (mPt/kWh)		27.3	27.0	29.3	29.8	30.4	26.2	28.2	26.5	28.5	32.5	36.3	29.7

** 10^{-3} accuracy needs a nuanced interpretation*

Table 37: CLCA scenarios - composition market mixes and life cycle impact

	Single score impact (mPt/kWh)	Composition CLCA scenarios (%)										constraints for Belgium
		[H-]	[F- ref]	[F+ ref]	[F+ v1]	[F+ v2]	[F+ v3]	[F+ ref] FR	[F+ ref] DE	[F+ ref] NL	ecoinvent 3.1	
Generation												
Coal	90.9										9.94%	political
Gas	47.0		16.4%	10.0%	2.28%	9.71%			21.7%			-
Oil	93.1								0.432%	1.56%		-
Nuclear	2.60									3.49%	85.3%	political
Hydro (mix)	14.6							2.50%	2.06%		3.46%	natural
Wind (mix)	3.50	50.8%	59.4%	36.2%	42.7%	37.9%	45.7%	76.6%	59.2%	83.0%	1.25%	-
Solar (mix)	17.2	34.9%	14.5%	8.87%	9.22%	9.16%	9.00%	12.0%	11.3%	3.33%	0.07%	-
Biomass (mix)	28.9	14.3%	8.70%	5.30%	5.43%	4.28%	7.02%	7.93%	5.29%	8.59%		-
Geothermal	10.7		0.922%	0.562%	0.583%	0.559%	0.550%	0.920%	0.0382%			-
Import												
FR	9.00			25.5%	26.2%	25.2%	24.8%					-
DE	20.5			5.50%	5.53%	5.36%	5.27%					-
NL	9.04			7.98%	8.11%	7.84%	7.70%					-
total impact per scenario (mPt/kWh)		13.3	17.8	14.9	11.5	14.5	10.7	9.00	20.5	9.04	14.6	

** 10^{-3} accuracy needs a nuanced interpretation*

3.3 Impact assessment

The results are presented in Table 36 and Table 37, showing the environmental impact per generation type per kWh, the composition of the electricity mixes for al included scenarios with corresponding impact and the default ecoinvent 3.1 mix. The single score impacts of 1 kWh low voltage electricity by different production types are compared using the corresponding ecoinvent processes. Only the final single scores are included in the tables, more information on the midpoint categories can be found in the supplementary information (SI). An important remark is that due to transmission losses, the final impact per scenario is higher than the combination of the share per technology with its impact.

The results of the environmental impact per generation type show similar trends for both the attributional as the consequential system model. This makes sense since the impact is calculated per process regardless its contribution to a mix or potential constraints. Differences occur due to the modelling assumptions in the background system, but the order of magnitude is the same. It is seen in Table 36 that there is a large difference in environmental impact per kWh electricity depending on the generation type. In general, electricity production based on fossil fuels (in particular coal and oil) causes a large environmental burden. Besides, the cogeneration of heat and electricity with wood chips has an important environmental impact in the category agricultural land occupation (see SI for more details). This results in a high environmental impact for the electricity generation by the biomass mix. In the consequential system model, biomass based production is modelled with electricity as determining product instead of heat. The electrical production with low environmental impact stems from nuclear reaction (see also chapter 4), wind and hydro power (run of river). In the attributional biomass mix, no environmental impact is assigned to the electrical production by the combustion of municipal waste materials because the system model allocation recycled content is used (see section 2.2). On the other hand, the impact of the imported country mixes differs significantly between the two system models. In this case the differences are caused by the composition of the mixes induced by underlying assumptions of the system model and not by a difference in impact for the same generation type. Identical as for the Belgian mix, in the attributional mixes is worked with the average production (ecoinvent data used), while the consequential mixes only include the technologies that can respond to an increase in demand.

As the composition of the attributional electricity mixes changes over time, the environmental impact of these mixes changes as well. It can be seen from Table 36 that the environmental impact is slightly lower in 2006, 2007, 2011 and 2013; while high impact per kWh is seen in 2009, 2010 and 2015. The environmental impact of 1 kWh in 2015 is 23% higher compared to the impact of 1 kWh in 2013 and 11% higher compared to the impact of 1 kWh in 2008, the reference year. The lower impacts in 2006, 2007 and 2011 can partly be explained by the low amount of import from The Netherlands (the electricity mix of The Netherlands has a high environmental impact) and a high share of nuclear electricity (with a low environmental impact) in the mix. The low environmental impact in the electricity mix in 2013 is a consequence of an increasing amount of energy produced by wind power, solar and waste incineration; a constant amount of nuclear electricity and import from France and a low amount of import from Luxemburg with a high environmental impact. The high environmental impact of the electricity mix in 2009 and 2010 is caused by a high amount of electricity production from gas with a relative high environmental impact and less import from France. The high environmental impact of the electricity mix in 2015 is caused by the decreased production of nuclear energy with a low environmental impact and the increased electricity from biomass and import from The Netherlands with a higher environmental impact.

The consequential electricity mixes are subject to a large variation in the composition for the different scenarios. This is also reflected in the range of the environmental impacts, going from 10.7 to 17.8 mpt/kWh. The differences in the contribution of gas-based generation are the main reason for the fluctuations in the impact per scenarios. Gas is, together with biomass, the only type of unconstrained fuel that is fully flexible, and which can be used for the base load generation. The production cost per kWh however is higher compared to for example nuclear power. In the [H-] scenario, cheaper nuclear power is still the main base load technology, resulting in reduced share of gas-based generation. In most future scenarios though, natural gas and to a lesser extent biomass are the main domestic base load technologies, resulting in a noteworthy share in the mixes.

Solar power has an opposite evolution in comparison with natural gas: it is stronger represented in the historical mix (35%) than in the future ones (9-15%). This can be explained by strong financial incentives in the last decade for green power production, which mainly affected the installation of photovoltaic panels and biomass plants. These incentives have been cut back recently, thus the steep increase is not expected to last as can be seen in the future scenarios. Wind power appears to be the leading technology instead in all future scenarios.

In the [F+] scenarios, where trade is taken into account, the large share of French import is remarkable. In the reference year 2010 there was a net export to France, while in 2030 France is expected to be the main foreign supplier to the Belgian grid. The French consequential future mix is dominated by wind (77%) and solar (12%) power resulting in a reduction of the impact compared to the scenarios with only domestic generation. This reasoning is also valid for import from The Netherlands (83% wind).

Finally, the environmental impacts of the electricity in the different scenarios are compared to the electricity mix in ecoinvent according to the two system models.
The scenario ALCA [H+] is compared to the generic data in ecoinvent v3.1 kWh "Electricity, low voltage {BE}| market for | Alloc Rec, U". It is seen that the environmental impact for 1 kWh from the mix of 2015 is 9.4% higher compared to the mix in ecoinvent. Nevertheless, there are similarities in the order of magnitude for the contribution of different generation types in the electricity mix.
Despite significant differences between the consequential mixes, the general trend is the large share of renewable energy sources combined with a flexible technology such as natural gas. The consequential energy mix of ecoinvent 3.1 is completely the opposite and is almost entirely composed of constrained technologies. The impact of this mix (14.6 mpt/kwh) fits within the range of the other scenarios, but is not relevant to draw any conclusions based on this mix. The combination of a large share of nuclear energy (low impact) combined with a small share of coal (high impact) is averaged into a realistic values. However, this is rather coincidence instead of a causality.

4 DISCUSSION

In this study multiple scenarios are developed for the composition of the Belgian electricity grid mix according to an attributional and consequential modelling approach. Both a time series of historical data and outlook data were applied. The same source data has been used for both system models, but the goal and underlying modelling assumption differ. The mixes presented in the results section clearly indicate a growing trend of renewable energy sources in the Belgian power production. This can be directly explained by the European Energy policy, imposing quotas for the share of renewables by 2020 and beyond (European Commision, 2014; European Commission, 2010). However, the increasing capacity of renewables is reflected differently depending on the approach. In the attributional mix, the share in the total production volume is small in the historical scenarios. At the consequential mixes, on the other hand, these technologies are the most important marginal suppliers as they are the only ones with an increment in capacity and production volume. In the future scenarios, renewables are expected to have a larger share in the total production volume, making the differences smaller between the two approaches.
An extensive review of Masanet *et al.* based on a meta-analysis by the National Renewable Energy Laboratory (NREL) identifying nearly 300 LCA studies of electric power technologies, came to similar conclusions regarding renewable technologies. In most analysed mixes RES technologies have only a small share in the mixes. If future scenarios are taken into account most analysed studies are restricted to a '*set*

of scenarios with a priori backgrounds of how the technology might function and are conducted based on understandings of the current or previous technology, costs, and market' (Masanet et al., 2013; National Renewable Energy Laboratory, 2013). As a result, coal appears often as marginal technology in the few consequential studies.

Limited research is available concerning the Belgian grid mix. Rangaraju *et al.* and Messagie *et al.* analyzed the composition of the Belgian grid mix for the year 2011 on hourly basis (Messagie et al., 2014; Rangaraju et al., 2015). The studies focus more on a detailed temporal resolution in relation with smart grids, rather than on developments on a longer time horizon. For the analysed year, the results are similar, but neither future nor consequential scenarios are included.

It is important to note that the current impact assessment analysis does not take into account all environmental issues. It is known (Messagie et al., 2014) that the Belgian power plant Rodenhuize 4 imports 30% of its wood chips from British Columbia (Canada) resulting in very long transport distances (transport by ship) causing an environmental impact which is not included in this comparison. Besides, for nuclear power generation, there are some safety issues that are not included in the current impact assessment. There is an ongoing discussion between supporters and opponents of nuclear energy. There is always a risk of a nuclear disaster with potentially huge social and environmental consequences. Besides, the radioactive residual waste from the electricity production by nuclear reaction will be a burden for various following generations, which is in contradiction to the definition of sustainable development. Furthermore, nuclear energy is politically constrained in the consequential modelling approach, which is an uncertain factor as such decision might be reversed. At the time of writing, the stepwise phase-out is postponed, but the final closing date of 2025 is still the policy target. In future research, these topics could be elaborated more in detail.

The Belgian electricity consumers can influence the environmental impact of the current electricity mix by choosing an energy supplier that invests in the construction of power plants for low impacting, renewable energy production.

As mentioned in section 2.1, technological evolutions in the generation processes are beyond the scope of the current study. Data on these evolutions are not available. The authors of the study recognise that this is a pragmatic limitation of the study. The technological evolutions in the generation processes can be the subject for further research.

5 CONCLUSION

The aims of the paper are (1) to verify whether the records in ecoinvent v3.1 represent the Belgian low voltage electricity mixes correctly for the different system models, and (2) how this is reflected in the environmental impact per kWh. The analysed system models are an attributional model ('allocation, recycled content') and the consequential model. Multiple scenarios are included, based on historical statistics and future prediction. In the case of the attributional model, the scenarios represent the historical and expected average, while the consequential scenarios represent the historical and future trend of increasing technologies.

The composition of the historical attributional mixes is fluctuating over time, but the order of magnitude of the different technologies remains the same. These mixes are quite well represented by the ecoinvent 3.1 mix. The future scenario, on the other hand, is completely different, with a large share of renewable technologies.

The analysis of the consequential scenarios is the opposite. Current trends of increasing capacity of renewables is expected to continue in the future, though with a shift of importance from solar to wind power. These results also point out that the ecoinvent 3.1 is composed for 99% of constrained technologies.

The impact assessment shows no clear trend and is scenario dependent, especially on the case of future predictions. The attributional scenario shows an increase in impact due to elimination of nuclear power, while in the case of consequential scenario the situation might improve or become worse depending on the base load technology.

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PAPER VIII: REUSE OF BITUMINOUS PAVEMENTS: A MINI-REVIEW OF RESEARCH, REGULATIONS AND MODELLING

Authors: Joke Anthonissen, Wim Van den bergh, Johan Braet

Abstract: Bituminous pavement can be recycled – even multiple times – by reusing it in new bituminous mixtures. If the mechanical properties of the binder get worse, this reclaimed asphalt is often used in the sub-structure of the road. Apparently, up till now no end-of-life phase exists for the material. Actually, defining the end-of-life and the end-of-waste stage of a material is important for life cycle assessment modelling. Various standards and scientific studies on modelling life cycle assessment are known, but the crucial stages are not yet defined for reclaimed asphalt pavement. Unlike for iron, steel and aluminium scrap, at this moment, no legislative end-of-waste criteria for aggregates are formulated by the European commission. More research is necessary in order to develop valuable end-of-life criteria for aggregates. This contribution is a mini-review article of the current regulations, standards and studies concerning end-of-life and end-of-waste of reclaimed asphalt pavement. The existing methodology in order to define end-of-waste criteria, a case study on aggregates and the argumentation used in finished legislative criteria are the basis to clarify some modelling issues for reclaimed asphalt material. Hence, this contribution elucidates the assignment of process environmental impacts to a life cycle stage as defined by EN15804 i.e., end-of-life stage (C) and the supplementary information module D with benefits and loads beyond the system boundary.

Keywords: end-of-life (EOL), end-of-waste (EOW), life cycle assessment (LCA), bituminous pavement, reclaimed asphalt pavement (RAP), closed loop recycling, regulations, Flanders

Abbreviations:

BENOR	A registered collective mark of conformity indicating that a product complies with a Belgian standard
CDW	Construction and demolition waste
Certipro	Certification and inspection service incorporated by VITO, mainly focusing on small-scale wastewater treatment plants and recycled aggregates
COPRO	(control of products) Belgian impartial certification body in the construction sector
CRT	Certification regulation (for recycled aggregates)
CW	Construction products waste
DW	Disposal waste
EAPA	European Asphalt Pavement Association
EOL	End-of-Life
EOW	End-of-waste
EPD	Environmental product declaration
HMA	Hot mix asphalt
JRC	Joint Research Centre
IS	Industrial symbiosis
L/S	Cumulative liquid-to-solid ratio
LCA	Life cycle assessment
OVAM	The public Waste Agency of the Flemish region
OECD	Organisation for Economic Co-operation and Development
PCR	Product category rules
PCODW	Production, construction or demolition waste
PET	Polyethylene terephthalate
PW	Production waste
RAP	Reclaimed asphalt pavement
REACH	Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals
SB250	Flemish Road Standard
TRA	Implementing regulation
UW	Use waste
VITO	Flemish institute for technological research
VLAREMA	Decree of the Flemish Government adopting the Flemish Material Cycles and Waste Regulations
WFD	Waste Framework Directive
WMA	Warm mix asphalt

1 INTRODUCTION

An enormous expansion of the global demand for construction materials caused a strong increase of the raw material prices and even partial shortages during the first years of the 21th century (Chowdhury et al. 2010, Huang et al. 2007, Tölle 2007). The reduced availability, high prices and long transport distances, led to a search for alternatives. The asphalt sector therefore has a growing interest for the whole material cycle and uses reclaimed asphalt pavement (RAP) as well as secondary materials from other sectors in new bituminous mixtures.
Life cycle assessment (LCA) studies are used to investigate the environmental impact of using these materials as an alternative for virgin raw materials in bituminous mixtures for road pavements. The end-of-life (EOL) status of bituminous pavement and the end-of-waste (EOW) status of reclaimed material (i.e. RAP) should be known in order to make an adequate model for LCA calculations.
To date, plenty of research has been done on life cycle assessment of bituminous pavements. Nevertheless, at this moment, the definition of EOL for bituminous road pavement and EOW for RAP have not been found in literature.

The goal of this research is therefore to make a well-founded decision on both EOL and EOW for bituminous road pavements, by conducting an extensive literature review of both European and Flemish legislations and research. The main focus of the current research is Flanders, a Dutch-speaking region in Belgium. Belgium has three regions: the Flemish Region (Flanders), the Walloon Region (Wallonia), and Brussels (the Capital Region). However, depending on the subject and publisher, this study includes Belgian and European figures and regulations as well.

2 BACKGROUND

2.1 Materials in the asphalt sector

Asphalt is constituted for about 95% of aggregates. These aggregates can be i) natural aggregates, produced from mineral sources; ii) secondary aggregates, arising from industrial processes; or iii) recycled aggregates. According to estimates of production data by the European Aggregates Association (European Aggregates Association 2013), an average of 81 million tons aggregates were produced annually in Belgium between 2006 and 2012, of which 81%(±) are natural, 18%(±) are recycled and 2%(±) are secondary aggregates. As a European average, 10% of all produced aggregates are used in asphalt products.
Delgado et al. (2009) state that in 2006, about 9 million tons construction and demolition waste (CDW) were produced in Flanders, of which 92% is reused or

recycled and 8% has an unknown application. Together with the Netherlands, Denmark and Germany, Flanders already reached a high rate of reuse and recycling of CDW.

The asphalt production sector is inseparable from other sectors in the product chain, with which energy and material streams are exchanged (Leyssens et al. 2013). The output of one sector can be the input for another sector. In Flanders, materials from other sectors are being used in asphalt mixtures: steel slag can replace mineral aggregates and roofing felt waste can replace binder (Leyssens et al. 2013, Van den bergh & Stoop 2009). With regard to sustainable material management, it is important to take into account the impacts from both the studied sector and the interaction with other sectors.

For the Belgian asphalt sector, two organisations keep a record of production data: EAPA (the European Asphalt Pavement Association) and COPRO (abbreviation of 'Control of Products', representing the Belgian Impartial Certification Body in the Construction Sector). The data from EAPA are an estimation of the national industry sector, made by the Belgian association of asphalt producers. COPRO publishes the results of measurements on certified asphalt mixtures and certified asphalt plants. In December 2015, 17 Flemish and 4 Walloon asphalt production plants were COPRO certified (meaning 1 Flemish, 1 Brussels and 15 Walloon asphalt plants are not and thus excluded from this COPRO data collection). The annual reports of both organisations from 2012, 2013 and 2014 are summarized in Table 38. The figures from EAPA and COPRO vary significantly, due to the different scopes of the reports. Nevertheless, the figures indicate the order of magnitude of production figures.

Table 38: Figures for Belgian asphalt sector in 2012, 2013 and 2014

	2012		2013		2014	
	EAPA	COPRO	EAPA	COPRO	EAPA	COPRO
Number of production sites	38	21	38	21	38	22
HMA and WMA production (million tons)	5.6	3.7	5.3	3.3	5.2	3.3
Available amount of RAP (million tons)	1.5	1.9	1.5	2.0	1.5	1.6
Available RAP used in asphalt (%)	61	50	61	43		61
Mixtures containing RAP (%)	49	58	51	58		61
Average RAP content in mixtures with RAP (%)		39		45		43

Reference: (COPRO 2015, 2014, 2013; European Asphalt Pavement Association 2015, 2014, 2013)

The Flemish Road Standard SB250 prescribes the requirements (from material characteristics up to performance tests on the pavement) for all public road works in Flanders. Before 2013, the SB250 limited the amount of RAP for base course mixtures to 50%. Since 2013, performance requirements were integrated in SB250 for the specification of asphalt mixtures for base courses according to the fundamental method as an alternative for the empirical method. The EAPA and COPRO data (see Table 38) show that, more than half of all produced asphalt mixtures contained RAP. Hence, the use of RAP in new asphalt mixtures became common practice; even recycling rates up to 100% would be possible in the future by fractionating the RAP and adding a natural resin (Leyssens et al. 2013).

2.2 Environmental impacts of RAP and secondary materials in asphalt

Peuportier et al. (2011) defined under which condition the use of RAP (or recycling in general) is beneficial: if the impact from the processes in order to recycle the product (I_r) and the impact from the transport (I_t) are smaller than the avoided impact from the production of a virgin alternative (I_n) and the impact from the waste treatment (I_w), then recycling should be promoted (see equation 15).

$$I_r + I_t < I_n + I_w \qquad \textit{(Eq. 15)}$$

LCA is used in order to assess the environmental impact of these different aspects. As recognized by Silvestre et al. (2014), a detailed LCA approach for a building material is complex because of its long life cycle and the dynamics during the execution, in-service and EOL phases. The analysis of the EOL is particularly difficult due to the high uncertainty of e.g. service life and waste management in the future.

Recently, Butt et al. (2015) stated that no EOL phase exists for a pavement, because the material will be used in the substructure when the bitumen is no longer useful as a binder material for the road surface. As a consequence, the boundaries of an LCA study are defined in various ways whether or not to include the use phase or the EOL phase. For road pavements, the most common scopes of an LCA study are: cradle-to-gate (all impacts until the asphalt mixture reaches the gate of the asphalt plant (Anthonissen et al. 2014)), cradle-to-laid (variant of cradle-to-gate specific for road pavements; all impacts until the road is constructed (Huang et al. 2012)), cradle-to-grave (all impacts until the road reaches end-of-life (Hoang et al. 2005)), or cradle-to-cradle (all impacts, including the reuse, recovery and/or recycling potential (Silvestre et al. 2014)).

Multiple LCA studies (Chiu et al. 2008, Ventura et al. 2008, Vidal et al. 2013, Wayman et al. 2012) investigated the environmental impacts of including RAP into new bituminous mixtures. Some LCA studies (Chiu et al. 2008, Chowdhury et al. 2010, Huang et al. 2007) investigated the environmental impacts of using secondary materials (i.e., rubber, glass, steel slag, coal fly/bottom ash, recycled concrete pavement, or plastics) in asphalt mixtures. The LCA study by Mladenovič et al. (2015) found that the use of steel slag aggregates for the construction of asphalt surface courses is more sustainable compared with the use of virgin siliceous aggregates.

Nevertheless, none of these studies clearly describes the EOL stage with the definition of the EOL of the pavement and the EOW of the reclaimed materials or how the EOL stage is modelled in the LCA study.

2.3 Definition of waste

When a construction product is replaced, dismantled or deconstructed from a building or a road, it reaches the end-of-life stage. All outputs of this stage are at first considered to be waste. Demolition or maintenance of roads is mainly carried out by a contractor, and hence, the material released (i.e. RAP) is considered to be industrial waste and is catalogued as construction and demolition waste (CDW).

Silvestre et al. (2014) defined three waste flows in CDW, which are also applicable for a bituminous road pavement (see Figure 84):

- Production waste (PW) [1] at the asphalt plant e.g., batches from production cycles with aberrant mixture composition and insufficient quality.
- CDW outputs [2] at the worksite:
    - Construction products waste (CW) e.g., surplus material when the quantity of asphalt mixture for the road construction is overestimated;
    - Use waste (UW): due to maintenance operations e.g., reclaimed material from repaving surface course;
    - Disposal waste (DW): at the end of the service life of the pavement.
- Secondary material input [3]:
    - Production, construction or demolition waste (PCODW): secondary material input from the construction industry (can include both [1] and [2]);

Industrial symbiosis (IS): secondary material input from other industries e.g., waste tires, waste glass, waste plastic, steel slag or roofing felt waste (Huang & Bird 2007, Huang et al. 2007, Van den bergh & Stoop 2009).

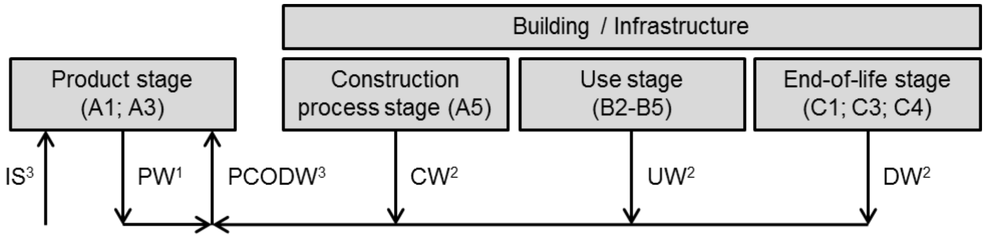

Figure 84: Construction and demolition waste input and output flows with refence to the European Standard EN 15804 (Silvestre and Lasvaux, 2012)

During the asphalt production process, production waste is limited (Leyssens et al. 2013). Few packing materials are involved because most raw materials are bulk, except some additives like fibres. Furthermore, most of the residues are reused. Waste coming from offices and laboratories of the asphalt plant are not considered in the current study.

Waste can cease to be waste and attain the status of product or secondary raw material if they reach the end-of-waste state (see section 2.5). It is important to know if a product is waste or ceased to be waste and is considered as a secondary or raw material again. This makes an important difference in the perception of people towards a certain material and there are some regulatory differences involved.

2.4 Trade of waste

While one of the European Union founding principles is the free trade among its members, the trade of waste is strictly regulated. In Belgium, the responsible authorities for the international trade of waste are the regional authorities. Hence, the procedures may vary for Flanders, the Walloon Region and Brussels, but the differences will be small due to the binding European legislation.

Each shipment of waste crossing a border, is subjected to the regulation (EC) number 1013/2006. For reclaimed asphalt pavement, this involves two different situations (see Table 39) (OVAM 2007). Export of RAP containing tar, destined for recovery in countries where the OECD (The Organisation for Economic Co-operation and Development) decision does not apply, is prohibited. Trading RAP without tar across borders is possible, but there are some general information requirements: i) the treated waste material should be accompanied by an information document (see Annex VII of 1013/2006/EC), prepared by the person who arranges the shipment; ii) at the moment the shipment starts, there shall be an effective contract between the person who arranges the shipment and the consignee for recovery; iii) in accordance with national legislation, Member States may require more information.

Table 39: Regulations on the international trade of waste

	RAP without tar	RAP with tar
Basel Convention (22 March 1989)	Annex IX	Annex VIII
Regulation 1013/2006/EC	Annex III	Annex IV
	Green listed waste	Amber listed waste
	General information requirements laid down in article 18	Prior written notification and consent (Annex II)
	Annex V – Part I – List B	Annex V – Part I – List A
		Export prohibition in article 36

2.5 End-of-waste principle

The concept of end-of-waste was introduced in 2005 by the thematic strategy on the Prevention and Recycling of Waste (European Commission 2005), and was adopted by the European Parliament and the Council in 2008 in the revised Waste Framework Directive (WFD) (European Commission 2008). The revised WFD introduces the possibility that certain waste streams having undergone a recovery operation and fulfilling certain criteria – so-called end-of-waste criteria – can cease to be waste and could be regarded as a non-waste material to be freely traded as such on the open market (Delgado et al. 2009, Villanueva et al. 2010).

The purpose of defining EOW criteria and the clarification of the quality and applications of such material streams, contribute to create more transparent market conditions, protect human health and the environment, and promote the recycling of the streams by reducing the consumption of natural resources and the amount of waste sent for disposal (Delgado et al. 2009, Villanueva et al. 2010). The study by Srour et al. (2013) emphasizes the significance of establishing markets for recycled CDW. Materials not fulfilling the EOW requirements can be recycled and reused under the waste regime (see section 2.4).

The lack of harmonisation creates legal uncertainty for waste management decisions and for the different actors dealing with specific waste streams, including producers and users of the recycled material (Delgado et al. 2009). Some Member States have developed different, and not always compatible, frameworks for regulating the recovery and reuse of secondary materials. In some cases, materials generated in one country are not considered to be waste, however if transported to countries with different regulatory approaches, they might be considered waste and require waste management control. Consequently, producers and users tend to restrict themselves to national markets avoiding administrative and judicial costs or risks of an unclear waste status of the materials.

3 RESEARCH AND REGULATIONS

Research and regulations concerning waste are published at European level as well as at international or Flemish level.

3.1 Europe

3.1.1 Standards related to sustainability aspects

CEN/TC 350 (Comité Européen de Normalisation, technical committee) is responsible for the development of standardized methods for the assessment of the sustainability aspects over its life cycle of new and existing construction works and for standards for the environmental product declaration of construction products (Afnor Normalisation 2012). The purpose of this series of European Standards is to enable comparability of the results of assessments. CEN/TC 350 includes environmental as well as social and economic performances at framework, building and product level (see Figure 85). However, the current study only focuses on the environmental impacts during the life cycle of the bituminous pavement.

The newest of the seven workgroups in CEN/TC 350 works on civil engineering works. A standard that will be relevant for road construction works is under enquiry (CEN 2015), namely prEN 15643-5 "Sustainability of construction works – Sustainability assessment of buildings and civil engineering works – part 5: framework on specific principles and requirement for civil engineering works".

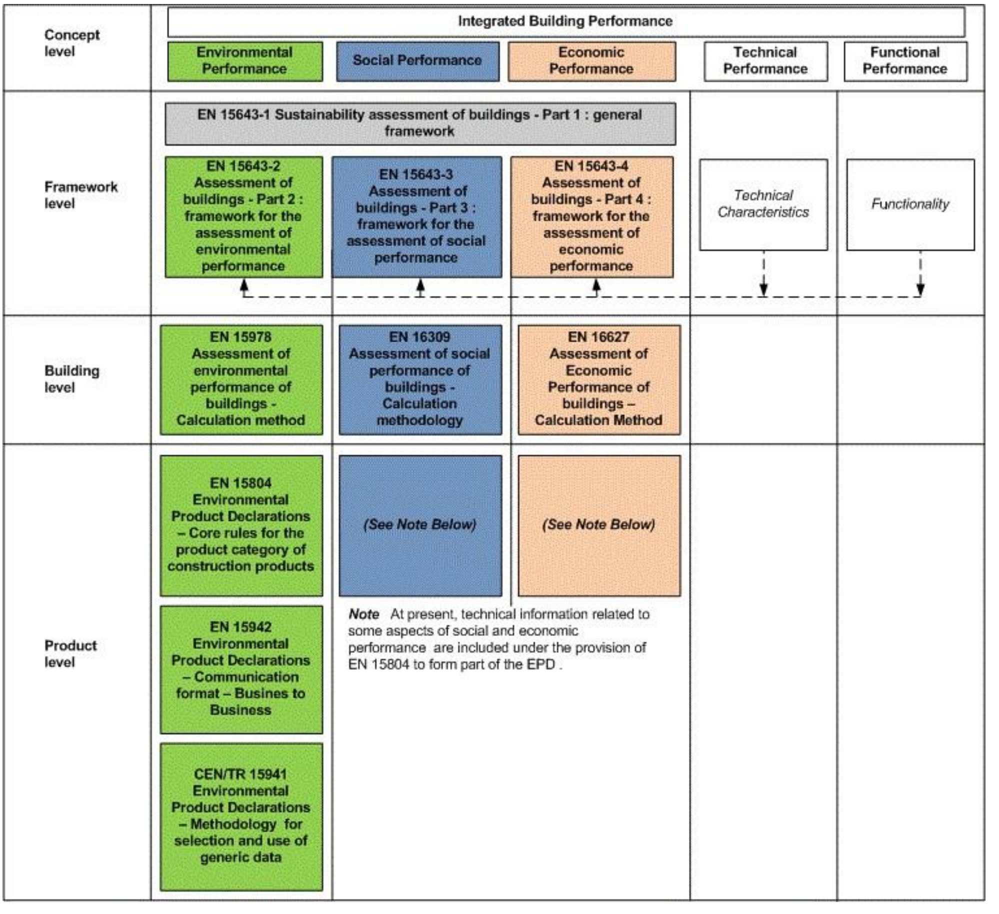

Figure 85: Overview of standards written by CEN/TC 350 (Afnor Normalisation 2012)

Standard EN 15804 is most related to the current research and provides core product category rules (PCR). These core PCR describe, among others, which stages of a product's life cycle are considered in Environmental Product Declarations (EPD) and which processes are to be included in the life cycle stages.

An important modelling issue is the allocation of processes between the end-of-life stage (C1-4 in EN 15804) and the supplementary LCA information module D: 'benefits and loads beyond the system boundary'. The definition of EOL and EOW is crucial for this modelling issue.

Generic LCA data (like the ecoinvent database) do not contain data about the benefits and loads beyond the system boundary (module D). These types of data are sometimes included in EPD. As described by Silvestre et al. (2014) and in CEN (2012) the net impacts in module D are calculated applying a justified value-correction factor in order to reflect the difference in functional equivalence where the output flow does not reach the functional equivalence of the substituting process. This aligns for RAP because there is not a total functional equivalence due to the aging of the binder inducing different rheological and mechanical properties.

Besides, as explained by Buyle et al. (2015), stages A, B and C apply a cut-off approach whereby the benefits and burdens of recycled products are assigned to the production phase (recycled content), while module D relies on the concept of system expansion (or avoided products or substitution methodology). In order to avoid double counting of the impacts of the recycling process, this substitution methodology in module D is only calculated for the net flow of secondary fuels or materials exiting the product system. The net output flows of the system under study is the amount of secondary material exiting the product system minus the amount of secondary material entering the system, assuming the same properties. The amount of secondary material that replaces one to one the input of secondary material as closed loop is allocated to sub-stage A1 of the system under study.

3.1.2 Waste framework directive and Joint Research Centre

As Figure 86 illustrates, the revised Waste Framework Directive (European Commission 2008), Article 6(1-2) defines four conditions that should be fulfilled in order to achieve the end-of-waste state. These conditions are general and applicable for all waste streams. EOW criteria should be set for specific materials using the procedure described in the committee procedure, Article 39(2) of the WFD.

A methodology to develop the EOW criteria for specific materials has been elaborated by the Joint Research Centre (JRC) (Delgado et al. 2009, Villanueva et al. 2010) and has been agreed on with the Member States. The interaction between both scientific JRC reports and the WFD is illustrated in Figure 86.

The report by Villanueva et al. (2010) proposes a list of material streams that qualify for an assessment on their suitability for the development of EOW criteria. Bituminous mixture; asphalt; bricks, tiles and ceramic; and concrete are grouped into CDW aggregates. Villanueva et al. (2010) assigned CDW to the first category with waste streams that are in line with the basic principles of EOW and suited for further EOW criteria assessment. The heterogeneous CDW stream should be disaggregated into subcategories with high value recyclables and low value sub fractions that contain contaminants (Kourmpanis et al. 2008). When applicable, EOW criteria will be restricted to specific applications and not to all the outputs of the stream. Some of the materials are almost always recyclable without further processing, some others are not.

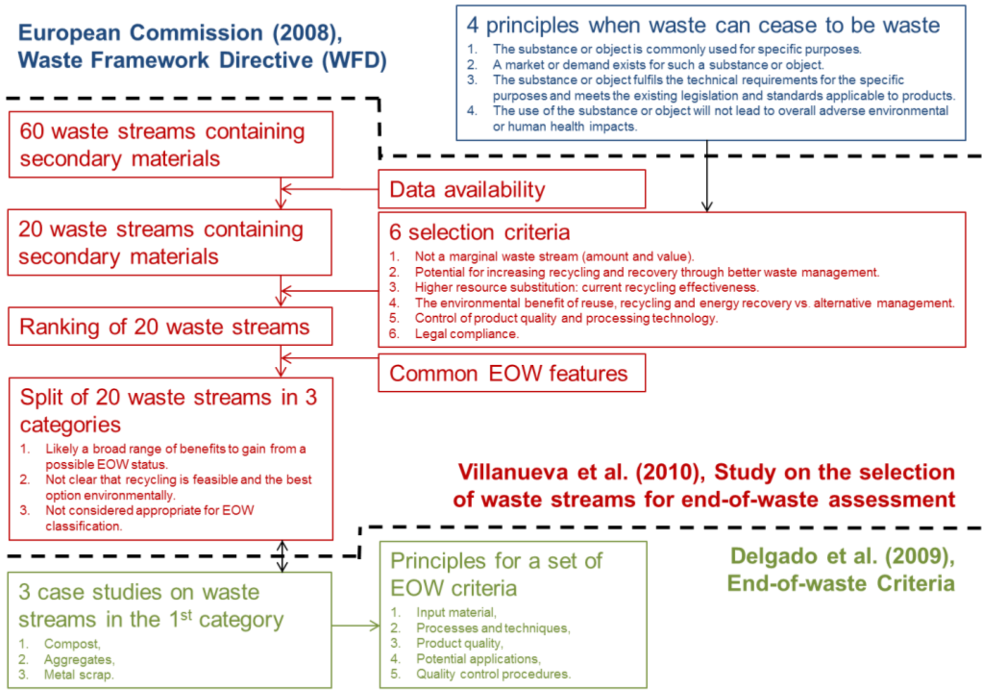

Figure 86: European research and regulations on the end-of-waste principle

Delgado et al. (2009) looked into a possible methodology for developing EU wide EOW criteria and applied this to three different case studies e.g., on aggregates. The methodology contains three parts: i) five principles for the definition of a set of EOW criteria; ii) guidelines for impact assessment and iii) an operational procedure guideline in order to develop EOW criteria.

The five principles for the definition of end-of-waste (see Figure 86, first part of the methodology) are listed and clarified with examples for road residues (RAP).

1. Input material: Hazardous substances should be identified and an assessment should reveal in which way the hazard can be controlled (during processing or need to be removed at source). An initial assessment on the composition of the road must be done, prior to the recovery process e.g., with a marker for the detection of tar (Opzoekingscentrum voor de Wegenbouw 2006). Different rules apply to different categories of road residues: i) RAP containing tar; ii) RAP containing mineral wastes (e.g., bottom ash from municipal waste incineration); iii) RAP not containing tar nor mineral wastes.
2. Processing: Process control parameters to guarantee quality may be used as part of the EOW requirements. For example: i) defining the maximum temperature for RAP as 130 °C (Leyssens et al. 2013) in order to avoid further oxidation of the binder and associated worse mechanical behaviour of the mixture or ii) the size fraction of the RAP: large pieces are broken in order to reach a certain level of

homogeneity and the foreseen quality of the new asphalt mixture (De Lira et al. 2015, Lopes et al. 2015).

3. Product requirements: Often the material will need to be tested to demonstrate compliance with the applicable quality standards e.g., EN 13043 for RAP (CEN 2013). Additional product quality requirements, such as pollutant limit values (e.g., study for aggregates by Saveyn et al. (2014)) or maximum content of impurities may be part of the end-of-waste requirements, in order to ensure that risks are reduced or minimized.
4. Product application: An analysis of potential uses is required in order to conclude on a potential market or demand and to assess the environmental risks associated with such uses. RAP is used in new mixtures or as foundation material or for unpaved tracks. An LCA study on the environmental impact of using RAP as applied in Flanders should be part of this analysis.
5. Quality control procedures: If conditions on source control, processing parameters and product quality standards are defined as part of end-of-waste requirements, these should be under acknowledged quality control procedures in order to guarantee the actual fulfilment of end-of-waste product quality requirements. Quality requirements for asphalt mixtures for public works are described in the Flemish road standard SB250 and are verified by COPRO and BENOR.

In accordance with the third principle, the European Joint Research Centre investigated how pollutant limit values could be elaborated in a possible EOW framework for aggregates (Saveyn et al. 2014). Compliance with the limit values for acceptance of waste at inert waste landfills has been evaluated for recycled asphalt (and others) and the potentially most critical substances (on this basis) have been identified. The potential final EOW criteria may be more stringent than the EU leaching limit values for landfilling of inert waste.

Based on 10 datasets with the release as a function of pH and 38 datasets with the release as a function of L/S-ratio, the potentially most critical substances from leaching of recycled asphalt are evaluated. The selenium (Se) amount is consistently close to the limit value if tested with the pH-dependence test, but strictly, the recycled asphalt do not exceed the EU leaching limit values for landfilling of inert waste.

Flanders, Finland, Netherlands and Sweden use a leaching test according to CEN/TS 14405, while most other EU Member States use a test based on EN 12457. Flanders includes fewer substances than other EU Member States for the leaching limit values for waste-derived aggregates. Additionally, the substance selenium is not included in the Flemish regulation.

The second part of the general methodology (Delgado et al. 2009) includes the assessment of the potential impacts of an end-of-waste scenario compared with a waste scenario. Such impact assessment should include impacts in various domains: environmental and health, economic, market, legislative and other socioeconomic impacts. Examples of such studies were found in literature: Butera et al. (2015) evaluated the environmental impact of the EOL phase of CDW, either used as unbound aggregate in road construction or landfill disposal; Weil et al. (2006) investigated closed loop recycling of CDW in concrete production; and the validity of the waste hierarchy by using life cycle assessment on recycling, incineration and landfilling was investigated by Moberg et al. (2005) for newsprint and PET waste fractions and by Huysman et al. (2015) for plastics from small domestic appliances or for household plastics waste.

Delgado et al. (2009) includes also an operational procedure guideline as the third part of the general methodology for developing EU wide EOW criteria. Although the procedure includes nine steps, these can be summarized to four iterative steps:

1. Initial investigation and selection of relevant waste streams (Villanueva et al. 2010);
2. Methodology and pilot case studies (Delgado et al. 2009);
3. Technical proposal;
4. Drafting and voting regulations.

Steps 3 and 4 should be completed for the development of EOW regulations for aggregates. Nevertheless, elements from completed studies will be used (Delgado et al. 2009, Saveyn et al. 2014, Villanueva et al. 2010). The iterative procedure is guided by a technical work group, consulting an expert group for feedback. Finally, the regulation could only become effective after formal adoption process following the regulatory procedure foreseen in the revised WFD, Article 39(2).

The first EOW Regulation was adopted and entered into force in 2011 and was on steel and aluminium scrap (333/2011). Other technical studies have led to the development of regulations on glass cullet (1179/2012) and copper scrap (715/2013).

3.1.3 REACH regulation

REACH regulation of the European Parliament and the Council is the Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals. The REACH regulation includes specific obligations on manufacturers, importers and downstream users of substances on their own, in preparations and in articles. The main principle of the legislation is that the product cannot be placed on the market if no data are provided.

The function of aggregates from construction and demolition waste is mainly determined by the shape and surface of the particles rather than by the chemical properties (e.g. maximum of allowed solubility). These particles are therefore considered to be articles and hence may be exempted from registration under REACH (Delgado et al. 2009).

3.2 Flanders

The European Waste Framework Directive (European Commission 2008) has been converted by the Flemish region into a Material Decree (23 December 2011) (Flemish Government 2011) and the connected implementation decision VLAREMA (17 February 2012): Decree of the Flemish Government adopting the Flemish Material Cycles and Waste (Sustainable Management) Regulation (Flemish Government 2012). In Flanders, the management of waste is legally regulated by VLAREMA. Furthermore, the Public Waste Agency of the Flemish region (OVAM) is responsible for the achievement of waste management objectives. In general, Flanders follows the European waste hierarchy: prevention, re-use and recycling.
The Material Decree and VLAREMA use the same assessment framework for waste materials ceasing to be waste and for residual materials qualifying for being secondary materials and aims to substitute primary raw material by recycled materials or residual materials in an environmentally safe way (OVAM 2013). VLAREMA merely makes the distinction between 'waste materials' and 'resources'. There is no longer a way in between, formerly defined as 'secondary raw materials'.

In Flanders, there is a certain hierarchy of regulations considering the waste status of a material. No European EOW Regulation for recycled asphalt is into force and hence the waste stream should comply with specific Flemish regulations. The Flemish region specified some criteria for four utilisation areas of materials for a specific purpose (fertilizer or soil improver, building material, soil, or artificial waterproofing layer of alkali silicate on landfill sites) and two materials streams (resources produced by or for use in metallurgic production processes for non-ferrous metals; and resources produced by metallurgic production processes for ferrous metals). Recycled asphalt is classified according to the utilisation area 'building materials'. The compliance of the materials with the criteria might be proved based on a declaration of raw material or another control system e.g., unity rules for recycled aggregates.

The Flemish Government has a considerable progressive waste legislation. For example, the Flemish target is to recycle 90% of the CDW by 2020. Furthermore, Flanders has carried out specific scenario-based risk and impact assessments instead of following the EU leaching limit values for landfilling of inert waste as a basis for the leaching criteria for the use of waste-derived aggregates as construction materials. In Flanders, the use of waste-derived aggregates is governed by waste legislation.

Dierckx et al. (2014) gives more information related to recycled asphalt, the use in asphalt and other applications and the related legislation in Flanders.
Recycled asphalt, which will be used in new asphalt mixtures, is not assessed to be waste and hence the material is not subjected to VLAREMA or the unity rules for recycled aggregates. Nevertheless, a maximal aggregate size is defined as 40 mm for homogeneity class HE and H+, which must be reached when using the fundamental method to design an asphalt mixture for a base course. Furthermore, a voluntary technical certification by COPRO is possible according to TRA13 (4.0).
Recycled asphalt, used for other applications, is subjected to the VLAREMA Articles 2.3.2.1; 2.3.2.2; 5.3.3 and the unity rules. In some cases, a declaration of raw material might be necessary and a voluntary technical and environmental certification by COPRO or Certipro is possible according to TRA10, TRA11, and CRT-LB001.
Recycled asphalt, containing tar is subjected to VLAREMA 5.3.3.4 and can only be used with a user certificate from OVAM and only in cold applications like foundation in asphalt cements. This is only applicable for big projects (at least 1500 m^3 tar containing asphalt) that should be inventoried. OVAM aims to remove tar from the material cycle and by 2020 tar must no longer be entering the material cycle through recycling. Thermal processing of tar containing asphalt gives a granulate without tar. This processing is investigated in a Flemish pilot project.

4 DISCUSSION

The discussion on end-of-life and end-of-waste state is important for (LCA) modelling. As stated by Allacker et al. (2014), there is currently no single, widely accepted approach to modelling EOL for environmental assessment of products. The influence of different EOL allocation methods (to allocate the impacts and benefits of recycling within the life cycle) on the environment by a product are investigated by different researchers. The differences between the cut-off and the substitution approach were illuminated in the study by Huang et al. (2012). Nicholson et al. (2009) include additional allocation methods (loss of quality, closed loop and 50/50) and found that these different approaches can result in different rank ordering of materials preference.

The authors of the current contribution generated Figure 87 for bituminous road pavements, based on the principles as described in the literature (Leroy et al. 2012, Silvestre et al. 2014). The end-of-life (EOL) and the end-of-waste (EOW) stage, the different stages of EN 15804 and the different waste and material streams as defined by Silvestre & Lasvaux (2012) are indicated. Figure 87 is only designed in analogy with the metal scrap regulations, but is not based on EOW regulations on aggregates or CDW.

If the asphalt material is released from the road construction by milling the old pavement, it has reached the end-of-life (EOL) stage. A material can only reach the end-of-waste (EOW) state after a sequence of treatment processes that prepares it for use as a direct input into the next product system. Crushing and sieving RAP are seen as processes before the EOW state and thus assigned to the end-of-life (EOL) stage C of EN 15804. The end-of-waste (EOW) state is indicated on Figure 87. Only the impacts from the net material flow (RAP) are assigned to module D.

The authors recognize an inconsistency in Figure 87 since the material flows PW, CW and UW never passed the EOL stage and therefore, theoretically these are not waste streams. Moreover, according to the standard, the impact of the waste processing operations of these material streams are not included in stage C, but are accounted for in the remaining life cycle stages A3, A5 and B2. However, in practice, crushing and sieving is applied for PW, CW and UW before they are reused in new asphalt mixtures. According to the standard, only the impact from crushing and sieving DW is assigned to stage C3.

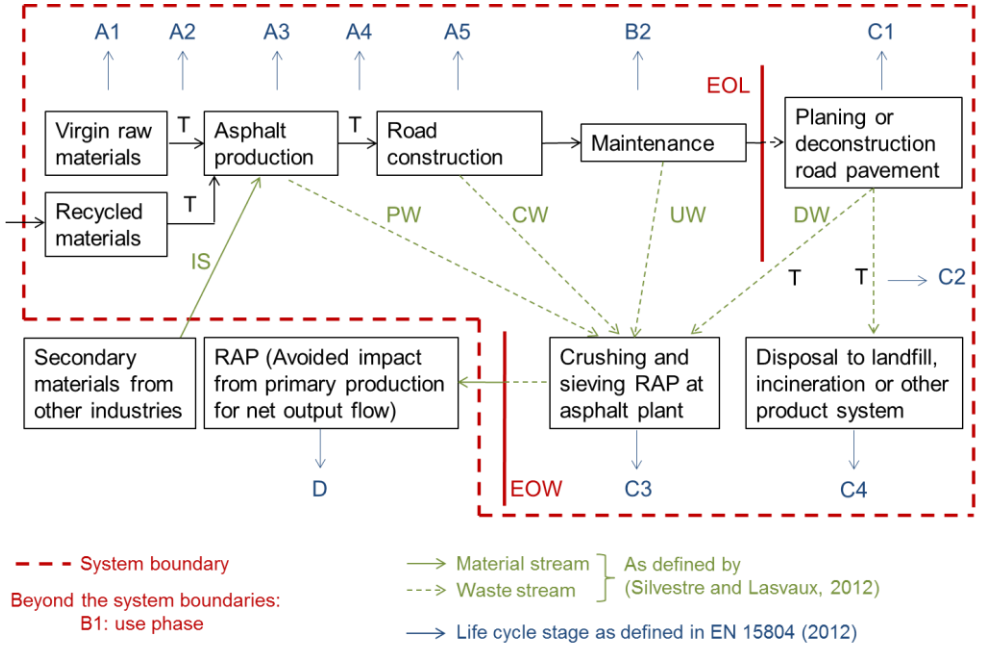

Figure 87: Life cycle of bituminous road pavement with the indication of the stages as defined in EN 15804

In the first place, RAP seems to be 100% recyclable. New asphalt mixtures can contain 50% and more RAP, without decreased performance characteristics. However, if RAP is multicycled, the binder will be aged and no longer fulfil the required performance characteristics for a bound asphalt mixture. RAP can then be used as unbound material in the sub-structure of the road or has to be rejuvenated.
Based on the figures of COPRO (2015) in Table 38, the recycled content in asphalt mixtures can be calculated as the rate of asphalt mixtures containing RAP (61%) multiplied by the average RAP content in mixtures that contain RAP (43%). The recycled content in asphalt mixtures then is 26%. The recycling rate from bituminous road pavements is 61%. This means that 61% of the available RAP is used to produce the same material i.e., asphalt mixtures for road pavements. The recycled content and the recycling rate are used for the calculation of the net output flows of the system under study as described in subsection 3.1.1. For example, for the asphalt production of 10 ton, the end-of-life recycling will generate 6.1 ton RAP (recycling rate), while only 2.6 ton RAP has been used at the production stage (recycled content) (module A1 in EN 15804). Hence the product system is a net producer of 3.5 ton RAP, of which the environmental aspects will be reported in module D.
As described above, a justified value-correction factor must be applied in order to reflect the difference in functional equivalence. Although this is applicable to RAP, it is not clear how to calculate this value-correction factor.

In Flanders, the use of tar containing RAP is allowed in cold bound applications if some specification are met, e.g. a user certificate from OVAM. In this way, tar remains in the material cycle. Therefore, a technique with definitive exclusion of tar is preferable. In the Netherlands, tar containing RAP is burned. In practice, RAP is rarely if ever traded internationally and even the trade of RAP between different Flemish asphalt plants is limited.

5 CONCLUSIONS

At this moment, no European end-of-waste (EOW) regulations for construction and demolition waste (CDW) aggregates are into force. Implying that European Member States make up own regulations is causing incommensurability. The authors of this contribution suggest the definition of the end-of-life (EOL) stage as the moment before the milling or deconstruction of the road pavement; and the EOW stage as the moment after crushing and sieving the reclaimed asphalt pavement (RAP) (at the asphalt plant) and before the RAP is heated (in the parallel drum) in order to add in a new asphalt mixture. Therefore, this heating of RAP in the parallel drum is beyond the system boundaries and is assigned to module D as described in EN 15804. All processes between the EOL and the EOW are assigned to life cycle

stage C (end-of-life stage as defined by EN 15804) i.e., i) planning or deconstruction the pavement; ii) incineration, disposal to landfill, or to another product system; and iii) crushing and sieving the RAP at the asphalt plant.
Although Flanders has at this moment a good waste strategy and a high recycling rate compared with other European countries, an effort is necessary in the field of tar containing bituminous road residues. The ambitious, Flemish objective to refuse tar to enter the material cycle through recycling by 2020 needs a practical approach.

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