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TOTEM potential

PART 2: ESTIMATION OF THE POTENTIAL OF TOTEM FOR EXTENSION TO SUBSECTORS IN CONSTRUCTION

Study commissioned by public waste agency of Flanders

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Date of publication: October 2020

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Document information

Reference	OVAM number 5938 Potentieelinschatting van de MMG-tool inzake milieu-impactreductie en bij uitbreiding naar andere subsectoren in de bouw
Contracting authority	Openbare Vlaamse Afvalstoffenmaatschappij (OVAM) Team Bouw en team Onderzoek & Monitoring Stationsstraat 110 2800 Mechelen
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Version	2020-08-03

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Executive summary

Buildings have a significant impact on the environment. This impact is due to both operational energy use and the use of construction materials. The online TOTEM tool allows to calculate and optimise the environmental impact of buildings in Belgium. The first version of the tool was released in 2018. The three regional authorities (OVAM, IBGE-BIM and SPW), who designed the tool, have the ambition to further develop it and have already taken various steps in that direction, including the present TOTEM potential study. This study has two main objectives:

- to estimate the potential reduction in environmental impact of buildings that could be achieved by using the TOTEM tool during the design phase and therefore the potential of TOTEM to help achieve policy goals (Part 1);
- to assess the potential of the TOTEM methodology to improve the environmental performance of non-building related construction works (mainly civil engineering works) (Part 2).

Within this part of the study (Part 2), specific aspects and attention points regarding the environmental impact assessment of infrastructure works are investigated based on a literature study and a case study analysis for road construction. Based on these insights, the potential to extend the TOTEM tool and methodology to subsectors in construction is discussed and specific recommendations for the further development of the TOTEM tool are formulated.

The literature study focuses on ongoing developments in standards and regulations, existing studies and research projects and foreign experiences regarding the environmental performance of infrastructure works. The review of standards and regulations shows that this topic is still developing and lagging on developments in the building sector in general. Standards, which were originally developed for buildings, now serve as a source of inspiration for extensions to the infrastructure works sector, with a focus on the necessary adaptations for specific conditions related to this type of works. The review of existing studies and research projects shows that the calculation of this impact is not always done in a uniform manner. Different service lives, system boundaries, methods, scenarios, … are used, making the results of the different studies incomparable. The scope also strongly influences the results: in addition to the building materials used, other aspects such as construction activities, the use phase and traffic pressure can play an important role. In the Netherlands, an evaluation method, a database and a calculation tool especially developed for the environmental evaluation of infrastructure works already exist. These are based on the calculation rules and tools for buildings and contain additional calculation rules, provisions, and environmental information for GWW works.

To evaluate whether the TOTEM methodology can be used practically for constructions other than buildings, two road variants, i.e. a bituminous road and a concrete road, have been analysed for their environmental impact using life cycle analysis (LCA). The composition of the roads represents current practice in Belgium. For the bituminous road, also a variant road was defined based on current

optimisation options for the different layers in the road structure (i.e. use of recycled aggregates and lower production temperature).

The results for the bituminous roads indicate that the asphalt sublayer has the largest environmental impact, followed by the foundation and the asphalt top layer. For the asphalt layers, the production process has the largest impact. When comparing the variant bituminous road with the reference bituminous road, a maximum reduction in environmental impact of about 20% can be achieved when applying optimisation options to all three layers. The optimisation potential for the individual layers varies between 7% and 46%. Similar results are obtained when only looking at the global warming potential indicator (CO_2 emissions). The results for the concrete road indicate that the concrete top layer (including concrete and reinforcing steel) has the largest environmental impact, followed by the foundation and the asphalt sandwich layer. The relative importance of the steel reinforcement is higher when considering the total environmental impact than when only looking at the global warming potential indicator (CO_2 emissions).

To get an idea on the relevance of the impact of the road construction sector compared to the residential building sector in Flanders, a rough scaling-up exercise comparing the environmental impact of the yearly installation of bituminous roads and the yearly construction of new houses in Flanders was carried out. This exercise pointed out that the total environmental impact of roads could be as important as the total environmental impact of new houses in Flanders, in case the operational energy use of the houses is not considered. However, these numbers should be used with a lot of care since many assumptions had to be made.

In the final chapters, the most important lessons learned regarding the potential use of TOTEM for other sectors are summarized and concrete recommendations are formulated regarding the necessary functionalities of TOTEM in case of an extension to other sectors. The most relevant differences and points of attention that are identified for the environmental performance assessment of infrastructure works are:

- There is a need for additional life cycle stages when evaluating civil engineering works. For example, the “users’ use stage” (B8) includes the environmental impact caused by the users of the infrastructure (e.g. emissions or energy use by the vehicles using the road) and can represent more than 80-90% of the total impact of a road over its entire lifecycle.
- The reference study period might vary significantly depending on the type of infrastructure work.
- An important optimisation potential is situated at the material level, so insights and the possibility to make modifications at the “sub-material” level are necessary.
- The library of the available work sections in the TOTEM tool would have to be expanded to cover the typical materials and processes used in engineering and infrastructure works.
- It is necessary to develop sector-specific scenarios for transport to site (module A4) and end-of-life (EOL, modules C1-4).

- Only limited data is available regarding construction site impacts. On the one hand additional research and data collection is needed for this. On the other hand, it appears that the potential for optimisation of construction site impacts is rather situated in the companies' machine parks than in the material selection process.

In conclusion this study shows that the general TOTEM methodology can be used to assess the environmental performance of construction works other than buildings. However, in terms of practical implementation, this would require the definition of additional scenarios (e.g. transport, EOL) and default values (e.g. for the reference service life) specific to the construction types to be evaluated. Also, the library of materials and processes would have to be extended, and there appears to be an important need to allow for modifications at the level of the material composition. Finally, this study also reveals that additional modelling options or tools might have to be developed to assess and optimise the environmental performance of the installation phase (construction activities).

Samenvatting

Gebouwen hebben een belangrijke impact op het leefmilieu omwille van het operationeel energieverbruik en het gebruik van bouwmaterialen. De online TOTEM tool laat toe om de milieu-impact van gebouwen in België te berekenen en te optimaliseren. De eerste versie van de tool werd gelanceerd in 2018. De drie regionale overheden (OVAM, BIM en SPW), die de tool uitgewerkt hebben, willen deze verder ontwikkelen en hebben hiertoe al verschillende stappen ondernomen, waaronder deze TOTEM Potentieelstudie. Deze studie omvat twee grote doelstellingen:

- het inschatten van de potentiële reductie in milieu-impact van gebouwen door het gebruik van de TOTEM tool tijdens de ontwerpfase en zo ook het potentieel van TOTEM om beleidsdoeleinden te bereiken (Deel 1)
- het inschatten van het potentieel van de TOTEM methodologie om de milieuprestaties van niet-gebouwgerelateerde bouwwerken (vooral infrastructuurwerken) te verbeteren (Deel 2).

In dit deel van de studie (Deel 2) worden specifieke aspecten en aandachtspunten aangaande de milieuevaluatie van infrastructuurwerken geanalyseerd met behulp van een literatuurstudie en een casestudieanalyse van wegen. Op basis van deze inzichten wordt het potentieel van een uitbreiding van de TOTEM tool en methodologie naar andere subsectoren in de bouw besproken en worden specifieke aanbevelingen geformuleerd aangaande de verdere ontwikkeling van de TOTEM tool.

De literatuurstudie spitst zich toe op lopende ontwikkelingen in normen en regelgeving, bestaande studies en onderzoeksprojecten en buitenlandse ervaringen aangaande de milieuprestaties van infrastructuurwerken. Het literatuuronderzoek van normen en regelgeving toont aan dat dit onderwerp nog volop in ontwikkeling is en achteroploopt op de ontwikkelingen in de algemene bouwsector. Normen, die aanvankelijk opgesteld werden voor gebouwen, dienen nu als inspiratiebron voor uitbreidingen naar infrastructuurwerken, met focus op de nodige aanpassingen voor specifieke omstandigheden bij dit soort werken. De studie van bestaande studies en onderzoeksprojecten toont aan dat de berekening van deze impact niet altijd op een uniforme manier gebeurt. Er worden verschillende levensduren, systeemgrenzen, methodes, scenario's, … gebruikt, waardoor de resultaten van de verschillende studies onderling niet vergelijkbaar zijn. De uitgangspunten beïnvloeden ook sterk de resultaten: naast de gebruikte bouwmaterialen, kunnen ook andere aspecten, zoals bouwactiviteiten, gebruik en verkeersdruk, een belangrijke rol spelen. In Nederland bestaan er reeds een bepalingsmethode, een databank en een rekeninstrument, speciaal ontwikkeld voor de evaluatie van infrastructuurwerken. Deze zijn gebaseerd op de rekenregels en tools voor gebouwen en bevatten bijkomende rekenregels, bepalingen en milieu-informatie voor GWW-werken.

Om na te gaan of de TOTEM methodologie in de praktijk gebruikt kan worden voor andere bouwwerken dan gebouwen, wordt de milieu-impact van twee varianten voor wegen, nl. een asfaltweg en een betonweg, bepaald aan de hand van

levenscyclusanalyse (LCA). De samenstelling van de wegen komt overeen met de huidige praktijk in België. Voor de asfaltweg wordt ook een variant gedefinieerd, gebaseerd op huidige optimalisatiemogelijkheden voor de verschillende lagen van de wegstructuur (nl. gebruik van gerecycleerde granulaten en een lagere productietemperatuur).

De resultaten voor de asfaltweg tonen aan dat de asfaltonderlaag de grootste milieu-impact heeft, gevolgd door de fundering en de asfalttoplaag. Bij de asfaltlagen heeft het productieproces de grootste impact. Een vergelijking tussen de referentieweg en de variant toont aan dat een maximale reductie in milieu-impact van zo'n 20% bekomen kan worden wanneer de optimalisatie toegepast wordt op de drie lagen. Het optimalisatiepotentieel voor de individuele lagen varieert tussen 7% en 46%. Gelijkaardige resultaten worden bekomen voor de indicator voor klimaatopwarming (CO_2-emissies). De resultaten voor de betonweg tonen aan dat de betonnen toplaag (bestaande uit stortklaar beton en wapeningsstaal) de grootste impact heeft, gevolgd door de fundering en de asfalttussenlaag. Het relatieve belang van het wapeningsstaal is hoger bij de totale milieu-impact dan bij de indicator voor klimaatopwarming (CO_2-emissies).

Om een idee te krijgen van het belang van de milieu-impact van de wegenbouwsector in vergelijking met de residentiële bouwsector in Vlaanderen, wordt een ruwe opschaling uitgevoerd waarbij de impact van de jaarlijkse installatie van asfaltwegen vergeleken wordt met de jaarlijkse bouw van nieuwe woningen in Vlaanderen. Hieruit blijkt dat de totale impact van de wegen even groot kan zijn als de totale impact van de nieuwe woningen in Vlaanderen, indien de bijdrage van het operationeel energieverbruik van de woningen buiten beschouwing gelaten wordt. Deze cijfers moeten echter met voorzichtigheid behandeld worden, omdat hiervoor meerdere aannames gemaakt moeten worden.

In de laatste hoofdstukken worden de belangrijkste lessen aangaande het potentiële gebruik van TOTEM voor andere bouwsectoren samengevat en worden concrete aanbevelingen geformuleerd over de nodige functionaliteiten van TOTEM in geval van een uitbreiding naar andere sectoren. De belangrijkste verschillen en aandachtspunten voor de milieuprestatie van infrastructuurwerken zijn:

- Er is nood aan bijkomende levenscyclusfasen voor de milieu-evaluatie van infrastructuurwerken. Zo bevat de gebruikersfase (B8) de milieu-impact veroorzaakt door de infrastructuurgebruikers (vb. emissies of energieverbruik door voertuigen op de wegen). Deze kan tot meer dan 80-90% van de totale milieu-impact van een weg over zijn gehele levenscyclus vertegenwoordigen.
- De referentiestudieperiode kan sterk variëren in functie van het type infrastructuurwerk.
- Een belangrijke mogelijkheid tot optimalisatie situeert zich op het materiaalniveau. Bijgevolg zijn inzichten in en de mogelijkheid tot wijzigingen op 'sub-materiaalniveau' noodzakelijk.

- De bibliotheek van beschikbare verwerkte materialen in de TOTEM tool moet uitgebreid worden met typische materialen en processen voor infrastructuurwerken.
- Sectorspecifieke scenario's voor transport naar de werf (module A4) en voor de levenseindefase (EOL, modules C1-4) moeten ontwikkeld worden.
- Er zijn slechts beperkte gegevens beschikbaar over de milieu-impact tijdens de werffase. Hiervoor zijn enerzijds bijkomend onderzoek en dataverzameling noodzakelijk. Anderzijds blijkt het optimalisatiepotentieel voor impact op de bouwwerf eerder te liggen in het machinepark van de aannemer dan in de selectie van bouwmaterialen.

Deze studie toont aan dat de algemene TOTEM methodologie gebruikt kan worden om de milieuprestatie van andere bouwwerken dan gebouwen in te schatten. Wat de praktische implementatie betreft, zou dit echter de definitie vereisen van bijkomende scenario's (vb. transport, EOL) en default-waarden (vb. voor referentielevensduur) specifiek voor deze bouwwerken. Bovendien zou de bibliotheek van materialen en processen uitgebreid moeten worden en bestaat er een nood om wijzigingen op materiaalniveau toe te laten of te ondersteunen. Tot slot toont deze studie aan dat bijkomende modelleringsopties of tools ontwikkeld zouden moeten worden om de impact van de werffase (bouwactiviteiten) beter in te schatten en te optimaliseren.

Résumé Exécutif

Les bâtiments ont un impact élevé sur l'environnement. Cet impact s'explique à la fois par la consommation d'énergie opérationnelle du bâtiment mais aussi par l'utilisation des matériaux de construction. L'outil en ligne TOTEM permet de calculer et d'optimiser l'impact environnemental des bâtiments en Belgique. La première version de cet outil a été lancée en 2018. Les trois services publics régionaux (OVAM, IBGE-BIM et SPW) qui ont conçu l'outil, ont l'ambition de le développer encore d'avantage. Ils ont d'ailleurs déjà pris diverses mesures en ce sens, dont la réalisation de la présente étude Potentiel de TOTEM. Cette étude a deux objectifs principaux :

- Estimer la réduction de l'impact environnemental des bâtiments qui pourrait potentiellement être atteinte en utilisant l'outil TOTEM au cours de la phase de conception et ainsi évaluer le potentiel de TOTEM pour aider à atteindre les objectifs politiques (partie 1) ;
- Evaluer le potentiel de la méthodologie TOTEM pour améliorer la performance environnementale des travaux de construction qui n'ont pas pour objet des bâtiments (principalement les travaux de génie civil) (Partie 2).

Dans cette partie de l'étude (Partie 2), les aspects spécifiques et les points d'attention concernant l'évaluation de l'impact environnemental des travaux de génie civil (infrastructures) sont étudiés sur base d'une étude bibliographique et d'une analyse d'étude de cas pour la construction de routes. A partir de ces informations, la possibilité d'étendre l'outil et la méthodologie TOTEM à des sous-secteurs de la construction est examinée et des recommandations spécifiques pour le développement ultérieur de l'outil TOTEM sont formulées.

L'étude bibliographique se concentre sur les développements en cours en matière de normes et de réglementations, sur les études et les projets de recherche existants et sur les expériences étrangères concernant la performance environnementale des travaux d'infrastructure. L'examen des normes et réglementations montre que ce sujet est encore en développement et en retard sur les évolutions du secteur de la construction en général. Les normes, qui ont été initialement développées pour les bâtiments, servent maintenant de source d'inspiration pour des extensions au secteur des travaux d'infrastructure, avec un accent sur les adaptations nécessaires pour les conditions spécifiques liées à ce type de travaux. L'examen des études et des projets de recherche existants montre que le calcul de cet impact n'est pas toujours effectué de manière uniforme. Différentes durées de vie, frontière de l'étude, méthodes, scénarios, etc. sont utilisés, ce qui rend les résultats des différentes études incomparables. La portée de l'étude influence aussi fortement les résultats : outre les matériaux de construction utilisés, d'autres aspects tels que les activités de construction, la phase d'utilisation et la charge du trafic peuvent jouer un rôle important. Aux Pays-Bas, il existe déjà une méthode d'évaluation, une base de données et un outil de calcul spécialement développés pour l'évaluation environnementale des travaux d'infrastructure. Ils sont basés sur les règles et les outils de calcul pour les

bâtiments et contiennent des règles de calcul, des dispositions et des informations environnementales supplémentaires pour les travaux de génie civil.

Pour évaluer si la méthodologie TOTEM peut être utilisée de manière pratique pour des constructions autres que des bâtiments, deux variantes de route, à savoir une route bitumineuse et une route en béton, ont été analysées au niveau de leur impact environnemental à l'aide de l'analyse du cycle de vie (ACV). La composition des routes est représentative de la pratique actuelle en Belgique. Pour la route bitumineuse, une variante de route a également été définie sur base des options d'optimisation actuelles pour les différentes couches d'une chaussée (c'est-à-dire l'utilisation d'agrégats recyclés et une température de production plus basse).

Les résultats concernant les routes bitumineuses indiquent que c'est la couche bitumineuse de base qui a le plus grand impact sur l'environnement, suivie par la fondation et la couche de roulement. Pour les couches bitumineuses, c'est le processus de production qui a l'impact le plus important. Si l'on compare la variante de route bitumineuse avec celle de référence, on peut obtenir une réduction maximale de l'impact environnemental d'environ 20% en appliquant les options d'optimisation aux trois couches. Le potentiel d'optimisation pour les différentes couches varie entre 7 et 46%. Des résultats similaires sont obtenus en ne tenant compte que de l'indicateur de potentiel de réchauffement climatique (émissions de CO_2). Les résultats pour la route en béton indiquent que la couche de roulement (comprenant le béton et l'acier d'armature) a l'impact environnemental le plus important, suivie par la fondation et la couche sandwich bitumineuse. L'importance relative de l'armature en acier est plus élevée si l'on considère l'impact environnemental total que si l'on ne considère que l'indicateur de potentiel de réchauffement climatique (émissions de CO_2).

Pour avoir une idée de la pertinence de l'impact du secteur de la construction routière par rapport au secteur de la construction résidentielle en Flandre, un exercice de comparaison grossière de l'impact environnemental de l'installation annuelle de routes bitumineuses et de la construction annuelle de nouvelles maisons en Flandre a été réalisé. Cet exercice a montré que l'impact environnemental total des routes pourrait être aussi important que l'impact environnemental total des nouvelles maisons en Flandre, dans le cas où la consommation d'énergie opérationnelle des maisons n'est pas prise en compte. Cependant, ces chiffres doivent être utilisés avec beaucoup de prudence car de nombreuses hypothèses ont dû être faites.

Dans les derniers chapitres, les principaux enseignements tirés de l'utilisation potentielle de TOTEM pour d'autres secteurs sont résumés et des recommandations concrètes sont formulées concernant les fonctionnalités nécessaires de TOTEM en cas d'extension à d'autres secteurs. Les différences et les points d'attention les plus pertinents qui sont identifiés pour l'évaluation de la performance environnementale des travaux d'infrastructure sont les suivants :

- Il est nécessaire de prévoir des étapes supplémentaires du cycle de vie lors de l'évaluation des travaux de génie civil. Par exemple, la «phase d'utilisation par les usagers » (B8) comprend l'impact environnemental causé par les usagers de l'infrastructure (par exemple, les émissions ou la consommation d'énergie

des véhicules qui utilisent la route) et peut représenter plus de 80-90 % de l'impact total d'une route sur l'ensemble de son cycle de vie.
- La période de référence de l'étude peut varier considérablement selon le type de travaux d'infrastructure.
- Un important potentiel d'optimisation se situe au niveau des matériaux, de sorte qu'il est nécessaire d'avoir une vue sur le niveau sous-jacents et la possibilité d'apporter des modifications à ce niveau.
- La bibliothèque des matériaux disponible dans l'outil TOTEM devrait être élargie pour couvrir les matériaux et les processus typiques utilisés dans les travaux d'ingénierie et d'infrastructure.
- Il est nécessaire de développer des scénarios sectoriels spécifiques pour le transport vers le chantier (module A4) et la fin de vie (EOL, modules C1-4).
- Les données disponibles concernant l'impact de la phase de construction sont limitées. D'une part, des recherches et des collectes de données supplémentaires sont nécessaires à cet effet. D'autre part, il semble que le potentiel d'optimisation de cette phase se situe plutôt dans le choix des machines utilisées par l'entrepreneur plutôt que dans le processus de sélection des matériaux.

En conclusion, cette étude montre que la méthodologie générale TOTEM peut être utilisée pour évaluer la performance environnementale des travaux de construction autres que les bâtiments. Toutefois, en termes de mise en œuvre pratique, cela nécessiterait la définition de scénarios supplémentaires (par exemple, transport, EOL) et de valeurs par défaut (par exemple, pour la durée de vie de référence) spécifiques aux types de construction à évaluer. En outre, la bibliothèque de matériaux et de procédés devrait être élargie, et il semble qu'il soit important de permettre des modifications au niveau de la composition des matériaux. Enfin, cette étude révèle également que des options ou des outils de modélisation supplémentaires pourraient devoir être développés pour évaluer et optimiser la performance environnementale de la phase de construction (A5). ....

1. Context of the study

Buildings have a significant impact on the environment. An important part of this impact is due to the operational energy use. Therefore, in recent years numerous initiatives have been taken to make buildings more energy efficient. However, as buildings become more energy efficient, the absolute and relative impact of the building materials increases. Moreover, a lot of precious (primary) resources are used to produce those materials. Therefore, designers need reliable information concerning the lifecycle impact of building materials, in order to make more environmentally friendly choices during the design process.

To meet the demand of the Belgian building sector, three regional authorities (OVAM, BIM and SPW) decided to collaborate on the development of an online tool to calculate and optimise the environmental impact of buildings in Belgium. As a result of this collaboration, the first version of the TOTEM tool was released in 2018. The regions have the ambition to further develop the tool and have already taken various steps in that direction, including the present project.

The present TOTEM potential study has two main objectives.

The first objective is to estimate the potential reduction in environmental impact of buildings that could be achieved by using the TOTEM tool during the design phase and therefore the potential of TOTEM to help achieve policy goals. The results of this research are presented in a separate report (Part 1).

A second objective is to assess the potential of the TOTEM methodology to improve the environmental performance of non-building related construction works (mainly civil engineering works). The results of this research are presented in this report (Part 2).

1.1 Vision and general approach

The TOTEM methodology allows to gain insight into the environmental impact of buildings and therefore, it works as a leverage to further reduce it. By extension, TOTEM could also be used to reduce the impact of other construction works.

This study considers the potential of the TOTEM tool for use within non-building related construction works and more specifically civil engineering works. Specific aspects and attention points regarding the environmental impact assessment of infrastructure works are investigated based on a literature study. Furthermore, two case studies provide information on the environmental impact of roads, as well as on the relative potential to reduce this impact. Finally, it is evaluated to which extent the TOTEM tool and methodology are useful for the evaluation of the environmental impact of this type of construction works and recommendations for further development of the TOTEM tool are formulated.

1.2 Project team

The Laboratory of Environmental Performance of the BBRI (Wetenschappelijk en Technisch Centrum voor het Bouwbedrijf) has a broad experience in environmental evaluation of construction materials, building elements and entire buildings using Life Cycle Analysis (LCA) and a good knowledge of the European and Belgian legislation regarding this subject. More specifically, the BBRI is/was always actively involved in the different developments of the TOTEM tool.

The BRRC (Opzoekingscentrum voor de Wegenbouw) has a large experience in sustainability evaluation of road construction, including environmental impact assessment using LCA, as well as in the European and Belgian evolutions in this matter.

2. Objectives and approach

The main goal of this research is to gain insight in the potential of the TOTEM tool for use within other non-building related construction sectors and more specifically civil engineering projects.

The specific goals of the study (Part 2) are the following:

- to gain insight in the specific aspects and parameters that are of importance when considering the environmental impact of infrastructures. Points of attention regarding the environmental performance of civil engineering works will be identified.
- to gain insight in the optimisation potential for civil engineering works.
- to evaluate the practical usefulness of the TOTEM tool and methodology for the evaluation of the environmental impact of civil engineering works and to identify which additional functionalities would be needed to extend TOTEM to infrastructures.

An extensive literature study (see chapter 3) represents the basis to gain insight in the characteristics of the environmental evaluation of large civil engineering works. Both developments in standards and legislation and existing studies and research projects on this subject are screened, as well as foreign experiences.

The context of road construction is used to further refine the study (see chapter 4). Two case studies for roads are established to evaluate whether the TOTEM methodology can be used for constructions other than (residential) buildings. More specifically, the road cases provide insights in the potential needs in terms of data or specific functionalities for other construction sectors. Additionally, the insights in the environmental impact of different road constructions allow to evaluate the potential for environmental impact reduction in this sector. The results can be compared with the reduction potential for buildings as determined in Part 1 of the study (see chapter 5).

In conclusion, the most important lessons learned regarding the potential use of TOTEM for other sectors are summarized (chapter 6) and concrete recommendations are formulated regarding the necessary functionalities of TOTEM in case of an extension to other sectors (chapter 7).

3. Literature study: environmental impact of large construction and infrastructure works

Through a screening of existing (inter)national literature on the theme of environmental impact analysis specific to the infrastructural works sector, insights into the specific characteristics of that sector and its possibilities and limitations are gained. Based on this screening, the most relevant points of attention that are of importance for further evaluation of infrastructural works are identified.

Three important sections are distinguished within the literature study:

1. Standards and regulations (existing and under development)
2. Existing case studies and research
3. Developments and approach in the Netherlands

3.1 Standards and regulations

Several existing standards, standards under development and regulations were reviewed, being:

- CEN TC 350 WG 6 Civil engineering works
    - EN 15643-5:2017 - Sustainability of construction works - Sustainability assessment of buildings and civil engineering works - Part 5: Framework on specific principles and requirement for civil engineering works (published)
    - prEN 17472:2020 - Sustainability of construction works - Sustainability assessment civil engineering works - Calculation methods (draft)
- CEN Workshop Agreement
    - CWA 17089:2016 - Indicators for the sustainability assessment of roads
- CEN TC 227 Road materials
    - PCR document - Sustainability of construction works - Environmental product declarations - Core rules for road materials Part 1: Bituminous Mixtures
- ISO 21929-2 Sustainability in building construction - Sustainability indicators - Part 2: Framework for the development of indicators for civil engineering works

3.1.1 CEN TC 350 – WG 6 Civil engineering works

At European level, standards for the sustainability assessment of construction works are being developed in the context of the Technical Committees for Standardisation under the coordination of CEN in the CEN TC 350. The WG6 working group deals with specific aspects of infrastructure works, the so-called Civil engineering works.

In addition to a general framework that is rather focused on buildings, such as residential buildings (apartment buildings and individual homes) and offices, there is also a working group (WG6) which specifically deals with infrastructure works ("civil engineering works", CEW). The aim of this working group is to prepare the publication of a European standard for the methodology for calculating and evaluating the sustainability of infrastructure works. The construction works covered are very diverse, including transportation infrastructure (roads, bridges, airports, railways, ...), hydraulic engineering works (canals, ports and marine infrastructure, ...), utility infrastructure (power plants, dams, ...), hospitals, schools, military infrastructure, ...

The series of standards EN 15643-1 to -5 (Sustainability of construction works - Sustainability assessment of buildings and civil engineering works) provides the general framework [1]. Parts -1 to -4 focus mainly on the buildings sector, part 5 (published in 2017) provides specific points of attention for infrastructure works (EN 15643-Part 5: Framework on specific principles and requirements for civil engineering works). As there is a large overlap between the 5 parts at the (highest) level of general principles (Framework), a revision of this series is currently ongoing to achieve a single document EN 15643 covering both buildings and infrastructure works.

The indicators and categories of impacts to be considered are listed below.

For the "environment" section:

- water consumption (quantity, quality, regulations),
- energy consumption,
- consumption of raw materials (renewable and non-renewable, toxic substances),
- waste materials,
- pollution, emissions to air, to soil and to the aqueous environment,
- noise and vibrations,
- landscape (impacts such as habitat fragmentation, cultural heritage, visual pollution, recreation),
- biodiversity (impacts such as barrier effects, casualties, disturbance, invasive species, loss of biotopes),
- risks and resilience (including climate adaptation and compensation).

For the "social" section:

- accessibility,
- adaptability for the less mobiles,
- health and comfort,
- impacts on the neighbourhood (including nuisance to pedestrians and road users),
- noise and vibrations,
- safety and security,
- purchase of materials and services,
- stakeholder involvement,

> creation of employment,
> demographic developments,
> elements of cultural heritage.

For the "economic" section:

> life-cycle costs,
> external costs,
> urban planning (for city and country),
> effects on the local economy.

At the (more detailed) level of the structures themselves, the calculation methods for the part of the infrastructure works are documented in the prEN 17472:2020 (Sustainability of construction works - Sustainability assessment civil engineering works - Calculation methods (draft)) [2]. Currently only a draft version of this prEN exists, which is in the consultation phase. In the environmental part of this standard (the standard covers social, environmental and economic aspects), there are some differences compared to a building assessment (EN 15978: 2012) [3]. For example, there are two new modules in the standard for infrastructure works: modules A0 and B8. Module A0 covers everything that takes place before the start of the construction site. Module A0 concerns the planning phase and may include planning costs, land costs, professional fees and taxes incurred. In general, all costs and impacts before the tender may be included in the A0 stage. This phase is particularly important for the economic aspect, but in general less relevant for the environmental aspect. In module B8 'users' use', the impact related to road use (emissions from vehicles) is taken into account. Module A5 also includes the transport of people and equipment to and from the construction site. In addition, the scenarios for Module B must include the impact on climate change. The social aspect of the standard also includes a specific section on resilience against the consequences of climate change. Finally, the section 'indicators, impacts and aspects not considered in EN 15804' contains a set of non-LCA environmental indicators (water use, land use, ...) for infrastructure works.

3.1.2 CEN TC 227 – Road materials [4]

Also at the CEN (same organisation), a draft standard prEN 17392-1 (Sustainability of construction works - Environmental product declarations - Core rules for road materials, Part 1: Bituminous Mixtures) [5] is being prepared in the Technical Committee for Road Materials (CEN TC 227 Road materials), more specifically in working group 6. The standard states the rules to which an environmental performance declaration (EPD) must comply in the case of asphalt mixtures for road construction. This standard is intended as an addition to EN 15804 [6], which establishes PCR or product category rules for construction products (in general) that wish to communicate a type III environmental performance declaration. The text indicates how certain concepts from EN 15804 are to be understood when it comes to the production of asphalt, which parts of the life cycle of asphalt are (not) included in the preparation of an EPD, whether the environmental impact of certain production equipment is (not) included, etc. The EPDs developed according to this PCR could thus be used as a data source for the TOTEM tool, replacing the generic environmental data for bituminous products.

3.1.3 CEN Workshop Agreement - CWA 17089:2016 [7]

Apart from the TC350 mentioned above, certain experts sometimes organise separate standardization initiatives in a European context, such as a CEN Workshop Agreement (CWA). Unlike other developments, such as a standard (EN), technical specification (TS) or technical report (TR), a CWA is developed by a limited group of experts and without consultation via the national standardisation bodies. Under the denominator CWA 17089:2016 (Indicators for the sustainability assessment of roads) [7], a document was drafted in 2016 that lists specific indicators for the evaluation of the sustainability of infrastructure works, with a focus on roads. This document is publicly available as a reference document, but with a slightly less formal status than an official EN standard. The focus of this document is on the road structure itself as part of the infrastructure works. Auxiliary infrastructures, such as noise barriers and safety bumpers, lighting, signage, etc. are not treated as part of the working group's objective, but these elements can help determine the overall sustainability of the road.

The document recommends the use of the indicators in accordance with the modularity provided in the standard prEN 15643-5 [5]. Obviously, not all indicators are equally relevant for each individual information module. In general, the indicators "climate change potential" and "energy consumption" are dominant and mainly caused by the emissions of the vehicles during the use phase of the road. These emissions can also partly be influenced by the (surface) characteristics of the road surface, such as roughness, longitudinal and transverse unevenness, texture (at macro or micro level) or rolling resistance.

The list of indicators (21 in total) and categories of environmental impacts studied includes among others:

- Primary material consumption,
- Consumption of recycled materials,
- Potential for recycling of materials, and surplus production of energy,
- Climate change potential,
- Road comfort index,
- Adaptation to climate change, resilience,
- Interaction between road surface and vehicle tyre: annoyance due to road noise,
- Responsible procurement of materials and services,
- Capacity reduction and traffic jams due to maintenance work.

See also Figure 1 (corresponding to table A.1 in this document [7]) for an example of how the results could be summarised.

Sustainability Pillar			Sustainability Performance Indicator (SPI)	Declared value	Unit	Method Used	Report name and number
Environmental	Parameter	1	Primary materials consumption		t		
		2	Secondary materials used		t or %		
		3	Materials or components to be reused or recycled, and exported energy		kg, t or MJ		
		4	Energy use		MJ		
		5	Waste		t or %		
		6	Global warming potential (GWP)		kg CO_2 equiv		
		7	Formation potential of tropospheric ozone (POCP)		kg Ethene equiv (POCP)		
	Impact categories	8	Depletion potential of the stratospheric ozone layer (ODP)		kg CFC 11 equiv		
		9	Acidification potential of soil and water (AP)		kg SO_2 equiv		
		10	Eutrophication potential (EP)		kg $(PO_4)^{3-}$ equiv		
		11	Abiotic depletion potential for non-fossil resources (ADP-elements)		kg of antimony		
		12	Abiotic depletion potential for fossil resources (ADP-fossil fuels)		MJ		
		13	Human Toxicity Potential (HTP)		kg of 1,4-Dichlorobenzene equivalent		
		14	Ecotoxicity Potential (ETP)		kg of 1,4-Dichlorobenzene equivalent		
Economic	Cost	15	Whole Life cycle cost		*local currency*		
Social	Comfort	16	Comfort Index		—		
	Safety	17	Safety audits & safety inspections		—		
	Sources	18	Adaptation to climate change		—		
		19	Tyre-pavement noise		dB		
	Noise	20	Responsible Sourcing		—		
	Congestion	21	Traffic congestion due to maintenance activities		Vehicle lost hours		

Figure 1: Table with overview of declared performances as taken from [7] (p. 41).

3.1.4 ISO work - ISO 21929-2 [8]

Outside Europe, standardisation is done in a similar way under the coordination of the International Organisation for Standardisation (ISO). The standard ISO 21929-2 (Sustainability in building construction - Sustainability indicators - Part 2: Framework for the development of indicators for civil engineering works) [8] focuses on similar sustainability aspects as previously discussed. Since this development within ISO is less specific than within CEN and since the TOTEM tool is based on the European standards, these international ISO standards are not further discussed here.

3.2 Existing case studies and research

An extensive screening of publications on LCA of infrastructure works (bridges, roads, quays, ...) was conducted. In first instance, the goal is to obtain an overview of the specific assumptions and starting points that are considered in this type of LCA studies. Next, the environmental impact of the different life cycle phases and the material and non-material aspects of infrastructure works are investigated in more detail. Then, a more in-depth study of the possible measures to reduce the environmental impact of infrastructures and the order of magnitude of this achieved reduction is carried out. Various aspects which, according to the studies, influence the environmental impact of infrastructure works are listed. Finally, some tools for calculating the environmental impact of infrastructure works are presented.

3.2.1 LCA studies of infrastructure works

Most of the publications consulted relate to life cycle analysis of roads (10 studies [9][10][11][12][13][14][15][16][17][18]), railways (3 studies [19][20][21]) and bridges (12 studies [22][23][24][25][26][27][28][29][30][31][32][33]) (see also Table 1). Few publications deal with the environmental impact of other infrastructure works, such as quays [34], piles [35] and sheet piling [36][37].

Parameters and life cycle stages

Table 1 provides an overview of the functional unit, the indicators and the service life considered in the various studies. The life cycle stages considered are also marked and an indication of the relative contribution of the different life cycle stages to the overall environmental impact of the construction works is given (if available).

The table shows that the different LCA studies are based on different assumptions, functional units, service lives, analysis methods, indicators, life cycle stages, and scenarios, which implies that the results of the different studies are not comparable as the underlying conditions vary considerably. This corresponds to the findings of an extensive literature study on several scientific studies conducted in Europe using life cycle assessment to study roads and pavements [39]. A common understanding in these studies is that all roads are unique and have their own specific conditions. It is therefore concluded that a flexible method is needed that can be adapted to the specific road under study. Nevertheless, some general insights into the different parameters that play a role within an LCA study of infrastructure works can be obtained based on the studies mentioned in Table 1.

The production phase is taken into account in all studies, but the other life cycle phases (transport, construction, use, EOL) may (not) be taken into account depending on the objectives and scope of the studies (e.g. cradle-to-gate, cradle-to-grave with options, cradle-to-grave). Moreover, the division between the various phases is not the same everywhere. The studies use different definitions for the phases and divide the life cycle or considered period into different phases. For example, not all studies make a distinction between the production, transport, construction, use and EOL phases, but look at, for example, the different aspects of or steps in the construction of a structure (e.g. preparatory work, construction of roads, construction of surroundings and waste processing or hiring services, asphalt products, purchasing materials, own services, equipment, road work and transport). Within these aspects, for example, production, transport and construction are considered without making the distinction. Moreover, the processes that are considered within the different phases (e.g. transport of materials, equipment and/or personnel, only energy consumption of the construction machines or also electricity and/or water consumption and/or transport on site) sometimes differ. Therefore, it is not always possible to deduce from the studies the contribution of the different life cycle phases considered within the European standard for buildings (EN 15978).

Table 1: Overview of LCA parameters and life cycle phases considered within different LCA studies of civil engineering works (x = taken into account, but no data available).

Literature SOURCE	Functional unit	Reference service life (years)	Indicators	Production (A1-A3)	Transport to site (A4)			Construction (A5)				Use (B)				EOL (C1-C4)
					Material	Equipment	Staff	Energy use	Transport	Staff	Waste	Mainte-nance	Replacements	Energy use	Traffic	
ROADS																
[9]	mean asphalt road, 10 km x 10 m	20	CO_2 emissions	4%	x			x		x	x	x	dense asphalt: 15 y / open asphalt: 8 y		96%	<1%
[11]	mean road within built-up area, 1 m	20	CO_2 emissions	59% (transport of materials 29%)								x				x
[12]	mean road		CO_2 emissions	60%	8%			19%	x		13%					
[13]	entire road project		CO_2 emissions	30-99%	1%	1%	x	x		0-3%	0-17%					
[14]	provincial road/bridge / tunnel, 8,5 km long	60	CEN indicators EN 15804	10-30%	4-5%	x		20-40%[1]				<1%	x	x	53-80%	
[15]	two-lane urban road, 1 km x 7,3 m	40	resource consumption and GHG emissions	75-90%									6-20% (asphalt every 20 years)			2-4% (80% recycling, 20% discharge)
[16]	asphalt road	18	energy and GWP	x	x			x				(every 15 years)				x
[17]	flexible pavement	60	energy and GWP	2,4-4%				1%					3%		91-92%	0,30%

[1] This object of the study is a mountainous road (including a bridge and tunnel). The impact related to the construction/installation phase (A5) is mainly caused by diesel machines for earth moving, tunnel excavation and cement grouting.

Literature SOURCE	Functional unit	Reference service life (years)	Indicators	Production (A1-A3)	Transport to site (A4)			Construction (A5)				Use (B)				EOL (C1-C4)
					Material	Equipment	Staff	Energy use	Transport	Staff	Waste	Mainte-nance	Replacements	Energy use	Traffic	
RAILWAYS																
[19]	passenger traffic (impact per km)		CO_2 emissions	x												x
[20]	passenger traffic (impact per km)		CO_2 emissions	12%										5%+5%	70%	x
[21]	passenger traffic (impact per km)		Cumulative Energy Demand (CED), Cumulative Material input per service unit (MIPS) and CO2 emissions	x				x				x	x		87%	
BRIDGES																
[22]	bridge for car traffic, 6,3 m x 9 m	80	CO_2 emissions	93-94%	1,5-3%			1,5-3%				x	2-3% (2 times)			
[23]	four-lane toad traffic bridge	100	CO_2 emissions	81%	15%			4%								
[24]	1 bridge		CO_2 emissions	75%	6%			14%								x
[25]	1 bridge			10%	10%			10%				22%				x
[26]	1 m bridge	100	Ecoindicator 99 indicators	40%	x			x				16%	12%+4%		50%	x
[30]	1 bridge		27 mid-point indicators, cumulative energy demand CED), monetary value weighting	x	x			x					x		x	x
[28]	1 bridge		11 indicators	x												

Literature SOURCE	Functional unit	Reference service life (years)	Indicators	Production (A1-A3)	Transport to site (A4)			Construction (A5)				Use (B)				EOL (C1-C4)
					Material	Equipment	Staff	Energy use	Transport	Staff	Waste	Mainte-nance	Replacements	Energy use	Traffic	
[29]	1 bridge	50	11 indicators of SBK bepalings-methode	most important	relevant			x				x	(metalling or lacquer every 25 years)			x
[27]	1 bridge, 320 m x 19 m	100	ReCiPe + monetarisation	most important	x			second most important				x	x			x
[31]	1m² bridge surface	100	ReCiPe GWP 100	second most important	x		x	x	x		x	x	x	x	79%	x
[32]	railway bridge	100	6 US EPA indicators	64%			x		<1%				3%			33% (discharge of wood and recycling of steel)
[33]	1 bridge		6 US EPA indicators	most important				x				x				-
[38]	9 m bridge	variable		x												
QUAYS																
[34]	1 m quay	100	CO_2 emissions	75-77%	3-4%											20-22% (recycling of steel and concrete)
PILES																
[35]	pile, 6 m long		CO_2 emissions	x	x											
SHEET PILING																
[36]	1 m² sheet piling		CO_2 emissions	x	x											
[37]			CO_2 emissions	x	x			x								

The choice of life cycle phases within the study strongly influences the results and the relative contribution of the different phases. For example, if user energy consumption (impact of road or rail traffic) is not included in the study, the production phase of the materials used is almost always the most important phase. However, if the impact of road or rail traffic is included in the analysis, this phase often turns out to be (much) more important than the production phase. However, the impact strongly depends on the assumed traffic pressure. With higher traffic pressure, the energy consumption for production, transport, construction, maintenance and EOL of the (rail) road is usually limited compared to the energy consumption of the traffic, while with lower traffic pressure the contribution of the materials (impact of production and construction, use and EOL) can be as large as the contribution of the use of the road. The contribution of the transport of materials, equipment and/or personnel to the site varies between 1% and 15% within the different studies for infrastructure works. The construction phase (mainly energy consumption of the equipment used) contributes between 1% and 20% to the total environmental impact. The contribution of maintenance and replacements (between <1 and 20%) depends highly on the assumptions concerning the service life, maintenance processes and maintenance frequencies for the different parts of the construction and the materials used (e.g. replacement of asphalt layer after 8, 15 or 20 years; maintenance after 1-2-3-4-5-10 years; replacement of joints or coating after a few years). Finally, the EOL phase usually contributes a few percent to the total impact.

Not all phases of the lifecycle of an infrastructure work are completely material related. The chosen building materials strongly determine the impact of the production phase, as well as the service life and related replacements and maintenance and the EOL phase. However, certain construction site tasks, as well as transport (distance and means), maintenance and energy consumption by the user, depend amongst others on the specific site, the chosen construction method, the means of transport of the user, the traffic pressure, … These insights point to the relevance of the selection of the contractor in the overall impact of construction works.

In the research project EDGAR (Evaluation and Decision Process for Greener Asphalt Roads) [40], the use of new technologies and materials for bituminous applications was studied from a sustainability perspective, with the aim of making environmentally-friendly asphalt roads. It concluded, among other things, that techniques such as recycling asphalt granulate as a raw material for the production of new asphalt and production at a reduced temperature (for *warm-mix asphalt* instead of *hot-mix*) can make a substantial contribution to the greening of asphalt for road surfacing.

Possible reduction of the environmental impact of infrastructure works

The literature studies indicate which measures can lead to the greatest reduction in environmental impact. Some examples are included below:

- Preparation phase [13][31]
    - Optimal logistics

- Better/optimal material design (e.g. fewer materials, more sustainable materials)

> Production phase [19][20][12][22][34][36][37][35][13][23][14][16][31][32]:
  - More environment/energy-friendly materials (e.g. 10 to 20% reduction in energy consumption by using AVT asphalt (asphalt prepared at a reduced temperature) and up to 25% CO_2 reduction by using eco-asphalt with a high proportion of recycled raw materials; cold rolled steel instead of hot rolled steel; reduction in CO_2 emissions by using concrete with other cements (CEM III instead of CEM I); reduction of 1.8% in CO_2 emissions by using wooden safety barriers instead of steel safety barriers; up to 50% reduction in CO_2 emissions by using concrete with alternative materials (e.g. fly ash).
  - Fewer materials (e.g. reduction of up to 80% due to thinner sheet piles; reduction of up to 15% in the quantity of concrete and 1% in CO_2 emissions related to the use of concrete beams with cavities instead of solid beams).
  - Reuse of materials (e.g. reduction up to 80% by reusing sheet piling)
  - Use of recycled materials (e.g. steel)

> Transport phase: optimisation of logistics:
  - Shorter transport distances [34][13][15][16][32]
  - Transport outside rush hours
  - More sustainable transport [23]
  - Transport by boat [23][34][36]

> Construction phase:
  - Different installation methods [23] (e.g. 4% reduction of CO_2 emissions by pouring concrete with cavities instead of using precast concrete)
  - Construction equipment [37] (e.g. use of combined machine, more efficient machines and reduced idling time)

> Use phase:
  - Optimisation of maintenance [19][20][35][29][32] (e.g. use of maintenance-free or wear-insensitive materials; longer maintenance intervals; better maintenance schedules)
  - Energy consumption by the user [9][19][20][22][14][21] (e.g. more energy efficient and environmentally friendly vehicles (cars, trucks, trains); reduction of 2-3% in CO_2 emissions by using road surfaces with lower rolling resistance).
  - Longer service life [32] (e.g. extending the service life of the structure through proper maintenance of the various components)

> EOL phase:
  - Demolition equipment [37] (e.g. use of combined machines, more efficient machines and reduced idling time)
  - Shorter transport distances [32]

Parameters affecting the environmental impact of infrastructure works

The consulted studies suggest that it is difficult to create an unambiguous framework for environmental evaluation of infrastructure works (roads, bridges, etc.). Each project is unique and has specific characteristics (which is also the case for buildings). The most important parameters, which, according to the different studies, influence the environmental impact of infrastructure works, are the following:

> Specific geographical, social and operational conditions, such as location and topography and other boundary conditions [22][14][16][27]
> The non-material-related specifications of the structure [22][27]: technical and functional requirements and properties, such as length, width, service life, load, vibration, impact resistance, fire resistance, fatigue, finishing, foundation, etc. These have a significant impact on the design and material use of the structure and therefore directly influence the environmental impact.
> Use of materials [38]: determines the materials used and thus the impact of the construction work (impact of production, transport, construction, use and EOL).
> Construction method [29]: determines amongst others the equipment used and thus the impact of the construction phase (e.g. mobile crane).
> LCA parameters: system boundaries [14][27], transport distances [29], service life and replacements [29], maintenance scenarios and frequencies [18][31][29], disposal scenario [29].
> Traffic pressure [14][16][32]: determines energy consumption and environmental impact during road/tunnel/bridge/railway operation, as well as the number of replacements and the frequency of maintenance.

As the road manager determines the specifications on what the design of the infrastructure work includes, what materials may be used, etc., he has the greatest influence on the choices which influence consumption in construction, maintenance and operation. The contractor only has an influence on the way in which the infrastructure is constructed.

Some studies have shown that the use of a road or railway has a significant environmental impact. This impact depends on a number of parameters, including the following [9][19][20][17][18]:

> Energy consumption of the vehicle
> Layout of the road
> Location of signaling
> Control of signaling
> Road user behavior
> Albedo (higher reflection of sunlight on whiter surfaces (=having higher albedo) leads to lower use of energy for lighting up the surroundings)
> Concrete carbonation
> Lighting
> Leaching

> Endurance/wear of car tires
> Inertia in design: A large part of the energy required to move a vehicle comes from inertia (acceleration/deceleration of traffic) in road design. Three factors that influence this are road layout, driving behavior and traffic management. It is important that traffic is able to continue driving at a reasonably constant speed for as long and as much time as possible.
> Rolling resistance: Some studies show differences in rolling resistance of up to 10% between different types of road surface; this lower rolling resistance can then further lead to approximately 1 to 2% less fuel consumption by the traffic. According to [41] and [42], the improvement of road surfaces on provincial roads can lead to a reduction in rolling resistance of between 2 and 12%. This could lead to a 2-3% reduction in CO_2 emissions from traffic. The influencing parameters (for the rolling resistance part) are the structure of the road pavement, the temperature of the tires and of the road surface, the roughness of the road and the tire profile. In addition to rolling resistance, resistance to gravity and aerodynamic resistance also play a (greater) role in fuel consumption. The determining parameters in this respect are, above all, the mass of the vehicle, the gradient of the road and the speed of the vehicle, as well as the efficiency of the engine to convert fuel to motion.

3.2.2 Tools to calculate the environmental impact of infrastructure works

Arcadis NL has developed a tool for calculating the environmental impact of roads or railways (CO_2 tool wegen) [9][10][19]. Currently, only the CO_2 emissions for the use of materials are available. The impact of the construction and use of (rail)road has yet to be worked out.

The online tool One click LCA - life cycle assessment software for buildings and infrastructure allows to calculate the environmental impact of buildings and infrastructure works (airports, bridges, canals, transmission systems, roads, flooding schemes, parking lots, waste water treatment plants, pipelines, repair works, railway stations, marine works, pumping stations, reservoirs and recycling facilities) according to various international evaluation and/or certification systems (e.g. BREEAM, LEED, the European standard for the environmental evaluation of buildings (EN 15978) and Level(s) and various country-specific systems (e.g. the Dutch “MilieuPrestatie Gebouwen”). The system boundaries and life cycle phases considered are those of the chosen evaluation system. When modelling the structure, the materials and quantities used within the structure must be filled in, as well as the following material parameters: life span of materials, transport distances for materials, material production location (production method and target country), EOL scenarios and Module D scenario (energy recovery) (choice from list of possibilities). The underlying environmental information for the materials is extracted from various EPD databases, from which one can choose (e.g. INIES, IBU). Also the following items have to be filled in: service life of the construction work (calculation period), construction surface area, energy and water consumption during the use phase (available for different countries) and scenarios concerning the construction site activities (i.e. average climate and site impact, earthworks, energy consumption (electricity and heating), fuel and water consumption, waste production, possible extra journeys for transport to the construction site). The results are expressed according to the indicators and life cycle phases of the chosen evaluation or certification system and are presented in different ways (e.g. per phase, per component, per material category, per year, ...).

Maeck [43] proposes a comparative study of software tools to assess the social sustainability of roadworks. The objective of this study was to investigate which tools are adequate and flexible when calculating a carbon footprint. Life cycle assessment of the road is closely related to this. To this end, a working group of the PIARC (World Road Association) produced the technical report [44].

3.3 Developments and approach in the Netherlands

In the Netherlands, there are various initiatives in which the environmental performance of infrastructure works is evaluated.

3.3.1 Evaluation method Environmental Performance of Buildings and GWW works and National Environmental Database

For example, the Environmental Performance of Buildings and GWW works [45] and the National Environmental Database (NMD) [46] also apply to infrastructure works.

The evaluation method [45] defines the calculation method for determining the environmental performance of buildings and GWW works during their service life. Some specific definitions for GWW works are literally the following:

> The functional unit corresponds to a product, which for GWW works can be a physical product, but also an activity. For GWW works, the Environmental Performance evaluation method defines the required performance in functional descriptions per chapter.

> The entire life cycle of a product in a structure, including module D, must be included in an EPD (this is not specific to GWW works). If no information is available from the LCA for the specific EPD, default values can be used for the use and maintenance phase of the structure.

> The product unit must be measurable and includes, for a GWW work item, a description, a specification, possible areas of application, service life, quantity, weight and materialisation.

> In the case of GWW works, the default transport distance of building materials to the construction site per work is included in the calculation tool.

> For GWW works, a reference service life of 100 years or a specific service life per project can be used.

The National Environmental Database for GWW [46] mainly contains materials and only a few processes (e.g. dredging) that are specific to earth, road and waterworks. The database to be consulted consists of a list of items with their constituent materials or processes (e.g. plastic sheet piling - VKK, glass fibres in vinylester (constructions)) (see Figure 2).

Non-material-related impacts (e.g. road traffic impact) are not included in these documents or database.

Inzage in Nationale Milieudatabase GWW versie 1 (januari 2012)

View database

RAWcode	RAWnaam	Item	Materiaal/Proces	Type	Categorie	U
52.36	BITUMINEUS GEBONDEN O	Waterbouwkundig asfaltbet	SMA 0/11, gemiddeld	Materiaal	3	VBW
52.80	BAGGERWERK	Onderhoudsbaggerwerk (cu	NULL	Materiaal	3	SBK
52.80	BAGGERWERK	Onderhoudsbaggerwerk (sl	NULL	Materiaal	3	SBK
52.80	BAGGERWERK	Saneringsbaggerwerk	NULL	Materiaal	3	SBK
52.91	ZANDSUPPLETIES	Strandsuppletie (groot)	Zand uit baggerwerk (werk met werk)	Materiaal	3	SBK
52.91	ZANDSUPPLETIES	Strandsuppletie (jumbo)	Zand uit baggerwerk (werk met werk)	Materiaal	3	SBK
52.91	ZANDSUPPLETIES	Strandsuppletie (middel)	Zand uit baggerwerk (werk met werk)	Materiaal	3	SBK
52.91	ZANDSUPPLETIES	Vooroeversuppletie (groot)	Zand uit baggerwerk (werk met werk)	Materiaal	3	SBK
52.91	ZANDSUPPLETIES	Vooroeversuppletie (jumbo)	Zand uit baggerwerk (werk met werk)	Materiaal	3	SBK
52.91	ZANDSUPPLETIES	Vooroeversuppletie (middel	Zand uit baggerwerk (werk met werk)	Materiaal	3	SBK
56.21	VERFSYSTEEM OP STAAL	coating staalconservering	Coating gemiddeld voor staalconservering	Materiaal	3	SBK
56.29	VERFSYSTEMEN ALGEMEEN	Acrylaatverf	Acrylaatverf (gemiddeld)	Materiaal	3	SBK
56.29	VERFSYSTEMEN ALGEMEEN	Alkydverf	Alkydverf (gemiddeld)	Materiaal	3	SBK
56.99	METALLISEREN	aluminiseren	Aluminium (gemiddeld)	Materiaal	3	SBK
61.03	AFRASTERINGEN	Secundair hout	Secundaire hout	Materiaal	3	SBK

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Figure 2: Example of some processes and materials from the National Environmental Database for GWW works in the Netherlands [46].

3.3.2 Tools to evaluate the environmental impact of infrastructure works

DuboCalc is the Dutch calculation instrument for determining the environmental performance of GWW works [47]. However, its use is not (yet) legally required in the Netherlands. For the calculation rules and backgrounds of DuboCalc, reference is made to a document from 2010 [48]. The instrument allows to create a project using items in the DuboCalc library. Four life cycle phases are linked to an item: construction phase (including extraction, production and transport of the required building materials and construction waste), use phase (only the aspects of the construction work itself and therefore not, for example, the impact of road traffic or the user), maintenance phase (only replacements, including occurring waste) and EOL phase (including abandonment of the work, demolition, waste processing, reuse). In the case of a road, the environmental impact of traffic in general is not considered. However, if the design variants differ in this respect, it is possible to determine the environmental impact of additional traffic. The tool uses default values, but the user can change transport distances and service lives himself. In addition, the user can move energy items from the use phase to the construction phase.

The objective of the CO_2 performance ladder [49] is to identify CO_2 reduction opportunities for a specific project or a specific company, define reduction targets, monitor progress and provide guidance for clients and implementers. This initiative provides, among others, a list of measures that companies can take to reduce their CO_2 emissions (e.g. for transport and logistics, on the construction site, on used equipment, on the production and treatment of waste and on the use of materials). The CO_2 performance ladder is also currently being implemented in Belgium as a system to identify and valorise a company's CO_2 reduction opportunities.

3.4 Conclusions from the literature study

A literature review of the developments in standards and regulations concerning the environmental impact of infrastructure works has shown that this topic is still developing and lagging on developments in the construction sector in general. Standards, which were originally developed for buildings, now serve as a source of inspiration for extensions to the infrastructure works sector, with a focus on the necessary adaptations for specific conditions related to this type of works.

A literature review of existing studies and research projects on the environmental impact of infrastructure works has shown that the calculation of this impact is not always done in a uniform manner. Different service lives, system boundaries, methods, scenarios, ... are used, making the results of the different studies incomparable. The scope also strongly influences the results. In addition, the impact does not only depend on the building materials used, but other aspects (such as construction activities, use and traffic pressure) also play a role.

In the Netherlands, an evaluation method, a database and a calculation tool specially developed for the environmental evaluation of infrastructure works already exist. These are based on the calculation rules and tools for buildings and contain additional calculation rules, provisions and environmental information for GWW works.

4. Case study analyses

Case studies are used to gain insights in the "typical" environmental impact of roads, as well as on the potential to reduce this impact. Furthermore, these case studies provide specific insights linked to the use of the TOTEM methodology for non-building related construction works and the functionalities and data available within the current TOTEM tool for buildings.

This chapter describes the selected cases, their technical characteristics and performance, the scope and methodology of the environmental impact assessment (using LCA) and the LCA results. More details on the technical aspects of roads are available in ANNEX 1. More details on the data inventory, LCA modelling and additional LCA results are included in ANNEX 2.

4.1 Cases in road construction

4.1.1 Standard road structures and traffic classes

In Flanders, roads are designed using the so-called standard structures for road construction, which are determined by the type of road pavement material (this is of the type "stiff", with concrete, or type "flexible", with asphalt) [50].

The dimensioning of the road structure is mainly determined by considering the expected traffic load over the entire service life, which is expressed in so-called ESALs or a number of equivalent standard axle loads of 100 kN. For a road surfacing in asphalt, a service life of 20 years is considered; for a concrete road surfacing the considered service life is 30 years. The result of this calculation determines the so-called traffic class (*bouwklasse* in Dutch) of the road in question, as is shown in Table 2.

Table 2: Traffic classes in function of the number of equivalent 100 kN standard axle loads [50].

Traffic class	Number of 100 kN standard axle loads
B1	< 128 million
B2	< 64 million
B3	< 32 million
B4	< 16 million
B5	< 8 million
B6	< 4 million
B7	< 2 million
B8	< 1 million
B9	< 500 000
B10	< 250 000

Figure 3 schematically shows that a road structure is composed of a foundation layer, (one or more) sublayers and finished with a top layer. The asphalt or concrete pavement is always laid on top of a foundation layer that supports the top layers and distributes the forces of the traffic load to the subbase and the underground. For low and moderately loaded roads, the foundation layer usually consists of a crushed stone mix with a continuous grain distribution curve which is compacted as strongly as possible. For heavily loaded roads, a similar crushed stone mixture is typically used including cement as a binding agent in the mixture. The dimensioning of the road structure strongly depends on the expected traffic load: the higher the traffic load, the stronger the road structure.

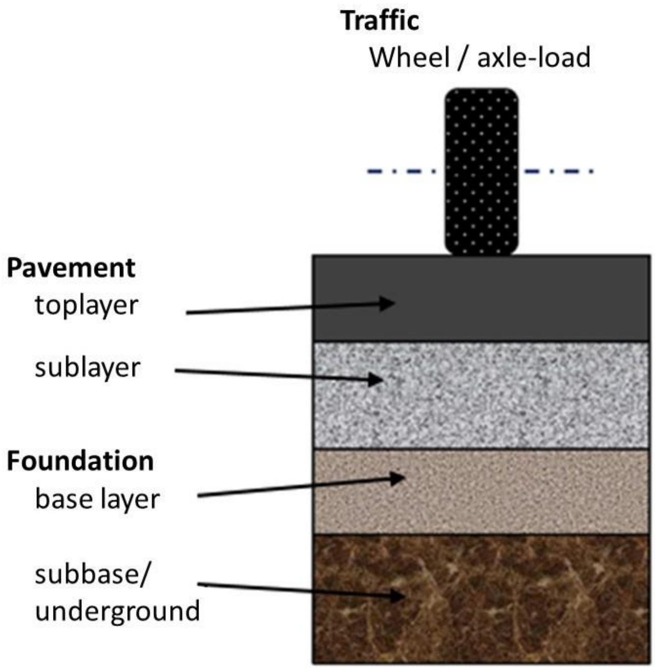

Figure 3: Vertical cross-section of road structure (not to scale).

4.1.2 Selection and definition of case studies

In this study, two road cases are investigated. First, a typical road in traffic class B5 with an asphalt pavement is considered. This road type could correspond to a connecting road between two cities, a connecting road between an industrial zone and the entrance/exit of a motorway, or a regional urban ring road. Second, a typical road in traffic class B1 with a concrete pavement is considered. This road type could correspond to motorways with much and heavy traffic (e.g. E19 between Brussels and Antwerp, the ring road around Brussels, the ring road around Antwerp, ...).

It is important to note that both road types belong to different traffic classes. This is due to the fact that in Belgium concrete road pavements are typically selected for roads with a heavy traffic load (e.g. B1), while asphalt road pavements are chosen more often for roads with a lower traffic load (thus for higher traffic classes, e.g. B5). The flexibility of installation of bituminous roads partially explains this choice for their use in lower loaded and local roads. Concrete pavements could also be used for roads of class B5 but this would require a completely different road structure (based on concrete slabs instead of a continuously reinforced concrete pavement) and does not correspond to common practice. Furthermore, also the reference design service life differs between both road types (see above; 20 years for a road with an asphalt pavement and 30 years for a road with a concrete pavement). Due to these differences in traffic class and road design service life, the functional unit is different for both cases. Consequently, the environmental impact results for both road types can and should not be compared as such.

For each road type described above, a reference case is defined. This case includes a classic approach with the materials commonly used in practice and without any innovative elements in the design of the road paving. For the bituminous roads, the reference case is extended with a variant case. This case considers more innovative elements in the design of the road pavement that are particularly selected to lower the environmental impact of the road. For the concrete road, a variant case is not defined, because little alternative concrete compositions are already being used in standard practice. But mainly because this additional variant would not specifically lead to additional insights around the use of TOTEM for environmental impact assessment and optimisation.

4.2 Scope of the environmental impact assessment

The different road structure variants are evaluated for their environmental impact using life cycle analysis (LCA). For these LCAs, the MMG methodology [51], which forms the basis for the online TOTEM tool[2], was followed as much as possible. This methodology considers 17 environmental impact indicators and expresses the environmental impact as a monetised (single) score (given in euros) (see ANNEX 2 for more details).

The LCA analyses in this study are all cradle to grave: the product stage (A1-A3), the construction process stage (A4-A5), the use stage (B1-B8) and the EOL-stage (C1-C4) have been considered. Module D was neglected (as is also the case in TOTEM). Regarding the use stage (module B), only replacements (B4) have been calculated. Maintenance of the roads (B2) is probably also necessary but was not considered due to a lack of data and scenarios. Operational energy use (B6) was not considered. According to prEN 17472:2020 [2], the additional phase B8 "Users' use" can be specified for civil engineering works. Although the latter can have a very high environmental impact (cf. the literature study points to up to 80-90% of the total life cycle impact of a road), this phase was not considered in this LCA study. This is partially because of lack of data, but also because the impact of the use of the roads (users' use) will rather depend on the optimisation of the vehicles and the topography of the road than of the actual material choice for the road.

In comparison to the scenarios already available in TOTEM for the building context, some additional specific scenarios had to be developed for the transport (A4), the installation (A5) and the EOL (C1-4) of some road materials. These scenarios were elaborated following the TOTEM principles and logic.

[2] www.TOTEM-building.be

Figure 4 visualises the different life cycle stages that are considered for the study (marked in green). The modules marked in red are not considered for this study and indicate a difference with the current TOTEM methodology for buildings.

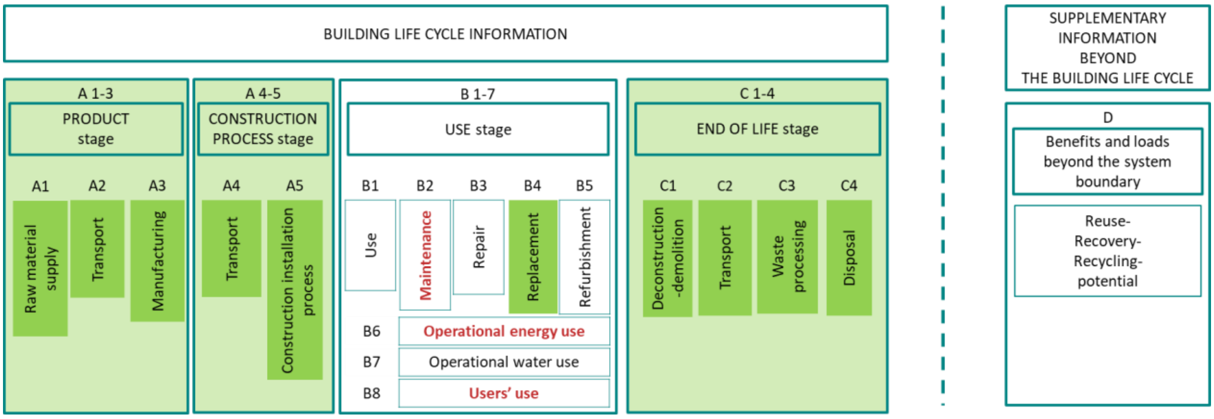

Figure 4: Indication (in green) of the different life cycle stages considered for the LCA study of road variants (according to the modules specified in EN 15978 [3] and prEN 17472 [2]). The life cycle stages indicated in red are different from the current TOTEM methodology for buildings and are not considered in this study.

The life cycle analyses were performed using the specialised LCA-software SimaPro and the Ecoinvent database[3]. These allow detailed modelling of the different materials composing the roads, as well as their production, transport, installation and EOL phases. Table 3 summarizes the scope and main parameters of the life cycle analyses carried out within this study.

Table 3. Scope of the life cycle analyses carried out within this study

Software	SimaPro v9.0.0.48
Database (Life Cycle Inventory)	Ecoinvent v3.5, allocation cut-off by classification
Reference study period (RSP)	Bituminous roads: 20 years Concrete roads: 30 years
Reference service life (RSL) of materials/layers	Bituminous roads - Asphalt top layer: 10 years - Asphalt sublayer: 20 years - Foundation: 30 years Concrete roads - Concrete top layer: 30 years - Asphalt sublayer: 30 years - Foundation: 30 years These RSL represent mean service life values for the different composing layers of the roads.

[3] www.ecoinvent.ch

	The number of replacements is calculated as the nearest integer value of (RSP/RSLmaterial-1).
System boundaries	According to NBN EN 15978 [3] and prEN 17472 [2] The analysis considers the following modules: ▪ A1-A3 Product stage (raw materials supply, transport, manufacturing) ▪ A4 Transport of materials to the construction site ▪ A5 Installation of materials on the construction site ▪ B4 Replacements ▪ C1-C4 Demolition, transport, waste processing and disposal of materials
Scenarios	▪ Scenarios for transport (module A4), installation on site (module A5) and end-of-life (modules C1-C4) are specifically developed for the materials ▪ Scenarios for end-of-life (modules C1-C4) are representative for the Belgian context [51]
Life Cycle Impact Assessment (LCIA)	MMG method 2014, update December 2017 (v1.05) [51] 17 environmental impact indicators and single score based on monetisation

4.3 Case study 1: Bituminous roads

In a first case study, two variants of a bituminous road have been analysed for their environmental impact. In the following paragraphs, first the general characteristics and composition of the considered bituminous roads are given. Then, the reference case and the variant case are described separately for their specific composition and modelling and, finally, the results of the environmental impact assessment of both variants are given.

4.3.1 Functional unit and composition

The functional unit for the bituminous roads analysed in this study is the following:

> '*To ensure the road structure of 1m² of road surface, for a road with a traffic load corresponding to a traffic class B5, for a period of 20 years.*'

According to the Flemish Road Authority (AWV) standard structures [50] (see also Figure 5), the recommended road structure for this type of road (class B5) consists of:

- Paving in asphalt with a total thickness of 23 cm
- Foundation type 'unbound broken stone mixture' with a total thickness of 35 cm

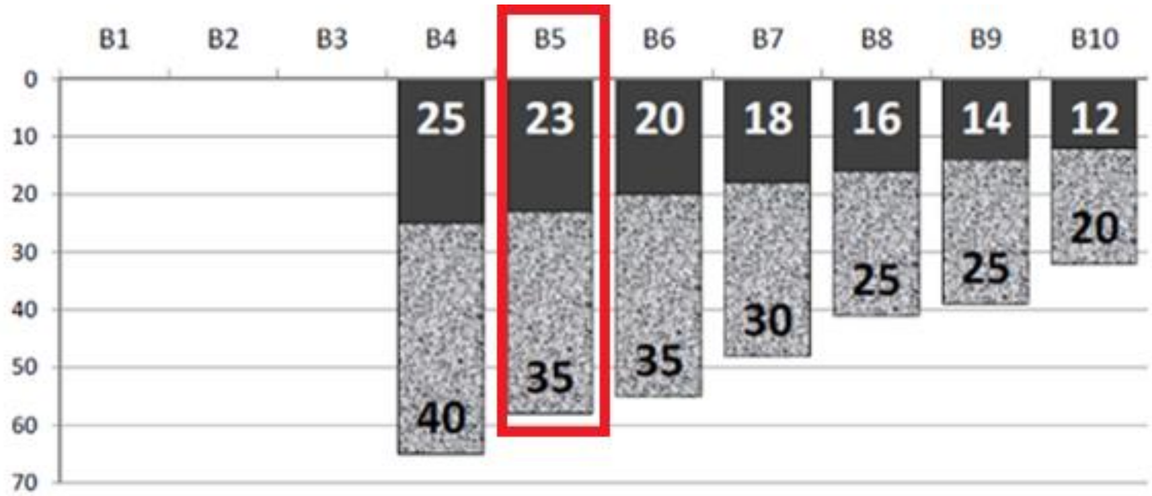

Figure 5: Recommended road structure for bituminous roads in relation to the different traffic classes (following AWV [50])[4].

The asphalt pavement consists of a top layer with a thickness of 4 cm and a service life of 10 years and a sublayer with a thickness of 19 cm (processed in three layers) and a service life of 20 years. The foundation is supposed to have a service life of 30 years. This means that for the considered study period of 20 years, the asphalt top layer will have to be replaced once, while the asphalt sublayer and the foundation do not have to be replaced. The specific composition of the asphalt layers and the foundation differs between the reference case and the variant case and is given in the following paragraphs.

4.3.2 Reference case

The reference case considers a “classic” approach of a bituminous road structure with the materials commonly used in practice and without any innovative elements in the design of the road paving. This means that for the asphalt layers and for the foundation, only new or primary raw materials are used, i.e. aggregates mined in the quarries and bitumen coming from the petroleum refinery. The use of recycled aggregates is explicitly excluded from this reference case (even though this is common practice).

An overview of the specific composition of the three layers, composing the reference bituminous road, is given in Table 4 (see ANNEX 2 for more details on the composition and modelling of the layers).

For modelling, available records within the Ecoinvent database v3.5 were used. These records were harmonised for Belgium and adapted if necessary (e.g. record for asphalt). For the production (modules A1 and A3) of some resources and materials (e.g. porphyry and PmB bitumen), a proxy had to be used due to lack of a specific Ecoinvent record. For transport of resources towards the asphalt factory (located centrally in Flanders; module A2) and of the asphalt and foundation materials towards the construction site (module A4), a heavy truck (16-32 tonnes) and mean transport distances relevant for Flanders were applied. Due to a lack of

[4] All thicknesses are stated as the vertical dimension after compaction of the mixtures.

detailed data on the machinery used on the construction site (e.g. shuttle buggy, asphalt machine and steamroller), the impact of the installation phase (module A5) was approximately modelled using a hydraulic digger. For the EOL-phase (modules C1-C4), available MMG scenarios 2017 [51] were used if possible, or adapted, if necessary. For some materials (e.g. asphalt), additional EOL scenarios were developed following TOTEM principles and logic.

Table 4: Composition of the reference bituminous road.

Layer	*Thickness*	*Service life*
Asphalt top layer (SMA-C asphalt) - Filler (composite type II) - Coarse aggregates (crushed porphyry 6.3/10 and 4/6.3) - Fine aggregates (crushed porphyry 0/2) - Bitumen (PmB bitumen)	4 cm	10 years
Asphalt sublayer (APO-B asphalt) - Filler (limestone type Ib) - Coarse aggregates (crushed limestone 10/14, 6/10 and 2/6) - Fine aggregates (crushed limestone sand 0/2 and round river sand) - Bitumen (paving grade bitumen B50/70)	19 cm (8+6+5 cm)	20 years
Foundation (crushed limestone) - Broken stone (crushed limestone 0/40)	35 cm	30 years

4.3.3 Variant case

In the variant case, different optimisation options, considering more innovative elements, have been applied to the three layers composing the bituminous road structure in order to lower the environmental impact of the road.

The main differences between the reference case and the variant case are the following (see also Table 5 and ANNEX 2 for more details):

- Asphalt top layer: use of low-temperature SMA-C asphalt with foamed bitumen (SMA-C AVT asphalt) instead of classic SMA-C asphalt
- Asphalt sublayer: use of APO-B asphalt with 50% reclaimed asphalt aggregates (APO-B 50% RA asphalt) instead of APO-B asphalt with only primary raw materials
- Foundation: use of recycled concrete aggregates instead of primary resources

Table 5: Composition of the variant bituminous road (the differences with the reference road are underlined).

	Thickness	*Service life*
Asphalt top layer (SMA-C AVT asphalt) - Filler (composite type II) - Coarse aggregates (crushed porphyry 6.3/10 and 4/6.3) - Fine aggregates (crushed porphyry 0/2) - Bitumen (PmB bitumen) - Water	4 cm	10 years
Asphalt sublayer (APO-B 50% RA asphalt) - Filler (limestone type Ib) - Coarse aggregates (crushed limestone 10/14, 6/10 and 2/6) - Fine aggregates (crushed limestone sand 0/2 and river sand) - Recycled aggregates (recycled minerals from reclaimed asphalt) - Bitumen (paving grade bitumen B50/70) - Recycled bitumen (recycled bitumen from reclaimed asphalt)	19 cm (8+6+5 cm)	20 years
Foundation (recycled concrete aggregates) - Recycled aggregates (recycled concrete aggregates)	35 cm	30 years

For the SMA-C asphalt top layer, an AVT asphalt is selected. This asphalt is produced at lower temperature than standard SMA-C asphalt (at 110-140°C instead of 170-190°C). As a result, the aggregates can be heated at a lower temperature and an energy reduction of 10 to 20% can be achieved. To control the viscosity of the mixture, specific additives must be used, or water is added under high pressure to produce foamed bitumen. For this study, an AVT asphalt with the foamed bitumen technique was chosen. An energy reduction for heating the aggregates of 15% was assumed. According to literature [52], also a reduction in VOC emissions of 15% can be seen for AVT asphalt. Given the limited experience with this technique in practice, it is not clear whether the technical performance is the same as for "standard" bitumen. It has, for example, been shown that the mixtures with the foam technique perform less good in terms of water sensitivity. The uncertainty about the technical performance partly explains why these techniques are not exploited fully in practice. More information on the AVT asphalt and the points of attention are described in ANNEX 1.

For the APO-B asphalt sublayer, a substitution of 50% of the primary aggregates and bitumen by recycled asphalt aggregates is supposed. Consequently, the quantities of the primary coarse aggregates and the new bitumen used in the asphalt sublayer decrease substantially. The recycled aggregates originate from old asphalt roads that are demolished. The old asphalt is milled on site, transported to the asphalt plant, sorted and crushed if necessary, and then reused in new asphalt. In the latter step, the recycled asphalt aggregates are heated separately before they are added to the heated mixture with primary aggregates. Within this study, it is supposed that the end-of-waste point for recycled asphalt aggregates falls after sorting and crushing, so that the production impact of the recycled aggregates (A1) is included in the former lifecycle and thus equals zero when being reused. Since sorting and crushing take place with machinery stationed within the site of the asphalt production plant, no transport to the production site (A2) is necessary, so this impact is also zero. The heating of the recycled asphalt aggregates before adding them to the new asphalt mixture is included in module A3 of the asphalt production phase. The technique of using reclaimed asphalt in the mixture has proven itself for many years. However, the old bitumen in the reclaimed asphalt has "aged" due to the many years of use before, which has to be compensated by the addition of new bitumen with "better" characteristics than in mixtures without reclaimed asphalt.

Regarding the foundation, recycled concrete aggregates are used for the variant road instead of primary broken limestone aggregates. The recycled concrete aggregates originate from crushing of concrete rubble from buildings and roads. Since it was supposed that the end-of-waste point for recycled concrete aggregates falls after sorting and crushing in the sorting plant, the production impact of the recycled aggregates (A1-3) is included in the former lifecycle and thus equals zero when being reused. Only transport (A4) from sorting plant to construction site has to be taken into account. Concerning the technical performance, an equivalent performance is seen in practice using recycled or virgin aggregates in the foundation. In this case, the quality depends on both the intrinsic quality of the materials used and the quality of their processing on site.

Given that some of these new techniques considered for the variant case are not being applied for a long time yet, it cannot be guaranteed to 100% that the (technical) long-term durability and performances of the layers are the same as for the reference bituminous road. Tests have shown that in general the same quality can be obtained with these new techniques as with the traditional way of working, but additional research and experience is necessary.

4.3.4 Results of the environmental impact assessment

The reference and the variant bituminous roads were analysed for their environmental impact using LCA. The main results of these analyses are described in the following paragraphs. More detailed results on the different layers composing the roads are given in ANNEX 2.

Reference case

Figure 6 shows the total environmental impact of 1m² of the reference bituminous road for a period of 20 years, per layer and per lifecycle phase. The APO-B asphalt sublayer has the largest impact, followed by the SMA-C asphalt top layer. The larger impact of the asphalt sublayer can be explained by the larger quantity used than for the top layer (cf. 19 cm of APO-B asphalt versus 2x4 cm of SMA-C asphalt). The impact of the asphalt top layer is largely determined by the fact that this layer must be replaced once during the considered study period of 20 years (module B4).

The production phase (modules A1-A3) has the largest contribution to the impact of both asphalt layers. When looking into detail at this production phase, it seems that the asphalt production process itself contributes most to the environmental impact. This is mainly due to the energy use for heating the aggregates. The most important environmental impact indicators for the production process are ‘global warming potential (GWP)’, ‘particulate matter (PM)’, ‘human toxicity – non-cancer effects’ and ‘eutrophication’. The high impact on these indicators is in this case mainly related to the use of heavy fuel to heat the asphalt aggregates. A sensitivity analysis showed that the impact of the production process decreases significantly when natural gas is used as a fuel (instead of heavy fuel). In practice, different types of fuels (heavy fuel, diesel, natural gas) are currently used in Belgian asphalt plants. Therefore, the impact of the production of asphalt can vary significantly between plants and is factory specific.

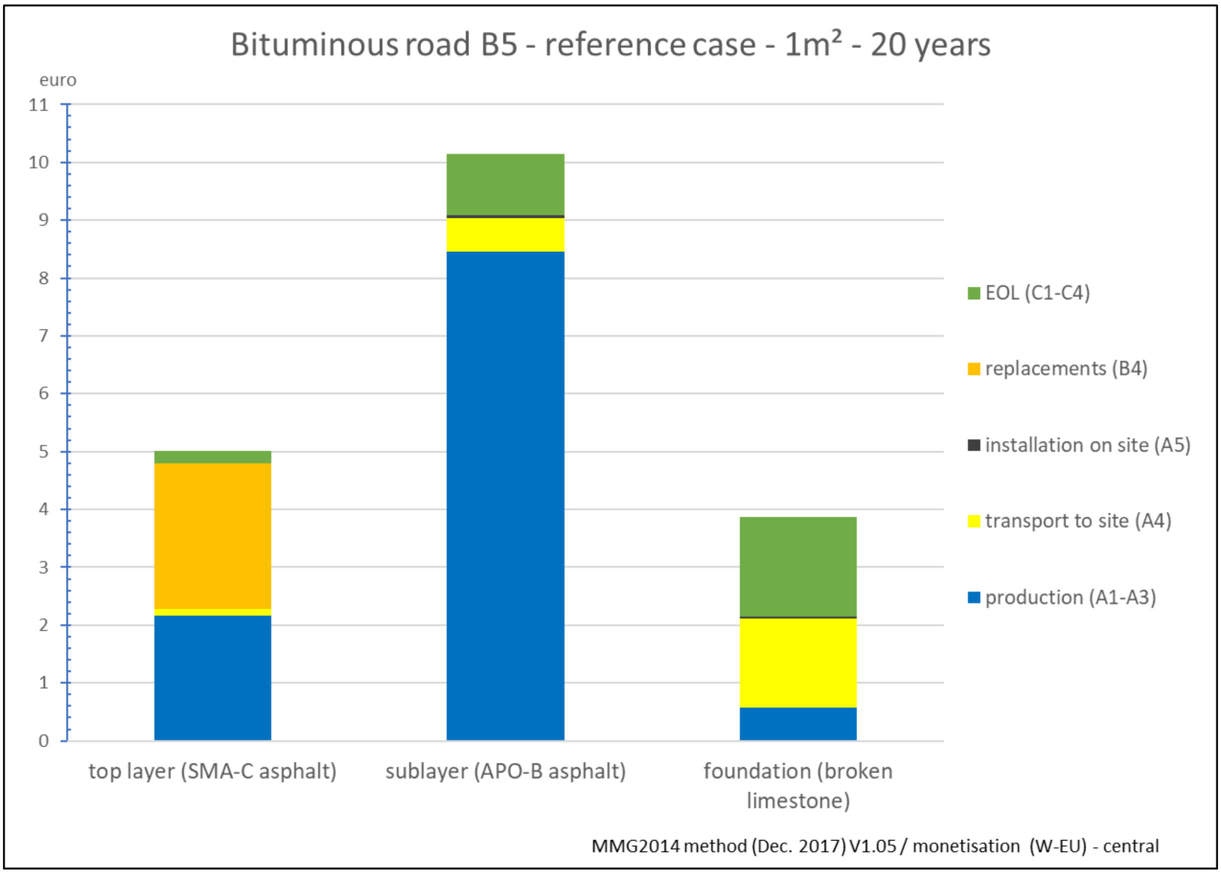

Figure 6: Environmental impact of 1m² of the reference bituminous road over 20 years, per layer and per lifecycle phase.

Regarding the foundation layer, the figure shows that the EOL-phase (modules C1-C4) and the transport of the broken limestone to the construction site (module A4) have the largest contribution. The impact of the EOL-phase is highly influenced by the particulate matter emissions. These emissions find their main origin in the demolition process for inert materials (dust during demolition and use of diesel for demolition). For this study, the EOL scenarios for inert materials as specified in the TOTEM-tool are being used. Further research into the emissions occurring during road deconstruction might be necessary to validate these results.

The represented impact for the installation phase (module A5) is an underestimation for all layers, given the approximations and lack of specific data used for the modelling. Nevertheless, it can be assumed that the impact of the construction phase remains very low in comparison to the impact of the asphalt production (modules A1-A3). Furthermore, the impact of the construction phase is probably mainly dependent on the type and age of the machinery used and thus will be contractor specific.

Finally, the most important environmental impact indicators (i.e. global warming potential, eutrophication, human toxicity, particulate matter, water resource depletion and land use) are the same for all three layers and are similar to those typically found for (residential) buildings in TOTEM. Detailed results presenting these indicators are available in ANNEX 2.

Variant case

Figure 7 shows the total environmental impact of 1m² of the variant bituminous road for a period of 20 years, per layer and per lifecycle phase. Similar conclusions can be drawn for the variant bituminous road. The APO-B 50% RA asphalt sublayer has the largest impact, followed by the SMA-C AVT asphalt top layer. Again, the larger impact of the asphalt sublayer can be clarified in relation to the larger quantities (cf. 19 cm of APO-B 50% RA asphalt versus 2x4 cm of SMA-C AVT asphalt), and the impact of the asphalt top layer is largely influenced by its required replacement after 10 years (module B4). The production phase (modules A1-A3) is the most impacting for both asphalt layers and the asphalt production process remains the most important.

Finally, the impact of the production phase (modules A1-A3) for the foundation layer equals zero since all production processes took place during the former lifecycle. Only transport to construction site (module A4), installation on site (module A5) and EOL-phase (modules C1-C4) cause an impact on the environment. The EOL impact can be clarified as for the reference case.

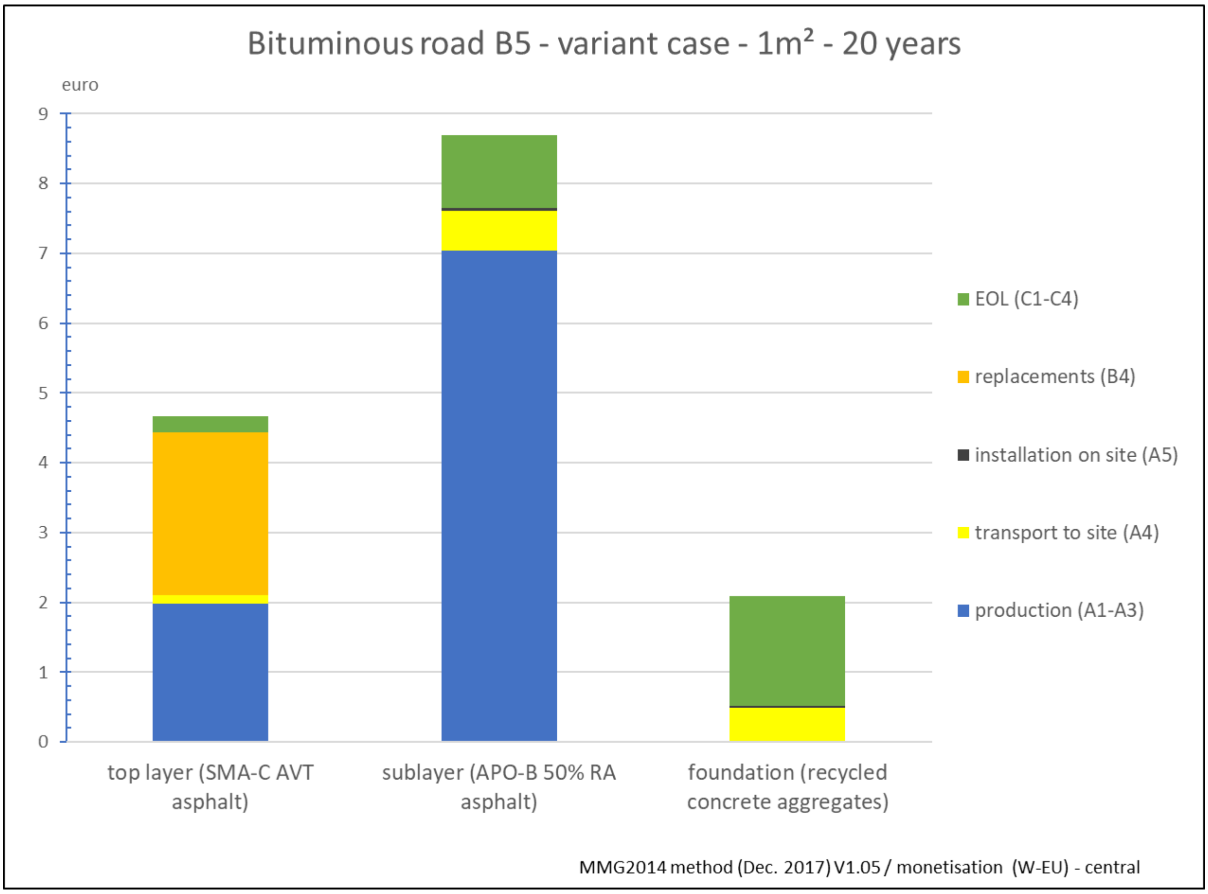

Figure 7: Environmental impact of 1m² of the variant bituminous road over 20 years, per layer and per lifecycle phase.

Reference case versus variant case

A comparison between the environmental impact of the reference bituminous road and the variant bituminous road provides insight in the reduction potential of bituminous roads (within traffic class B5).

According to Figure 8, a reduction in total environmental impact of 19% can be achieved. A closer look at the environmental indicators (see also results in ANNEX 2) shows that a reduction can be found in all indicators.

For the foundation layer, a reduction of 46% can be achieved by replacing broken limestone by recycled concrete aggregates. This reduction is related to the reduction in production impact (cf. no production impact for recycled concrete aggregates), in transport distance to the construction site (35 km instead of 100 km) and in amount (less kg/m² needed for the recycled foundation, due to lower density). Studies for concrete showed that the gain in environmental impact related to the use of recycled concrete aggregates (no production impact) can be counterbalanced when transport distances become larger. A careful evaluation of transport distances of recycled aggregates is therefore necessary.

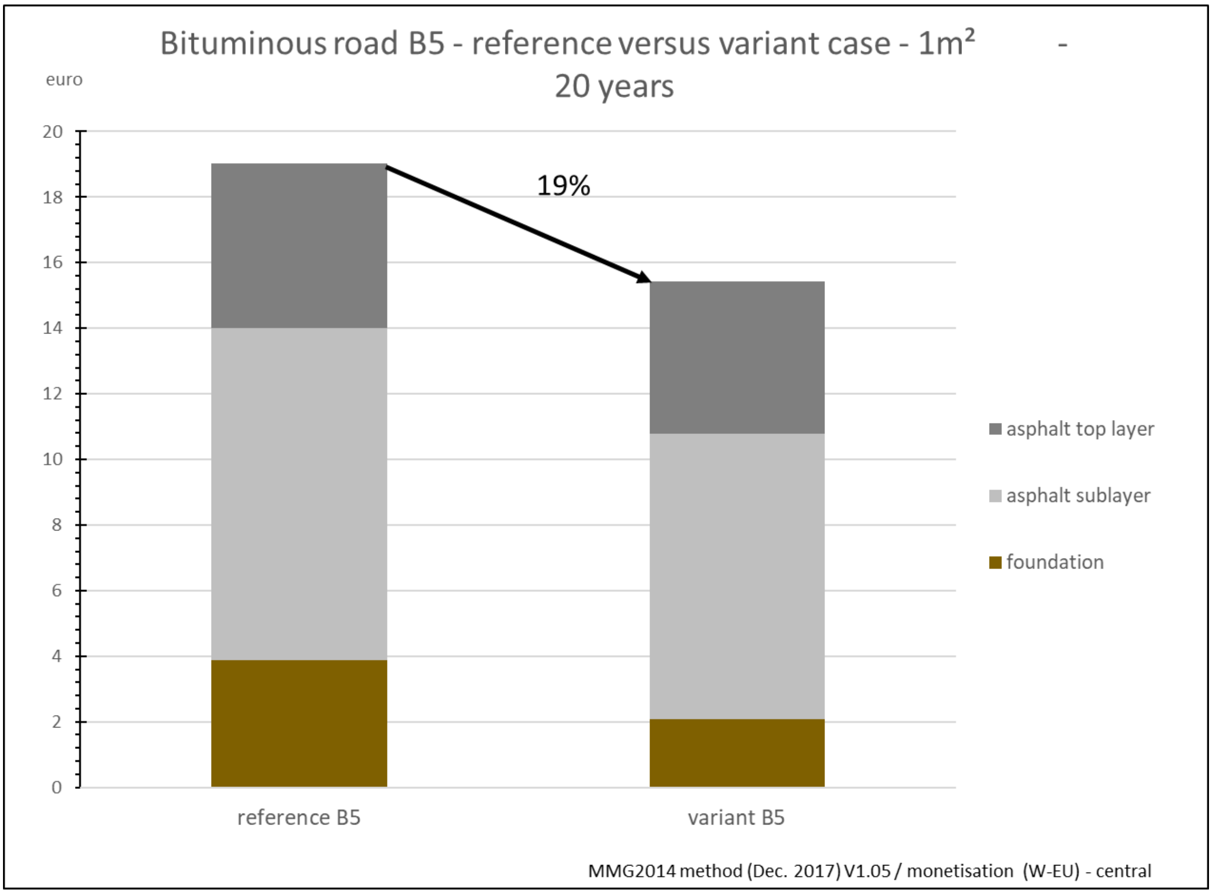

Figure 8: Environmental impact of 1m² of the reference bituminous road and the variant bituminous road over 20 years, per layer.

For the asphalt sublayer, a reduction of 14% can be achieved by replacing half of the primary aggregates and bitumen by reclaimed asphalt (recycled asphalt aggregates). The reclaimed asphalt provides free minerals and bitumen for the asphalt mixture. Furthermore, less primary resources are necessary, which leads to a reduction in impact of both production and transport to the asphalt plant.

For the asphalt top layer, a reduction in environmental impact of 7% can be achieved when considering an energy use reduction of 15% for the asphalt production and the use of water as a foaming agent. However, for AVT asphalt, also additives other than water can be used. The environmental impact of these additives, as well as their possible impact on the production circumstances, the technical performances and the service life of the asphalt, are unknown at this moment. It can be assumed that their impact might be relatively high. Consequently, it is possible that in some cases the reduction in environmental impact in relation to the lower energy use might be overruled by an increase in environmental impact due to the use of the specific additive(s). Further research is needed.

Figure 9 presents the results for the indicator “Global warming potential” (expressed as kg CO_2-equivalents) for the bituminous road variants over a period of 20 years. For the entire road, a reduction in CO_2 emissions of 17% is possible going from the reference case to the proposed variant. This implies a reduction of 49% for the foundation layer, a reduction of 11% for the APO-B asphalt sublayer and a reduction of 8% for the SMA-C asphalt top layer. Overall, it can be concluded that the reduction potential is similar for the monetised score and the individual indicator GWP.

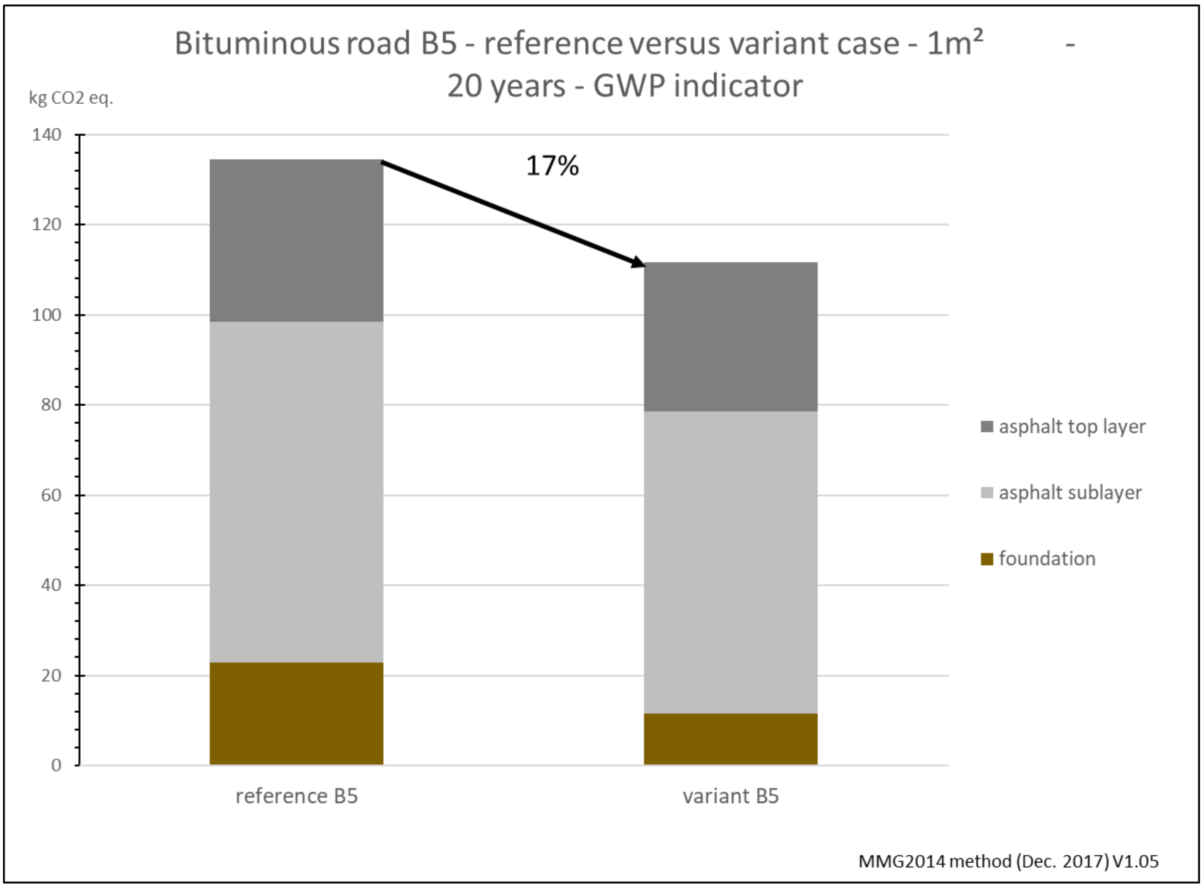

Figure 9: Global warming potential impact (expressed as kg CO_2 eq.) of 1m² of the reference bituminous road and the variant bituminous road for a period of 20 years, per layer.

4.4 Case study 2: Concrete roads

The second case study concerns a concrete road. In the following paragraphs, the characteristics and composition of the considered concrete road and the results of the environmental impact assessment are described.

4.4.1 Functional unit and composition of concrete roads

The functional unit for the concrete road analysed in this study is the following:

> *'To ensure the surfacing of 1 m² of road surface for a road with a traffic load, corresponding to a construction class B1, for a period of 30 years'.*

According to the Flemish Road Authority (AWV) standard structures [50] (see also Table 6), the recommended road structure for this type of road (class B1) consists of:

- Pavement in continuously reinforced concrete: total thickness 25 cm
- Bituminous intermediate layer (asphalt type ABT): thickness 5 cm

- Foundation type 'cement-bound crushed stone mix': thickness 30 cm

Table 6: Dimensioning of a road structure with pavement in continuous reinforced concrete on a stabilised stone mix foundation (Table 4.4.2.1. in [50])[5].

	Thickness of the layers in cm									
Traffic class	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Pavement	25	23	22	21	20	-	-	-	-	-
Sandwich layer	5	5	5	5	5	-	-	-	-	-
Foundation	30	30	30	30	30	-	-	-	-	-

The continuously reinforced concrete pavement consists of a freshly poured concrete mixture on top of a longitudinally continuous mesh of steel reinforcement bars. This pavement is 25 cm thick and has a service life of 30 years. The bituminous intermediate layer serves to decouple the road structure between the cement-bound foundation and the cement-bound concrete pavement in order to prevent cracking. Its composition is roughly comparable to the asphalt mixture for sublayers, used in bituminous roads. This layer has a thickness of 5 cm and a service life of 30 years. For the foundation, a stabilised crushed stone mix is used, bonded with cement and water. This foundation has a thickness of 30 cm and a service life of 30 years. During the reference study period of 30 years, no replacements are necessary.

4.4.2 Reference case

In this study, only a reference concrete road is analysed. This refers to a classical approach to design, without many innovative elements in the design of the road paving and with the materials commonly used in practice. A classical cement concrete composition is applied for the top layer and only new or primary raw materials, i.e. aggregates mined in the quarries and bitumen coming from the petroleum refinery, are used for all components of the road structure. The use of recycled aggregates is explicitly excluded from this reference case. The pavement in cement concrete is laid in one layer, over the entire thickness of the pavement. An overview of the specific composition of the three layers is given in Table 7 (more details are available in ANNEX 2).

For modelling, available records within the Ecoinvent database v3.5 were used. These records were harmonised for Belgium and adapted if necessary (e.g. record for concrete). For the production (modules A1 and A3) of some resources and materials (e.g. porphyry and air-entraining agent), a proxy had to be used due to lack of a specific Ecoinvent record. For transport of resources towards the concrete factory (module A2) and of the foundation materials towards the construction site (module A4), a heavy truck (16-32 tonnes) and mean transport distances, relevant for Flanders, were assumed. For the transport (module A4) and pouring of concrete (module A5), the MMG scenarios 2017 [53] were used. Due to lack of detailed data

[5] All thicknesses are stated as the vertical dimension after compaction of the mixtures.

on the machinery used on the construction site (e.g. concrete machine and steam roller), the impact of the installation phase (module A5) was approximately modelled using a hydraulic digger and a concrete pump. For the EOL-phase (modules C1-C4), available MMG scenarios 2017 [53] were used if possible, or adapted, if necessary.

Table 7: Composition of the reference concrete road.

	Thickness	*Service life*
Reinforced concrete top layer - Binder (CEM III/A 42,5 LA) - Coarse aggregates (crushed porphyry 14/20, 6/14 and 2/6) - Fine aggregates (round river sand 0/4) - Additives (plasticizer and air-entraining agent) - Water - Reinforcing steel	25 cm	30 years
Asphalt sandwich layer (ABT asphalt) - Filler (limestone type Ib) - Coarse aggregates (crushed limestone 10/14, 6/10 and 2/6) - Fine aggregates (crushed limestone sand 0/2 and river sand) - Bitumen (paving grade bitumen B50/70)	5 cm	30 years
Foundation (cement-bounded broken limestone) - Broken stone (crushed limestone 0/40) - Binder (cement CEM III/A 42,5 LA) - Water	30 cm	30 years

4.4.3 Results of the environmental impact assessment

The reference concrete road was analysed for its environmental impact using LCA. The main results of this analysis are described in the following paragraphs. More detailed results on the different layers composing the road are given in ANNEX 2.

Figure 10 shows the total environmental impact of 1m² of the reference concrete road for a period of 30 years, per layer and per lifecycle phase. The reinforced concrete top layer has the most important impact. This can be explained by the large amount of concrete and steel needed to produce the concrete pavement (25 cm thickness) versus the small amount of asphalt needed for the sandwich layer (5 cm thickness).

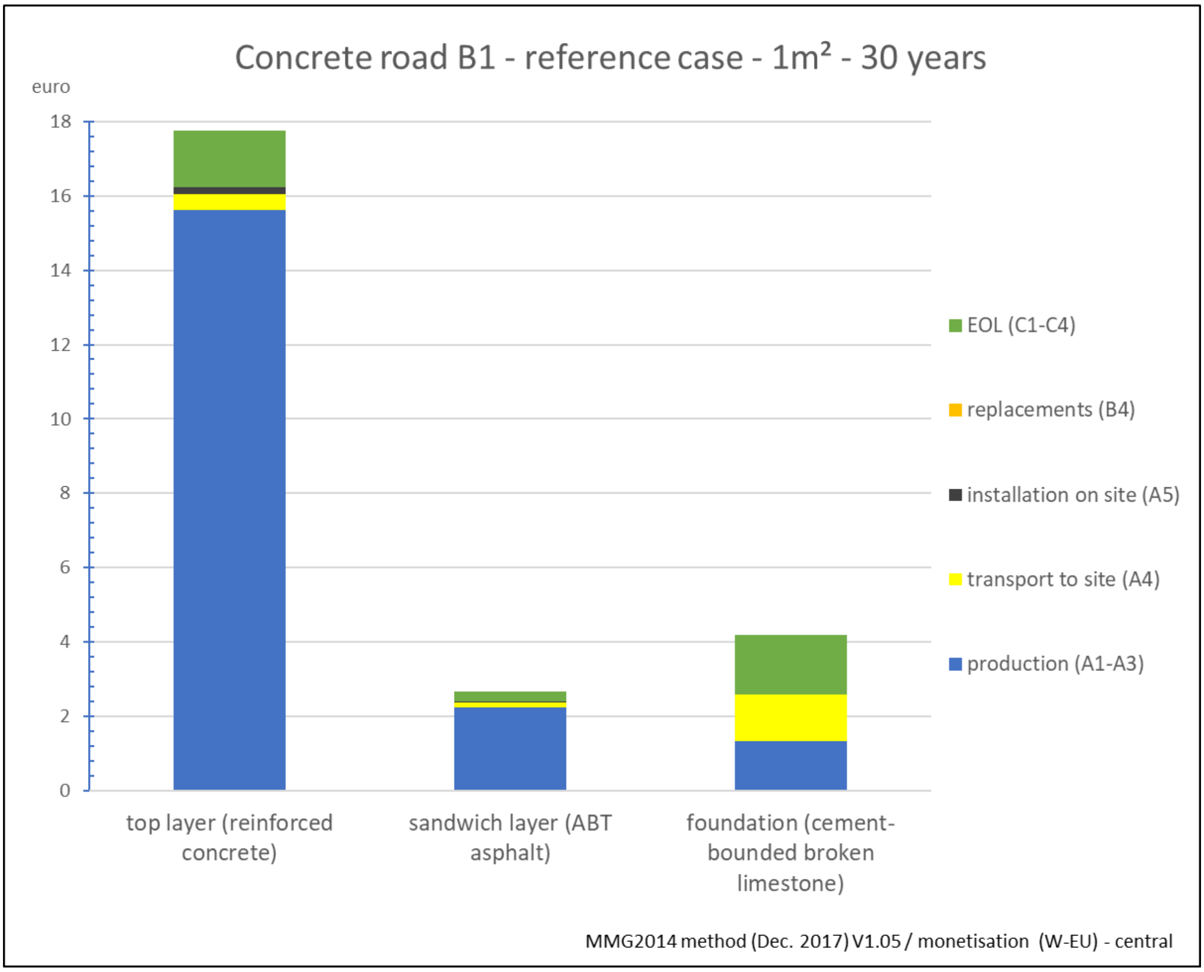

Figure 10: Environmental impact of 1 m² of the reference concrete road over 30 years, per layer and per lifecycle phase.

For both the concrete and the asphalt layers, the production phase (modules A1-A3) has the largest contribution. For the asphalt, the asphalt production process is most important (cf. bituminous road). For the reinforced concrete layer, the concrete and the reinforcing steel contribute equally to the impact. The binder is the most important component when looking at the concrete. Regarding the environmental impact indicators, the reinforcing steel has an important impact on the indicators 'human toxicity – cancer effects' and 'human toxicity – non-cancer effects', while the concrete has the largest impact on the indicator 'global warming potential'. For the foundation layer, the impact of the cement is more important than the impact of the broken limestone. The foundation layer has a significant impact on the indicators 'global warming potential', 'human toxicity', 'eutrophication', 'particulate matter' and 'water resource depletion' (see ANNEX 2).

For this case, transport of the fresh concrete from the concrete plant to the construction site (module A4) is considered. However, for large road constructions, often a mobile concrete plant on the construction site is used. In that case, there is almost no transport of the fresh concrete to the construction site but the transport distances for the (primary) resources for the concrete will change as they have to be delivered to the production site instead of at the concrete production plant. As for the case of the bituminous road, the impact of the installation phase (module

A5) represents an underestimation, given the approximations and lack of specific data used for the modelling.

There is no impact of replacements (module B4) for the concrete roads as all layers have a reference service life of 30 years.

As for the case of the bituminous road, the EOL phase represents an important part of the impact of the foundation layer. Again, this impact of the EOL phase is highly influenced by the particulate matter emissions which find their main origin in the demolition process for inert materials (dust during demolition and use of diesel for demolition).

In Figure 11, the contribution of the three layers (with subdivision between concrete and reinforcing steel for the top layer) to the total environmental impact of 1 m² of the reference concrete road is given for a period of 30 years. Figure 12 shows the contribution of the same three layers to the global warming potential indicator (expressed as kg CO_2 equivalents), for the same period. For both graphs the reinforced concrete layer is responsible for the largest environmental impact.

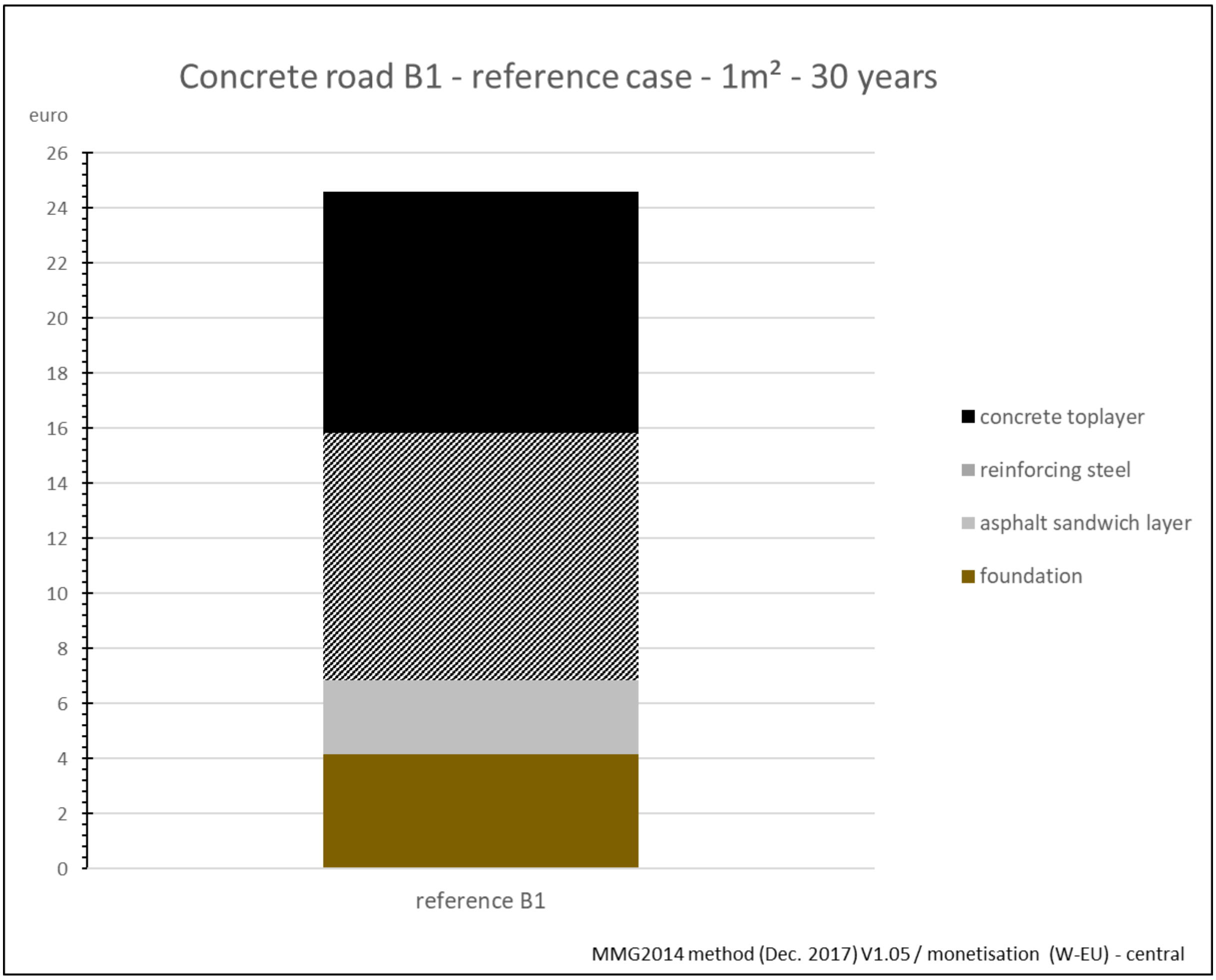

Figure 11: Environmental impact of 1 m² of the reference concrete road for a period of 30 years, per layer.

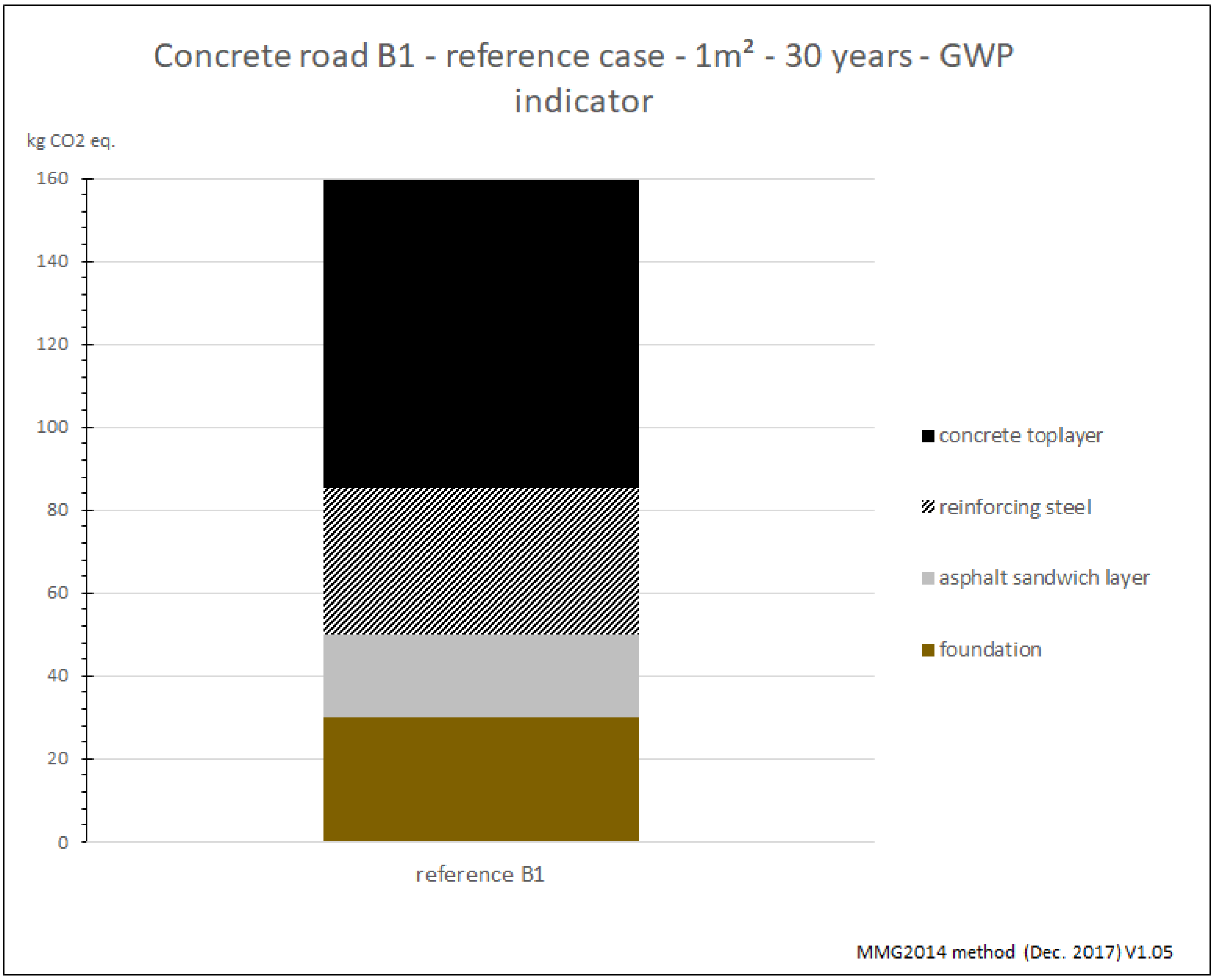

Figure 12: Global warming potential impact (expressed as kg CO_2 eq.) of 1m² of the reference concrete road for 30 years, per layer.

When considering the total environmental impact (Figure 11), the impact of the reinforcing steel is as important as the impact of the concrete in the top layer. However, when only considering the global warming potential indicator (Figure 12) the contribution of the concrete is larger than that of the reinforcing steel. The relative importance of the different layers (top layer, sublayer, foundation) remains the same when considering the total environmental impact or the global warming potential.

For the concrete road case study, only a reference concrete road is analysed for its environmental impact. The definition and calculation of a variant would go beyond the scope of this study.

Given the fact that the largest impact for the concrete road can be found in the concrete top layer (about 70% of the total impact), this layer probably has the largest potential for optimisation. However, since the amount of reinforcement is already optimised to a minimum and given that a cement type (CEM III/A) with a lower environmental impact is already selected for the reference case, optimisation options must be found elsewhere.

Optimisation options could be searched in:

- the use of recycled (concrete) aggregates to replace the primary aggregates within the foundation (see variant bituminous road) and the concrete top layer,
- the use of alternatives for cement within the concrete top layer and the foundation,
- the use of recycled asphalt aggregates in the asphalt sandwich layer (see variant bituminous road),
- the use of another type of reinforcement.

It should be noted that some of these changes might lead to a technically less performant road quality, which might result in a loss of any potential gains due to a resulting shorter service life.

4.5 Conclusions on the environmental impact of roads

In this study, two road variants, i.e. a bituminous road and a concrete road, have been analysed for their environmental impact using life cycle analysis (LCA). The composition of the roads represents current practice in Belgium. For the bituminous road, also a variant road was defined based on current optimisation options for the different layers in the road structure (i.e. use of recycled aggregates and lower production temperature).

The results for the bituminous roads indicate that the asphalt sublayer has the largest environmental impact, followed by the foundation and the asphalt top layer. For the asphalt layers, the production process has the largest impact. When comparing the variant bituminous road with the reference bituminous road, a maximum reduction in environmental impact of about 20% can be achieved when applying optimisation options to all three layers. Similar results are obtained when only looking at the global warming potential indicator (CO_2 emissions).

The results for the concrete road indicate that the concrete top layer (including concrete and reinforcing steel) has the largest environmental impact, followed by the foundation and the asphalt sandwich layer. The relative importance of the steel reinforcement is higher when considering the total environmental impact that when only looking at the global warming potential indicator (CO_2 emissions).

5. Scaling up results for the sector

5.1 Objective

To get an idea on the relevance of the impact of the road construction sector compared to the building sector in Flanders, in this chapter a rough scaling-up exercise is done. A rough comparison of the environmental impact of the yearly installation of roads and the yearly construction of new houses in Flanders is carried out.

5.2 Data for roads

Based on the results of the analyses performed in the previous chapter, in combination with information on the amount of roads (in m²) constructed each year in Flanders or Belgium, the environmental impact of roads could be scaled up to a "typical" yearly impact for Flanders or Belgium.

However, the basic data of how many m² of concrete road or bituminous road are constructed or renovated annually are not available, neither for the whole of Flanders, nor for the whole of Belgium. Also, the countless roadworks are so varied in terms of size (in m² of road surface) and in terms of sizing (type of road, traffic class, new construction versus partial or complete reconstruction, mixture type of concrete or asphalt, layer thicknesses of concrete or asphalt pavement, ...) that a global figure about the m² has little added value in terms of information.

Basic data are reported/available on the amount of asphalt produced annually (and asphalt is only used for road construction sites). The tonnages of the annual asphalt production could be converted into corresponding square meters of asphalt pavement if the correct dimensioning of the road construction would be known (layer thicknesses and densities) for all construction sites (or a regrouping in categories with the same specific layer thickness and density). However, also these data are not available.

Numbers are also available for the amount of "ready-mixed concrete" produced each year, however, the data do not distinguish between concrete for "general" construction and concrete for road pavements.

All that remains is the simplified approach by reducing the reality to one or more type cases, such as the type case described in the case studies above.

5.2.1 Bituminous roads in Flanders

Given the lack of specific data on the number and type of roads constructed each year, the starting hypothesis for this rough exercise is that all the asphalt produced is used to build the road pavements as described in the case study 'bituminous roads – variant scenario', i.e. a bituminous road for traffic class B5 consisting of 19 cm layer thickness for sublayers type APO-B (with 50% recycling of AG) plus 4 cm layer thickness for a top layer type SMA-C (prepared with the AVT technology). For 1m² of this typical road structure, a total quantity of 441.2 kg of asphalt is needed for the sublayer and 191.3 kg of asphalt for the top layer.

In order to know how much asphalt is produced annually, we can rely on the figures of COPRO, an independent body for the control of construction products, which is also the sectoral operator for the certification of asphalt (bituminous mixtures for road construction) in Belgium [54]. In practice, it appears that this asphalt production is mainly and exclusively consumed in Flanders; the Walloon Region does not impose the same obligation as the Flemish to use COPRO-certified asphalt on their road yards. Their annual report 2019[6] shows that total production of COPRO-certified asphalt amounted to around 3.4 million tons in 2019 (compared to 3.8 million tons in 2018). On the other hand, there are the statistics from EAPA (European Association of Asphalt Pavement)[7] that show an annual production in Belgium of approximately 5.8 million tons of asphalt in 2018.

With this simplified assumption (that the entire asphalt production would be used to construct only this type of road, once every 20 years), it can be calculated - as shown in Table 8 - that approximately 5.3 million square meters of road surface can be achieved annually, rounded off, based on an average annual asphalt production of 3.4 million tons according to COPRO (which roughly corresponds to the figures for the whole of Flanders). If we base this on the EAPA statistics for the whole of Belgium (an average of about 5.8 million tons of asphalt per year), this would correspond to about 9 million m² of road surface to be asphalted.

Table 8: Simplified estimation of the potential road surfacing m² (yearly, based on the typical road in the case study) [54].

	Sublayer	Top layer
Thickness of the layer	19 cm	2 times 4 cm = 8 cm
Proportion of the total asphalt mass	19/(19+8) = 70.4 %	8/(19+8) = 29.6%
Mass per m² of road pavement	0.441 ton	0,191 ton
Total amount of asphalt	3.4 million ton	
Distributed as	2.4 Mton	1.0 Mton
How many million square meters of road (Mm²) can be build?	5.4	5.3

When using the environmental impact results for the reference bituminous road in chapter 4 (i.e. 0.95 euro/m²/year), it can be calculated that the total environmental impact of 5.3 million m² of asphalt roads in Flanders equals a total of about 5.04 million euros (TOTEM score) per year (see Table 9). This also includes

[6] See https://www.copro.eu/sites/default/files/article/file/COPRO_Activiteitenverslag%202019_NL_0.pdf
Additional information: in 62 % of these asphalt tons RA was used (1 Mton in total), with on average 47 % recycling ratio. 0.19 Mton of warm-mix asphalt was produced (AVT). The ratio between asphalt tons for top layers versus sublayers is approximately 35 % / 65 % of total production.

[7] See https://eapa.org/wp-content/uploads/2020/02/Asphalt-in-figures_2018.pdf. The Belgian annual production of 5.8 Mton in 2018 would be distributed as follows: 53% for top layer mixtures and 47% for sublayers. This seems to be an overestimate of the ratio, which in practice would rather be around one-third / two-thirds.

the impact of the foundation of the asphalt roads. If the latter is omitted and only the impact of the asphalt itself is considered, 5.3 million m² of asphalt roads equals a total environmental impact of about 4.02 million euros (TOTEM score) per year. When using the environmental impact results for the variant bituminous road in chapter 4 (i.e. 0.77 euro/m²/year), the total environmental impact of 5.3 million m² of asphalt roads in Flanders equals a total of about 4.1 million euros (TOTEM score) per year.

5.2.2 Concrete roads in Flanders

A similar exercise is not possible for the concrete roads, since no data is available on the amount of concrete that is produced explicitly for roads in Flanders. Figures are available on concrete production in Flanders, but it is not known which part of this concrete goes to roads, to buildings and to other applications.

5.3 Data for buildings (new construction)

In Flanders, about 20 000 new houses are built every year[8]. One of the case studies in part 1 of this TOTEM Potential study (i.e. newly constructed semi-detached dwelling) pointed out that the total environmental impact of this house equals 2.37 euro/m²GFA/year (incl. operational energy use), and 1.32 euro/m²GFA/year (excl. operational energy use).

Assuming that this semi-detached house could be representative for newly constructed houses in Flanders, an estimation of the yearly total environmental impact of new construction in Flanders can be made. Given a GFA of 187.36 m² for a representative semi-detached house and a total amount of 20 000 houses per year, the total impact of the construction of new houses in Flanders equals about 8.88 million euros (TOTEM score) per year (incl. operational energy use), and about 4.95 million euros (TOTEM score) per year (excl. operational energy use) (see Table 9).

5.4 Comparison between roads and houses

A rough scaling-up exercise for bituminous roads and new houses in Flanders pointed out that the total environmental impact of roads could be as important as the total environmental impact of new houses in Flanders, in case the operational energy use of the houses is not considered (see Table 9).

In general, these numbers should be used with a lot of care. They do not claim to be a correct representation for the exact impact of each sector (this would require a larger and in-depth study at macro scale). For the road construction several assumptions had to be made concerning the quantities of asphalt, the type of roads and their composition, and concrete roads are left out of the equation due to a lack of data. For the building sector, only new construction is considered and not renovations. Also, for the new construction several assumptions are made

[8] https://www.wonenvlaanderen.be/woononderzoek-en-statistieken/algemene-cijfers-over-de-woningmarkt-vlaanderen

concerning the number of houses constructed each year and the representative building typology. The main intention of this comparison is to provide a rough view on the order of magnitude of the potential environmental impact of each subsector and their relative importance.

Table 9: Environmental impact of bituminous roads and new houses in Flanders (per year).

	Environmental impact	*Amount*	*Total environmental impact (TOTEM)*
Bituminous roads			
Reference case	0.95 euro/m²/year	5 300 000 m²	5 040 000 euro/year
Variant case	0.77 euro/m²/year	5 300 000 m²	4 100 000 euro/year
New houses (case semi-detached)			
Including operational energy use	2.37 euro/m² GFA/year	20 000 x 187.36 m²	8 880 000 euro/year
Excluding operational energy use	1.32 euro/m² GFA/year	20 000 x 187.36 m²	4 950 000 euro/year

6. Lessons learned

Based on the literature study (see chapter 3) and the case studies (see chapter 4), different insights can be grouped when considering an extension of the TOTEM tool to subsectors of the construction industry.

6.1 Insights on the general principles and methodology

6.1.1 Additional life cycle stages

The literature study showed that there is a need for additional life cycle stages when evaluating civil engineering works. The European standard defines the "pre-conception stage" (A0), however this stage seems relevant for economic assessments but less for environmental assessments. A second additional stage relevant for civil engineering works concerns the "users' use stage" (B8): this phase includes the environmental impact caused by the users of the infrastructure (e.g. emissions or energy use by the vehicles using the road).

The literature study reveals that the impact related to the use of the road is larger than the impact linked to the materials used for the road, and can represent more than 80-90% of the total impact of a road over its entire lifecycle. In the current TOTEM tool for buildings, energy consumption related to heating is also included in the calculations. However, for the heating of buildings, it is clear that adapting the building envelope (i.e. the materials) and the techniques can influence this energy demand. Therefore, in the case of buildings, a direct relationship exists between the impact linked to energy consumption and the impact linked to materials and technical installations. In the case of roads, this relationship is much less pronounced. The actual (fuel) consumption of road users will only be influenced to a limited extent by the road's material characteristics (e.g. rolling resistance of the road surface), but will largely be determined by the type of vehicle, type of fuel and for example the layout and topography of the road. These are all parameters that one cannot act upon by changing the use of materials. Determining the impact linked to the users' use therefore seems less relevant in a context of material selection and optimization, although it could be useful information in view of policy.

6.1.2 Reference study period

For the bituminous roads, the reference service life is set to 20 years, while for the concrete road, the reference service life is 30 years. As a consequence the functional unit differs for one type of road to the other, which makes comparisons more complex. For other civil engineering works (e.g. quays), the service life can be as large as 100 years. The study shows that the reference study period (RSP) has to be specified in relation to the specific engineering works that are studied. Whereas additional research might be necessary for each specific sector to get representative numbers, the concept of the RSP for infrastructure follows the same logic as for buildings, so this seems manageable.

6.1.3 Data structure: materials – components (work sections) – elements

The TOTEM tool uses a systematic logic to decompose a building into its materials by use of different "levels": building – elements – components (work sections) – materials. Analyses and optimisations in the TOTEM tool for buildings are done at the level of the elements (by changing the composing components), or at the level of the components (by changing the composing materials). The present study shows that for roads the analyses can also be done at the level of the elements and components (e.g. concrete versus asphalt; primary broken limestone versus recycled concrete aggregates). However, the study shows that also important variations and optimisation options occur at the level of the material composition (e.g. SMA-C asphalt versus APO-B asphalt) and the production process (e.g. traditional asphalt versus AVT asphalt). One could state that these differences could be defined as "different" materials, however, it becomes clear that multiple variations are possible for certain materials. Think for example of the concrete, where the ratio of reinforcement can vary, as well as the water/cement factor, and/or the type of cement. It becomes clear that for materials used in engineering, insights and modifications at a "sub-material" level are necessary. This means that either a large set of variants of one material must be available to the user (e.g. SMA-C asphalt, APO-B asphalt, AVT asphalt, asphalt with recycled asphalt aggregates, …) or the user himself is provided the option to vary the composing materials at sub-material level. For this, material specific EPDs might be useful to cover specific situations.

An important note to make in the case of road construction is that often non-material related parameters play a significant role in the basic material choice (e.g. amount of traffic, users' use, geographical circumstances, logistic, machinery available, way of building, …). The material choice is often determined at the start of a study, based on the type of infrastructure needed (cf. concrete for highways and asphalt for regional roads, depending on traffic classes), and technical aspects related to the maintenance and/or construction phase. Therefore it is important that optimisations can take place at a detailed level.

6.2 Insights on data availability

Because the use of materials for infrastructure works (with associated service life, maintenance and replacement scenarios) differs from the use of materials in buildings, it is necessary to expand the library of available components within the TOTEM tool and adapt it to their use in large structures. For example, it will be necessary to add additional categories (e.g. different types of soil, road surfacing, foundations, sheet piling, piles, utility pipes, road finishes, …) and to complement them with specific components (e.g. sand and soil, asphalt, concrete and other road surfacing, pipes for gas, electricity and water, sheet piling, …) and processes (e.g. dredging, earthworks, pile driving, …).

6.2.1 Ecoinvent data for production of materials

The case studies show that the Ecoinvent database is often not representative, specific or extensive enough to model production impacts of road materials (modules A1-A3). For example, for the modelling of asphalt only one single record for "mastic asphalt" is available in the database. When looking in detail at this record, it does not represent the different types of asphalt used in Belgian roads (SMA-C asphalt and APO-B asphalt). Consequently, the different types of asphalt used in this study have been modelled by adapting the Ecoinvent record (i.e. using other primary resources). Furthermore, within this record, heavy fuel is used to heat the aggregates during production of the asphalt. In practice, different types of fuels are being used in asphalt plants in Belgium (e.g. heavy fuel, diesel, natural gas). A sensitivity analysis showed that the impact of the production is largely dependent on the choice of fuel used for heating the aggregates. Consequently, the impact of asphalt production is largely factory-specific.

Also for the concrete, the PmB bitumen and the composite filler, the available Ecoinvent records had to be adapted to current practice in Belgium by changing the resources used. Furthermore, some materials are missing in the Ecoinvent database. Examples are porphyry, different types of sand, SBS polymer and plasticiser. For these records, a proxy had to be used. In conclusion, it seems that quite some additional modelling work or, if available, other databases with additional information on specific materials would be necessary to arrive to a representative set of material records for use in road construction and in extension other infrastructure works).

6.2.2 Scenarios for transport, installation and EOL

Regarding construction site impacts (module A5), only limited data is available from practice and only a limited number of records is present in the Ecoinvent database (or other available databases). There is, for instance, a lack of data on the impact of the shuttle buggy, the asphalt machine, the concrete machine and the steamroller. In this study proxies were used, but this probably leads to an underestimation of the installation impact. Nevertheless, both the case studies and the literature study suggest that the impact of the construction site is limited.

In any way, the approach taken for modelling of the installation stage in this study largely corresponds with the current approach within the TOTEM tool for buildings: the impact of construction is only taken into account when specific data is available and when it is directly related to the materials used (so a certain material dependency has to exist). When generalising the main impacts for the installation stage, it seems that these impacts are rather "company-specific" than material related. For example, for a broken limestone foundation and a foundation composed of recycled concrete aggregates, the same hydraulic digger and steamroller are necessary. The impact of the machinery is thus more dependent on the type of machine available within the contractor's company (e.g. age and fuel type) than on the actual materials installed. Therefore, it appears that the potential for optimisation of construction site impacts is rather situated in the companies' machine parks than in the material selection process. Tools, such as the CO_2 performance ladder, might be better suited to optimise these impacts.

According to prEN 17472:2020 [2], also transport of people and material to and from the construction site should be calculated. This was not included in the present study due to lack of data but this might highly influence the results for the installation stage (module A5), if taken into consideration. The building standard EN 15978 [3] does not include this, but the inclusion of person transport might have a high impact in a building context as well.

Finally, it is necessary to develop sector-specific scenarios for transport to site (module A4) and end-of-life (EOL, modules C1-4). The TOTEM scenarios can be used for some of the materials for infrastructures (e.g. reinforcing steel) but are not adequate for all materials. For instance, TOTEM has no EOL scenario for asphalt and foundations, and also the existing TOTEM transport scenarios (for buildings) are not necessarily representative for other types of construction.

6.3 Specific insights for road construction

Based on the case studies for the roads, some specific insights concerning the environmental impact of roads can be grouped. The case studies show that the main environmental impact of bituminous and concrete roads over their life cycle is related to the production phase (modules A1-3), followed by the EOL phase (modules C1-4).

When comparing the two variants for the bituminous road, an optimisation potential of about 20% could be achieved when optimising the three layers within the road. The optimisation potential for the individual layers varies between 7% and 46%. For the concrete road no optimisation variants were defined, because this was beyond the scope of the study. Optimisation could however be achieved by using recycled aggregates instead of primary resources within the concrete, the asphalt and the foundation, by using other types of cement or binder for the concrete and the foundation and/or by optimising the amount of reinforcing steel. Both cases illustrate the need for more detailed modelling at sub-material level for roads.

The relative importance of the different environmental impact indicators for roads is similar to that in building LCA. As for buildings, the most important indicators are 'global warming potential', 'eutrophication', 'acidification', 'human toxicity – cancer effects', 'human toxicity – non-cancer effects' and 'particulate matter'. For some components (e.g. concrete and asphalt), also the indicators 'water resource depletion' and 'land use: occupation – flows biodiversity, urban' are significant.

7. Recommendations for functionalities of TOTEM

Based on the literature study (chapter 3) and the case studies (chapter 4), it can be concluded that additional functionalities or adaptation would be needed to extend the TOTEM tool to civil engineering works.

At first, the reference study period and the service life of the composing elements and materials have to be defined for the different types of civil engineering works. Both the literature study and the case studies pointed out that these parameters are sector-specific and thus not the same for all types of works (e.g. reference study period of 20 years for bituminous roads and 30 years for concrete roads) (which might also be the case for different building typologies). For comparisons, it is important to work with the same functional unit (which appears not to be always possible for roads). However, it seems manageable to adapt these data and the results for each specific sector.

Secondly, the lifecycle phases and processes to be evaluated with the TOTEM tool for civil engineering works must be defined. The literature study pointed out that additional lifecycle phases could be included (i.e. A0 pre-conception phase and B8 users' use) for certain infrastructure works. The impact of the users' use phase seems to be far most important in many cases. However, it is difficult to model this phase due to lack of data and because in many cases users' use is not dependent on the materials chosen, but rather on other parameters. If this phase is to be included in the evaluation, impact data for different types of vehicles have to be included in the library. Furthermore, the case studies showed that the impact of the construction installation phase (module A5) is very limited and difficult to model due to lack of data. Moreover, this phase is also rather company-dependent than material dependent. Here, it could be chosen not to model this phase in detail and potentially use a complementary tool instead (e.g. CO_2 performance ladder to model CO_2 emissions). The production phase appears to be the (second) most impacting phase, so it seems necessary to model this phase in more detail.

The TOTEM logic (building – elements – components (work sections)) should be adapted to civil engineering works (work – elements – components). Furthermore, it would be necessary to expand the components library with additional material categories and additional components. Also, specific processes could be added to the library. Furthermore, additional scenarios for transport and EOL seem necessary for specific materials.

Important here is that variations in composition of roads not only occur by using different processed materials but also by variations in the processed materials themselves (different composition or different production circumstances). Variations thus occur at sub-material level. This means that in the TOTEM library either different variants of one material must be available for the user or the user himself can vary the composing materials at sub-material level (which is not possible in the current version of the TOTEM tool). So decisions must be taken regarding the composition of the available materials.

Finally, it seems that for roads the number of variants for components is rather limited to represent current practice. Innovation is mainly possible at sub-material level (composition or production circumstances) and the choice for a certain road paving is rather dependent on non-material related aspects. The question must be asked whether it is from this viewpoint useful to work out a new tool to model the environmental impact of roads. For other civil engineering work, a similar evaluation seems necessary.

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9. ANNEX 1: Detailed technical description of the selected case studies

9.1 General approach

In this study, we want to explore different scenarios of road construction based on a number of case studies, in particular a road construction with the material type "asphalt" on the one hand and a road construction with the material type "concrete" on the other hand. This description will allow us to provide the data needed for further processing in the calculations of the TOTEM tool for the part "road construction".

For each case, a reference scenario is defined: this scenario includes a classic approach with the materials commonly used in practice and without any innovative elements in the design of the road paving. For the bituminous roads, the reference is extended with a variant scenario: this scenario considers more innovative elements in the design of the road pavement that are particularly selected to lower the environmental impact of the road.

9.2 A short introduction to road construction

9.2.1 Standard structures and traffic classes

In Flanders, roads are designed using the so-called standard structures for road construction, which are determined by the type of road pavement material (this is of the type "stiff", with concrete, or type "flexible", with asphalt) [1].

The dimensioning of the road structure is mainly determined by taking into account the expected traffic load over the entire service life, which is expressed in so-called ESALs or a number of equivalent standard axle loads of 100 kN. For the service life to be considered, 20 years are taken into account in the case of road surfacing in asphalt and 30 years in the case of road surfacing in concrete. The result of this calculation determines the so-called traffic class (*bouwklasse* in Dutch) of the road in question, as is shown in Table 2 (p.20).

With regard to the vertical dimensions of the road structure, Figure 3 (p.21) schematically shows that an asphalt or concrete pavement (further built up from one or more sublayers and on top of that a top layer) is always laid on top of a foundation layer that supports it and further distributes the forces of the traffic load to the foundation and subsoil. For a detailed dimensioning of the road, it is of course necessary to take into account all elements of the local situation (and therefore also the characteristics of the subsoil and foundation, such as load-bearing capacity, deformation properties), but this goes beyond the scope of this study.

For low and moderately loaded roads, a foundation layer usually consists of a crushed stone mix with a continuous grain distribution curve and without additional cement as a binding agent, which is compacted as strongly as possible.

For heavily loaded roads, a similar crushed stone mixture is normally used as a foundation, but now with cement as a binding agent in the mixture.

9.2.2 Functional unit and choice of design service life

As the dimensioning of the road structure depends strongly on the amount of traffic it will carry - the higher the traffic load, the stronger the road structure has to be provided to withstand these loads - and we don't want to elaborate on all cases in detail here, we will concentrate as an example on 2 typical structures for 2 different cases, on the one hand an **asphalt pavement in traffic class B5** and on the other hand a **concrete pavement in traffic class B1**.

As a functional unit for the calculation of the different environmental impacts over the service life of the road (lifecycle analysis or LCA), we choose in these case studies for a road for a traffic load of a certain traffic class (as specified above) and for **a road surface of 1 square meter (1 m²)**. This way, the data can be extrapolated to all roads by multiplying by the correct width and length of the road in question.

Note here that the functional unit for the bituminous road and the concrete road is not the same due to the different traffic classes, so that the environmental impact results for both roads cannot be compared to each other.

9.3 Case study 1: Bituminous roads

9.3.1 Reference scenario: Road structure

As an example, we choose to carry out a case study for a road with asphalt pavement and suitable for a traffic load according to traffic class B5. This could be, for example, a connecting road between two cities or a connecting road between an industrial zone and the entrance and exit of a motorway or, for example, a regional urban ring road.

According to Table 2, over a period of 20 years, this type of road could be subject to a traffic load of between 4 and 8 million ESALs. We note that this calculation is only structurally oriented for a new road. In practice, functional maintenance will already be required earlier in order to provide the road user with the necessary comfort (such as for flatness, noise, roughness, ...) by renewing the top layer after, for example, 10 years. After on average some 20 years, it is common practice and experience that the sublayer and top layer will need to be renewed.

In this case study, we make such calculations for a period of 20 years. For this period, we take the following assumptions:

- We foresee a technical service life of 30 years for the foundation. This is longer than the calculation period under consideration, so we do not foresee any renovation or replacement of the foundation.
- For the asphalt pavement itself, we opt for a shorter service life, namely 20 years for the sublayer and 10 years for the top layer. This implies that the top layer will have to be renewed once and the sublayer will not need any renovation or replacement, but will reach the end of its technical service life in order to be able to function together for 20 years.

The functional unit for this analysis is therefore the following:

"To ensure the road structure of 1 m² of road surface, for a road with a traffic load corresponding to a traffic class B5, for a period of 20 years".

According to AWV's standard structures [50], the recommended road structure for this type of road is as follows (see Figure 5, p.25, in case a classic asphalt sublayer and unbound foundation is chosen; construction class B5 is second from the left):

- Foundation type 'unbound crushed stone mixture': thickness 35 cm
- Paving in asphalt: total thickness 23 cm

For the foundation layer in unbound crushed stone mix, a mixture of crushed limestone aggregates, calibre 0/56 or 0/40 or 0/32 (mm) is traditionally used. Origin of these stones are the limestone quarries in Wallonia (near Tournai or Liège). The density of the compacted foundation is 2.2 kg/dm^3, so 1 cubic meter of crushed limestone foundation contains 2200 kg of crushed limestone 0/40. Per m^2 surface area of the road (foundation) and per cm layer thickness of the foundation, this is 22 kg of crushed limestone.

For road surfacing in asphalt, a distinction is made in practice between 2 different types of asphalt, on the one hand a mixture for sublayers and on the other hand a mixture for the top layer. In the case we are discussing here, for example, the road structure is as follows:

- sublayer in asphalt concrete (AB), total thickness 19 cm
- top layer in split mastic asphalt or SMA, thickness 4 cm

The asphalt for sublayers is laid in 2 or 3 layers, first a first sublayer in a thickness of about 8 cm which has the function of absorbing the unevenness in the surface of the foundation, and on top of this a 2nd and possibly 3rd sublayer (e.g. in thicknesses of 6 and 5 cm respectively) which can then be finished to a reasonably uniform surface in terms of evenness.

The asphalt for the top layer is then laid in 1 layer and finished to the desired level. This layer has a thickness of 4 cm after compaction.

9.3.2 Reference scenario: Mix design and materials

The layers of the asphalt pavement consist of mixtures of hot-prepared asphalt, produced with the following raw materials: crushed stone, sand (both crushed sand and round sand), filler and bitumen as a binding agent.

Several types of asphalt are available for the sublayer mixtures, for example a type of asphalt concrete with performance requirements for sublayers (code APO). In this family, several mixture types are possible, e.g. APO-A or APO-B, which differ from each other in the maximum grain size of the crushed stone (of 20 and 14 mm respectively).

Several types of asphalt are also available for the top layer, here we choose an asphalt type with a stone skeleton SMA (split mastic asphalt), i.e. an SMA-C, with a maximum grain size of the crushed stone of 10 mm.

In this reference scenario for the asphalt composition, we only work with so-called "new" or primary raw materials, i.e. aggregates mined in the quarries and bitumen coming from the petroleum refinery. We therefore explicitly exclude the application of the recycling of Reclaimed Asphalt (RA, *asfaltgranulaat* AG in Dutch) as a raw material for new asphalt mixes.

In practice - at least for asphalt mixtures for sublayers - a significant proportion of asphalt production plants are equipped in terms of technology and quality control in such a way that they can successfully use Reclaimed Asphalt as a partial substitute for 'new' aggregates and for new bitumen. In this sense, the example given in detail below should really be regarded as a (theoretical) basic case. Because the use of RA as a raw material for new asphalt not only has economic advantages, but also probably scores better in ecological terms, we reserve mixtures with RA for the "variant" scenario to be discussed later.

Table 10 gives an overview of the nature and origin of the materials used (for both sub- and top layers).

Table 10: Overview of the nature and origin of the materials used for asphalt sub- and top layers

Type of material	*Description of material*	*Location of origin place*	*Distance to asphalt plant (e.g. in Zaventem) (km)*
stones	Crushed porphyry calibre 6,3/10	Quenast	60
	Crushed porphyry calibre 4/6,3	Quenast	60
	Crushed limestone calibre 10/14	Namen (Beez)	70
	Crushed limestone calibre 6,3/10	Namen (Beez)	70
	Crushed limestone calibre 2/6	Doornik	60
sand	Crushed porphyry calibre 0/2	Lessines	70
	Round sand (river sand or marine sand)	Oostende	125
	Crusher sand of limestone calibre 0/2	Doornik (Gaurain-Ramecroix)	110
filler	Composite filler	Maastricht (NL)	120
	Limestone filler type Ib	Doornik	110
binder	Pavement grade bitumen or polymer modified (PmB) bitumen	Antwerpen-harbour	60

In order to be able to use relevant figures in further calculations of the environmental impact for the component "transport of raw materials" from extraction site to production site, we have opted in this example for an asphalt production plant centrally located in Flanders. Data on the location of the manufacturing site and distance from quarry to asphalt plant (respectively penultimate and last column) are therefore only given as a typical example.

As far as bitumen is concerned, it can be noted that only the distance from the oil refinery in the Antwerp port area to the asphalt plant is given; the petroleum itself comes e.g. via pipelines from Russia or Norway or by oil tankers from the Middle East or even further (e.g. from South America).

The design process to calculate the desired volumetric composition of the asphalt mixture relies on the properties of the different types of aggregate (mainly grain distribution curve, density and angularity) to obtain a balanced mineral skeleton, with a continuous or discontinuous grain distribution. A carefully composed asphalt mixture contains a mineral skeleton that is as stable as possible and the necessary amount of binder to encapsulate all the minerals and fill a suitable part of the pores with mastic (bitumen plus filler). The mixture also contains a percentage of pores or hollow space. The composition must be chosen in such a way that the asphalt mixture can achieve the mechanical performance characteristics.

During construction, the asphalt mixture is spread over the surface of the road to be asphalted, in a certain over-thickness and then compacted by rollers. In this way, the asphalt mixture is finally brought into a shape that still contains a minimum amount of (air-filled) cavities. The correct amount of hollow space is determined by the composition, i.e. in function of the relative amounts of crushed stone, sand, filler and bitumen, and the angularity and granular distribution of the aggregates.

Asphalt mixture for sublayers

Table 11 shows the composition for a typical asphalt sublayer mixture (APO-B).

When it comes to the type of stone used for asphalt for sublayers, limestone is traditionally used, as it offers the best value for money for this application in our regions.

For the aggregates, this mixture uses limestone in different fractions: for the coarse aggregates (crushed rock) in the fractions 10/14 mm and 6/10 mm and fractions 2/6 mm, for the fine aggregates (sand) both crushed limestone sand in fraction 0/2 and round natural sand (river sand) 0/2 mm are applied. A limestone flour (fraction 0/0.063 mm) is also used as filler.

The binder is a classic bitumen (paving grade bitumen type B50/70).

Taking into account the characteristics of the limestone aggregates and the sand (round and crushed), the average density of the mineral skeleton in this example is 2.68 kg/dm^3 and the maximum volumetric mass of the aggregate and bitumen mixture is 2.495 kg/dm^3.

Table 11: Example of a typical asphalt mixture for sublayer (type APO-B).

Asphalt mix for sublayer (type APO-B)			Mix design		In compacted road pavement	
Material type	*Component*	*Density (t/m³)*	*Mass-% (on aggregates)*	*Volume-% (on aggregates)*	*in kg per ton asphalt*	*in kg per m³ asphalt road*
Filler	Type Ib (limestone)	2.698	5.0 %	4.97 %	48	113
Stones	Limestone 10/14	2.69	25.0 %	24.91 %	239	564
	Limestone 6/10	2.69	23.0 %	22.91 %	219	519
	Limestone 2/6	2.692	15.0 %	14.93 %	143	339
Sand	Crushed limestone 0/2	2.673	20.0 %	20.05 %	191	452
Sand (round)	Round river sand	2.63	12.0 %	12.23 %	114	271
total aggregates			100.0 %	100.0 %	954	2.258
Bitumen (% on aggregates)	Paving grade bitumen B50/70	1.025	4.82 %		46	109
Total			104.82 %		1.000	2.366

The binder content in this example (see fourth column, penultimate line in Table 11) is 4.82 %-m on 100 %-m total aggregate mass. In order to express this in relation to the total mass of the mixture (aggregates + binder), the figures must then be divided by 1.0482, thus obtaining as mass ratios in the total asphalt mixture the values proposed in the penultimate column of the table. Per ton of asphalt, this corresponds to 46 kg of binding agent (paving grade bitumen type B50/70).

The apparent volumetric mass (taking into account the 5.14 %-v hollow spaces in the total asphalt mixture) in this example is 2 366 kg/m³.

In order to be able to calculate more easily in relation to the functional unit of our case study, we will express everything in quantities (masses in kg) in the asphalt when compacted, per m² surface of the road and per cm layer thickness. This means that in this example, the asphalt mixture for sublayer has a mass of 23.66 kg per m² road surface area and per cm layer thickness of the asphalt pavement.

The raw materials needed to prepare this amount of asphalt are as follows:

- 14.22 kg of limestone (3.39 kg of crushed limestone in calibre 2/6 + 5.19 kg in calibre 6/10 + 5.64 kg in calibre 10/14)
- 4.52 kg crushing sand of limestone (calibre 0/2)
- 2.71 kg round sand
- 1.13 kg filler
- 1.09 kg road bitumen.

Asphalt mixture for top layers

Table 12 shows the composition for a typical top layer mixture (type SMA-C).

Table 12: Example of a typical asphalt mixture for top layer (type SMA-C).

Asphalt mix for top layer (type SMA-C)			Mix design		In compacted road pavement	
Material type	*Component*	*Density (t/m³)*	*Mass-% (on aggregates)*	*Volume-% (on aggregates)*	*in kg per ton asphalt*	*in kg per m³ asphalt road*
Filler	Type II (composite)	2.8	8.5 %	8.3 %	80	191
Stones	Porphyry 6,3/10	2.727	63.0 %	63.0 %	591	1 413
	Porphyry 4/6,3	2.711	9.2 %	9.3 %	86	206
Sand (crushed)	Porphyry 0/2	2.71	19.3 %	19.4 %	181	433
total aggregates			100.0 %	100.0 %	938	2 243
PmB bitumen (% on aggregates)	PmB bitumen 45/80-50	1.022	6.61 %		62	148
Total			106.61 %		1.000	2 391

Aggregates of the porphyry stone type are traditionally used for asphalt for top layers, as this type of stone offers the best value for money for this application in our regions. Limestone (as usual in the sublayer mixes) is not suitable, as it does not meet the higher requirements in terms of resistance against polishing (polished stone value or PSV). Alternative types of stone are sandstone (grès) or crushed gravel.

For the aggregates, this mixture uses porphyry in different fractions: for the coarse aggregates (crushed stone) only in the fractions 6.3/10 mm and 4/6.3 mm, for the fine aggregates (sand) only crushed porphyry in fraction 0/2 mm and no round sand. The absence of the crushed stone fraction 2/4 mm is especially wanted in order to create a certain discontinuity in the stone skeleton.

For the filler, a composite filler is chosen, i.e. a part of limestone flour (20 %) supplemented by other filler fractions (80 %) consisting of secondary (industrial waste) sources (20 % fly ash from waste incineration plants, 20 % fly ash from (water treatment) sludge incineration plants or biomass incineration plants and 40 % fly ash from coal-fired power plants). Because of their size as very fine aggregates and their compatibility or sensitivity to mixing with bitumen, these fly ashes can fulfil a function as a filler in asphalt. In comparison with a filler consisting solely of ground limestone (see APO mix for sub layers), the environmental impact calculations will also have to include a contribution that takes into account the preparatory work to make the fly ashes from the incineration plants a suitable raw material for asphalt filler, including drying of the ash and transport to the filler production plant [55]. Since these “secondary raw materials” do not arise out of nothing (a combustion process is needed to burn the pulverised coal, sludge or biomass, thereby creating a fraction of fly ash as a by-product), it is therefore logical to assign a certain 'impact' to them, i.e. part of the impact of the main product (e.g. the electricity produced by burning the pulverised coal) must/may be allocated to the by-product. How exactly this allocation of impacts is done - on the basis of the ratios in mass of the fractions or on the basis of the ratios in economic value, or different or none at all, is still a point of discussion according to LCA experts. It is clear, however, that an absence of this allocation can result in major underestimations and so the products composed with these fly ash (such as composite fillers) turn out to be much "greener" than they actually are, i.e. an underestimation and misrepresentation (greenwashing).

The binder is a polymer modified bitumen (PmB), i.e. a binder in which the paving grade bitumen is modified in its characteristics by an intrusion of a certain amount (about 3 to 4 % by mass) of a high performance polymer (such as the elastomer SBS).

Taking into account the characteristics of the porphyry granulates and broken porphyry sand, the average density of the mineral skeleton in this example is 2.728 kg/dm³ and the maximum volumetric mass of the mixture of aggregate and bitumen is 2.472 kg/dm³. The apparent volumetric mass (taking into account the 3,3 %-v hollow spaces in the total asphalt mixture) in this example is 2.391 kg/dm³.

The binder content in this example of asphalt mixture for top layer is 6.61 % by mass in relation to 100 % of the aggregate total. To express this in relation to the total mass of the mixture (aggregates + binder), the figures have to be divided by 1.0661, so as mass ratios in the total asphalt mixture we obtain the values proposed in the penultimate column of the table. For each ton of asphalt, 62 kg of binder PmB is thus needed, as well as 938 kg of aggregates.

In order to be able to calculate more easily in relation to the functional unit of our case study, we will express everything in quantities (masses in kg) in the asphalt when compacted, per m² surface area of the road surface and per cm layer thickness. This means that in this asphalt mixture for top layer when compacted, the asphalt has a mass of 23.91 kg per m² surface area of the road surface and per cm layer thickness.

The raw materials needed to prepare this amount of asphalt are as follows:

- 16.19 kg of porphyry aggregate (2.06 kg crushed porphyry in calibre 4/6.3 + 14.13 kg in calibre 6.3/10)
- 4.33 kg crushing sand of porphyry (calibre 0/2)
- 1.91 kg composite filler
- 1.48 kg PmB bitumen

Total mass for the whole road pavement over a period of 20 years

Taking into account the above mass ratios in this example, Table 13 summarises that for the reference road construction and the corresponding service life of the different layers of asphalt, about 641 kg of asphalt is needed to maintain the road in question over an area of 1 m² and for 20 years.

Table 13: Amounts of asphalt needed per m² road over the reference period.

	Density (kg/m³)	*Mass per m² and per cm layer thickness (kg)*	*Layer thickness (cm)*	*Number of layer construction times over a period of 20 years*	*Equivalent layer thickness (= indiv. layer thickness x times constructed) (cm)*	*Equivalent mass per m² road (= equiv. layer thickn. X mass per cm) (kg)*
sublayer	2 366	23.66	19	1	19	449.5
top layer	2 391	23.91	4	2	8	191.3

9.3.3 Variant scenario: Road structure

For simplicity of comparison between the scenarios, we assume a similar road layout as in the baseline scenario. In other words, a road of traffic class B5 constructed according to AWV's standard structures: a foundation of the unbound crushed stone type, with a layer thickness of 35 cm, and a pavement in asphalt with a thickness of 23 cm for the whole of the asphalt layers[9].

For road pavement in asphalt, we retain the same structure with sublayers and top layer in asphalt:

- sublayers in asphalt concrete (AB), total thickness 19 cm
- top layer in split-mastic asphalt (SMA), thickness 4 cm

9.3.4 Variant scenario: Mix design and materials

Variant versus reference scenario

In this variant scenario, changes are made to all three layers of the road structure:

- Asphalt top layer: use of low-temperature SMA-C asphalt with foamed bitumen instead of classic SMA-C asphalt
- Asphalt sublayer: use of APO-B asphalt with 50% reclaimed asphalt aggregates instead of APO-B asphalt with only primary raw materials
- Foundation: use of recycled concrete aggregates instead of primary resources

[9] All thicknesses are stated as the vertical dimension after compaction of the mixtures.

Foundation in unbound crushed stone mixture

For the foundation in unbound crushed stone mixture, we opt here for an alternative composed of recycled aggregates, e.g. crushed concrete aggregate (*gerecycleerd betongranulaat* in Dutch) of the same calibre (0/40 mm). This includes both coarse aggregates and sand, all obtained from the crushing and screening of rubble from the demolition of concrete structures (buildings and concrete roads).

For the density of the compacted foundation, we calculate with a value of 2.0 kg/dm³, so that 1 cubic meter of crushed stone foundation with concrete aggregate contains 2 000 kg of concrete aggregate 0/40. Per m² surface area of the road (foundation) and per cm layer thickness of the foundation, this means 20 kg of concrete aggregate. In this case, the origin is a nearby rubble treatment plant in Flanders, for which we assume a transport distance of 35 km on average.

Asphalt layers

The layers of the asphalt pavement consist of mixtures of hot-prepared asphalt, produced with the following raw materials: crushed stones, sand (crushed sand and/or round sand), filler and as a binding agent bitumen (ordinary paving grade bitumen or polymer modified bitumen).

Several types of asphalt are available for the sublayers, for example a type of asphalt concrete with performance requirements for sublayers (code APO). In this family, several mixture types are possible, e.g. APO-A or APO-B, which differ from each other in the maximum grain size of the crushed stone (of 20 and 14 mm respectively).

Several types of asphalt are also available for the top layer, here we choose an asphalt type with a stone skeleton SMA-C, with a maximum grain size of the crushed stone of 10 mm.

In this variant scenario, we not only work with new, primary raw materials (from the quarries and bitumen from the petroleum refinery, see Table 10), but specifically for this scenario we also work (for the sublayer mixtures) with the recycling of so-called reclaimed asphalt (RA, *asfaltgranulaat* AG in Dutch) as a raw material for new asphalt.

In current road construction practice, the recycling of reclaimed asphalt as a raw material for new asphalt is a well-known technique - at least for sublayer asphalt mixtures; this is not yet the case to the same extent for top layer mixtures.

When road pavements of asphalt roads are demolished, so-called asphalt debris is created; this is usually in the form of milled asphalt: asphalt plaques of a few centimetres in size that has been scraped off by asphalt milling work. This asphalt debris/milled asphalt then undergoes the necessary processing to produce a raw material that meets the required quality requirements, to produce homogeneous RA suitable as a raw material for new asphalt. It contains the same materials and in the same proportions as those used for the original asphalt mixture, i.e. crushed stone as well as sand, filler and old bitumen.

Recycling RA as a raw material for new asphalt offers significant advantages, especially in economic terms, as the old bitumen is reused, and this is the most valuable raw material in an asphalt mix. This recycling is more resource-efficient, because fewer primary raw materials have to be excavated or manufactured and no asphalt rubble has to be processed or dumped as waste.

A significant proportion of the asphalt producing plants in Belgium are equipped in terms of technology and quality control in such a way that they can successfully use RA as a partial substitute for "new" aggregates and for new bitumen.

Full recycling of RA into new asphalt is only a theoretical and not a practical possibility, because a loss of quality is assumed in the characteristics of the old bitumen (e.g. due to oxidation caused by years of exposure to sunlight on the road surface). In practice, a recycling rate of up to about 50 % is realistic and achievable.

In addition to the materials listed in Table 11, we therefore also use RA (at least for the mixtures for asphalt sublayers).

The asphalt rubble (as rubble and then in the form of RA) is usually temporarily stored on the storage site of the asphalt plant itself for further processing into new asphalt. Any processing steps required to transform the asphalt rubble into RA (mainly crushing and/or screening and/or homogenizing) take place on the site of the asphalt plant itself.

For these reasons, no additional transport is required between the "production site" of the RA raw material and the site where it is processed at the asphalt plant. The place of production of the asphalt rubble is the old road itself and the associated transport of the asphalt rubble to the asphalt mixing plant must be allocated to the demolition phase (end of life phase) of the previous asphalt road.

With regard to the asphalt for the top layer, where reuse is currently not yet permitted for this construction class, in this variant scenario we want to focus on the technique of asphalt produced at a reduced temperature (AVT or warm-mix asphalt).

In the AVT process, the conditions are adapted so that asphalt production can take place at a lower temperature than is traditionally the case, in particular the asphalt mixture at the moment of production and compaction has a temperature of approx. 130°C (min. 105 - max. 155°C) at AVT compared to approx. 180°C for a classically hot-prepared asphalt.

Because the bitumen has a more viscous flow behaviour (with a higher resistance to mechanical shear within the liquid phase) at less high temperatures and is therefore more difficult to mix with other components at the time of asphalt preparation in the asphalt mixing installation, additives must be used. This can be done in various ways and one of them is the use of the foaming technique. Another solution is the addition of viscosity reducing additives, such as waxes, chemical additives (e.g. surfactants), zeolite, and the like.

<u>Remark</u>: It is obvious that the various additives that could be used could also have a non-negligible or even (very) significant impact on the environment, which might even cancel out the reduction due to reduced energy consumption. The technique of AVT (asphalt prepared at a reduced temperature, or warm-

mix asphalt) is still in full development; experience with it in our country (Belgium) is still fairly limited, and not much concrete quantified data have yet been published. The different techniques do indeed differ from one another, in terms of materials and energy consumption, but also in terms of technical aspects and lifespan. Some published reports on these techniques show that the positive evolution (savings) in energy consumption can be outweighed by a negative evolution in other areas, such as ecotoxicity or human toxicity, depending on which additive is added. The technique of foamed bitumen stands out in this respect, because no special additive is added (only cold water at high pressure), and the energy saving is therefore a net gain. Producers of such additives reveal little information about the correct composition of their additive or focus in their information dissemination on other (positive for their product) elements, such as the ease of compaction, or expansion of the season for construction (because it cools down less rapidly in winter). This is a different marketing strategy, which of course conceals a bit the demand for environmental impact information.

Here we concentrate on the technique of foamed bitumen. During asphalt production, cold water is injected to the hot bitumen in a pressure chamber ("foaming unit"). By transforming water into steam, the bitumen is foamed and then injected into the mixing container. The physical shape of the foam (much larger in volume) allows a sufficient mixability of the bitumen even at a lower temperature.

The great advantage of the lower production temperature of the AVT compared to the classic asphalt production is the energy saving (addition of heating energy needed to heat the mass of aggregates to higher temperatures otherwise required for hot-mix asphalt production).

In terms of materials, we can refer to the situation as outlined in the previous chapter: the raw materials are the same, additional water is now added to allow the bitumen to froth, and possibly additives to improve adhesion. The frothing process takes only a short time, in the order of a few minutes, just enough to bridge the mixing time, then the foam bubbles burst open, the foam collapses and the water and water vapour gradually disappear from the asphalt mixture.

Remark: Does the variant asphalt road, with a maximum reduction of environmental impact at all layers, have the same performance as the reference road? As these new ways of working do not yet have many years of experience on the counter, there is still little information about the (technical) long-term sustainability (i.e. ten years or more). The scientific follow-up of test sites that have already been carried out (among others at the Belgian Road Research Center) shows that in general the same quality can be obtained with these new techniques as with the traditional way of working. But this will have to prove itself even further over the years. For the foundation consisting of recycled concrete aggregates to replace limestone, we see equivalent performance in practice. In road construction, performance depends not only on the intrinsic quality of the materials used, but also on the quality of their processing on site, and in particular, for foundations, on the compaction of the spread layer at the right water content and grain distribution curve of the mixture of crushed stone and sand. For asphalt with the use of reclaimed asphalt we see no problems in practice, this has proven itself for many years. However, it is of course true that the old bitumen in the reclaimed asphalt has "aged" due to the many years of use before. This has to be compensated by the addition of new bitumen with "better" characteristics than in mixtures without RA, otherwise those mixtures with RA would show too stiff and inflexible behaviour, which is an advantage for the resistance to rutting (in summer) but less good for their behaviour at low temperatures (in winter). For the mixtures produced as AVT, it has already been shown that the mixtures with the foam technique perform less well in terms of water sensitivity: the results obtained with the test to determine the indirect tensile strength (the so-called ITS-R value) are always lower and sometimes even insufficient to meet the minimum requirement. This is evident, as the foam allows a less good coating (will not penetrate the aggregate pores as a hot bitumen does) and still a small amount of water droplets remain in the bulk, which may then migrate to the interface bitumen/aggregate. On the other hand, there is also discussion about the relevance of the ITS-R test: is there a clear link between the result and lifespan? Are the requirements for this test not too high? If we do not see any premature damage (type of loss of stones or fatigue cracks), we cannot really say that there is a problem. Some caution in the conclusions is therefore appropriate, and more information from the longer-term follow-up of tests carried out on roads with foamed bitumen is very welcome. The uncertainty about the technical performance will also partly explain why these (from an environmental point of view better) techniques do not yet have full room to prove themselves.

Asphalt mixture for sublayers

For this case study, we assume a classic mixture for sublayer, the so-called APO mixture (asphalt mixture according to performance requirements for sublayer), with a recycling rate of 50 %. This means that in the new asphalt mixture, 50 % of the total binder mixture is supplied by reusing the old bitumen in the AG, supplemented by 50 % via new bitumen.

For the sake of simplicity, we assume that the RA has similar characteristics as the new asphalt mixture APO, i.e. a similar grain distribution curve of the crushed stone fractions and an equal binder content. Under these conditions, a recycling rate of 50 % also corresponds to a halving of the required quantities of aggregates and an equal quantity of new bitumen. If not, a slightly adjusted calculation is necessary.

Table 14 shows the composition for a typical asphalt sublayer mix (APO-B) with 50 % AG (= 50 % recycling rate).

Taking into account the characteristics of the aggregates and the RA, the average density of the mineral skeleton in this example is 2.642 kg/dm³ and the maximum volumetric mass of the aggregate and bitumen mixture is 2.464 kg/dm³. The apparent volumetric mass (taking into account 5.78 %-v hollow spaces in the total asphalt mixture) in this example is 2 322 kg/m³.

The binder content in this example (see fourth column, penultimate line in Table 14) is 4.82 %-m on 100 %-m total aggregate mass. To express this in relation to the total mass of the mixture (aggregates + binder), the figures must be divided by 1.0482, thus obtaining the values as proposed in the penultimate column of the table as mass ratios in the total asphalt mixture.

For each ton of asphalt, 46 kg of binder is thus needed, as well as 954 kg of mineral aggregates (half of which are recycled RA). The total quantity of binder (4.6 % by mass in relation to the total mass of the asphalt mixture) in this case consists for half of new road construction bitumen type B50/70 and for the other half of recovered bitumen present in the recycled RA.

So, the big advantage for this alternative composition lies in the fact that only half of the amount of "new" raw materials are needed. In each ton of asphalt according to the penultimate column of Table 14, only 0.5 ton of new raw materials are needed (477 kg of filler, sand and stones and 23 kg of new bitumen), the other half of the materials come from the recycling of the reclaimed asphalt (0.5 ton of RA, consisting of 477 kg recovered mineral fractions of filler, sand and stones, plus 23 kg of recovered binder).

Table 14: Example of a typical asphalt mixture (variant) for sublayer (type APO-B with 50 % recycling)

Asphalt mix for sublayer (type APO-B)			Mix design		In compacted road pavement	
Material type	*Component*	*Density (t/m³)*	*Mass-% (on aggregates)*	*Volume-% (on aggregates)*	*in kg per ton asphalt*	*in kg per m³ asphalt road*
Filler	Type Ib (limestone)	2.698	1.0 %	0.98 %	9.5	22.1
Stones	Limestone 10/14	2.690	12.0%	11.79 %	114.5	265.8
	Limestone 6/10	2.690	17.0%	16.70 %	162.2	376.6
	Limestone 2/6	2.692	8.0 %	7.85 %	76.3	177.2
Sand	Crushed limestone 0/2	2.673	12.0%	11.86 %	114.5	265.8
RA (mineral fractions)	RA 0/14	2.6	50.0 %	50.82 %	477.0	1 107.6
total aggregates			100.0 %	100.0 %	954	2 215
Recovered bitumen (% on aggregates)	from the RA		2.41 %		23.0	53.4
New bitumen (% on aggregates)	Paving grade bitumen 50/70	1.025	2.41 %		23.0	53.4
Total			104.82 %		1 000.0	2 322

In order to be able to calculate more easily in relation to the functional unit of our case study, we will express everything in quantities (masses in kg) in the asphalt when compacted, per m² surface of the road surface and per cm layer thickness.

This means that in this example, the asphalt mixture for sublayer has a mass of 23.22 kg per m² road surface area and per cm layer thickness of the asphalt pavement.

The raw materials required to prepare this amount of asphalt are as follows:

- 8.20 kg of limestone (1.77 kg of crushed limestone in calibre 2/6 + 3.77 kg in calibre 6/10 + 2.66 kg in calibre 10/14)
- 2.66 kg crushing sand of limestone (calibre 0/2)
- 0.22 kg filler
- 11.61 kg asphalt granulate (consisting of 11.08 kg *original* limestone in various fractions and 0.53 kg old bitumen)
- 0.53 kg new paving grade bitumen

The big difference compared to the reference scenario is that only about half of the quantities of the different fractions of limestone are needed and that the amount of bitumen to be added has also been halved. On the other hand, a significant quantity of RA is needed.

Asphalt mixture for top layer

For the asphalt mixture for the top layer, we refer to the description of the materials used as described above.

In the variant scenario, we are no longer talking about classically prepared hot-mix asphalt - in this case of the SMA type for top layer mixtures, as was already the case in the reference scenario - but consider a mixture produced using the technique of the AVT (warm-mix asphalt, as explained in previous section). In practice, for SMA mixtures, the technique of viscosity reducing additives may be chosen rather than the foam technique, because the latter technique is more difficult to implement for SMA mixtures (which are formulated with the slightly more viscous PmB as a binding agent).

Table 15 is therefore largely the same as the previous Table 12 (which shows the composition for a typical top layer mixture SMA), but now supplemented with a small fraction of water for the creation of the foaming technique.

Taking into account the characteristics of the porphyry aggregates and the crushed sand, the average density of the mineral skeleton in this example is 2.732 kg/dm³ and the maximum density of the aggregate and bitumen mixture is 2.461 kg/dm³. The apparent volumetric mass (taking into account the 4.55 %-v hollow spaces in the total asphalt mixture) in this example is 2 391 kg/m³.

The binder content in this example of asphalt mixture for top layer is 6.61 % (in mass-% compared to 100% of the aggregate total). To express this in relation to the total mass of the mixture (aggregates + binder), the figures must be divided by 1.0707, thus obtaining the values as proposed in the penultimate column of the table as mass ratios in the total asphalt mixture. For each ton of asphalt, 62 kg of binder PmB is thus needed, as well as 938 kg of aggregates.

Table 15: Example of a typical mixture for top layer (type SMA-C)

Asphalt mix for top layer (type SMA-C)			Mix design		In compacted road pavement	
Material type	*Component*	*Density (t/m³)*	*Mass-% (on aggregates)*	*Volume-% (on aggregates)*	*in kg per ton asphalt*	*in kg per m³ asphalt road*
Filler	Type II	2.8	8.5 %	8.3 %	80	191
Stones	Porphyry 6,3/10	2.727	63.0 %	63.0 %	591	1 413
	Porphyry 4/6,3	2.711	9.2 %	9.3 %	86	206
Sand (crushed)	Porphyry 0/2	2.71	19.3 %	19.4 %	181	433
total aggregates			100.0 %	100.0 %	938	2 243
PmB bitumen (% op aggregates)	PmB bitumen 45/80-50	1.022	6.61 %		62	148
Total			106.61 %		1 000	2 391
Water (for injection to form foam)	Tap water	1.000	2 à 3 % of the amount of bitumen		1.3 à 2.2	3 à 5

In order to be able to calculate more easily in relation to the functional unit of our case study, we will express everything in quantities (masses in kg) in the asphalt when compacted, per m² surface of the road surface and per cm layer thickness.

This means that in this asphalt mixture for the top layer when compacted, the asphalt has a mass of 23.91 kg per m² surface area of the road surface and per cm layer thickness.

The raw materials required to prepare this amount of asphalt are as follows:

- 16.19 kg of porphyry aggregate (2.06 kg of porphyry in calibre 4/6.3 + 14.13 kg in calibre 6.3/10)
- 4.33 kg crushing sand of porphyry (calibre 0/2)
- 1.91 kg composite filler
- 1.48 kg polymer modified bitumen (PmB).

Total mass for the whole road pavement over a period of 20 years

Taking into account the above mass ratios in this example, Table 16 summarises that for the variant road construction and associated service life of the different layers of asphalt, about 633 kg of asphalt is needed to maintain the road in question over an area of 1 m² and for 20 years.

Table 16: Amounts of asphalt needed per m² road over the reference period.

	Density (kg/m³)	*Mass per m² and per cm layer thickness (kg)*	*Layer thickness (cm)*	*Number of layer construction times over a period of 20 years*	*Equivalent layer thickness (= indiv. layer thickness x times constructed) (cm)*	*Equivalent mass per m² road (= equiv. layer thickn. X mass per cm) (kg)*
Sublayer	2 322	23.22	19	1	19	441.2
Top layer	2 391	23.91	4	2	8	191.3

9.4 Case study 2: Concrete roads

As an additional case study, we treat in this part a concrete road, a road with a road pavement consisting of concrete.

9.4.1 Reference scenario

We start with a reference scenario. Reference scenario means that we look at a classical approach to design, without many innovative elements in the design of the road paving and with the materials commonly used in practice.

The reference scenario could be extended with a variant, specifically looking for innovative elements in the design of the road paving that can achieve a more optimal approach in terms of the environment. However, this was not elaborated in this study. As far as concrete roads are concerned, in such an alternative scenario one could look for example at a concrete pavement in a 2-layer version instead of a single-layer version. The single-layer version is the classic way of working for concrete pavements in Belgium. It implies that the layer in its entire thickness of the concrete pavement is composed of the same type of concrete mix, and therefore that the same high quality components are used in the lower part of the concrete paving as in the upper part where the road surface is located, and which places very high demands on the quality of the aggregates (such as resistance to polishing, resistance to de-icing salts, etc.). The idea behind a two-layer version is that a different concrete mixture could be used in the upper and lower part of the layer thickness, each adapted to the specific requirements in that part of the layer thickness. For example, with the use of recycled concrete aggregates in the sublayer, and finely calibrated crushed stone of very high quality in the top layer, which can therefore provide better performance in terms of, for example, noise production (the finer surface texture ensures a quieter road surface). These alternative concrete compositions are already being experimented with here and there, but they are not yet commonly used as a standard solution. For these reasons, in this case study for concrete roads we will not elaborate further on such an alternative scenario.

Also, after performing the life cycle analyses for the first case (asphalt road) and the reference for the concrete road, it did not seem that additional conclusions or insights relevant for the potential of TOTEM would emerge from such an exercise.

9.4.2 Functional unit and choice of design service life

As a functional unit for the calculation of the various environmental impacts over the service life of the road (lifecycle analysis or LCA), we have chosen a road of traffic class B1 in this case study.

Traffic class B1 is the highest category, which corresponds to motorways with much and heavy traffic. Think for example of motorways, such as the E19 between Brussels and Antwerp, the Ring road around Brussels, the Ring road around Antwerp, ... For these roads in Belgium, the choice is often made for a road pavement in concrete.

According to Table 2 (p.20), over a period of 30 years, this type of road will be subject to a traffic load corresponding to 64 to 128 million equivalent standard axle loads of 100 kN (ESALs).

In this case study, such calculations are made for a period of 30 years. For this period, we assume the following assumptions:

- For the foundation layer, we foresee a technical service life of 30 years. This is as long as the calculation period under consideration, so we do not foresee any renovation of the foundation.
- For the concrete pavement layer, we also choose a service life of 30 years. This implies that the pavement layer will be laid once and does not require any further rebuilding, but will reach the end of its technical service life.

Other interim maintenance measures may be necessary to improve certain elements of performance, such as surface treatment to improve roughness or reduce noise production.

The functional unit for this analysis is therefore the following:

> *"To ensure the surfacing of 1 m² of road surface for a road with a traffic load corresponding to a construction class B1 for a period of 30 years".*

Remark: We opted for a different type of road than in the "bituminous road" case study (here we opted for an asphalt pavement in traffic class B5 - which corresponds to a not too heavily loaded regional road - and here for the concrete road we opted for a road with a higher traffic load, namely a traffic class B1 which corresponds to very heavily trafficked regional roads such as the Ring road around Antwerp or the Ring road around Brussels). In practice, both a B1 and a B5 (or any other traffic class) road can be designed with either concrete pavement or asphalt pavement, but then the thickness of the layers as well as the technique may vary considerably. For example, concrete (on a cement-stabilised crushed stone foundation, and with a bituminous intermediate layer) is more often used for (very) heavily loaded roads, and the asphalt pavement (in combination with an unbound crushed stone foundation layer) can better play off its flexibility and flexibility of laying in lower-loaded and local roads. Concrete roads for the highest traffic classes are usually constructed using the technique of continuous reinforced concrete, while for concrete roads in a lower construction class, the technique of slab concrete pavement is more commonly used. The concrete in slab pavement is not reinforced, but there is the use of steel dowels and cross bars to anchor the sheets longitudinally and transversely to each other or to avoid relative movements between them. The joints between the slabs require specific maintenance measures. The 2 case studies (concrete and asphalt pavement) therefore have a different functional unit (both 1 m^2 surface area, but with different traffic load and design service life). It is therefore not the intention here to juxtapose and compare the 2 road structures (asphalt and concrete); however, it is the intention here to use 2 different case studies to see if we can apply the TOTEM-method in practice for civil engineering construction works in the infrastructure sector, i.e. both for a concrete road and for an asphalt road. Any conclusions that would be drawn from a simple comparison of the calculations made for one case study and then placed next to the other case study would therefore be misplaced and erroneous. This is because the case studies are not designed and executed to focus on the LCA-results themselves (the actual numbers) but rather on the general principles, components and overall insights (we have deliberately omitted or simplified some parts; the calculations from these can therefore not be complete or accurate enough to make such conclusions).

9.4.3 Road structure

According to the Flemish Road Authority (AWV) standard structures [50], the recommended road structure for a concrete road (in the case of pavement in road concrete, traffic class B1) is as follows (see Table 6, p.34):

- Foundation type "cement-bound crushed stone mix": thickness 30 cm,
- Bituminous intermediate layer (asphalt type ABT): thickness 5 cm,
- Pavement in continuous reinforced concrete: total thickness 25 cm.

Foundation in stabilised crushed stone mix

For the foundation in stabilised crushed stone mix, a mixture of sand and crushed limestone aggregates is commonly used, with a continuous grain size distribution curve 0/40 or 0/20 (mm), which is bonded with cement and water. The cement dose is about 3 to 4 % by mass in relation to the total mass. As the density of the compacted foundation is approximately 2 000 kg/m^3, this corresponds to approximately 66 to 88 kg of cement per m^3; the water dosage is approximately 90 l of water per m^3 of crushed stone mixture. One cubic meter of crushed stone foundation therefore contains approximately 2 000 kg of crushed stone 0/40. Per m^2 surface area of the road (foundation) and per cm layer thickness of the foundation, this is 20 kg of crushed limestone. The origin of the limestone granulates are the limestone quarries in Wallonia (near Tournai or Liège).

Asphalt sandwich layer

The bituminous intermediate layer in asphalt serves to decouple the road structure between the cement-bound foundation and the cement-bound concrete pavement by placing a more flexible intermediate layer in between to prevent cracking from bottom to top. The composition of this asphalt intermediate layer (type ABT) is (for the low level of detail required in this case study) roughly comparable to the asphalt mixture for sublayers, as explained in the case study 'bituminous road – reference scenario'.

Continuously reinforced concrete top layer

The pavement layer in continuous reinforced concrete means that the fresh concrete mixture is poured on top of a longitudinally continuous mesh of steel reinforcement bars, which will reinforce the cured concrete to absorb the tensile stresses.

This reinforcement consists of a structure of interlocking reinforcing bars, which overlap each other sufficiently and in which the entire structure of reinforcement is anchored in the subsoil by means of an initial and final construction of anchoring massifs. Hence the designation 'continuous reinforcement'.

An example of reinforcement grid is presented in Figure 13, consisting of:

- Iron bars in the longitudinal direction, diameter 20 mm, spacing distance of 170 mm,
- Iron bars in the transverse direction (at an angle of 60 ° to the longitudinal direction), diameter 14 mm, each 0.7 m (measured obliquely),
- Distance between top of the reinforcement and the surface of the finished road pavement: 80 to 100 mm,
- The reinforcement rods lie on a support at a distance of 130 mm above the underside of the concrete layer.

Figure 13: Image of the continuous reinforcement mesh for concrete pavement in CRCP (Source: BRRC)

The amount of steel reinforcement is approximately 17 kg per m².

9.4.4 Mix design and materials

In this reference scenario for the concrete road, we work with a classical cement concrete composition, in which only so-called "new" or primary raw materials are used.

The pavement in cement concrete is laid in one layer, over the entire thickness of the pavement (in this case 25 cm).

Reinforcing steel

The mass of reinforcement steel in our example (of traffic class 1 and 250 mm concrete thickness) is 16.9 kg per square meter, this is 14.86 kg for the longitudinal reinforcement plus 2.04 kg for the transverse reinforcement (including 0.5 % overlap for the longitudinal bars and 0.5 % overlap for the iron feet under the transverse bars) (see Table 17).

Table 17: Amount of steel needed per m² concrete pavement.

Calculation of the amount of steel needed for the reinforcement in 250 mm thick CRCP							
	Diameter (mm)	*Cross section (mm²)*	*Mass (kg per meter)*	*Overlap (0.5 %)*	*Distance in-between (mm)*	*Number per m²*	*Mass per m² (kg)*
Longitudinal bars	20	314	2.51	1.005	170	5.88	14.86
Transverse bars	14	154	1.23	1.005	607	1.65	2.04

Concrete mixture

The concrete mixture consists of the following materials: crushed rock of different calibres (e.g. porphyry or sandstone or crushed gravel), coarse sand and fine sand, cement, water and additives, such as air-entraining agent, and plasticizer or water-reducer.

Table 18 gives an overview of the nature and origin of the materials used for the road concrete. The location of the manufacturing site and distance data from quarry to concrete plant are only given as a typical example.

Table 18: Type and origin of the raw materials used

Material type	*Material description*	*Location of extraction of raw materials*	*Distance to concrete mix plant (e.g. in Zaventem) (km)*
Crushed stones	Crushed porphyry calibre 4/6, 6/10 or 6/14, 10/20 or 14/20	Quenast	60
	Crushed sandstone (grès) calibre 4/6, 6/10 or 6/14, 10/20 or 14/20	Namen (Lustin)	80
	Crushed gravel calibre 4/6, 6/10 or 6/14, 10/20 or 14/20	Maaseik	115
Sand	Crushed porphyry sand calibre 0/2	Lessines	70
	Round sand (river sand or marine sand)	Oostende	125
Cement	CEM IIIA 42,5 LA	Doornik	95

Plasticiser		Antwerpen-haven	60
Air-entraining agent		Antwerpen-haven	60

In Belgium, crushed rock is mainly of the "porphyry" type, but sandstone (gravel) or crushed gravel are also eligible. Round gravel (which is very suitable for other concrete compositions such as for pumpable concrete in general construction) is not suitable for use in road concrete, due to insufficient resistance to polishing of the road surface due to the rounded shape of the aggregates.

A Portland cement type CEM I can be used as well as a slag cement type CEM III. In any case, the cement type must be of the "low alkali content" (LA) type.

> Remark: The advantage of the cement type CEM III is that the environmental impact expressed in terms of greenhouse gas equivalents is lower due to the fact that in the production of the cement, a large part of the clinker as raw material has been replaced by hydraulic blast furnace slag, and therefore less clinker needs to be produced. Because this has become the standard type of cement for road concrete, we are working with it further in this case study.

The dosage of the cement content in road concrete is fairly high, compared to conventional concrete mixes for general construction. This is because the quality requirements for road concrete are very high, which in turn is due to the high load and aggressive environmental factors with which concrete road pavements are confronted.

Remark: "Road pavements in cement concrete" are described in part 1 of chapter 6 "Pavements" of the Standard specification 250 for road construction in the Flemish Region (SB250) [56]. There, however, you will not find any regulations for the composition, but the statement that all concrete must be certified beforehand by means of a complete preliminary study in the laboratory that proves that the desired performance can be achieved. An independent conformity assessment body does the certification. Subchapter 5.4 in chapter 14 "measurements and tests" of the SB250 describes how experimental laboratory testing of mixtures for cement concrete pavements must be carried out in a preliminary study, and also what the minimum dosage of cement must be. For roads of traffic class B1 - B5, the minimum dosage of cement is 400 kg/m³ (in a single-layer version or in the top layer in a two-layer version). For mixtures with less coarse aggregates (max. grain size 6.3 mm), the cement content is at least 425 kg/m³. Another important requirement concerns the permissible water content; the water-cement factor (ratio) in the mixture is a maximum of 0.45 for concrete mixtures containing aggregates up to a grain size of 14, 20 or 32 mm and a maximum of 0.42 for concrete mixtures with a maximum grain size of 6.3 mm (this last is especially for the 2-layer execution method).

There are many different compositions for road concrete. In this example, we will continue with the composition shown in Table 19.

Table 19: Example of concrete composition for 1 m^3 road pavement.

Material	*Amount in kg/m³*
Crushed porphyry 14/20	310
Crushed porphyry 6/14	520
Crushed porphyry 2/6	370
Round sand (river sand) 0/4	595
Cement CEM IIIA 42,5 LA	400
Plasticizer	0.75
Air-entraining agent	0.38
Water	175
TOTAL	2 371

Taking into account the densities and volumetric ratios in the concrete mixture, the volumetric mass of the concrete mixture in this example is approximately 2 371 kg/m^3.

In order to be able to calculate more easily in relation to the functional unit of our case study, we will express everything in quantities (masses in kg) in the concrete when compacted, per m^2 surface of the road surface and for a layer thickness of 25 cm. This means that in this example, the 25 cm thick concrete mixture has a mass of 2371 / 4 = 593 kg per m^2 of road surface.

The raw materials needed to prepare this amount of concrete are as follows:

- 300 kg of porphyry mortar (92.5 kg in calibre 2/6 + 130 kg in calibre 6/14 + 77.5 kg in calibre 14/20),
- 149 kg round sand,
- 100 kg of cement,
- 0.28 kg additives (plasticizer and air-entraining agent),
- 44 kg of water,
- supplemented with 16.9 kg of reinforcement steel.

10. ANNEX 2: Additional data and results on the environmental impact assessment of the cases

In this annex, additional data on composition and modelling of the case studies and detailed information and results on the environmental impact assessment is given.

10.1 Scope of the environmental impact assessment

For the life cycle analyses carried in this study, the MMG methodology [51], which forms the basis for the online TOTEM tool[10], was followed for as much as possible.

An LCA considers the whole lifecycle of a product (including production, transport, installation, use, demolition and waste treatment) (see Figure 14). For each lifecycle phase, the inputs and outputs are identified and quantified. Subsequently, the impact of these inputs and outputs on 17 environmental impact indicators, representing different environmental issues, is calculated, and expressed using a specific unit for each indicator. In a next step, the results for the different indicators can be monetised (translated into euros) and aggregated into a single score. The euros represent the environmental cost the society would have to pay to solve the impact on the environment. The results are shown as an environmental profile (graph). By comparing different alternatives for a product, well-founded choices can be made and product improvement possibilities can be identified taking into account the environmental impact.

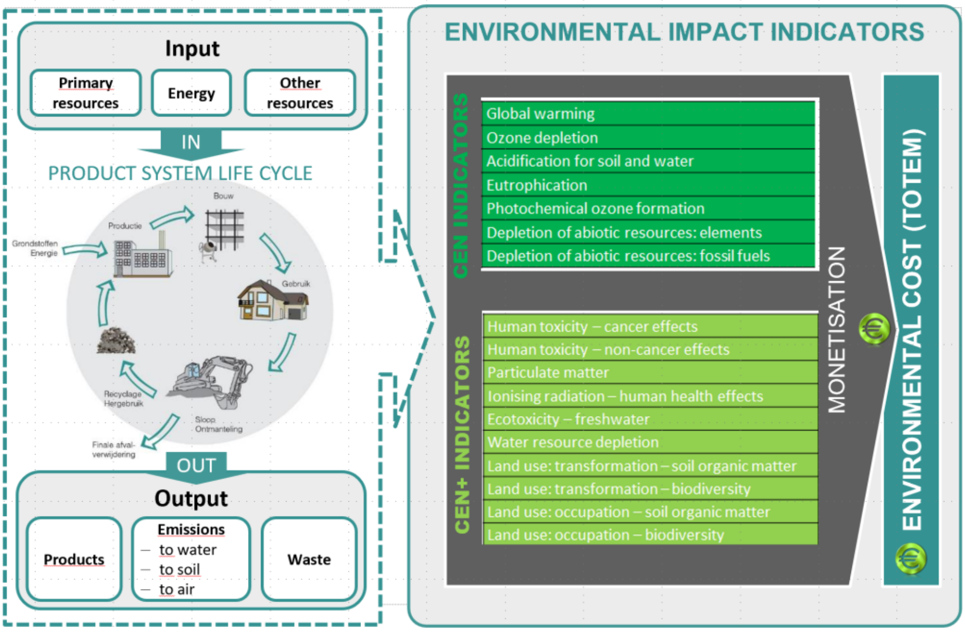

Figure 14: Life cycle analysis of a building product, a construction element or a building, according to the MMG methodology [51].

[10] www.TOTEM-building.be

10.2 Composition and modelling Case study 1: Bituminous roads

10.2.1 Reference case

In Table 20 and Table 21, the modelling of the different life cycle phases for the asphalt types and the foundation within the reference bituminous road is clarified.

Table 20: Modelling of the different life cycle phases of the asphalt types for the reference bituminous road.

Life cycle phase	Activities	Modelling assumptions
A1: Raw material supply	Extraction of primary resources	According to Ecoinvent records, harmonised for Belgium
A2: Transport	Transport of resources to asphalt plant	Transport with heavy truck (16-32 tons)
A3: Manufacturing	Production of asphalt in asphalt plant	According to Ecoinvent record for mastic asphalt, harmonised for Belgium, without (primary) resources, including internal transport of resources, electricity use by machinery, machinery, energy use for drying and heating the aggregates and the bitumen and keeping up temperature during stock
A4: Transport	Transport of asphalt to construction site	Transport with heavy truck (16-32 tons) over 65 km
A5: Construction installation process	Installation of asphalt on construction site	Using shuttle buggy, asphalt machine and steamroller no detailed information on this machinery available in the Ecoinvent database, so approximation by using hydraulic digger (1x for top layer and 3x for sublayer)
B4: Replacements	Replacement of asphalt top layer	One replacement of asphalt top layer after 10 years
C1: Demolition	Demolition of road	According to MMG scenarios 2017 [53]
C2: Transport	Transport of waste to sorting plant and to landfill	According to MMG scenarios 2017 [53]
C3: Waste processing	Sorting and crushing of asphalt waste	According to MMG scenarios 2017 [53]
C4: Disposal	5% landfill of asphalt waste + 95% recycling	Based on Ecoinvent record for landfill of asphalt waste

Table 21: Modelling of the different life cycle phases of the foundation for the reference bituminous road.

Life cycle phase	Activities	Modelling assumptions
A1-2-3: Product stage	Extraction of primary resources, transport and manufacturing	According to Ecoinvent records, harmonised for Belgium
A4: Transport	Transport to construction site	Transport with heavy truck (16-32 tons) over 100 km
A5: Construction installation process	Installation of foundation on construction site	Using hydraulic digger and steamroller => no data available for steam roller => only hydraulic digger considered
C1: Demolition	Demolition of road	According to MMG scenarios 2017 [53]
C2: Transport	Transport of waste to sorting plant and to landfill	According to MMG scenarios 2017 [53]
C3: Waste processing	Sorting of waste	According to MMG scenarios 2017 [53] – without crushing
C4: Disposal	5% landfill of limestone waste + 95% recycling	According to MMG scenarios 2017 [53]

In Table 22, a detailed overview of the composition of the three layers within the reference bituminous road is given, as well as additional information on the resources and their modelling.

Table 22: Composition and modelling of the reference bituminous road

SMA-C asphalt top layer (1 ton)					
Material type	*Component*	*Amount*	*Composition*	*Transport to asphalt plant*	*Remarks*
Filler	Composite type II	80 kg/ton	20% lime 80% fly ashes	120 km – heavy truck (16-32 tons)	Fly ash from different sources (20% waste combustion, 20% sludge combustion, 20% biomass combustion, 40% coal fired electricity power plants) – economic allocation [55]
Coarse aggregates	Porphyry 6.3/10	591 kg/ton		60 km – heavy truck (16-32 tons)	Ecoinvent record for basalt used due to lack of record for porphyry
	Porphyry 4/6.3	86 kg/ton		60 km – heavy truck (16-32 tons)	Ecoinvent record for basalt used due to lack of record for porphyry
Fine aggregates	Porphyry 0/2	181 kg/ton		70 km – heavy truck (16-32 tons)	Ecoinvent record for basalt used due to lack of record for porphyry
Bitumen	PmB bitumen	62 kg/ton	96.5% pitch 3.5% SBS polymer	60 km – heavy truck (16-32 tons)	Ecoinvent record for synthetic rubber used due to lack of record for SBS polymer
APO-B asphalt sublayer (1 ton)					
Material type	*Component*	*Amount*	*Composition*	*Transport to asphalt plant*	*Remarks*
Filler	Limestone type Ib	48 kg/ton	100% lime	110 km – heavy truck (16-32 tons)	
Coarse aggregates	Broken limestone 10/14	239 kg/ton		70 km – heavy truck (16-32 tons)	Limestone, crushed
	Broken limestone 6/10	219 kg/ton		70 km – heavy truck (16-32 tons)	Limestone, crushed
	Broken limestone 2/6	143 kg/ton		60 km – heavy truck (16-32 tons)	Limestone, crushed and washed

Fine aggregates	Broken limestone sand 0/2	191 kg/ton		110 km – heavy truck (16-32 tons)	Limestone, crushed and washed
	River sand (Schelde)	114 kg/ton		125 km – heavy truck (16-32 tons)	Only one Ecoinvent record for sand available
Bitumen	Road bitumen 50/70	46 kg/ton	100% pitch	60 km – heavy truck (16-32 tons)	
Broken limestone foundation (1 m³)					
Material type	*Component*	*Amount*	*Composition*	*Transport to construction site*	*Remarks*
Broken stone	Broken limestone 0/40	2 200 kg/m³		100 km – heavy truck (16-32 tons)	Limestone, crushed

10.2.2 Variant case

In Table 23 and Table 24, the modelling of the different life cycle phases for the asphalt types and the foundation for the variant bituminous road is clarified.

Table 23: Modelling of the different life cycle phases of the asphalt types for the variant bituminous road (the differences with the reference case are underlined).

Life cycle phase	Activities	Modelling assumptions
A1: Raw material supply	Extraction of primary resources <u>Production of recycled aggregates and bitumen</u>	According to Ecoinvent records, harmonised for Belgium <u>No impact of production, since end-of-waste point falls after sorting and crushing in former lifecycle and no additional activities are needed</u> – see Table 25
A2: Transport	Transport of resources to asphalt plant <u>Transport of recycled aggregates and bitumen</u>	Transport with heavy truck (16-32 tons) – see Table 25 <u>No transport to asphalt plant necessary since production of recycled aggregates and bitumen takes place at the asphalt plant.</u>
A3: Manufacturing	Production of asphalt in asphalt plant	For APO-B asphalt: According to Ecoinvent record for mastic asphalt, harmonised for Belgium, without (primary) resources, including internal transport of resources, electricity use by machinery, machinery, energy use for drying and heating the granulates and the bitumen and keeping up temperature during stock <u>For AVT asphalt: idem as for APO-B asphalt, but with 15% reduction in heat and 15% reduction in VOC emissions</u>
A4: Transport	Transport of asphalt to construction site	Transport with heavy truck (16-32 tons) over 65 km
A5: Construction installation process	Installation of asphalt on construction site	Using shuttle buggy, asphalt machine and steamroller => no detailed information on this machinery available in the Ecoinvent database => approximation by using hydraulic digger (1x for top layer and 3x for sublayer)
B4: Replacements	Replacement of asphalt top layer	One replacement of asphalt top layer after 10 years
C1: Demolition	Demolition of road	According to MMG scenarios 2017 [53]
C2: Transport	Transport of waste to sorting plant and to landfill	According to MMG scenarios 2017 [53]

C3: Waste processing	Sorting and crushing of asphalt waste	According to MMG scenarios 2017 [53]
C4: Disposal	5% landfill of asphalt waste + 95% recycling	Based on Ecoinvent record for landfill of asphalt waste

Table 24: Modelling of the different life cycle phases of the foundation for the variant bituminous road (the differences with the reference case are underlined).

Life cycle phase	Activities	Modelling assumptions
A1-2-3: Product stage	Production of recycled concrete aggregates	No impact of production and transport, since end-of-waste point falls after sorting and crushing in former lifecycle and no additional activities are needed – see Table 25
A4: Transport	Transport to construction site	Transport with heavy truck (16-32 tons) over 35 km
A5: Construction installation process	Installation of foundation on construction site	Using hydraulic digger and steamroller => no data available in the Ecoinvent database for steam roller => only hydraulic digger considered
C1: Demolition	Demolition of road	According to MMG scenarios 2017 [53]
C2: Transport	Transport of waste to sorting plant and to landfill	According to MMG scenarios 2017 [53]
C3: Waste processing	Sorting of waste	According to MMG scenarios 2017 [53] – without crushing
C4: Disposal	5% landfill of limestone waste + 95% recycling	According to MMG scenarios 2017 [53]

More details on the composition and the modelling assumptions for the variant layers are given in Table 25.

Table 25 : Composition and modelling of the variant bituminous road (the differences with the reference case are underlined)

SMA-C AVT asphalt top layer (1 ton)					
Material type	*Component*	*Amount*	*Composition*	*Transport to asphalt plant*	*Remarks*
Filler	Composite type II	80 kg/ton	20% lime 80% fly ash	120 km – heavy truck (16-32 tons)	Fly ash from different sources (20% waste combustion, 20% sludge combustion, 20% biomass combustion, 40% coal fired electricity power plants) – economic allocation [55]
Coarse aggregates	Porphyry 6.3/10	591 kg/ton		60 km – heavy truck (16-32 tons)	Ecoinvent record for basalt used due to lack of record for porphyry
	Porphyry 4/6.3	86 kg/ton		60 km – heavy truck (16-32 tons)	Ecoinvent record for basalt used due to lack of record for porphyry
Fine aggregates	Porphyry 0/2	181 kg/ton		70 km – heavy truck (16-32 tons)	Ecoinvent record for basalt used due to lack of record for porphyry
Bitumen	PmB bitumen	62 kg/ton	96.5% pitch 3.5% SBS polymer	60 km – heavy truck (16-32 tons)	Ecoinvent record for synthetic rubber used due to lack of record for SBS polymer
Water	Tap water	1.65 kg/ton			Harmonised for Belgium
APO-B 50% RA asphalt sublayer (1 ton)					
Material type	*Component*	*Amount*	*Composition*	*Transport to asphalt plant*	*Remarks*
Filler	Limestone type Ib	9.5 kg/ton	100% lime	110 km – heavy truck (16-32 tons)	
Coarse aggregates	Broken limestone 10/14	114.5 kg/ton		70 km – heavy truck (16-32 tons)	Limestone, crushed
	Broken limestone 6/10	162.2 kg/ton		70 km – heavy truck (16-32 tons)	Limestone, crushed

	Broken limestone 2/6	76.3 kg/ton		60 km – heavy truck (16-32 tons)	Limestone, crushed and washed
Fine aggregates	Broken limestone sand 0/2	114.5 kg/ton		110 km – heavy truck (16-32 tons)	Limestone, crushed and washed
	River sand (Schelde)	0 kg/ton		125 km – heavy truck (16-32 tons)	Only one Ecoinvent record for sand available
Recycled aggregates	Recycled minerals from reclaimed asphalt	477 kg/ton		No transport	No production impact since end-of-waste point falls after sorting and crushing in former lifecycle and no additional activities are necessary.
Bitumen	Road bitumen 50/70	23 kg/ton	100% pitch	60 km – heavy truck (16-32 tons)	
Recycled bitumen	Recycled bitumen from reclaimed asphalt	23 kg/ton		No transport	No production impact since end-of-waste point falls after sorting and crushing in former lifecycle and no additional activities are necessary.
Recycled concrete aggregates foundation (1 m³)					
Material type	*Component*	*Amount*	*Composition*	*Transport to construction site*	*Remarks*
Recycled aggregates	Recycled concrete aggregates	2 000 kg/m³		35 km – heavy truck (16-32 tons)	No production impact since end-of-waste point falls after sorting and crushing in former lifecycle and no additional activities are necessary.

10.3 Environmental impact assessment Case study 1: Bituminous roads

10.3.1 Reference case

Each of the three layers of the reference bituminous road was analysed in detail for its environmental impact. The results are presented in the following paragraphs.

Top layer of SMA-C asphalt

In Figure 15, the environmental impact of the production phase (modules A1-A3) of 1 ton of SMA-C asphalt is given. Here, the impact of the asphalt production process is far most important. This is mainly due to the energy use for heating the aggregates. The most important environmental impact indicators for the production process are 'global warming potential (GWP)', 'particulate matter (PM)', 'human toxicity – non-cancer effects' and 'eutrophication'. The high impact on these indicators (except for GWP) is in this case mainly related to the use of heavy fuel to heat the asphalt aggregates. A sensitivity analysis shows that the impact of the production process decreases significantly when natural gas is used as a fuel (instead of heavy fuel). In practice, different types of fuels (heavy fuel, diesel, natural gas) are currently used in Belgian asphalt plants. Therefore, the impact of the production of asphalt can vary significantly between plants and is factory specific.

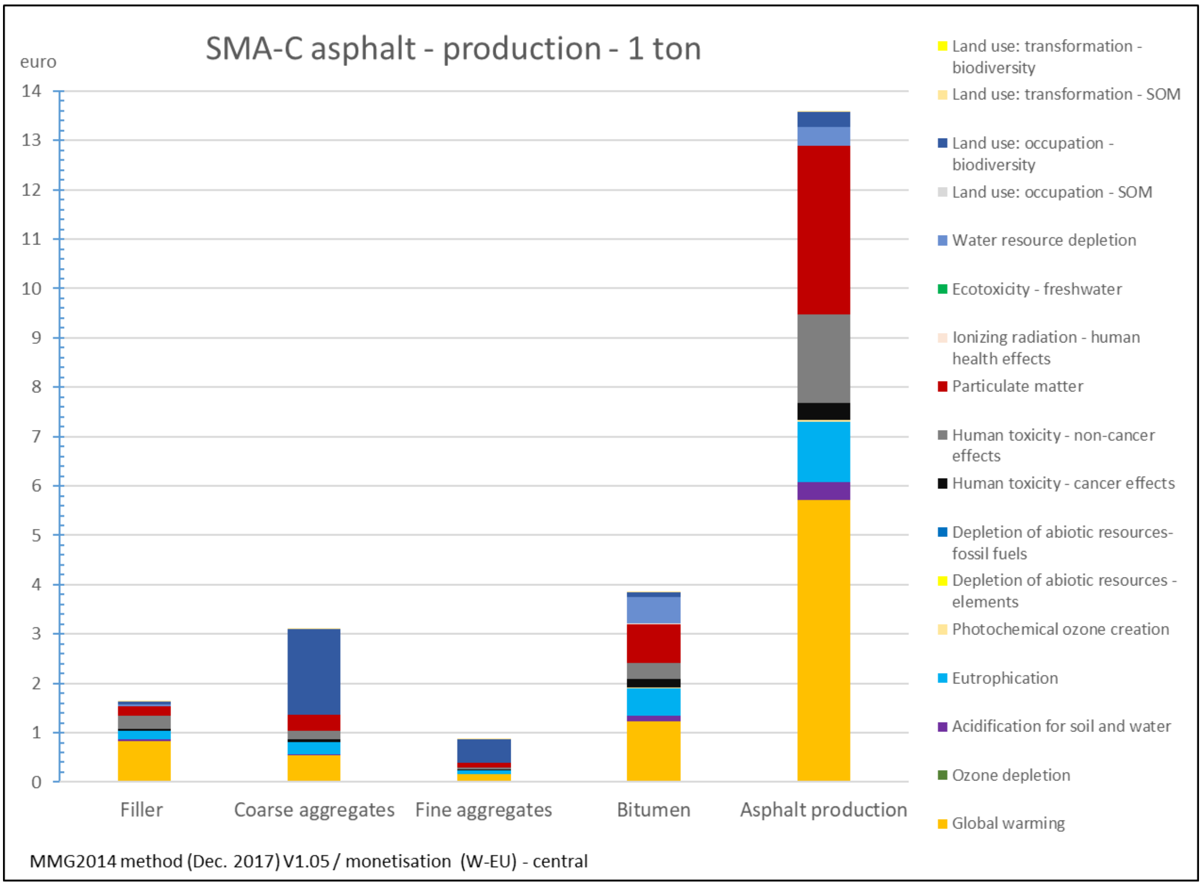

Figure 15: Environmental impact of the production of 1 ton SMA-C asphalt (modules A1-A3), per component and per indicator.

Sublayer of APO-B asphalt

Figure 16 shows the environmental impact of the production of 1 ton of APO-B asphalt (modules A1-A3). Similar conclusions as for the SMA-C asphalt can be drawn. The contribution of the fly ash filler and the porphyry coarse aggregates in figure 7 is clearly larger than the contribution of the limestone filler and limestone coarse aggregates in figure 9.

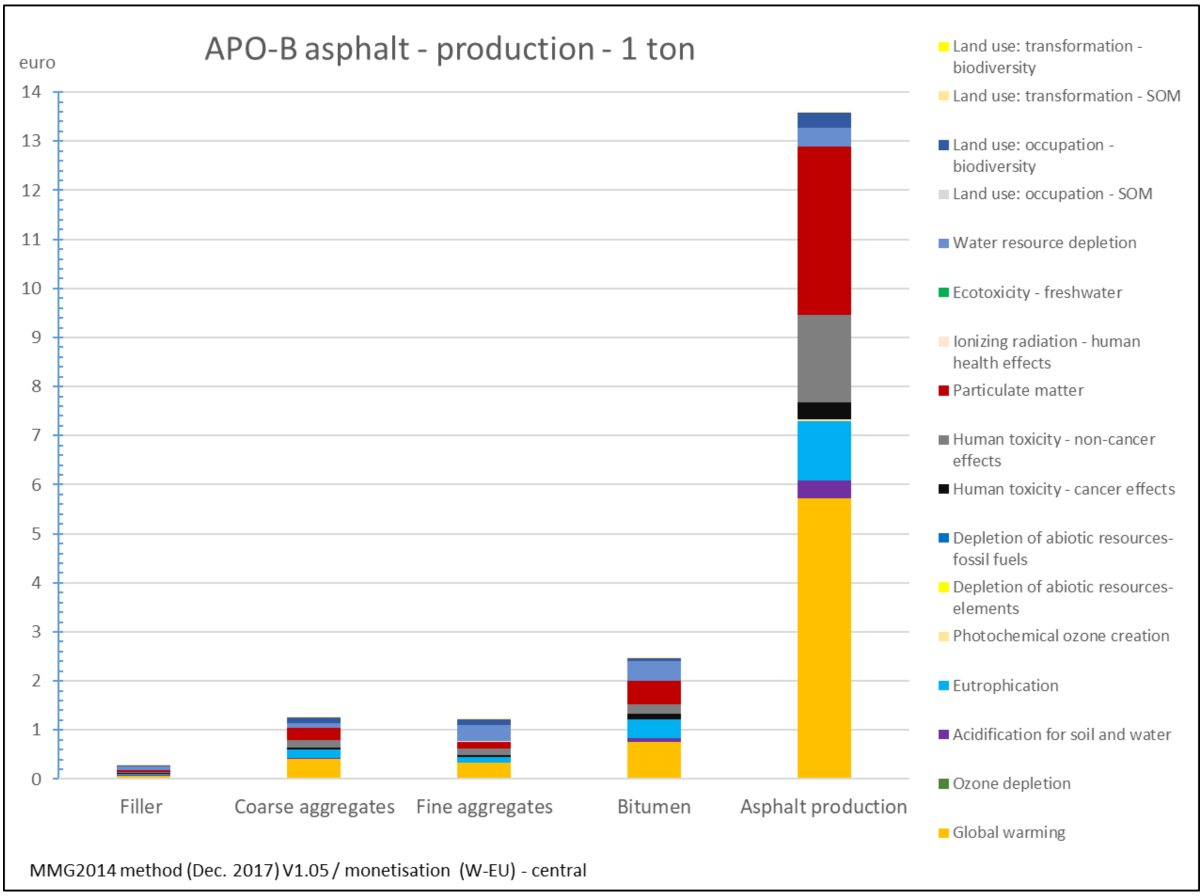

Figure 16: Environmental impact of the production of 1 ton APO-B asphalt (modules A1-A3), per component and per indicator.

Foundation layer of unbound broken limestone

In Figure 17, the environmental impact of the production of 1 ton of broken limestone foundation is given. The most important indicators are 'global warming potential', 'eutrophication', 'particulate matter' and 'water resource depletion'.

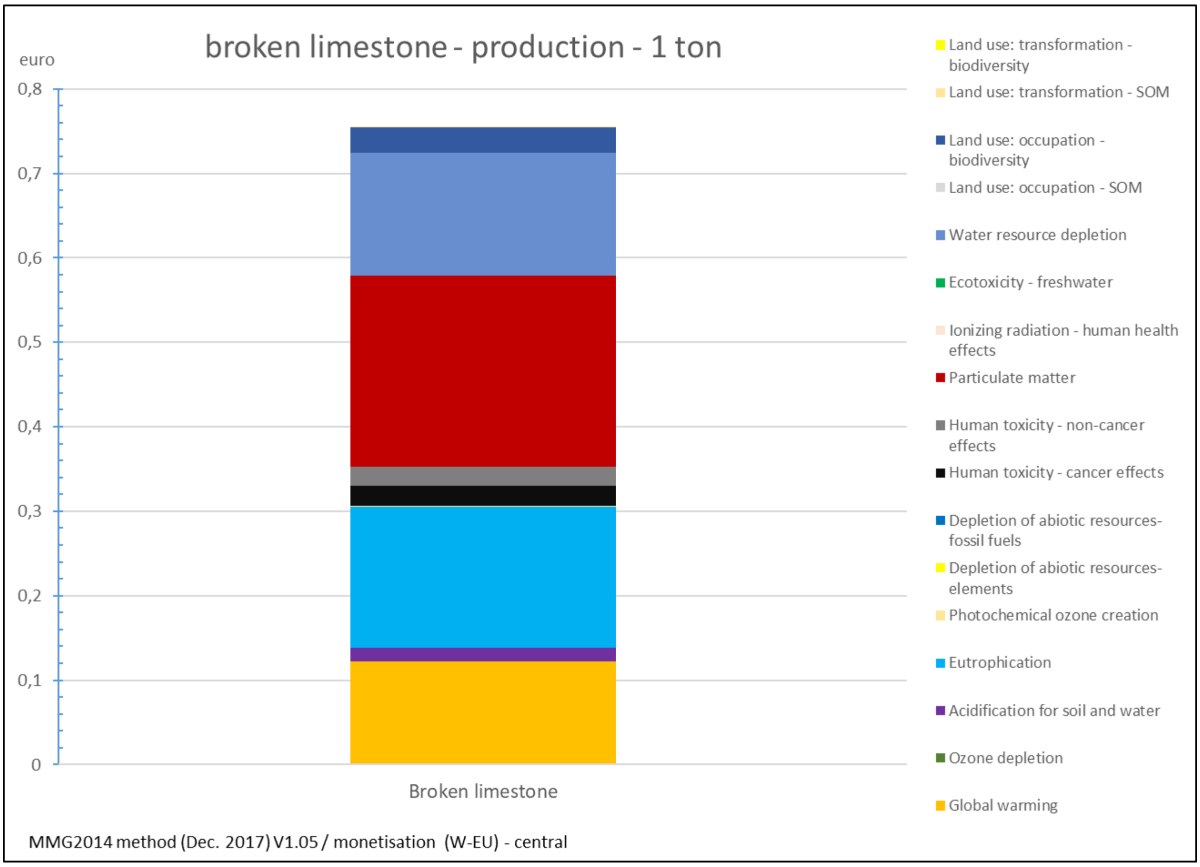

Figure 17: Environmental impact of the production of 1 ton broken limestone foundation (modules A1-A3), per indicator.

Whole road structure

In Figure 18, the total environmental impact of 1m² of the reference bituminous road is given for a period of 20 years. The impact of the asphalt sublayer is largest, followed by the impact of the asphalt top layer and the foundation. The most important indicators (i.e. 'global warming potential', 'eutrophication', 'human toxicity', 'particulate matter', 'water resource depletion' and 'land use') are the same for all three layers and are similar to those for buildings.

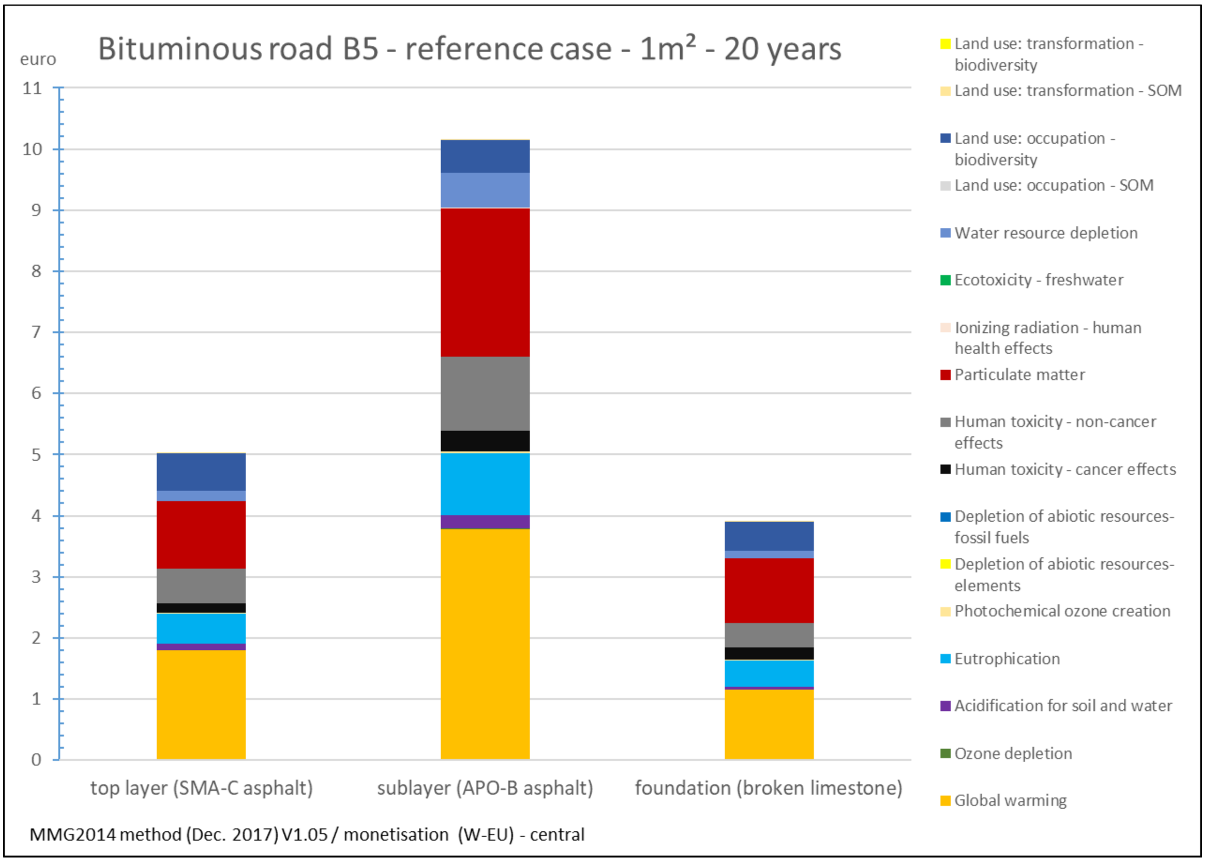

Figure 18: Environmental impact of 1m² of the reference bituminous road for a period of 20 years, per layer and per indicator.

10.3.2 Variant case

As was also done for the reference case, each of the three layers of the variant bituminous road was analysed in detail for its environmental impact. The results are presented in the following paragraphs.

Top layer of SMA-C AVT asphalt

In Figure 19, the environmental impact of the production of 1 ton of SMA-C AVT asphalt is given. Similar conclusions as for the SMA-C asphalt in the reference case can be drawn. The asphalt production process is still by far the most important, but its impact is smaller than for the reference SMA-C asphalt. The impact of the additional water used is very small.

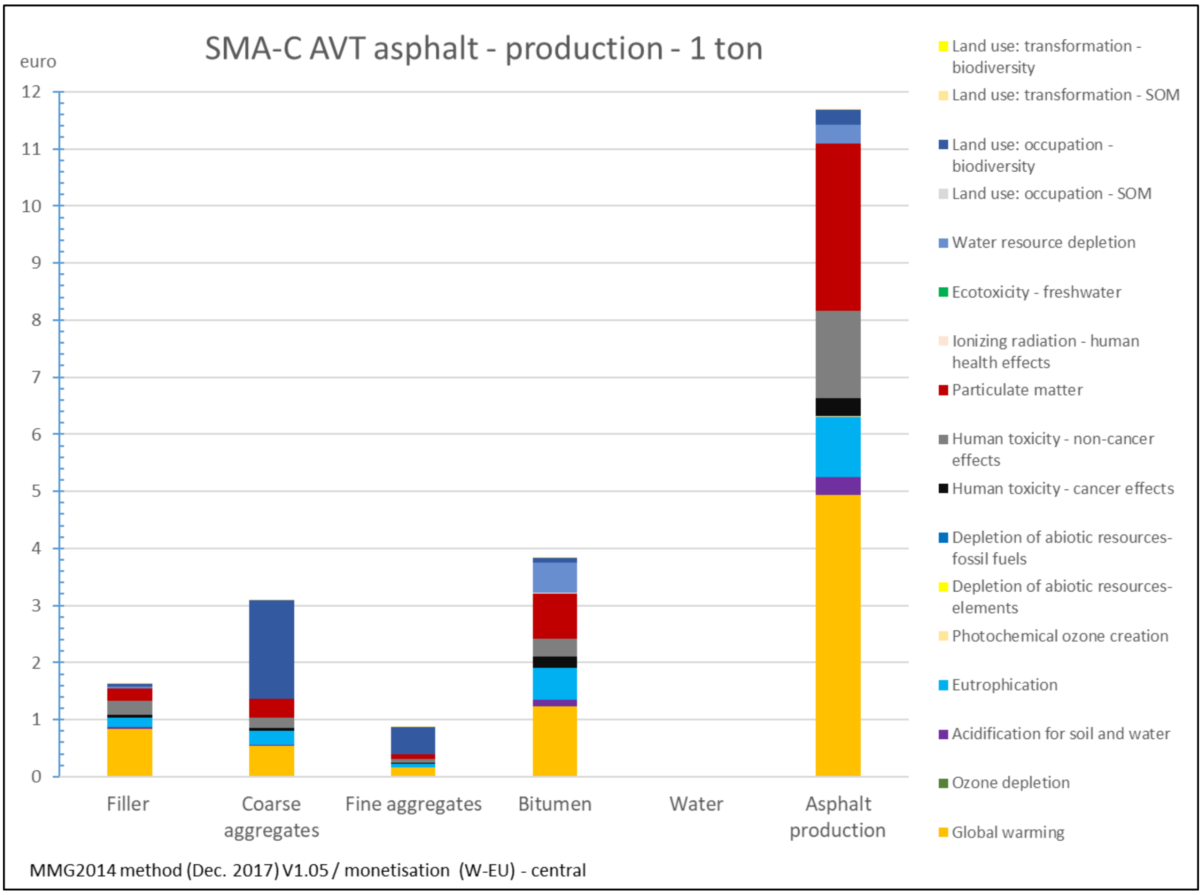

Figure 19: Environmental impact of the production of 1 ton of SMA-C AVT asphalt (modules A1-A3), per component and per indicator.

Sublayer of APO-B 50% RA asphalt

In Figure 20, the environmental impact of the production of 1 ton of APO-B (with 50% RA) asphalt is given. This figure shows that the asphalt production process is still by far the most important, while the impact of the fine and coarse aggregates and of the bitumen is lower than for the reference APO-B asphalt (due to lower quantities and no production impact for the reclaimed asphalt aggregates).

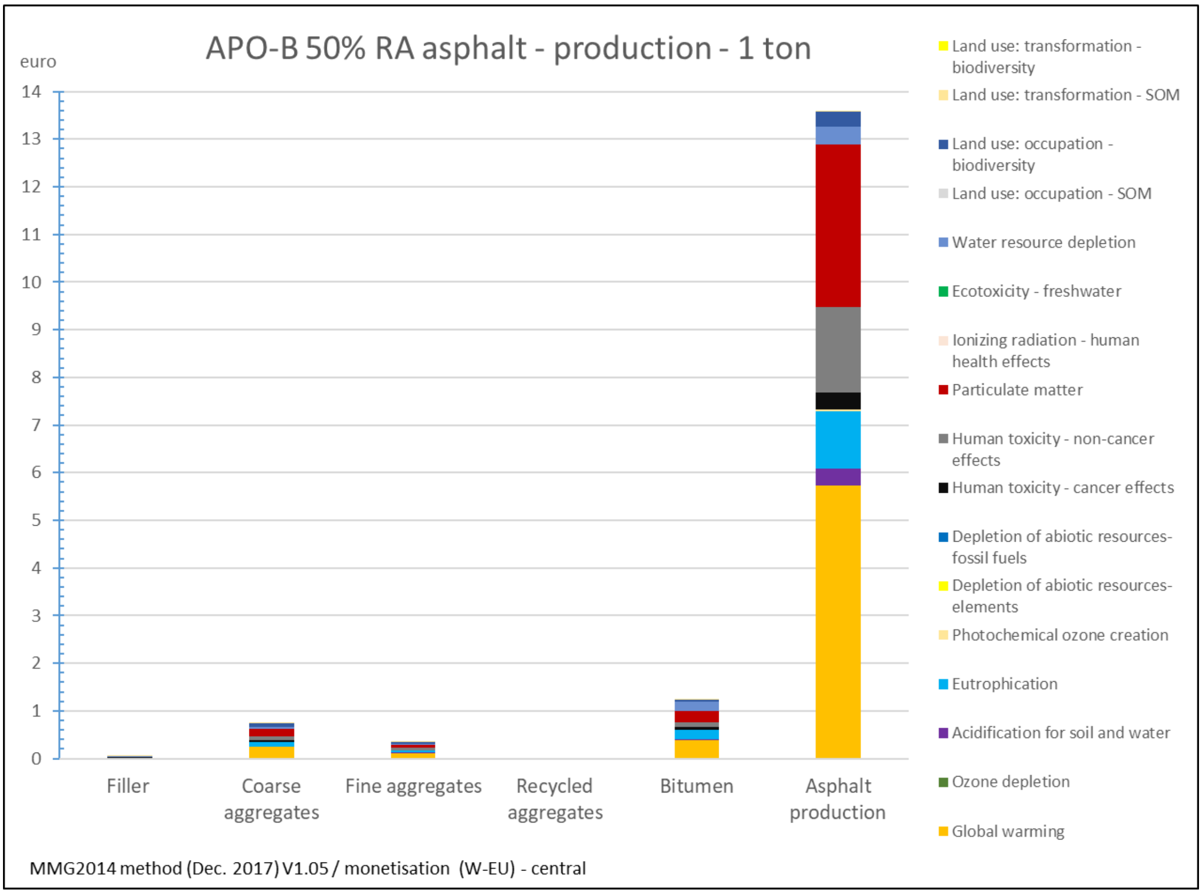

Figure 20: Environmental impact of the production of 1 ton of APO-B 50% RA asphalt (modules A1-A3), per component and per indicator.

Foundation layer of recycled concrete aggregates

The production impact of the foundation layer (modules A1-A3), composed of recycled concrete aggregates, equals zero since all production processes took place during the former lifecycle. Only transport to construction site (module A4), installation on site (module A5) and EOL-phase (modules C1-C4) cause an impact on the environment.

Whole road structure

In Figure 21, the total environmental impact of 1m² of the variant bituminous road is given for a period of 20 years. Similar conclusions as for the reference road can be drawn.

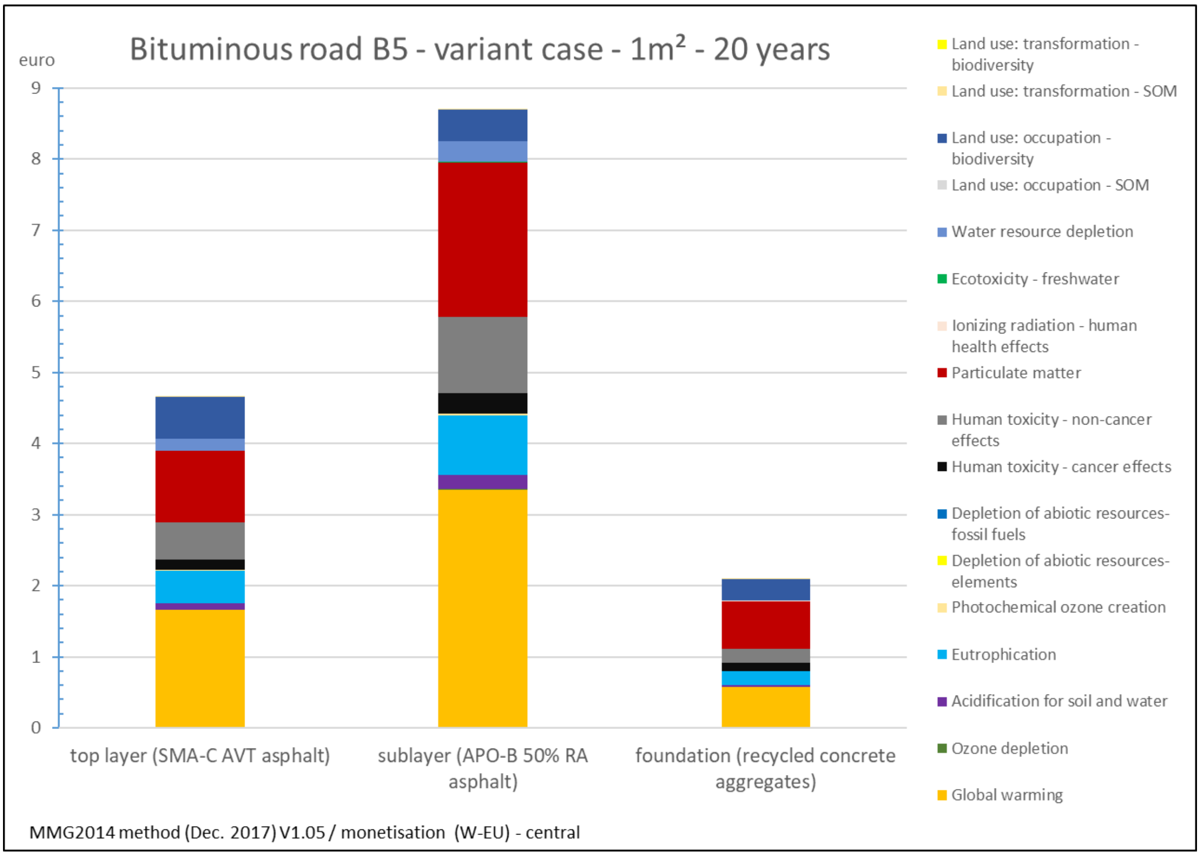

Figure 21: Environmental impact of 1m² of the variant bituminous road for a period of 20 years, per layer and per indicator.

10.3.3 Reference case versus variant case

In Figure 22, the total environmental impact of 1m² of the reference and the variant bituminous roads is given per indicator. When moving from the reference case to the variant case, an impact reduction is visible for all indicators.

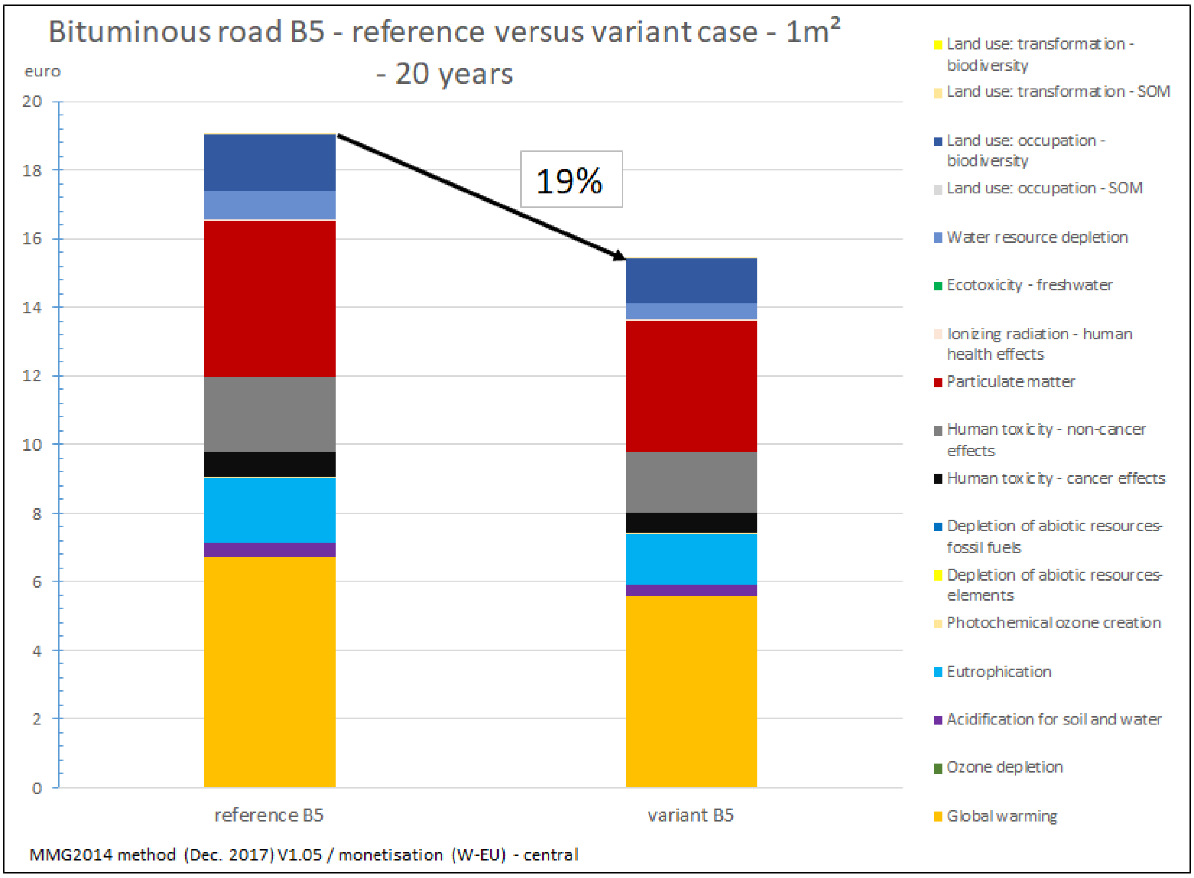

Figure 22: Environmental impact of 1m² of the reference bituminous road and the variant bituminous road over 20 years, per indicator.

10.4 Composition and modelling Case study 2: Concrete road

In Table 26, a detailed overview of the composition of the three layers composing the reference concrete road is given, as well as additional information on the resources and their modelling. In Table 27, Table 28, and Table 29, the modelling of the different life cycle phases for the concrete top layer, the reinforcing steel and the foundation is clarified. The modelling of the ABT asphalt sandwich layer is the same as for the APO-B asphalt within the reference bituminous road (see Table 22 and Table 23).

Table 26: Composition and modelling of the reference concrete road

Reinforced concrete top layer (1 m³)					
Material type	*Component*	*Amount*	*Composition*	*Transport to concrete plant or construction site*	*Remarks*
Binder	Cement CEM III/A 42.5 LA	400 kg/m³		95 km – heavy truck (16-32 tons)	Minimal value based on standard specifications SB250 [56], as well as practical value
Coarse aggregates	Broken porphyry 14/20	310 kg/m³		60 km – heavy truck (16-32 tons)	Ecoinvent record for basalt used due to lack of record for porphyry
	Broken porphyry 6/14	520 kg/m³		60 km – heavy truck (16-32 tons)	Ecoinvent record for basalt used due to lack of record for porphyry
	Broken porphyry 2/6	370 kg/m³		60 km – heavy truck (16-32 tons)	Ecoinvent record for basalt used due to lack of record for porphyry
Fine aggregates	Round river sand 0/4	595 kg/m³		125 km – heavy truck (16-32 tons)	Only one Ecoinvent record for sand available
Additives	Plasticizer	0.75 kg/m³		60 km – heavy truck (16-32 tons)	Specific record developed
	Air-entraining agent	0.38 kg/m³		60 km – heavy truck (16-32 tons)	Ecoinvent record for chemical, organic used due to lack of record for this additive
Water	Tap water	175 kg/m³			Harmonised for Belgium
Reinforcing steel	Reinforcing steel	16.9 kg/m²		60 km – heavy truck (16-32 tons)	

ABT asphalt sandwich layer (1 ton)					
Material type	*Component*	*Amount*	*Composition*	*Transport to asphalt plant*	*Remarks*
Filler	Limestone type Ib	48 kg/ton	100% lime	110 km – heavy truck (16-32 tons)	
Coarse aggregates	Broken limestone 10/14	239 kg/ton		70 km – heavy truck (16-32 tons)	Limestone, crushed
	Broken limestone 6/10	219 kg/ton		70 km – heavy truck (16-32 tons)	Limestone, crushed
	Broken limestone 2/6	143 kg/ton		60 km – heavy truck (16-32 tons)	Limestone, crushed and washed
Fine aggregates	Broken limestone sand 0/2	191 kg/ton		110 km – heavy truck (16-32 tons)	Limestone, crushed and washed
	River sand (Schelde)	114 kg/ton		125 km – heavy truck (16-32 tons)	Only one Ecoinvent record for sand available
Bitumen	Road bitumen 50/70	46 kg/ton	100% pitch	60 km – heavy truck (16-32 tons)	

Cement-bounded broken limestone foundation (1 m³)					
Material type	*Component*	*Amount*	*Composition*	*Transport to construction site*	*Remarks*
Broken stone	Broken limestone 0/40	2 000 kg/m³		100 km – heavy truck (16-32 tons)	Limestone, crushed
Binder	Cement CEM III/A 42.5 LA	70 kg/m³		95 km – heavy truck (16-32 tons)	
Water	Tap water	90 kg/m³			Harmonised for Belgium

Table 27: Modelling of the different life cycle phases of the concrete top layer in the reference concrete road.

Life cycle phase	Activities	Modelling assumptions
A1: Raw material supply	Extraction of primary resources	According to Ecoinvent records, harmonised for Belgium
A2: Transport	Transport of resources to concrete plant	Transport with heavy truck (16-32 tons)
A3: Manufacturing	Production of concrete in concrete plant	According to Ecoinvent record for concrete, harmonised for Belgium, without (primary) resources and water
A4: Transport	Transport of concrete to construction site	Transport with concrete mixer according to MMG scenario for poured concrete
A5: Construction installation process	Installation of concrete on construction site	No data available in the Ecoinvent database for concrete machine for roads => approximation by pouring of concrete using a concrete pump
C1: Demolition	Demolition of road	According to MMG scenarios 2017 [53]
C2: Transport	Transport of waste to sorting plant and to landfill	According to MMG scenarios 2017 [53]
C3: Waste processing	Sorting and crushing of inert waste	According to MMG scenarios 2017 [53]
C4: Disposal	5% landfill + 95% recycling	According to MMG scenario for inert material 2017 [53]

Table 28: Modelling of the different life cycle phases of the reinforcing steel for the reference concrete road.

Life cycle phase	Activities	Modelling assumptions
A1-2-3: Product stage	Extraction of primary resources, transport and manufacturing	According to Ecoinvent record – see Table 26
A4: Transport	Transport to construction site	According to MMG scenario 2017 for loose products [53]
A5: Construction installation process	Installation on construction site	Not considered due to lack of data
C1-C4: End-of-life	Demolition, transport to sorting plant and to landfill, sorting of waste, 5% landfill + 95% recycling	According to MMG scenario 2017 for reinforcing steel [53]

Table 29: Modelling of the different life cycle phases of the cement-bounded broken limestone foundation for the reference concrete road.

Life cycle phase	Activities	Modelling assumptions
A1-2-3: Product stage	Extraction of primary resources, transport and manufacturing	According to Ecoinvent records, harmonised for Belgium
A4: Transport	Transport to construction site	Transport with heavy truck (16-32 tons) over 100 km for broken limestone and 95 km for cement
A5: Construction installation process	Installation of foundation on construction site	Using hydraulic road grader and steamroller => no data available in the Ecoinvent database for steam roller nor road grader => only hydraulic digger considered
C1: Demolition	Demolition of road	According to MMG scenarios 2017 [53]
C2: Transport	Transport of waste to sorting plant and to landfill	According to MMG scenarios 2017 [53]
C3: Waste processing	Sorting of waste	According to MMG scenarios 2017 [53] – without crushing
C4: Disposal	5% landfill + 95% recycling	According to MMG scenarios 2017 [53]

10.5 Environmental impact assessment Case study 2: Concrete road

Each of the three layers of the reference concrete road was analysed in detail for its environmental impact. The results are presented in the following paragraphs.

Continuously reinforced concrete top layer

Figure 23 presents the environmental impact of the production phase (modules A1-A3) of 1m³ of the reinforced concrete (top) layer.

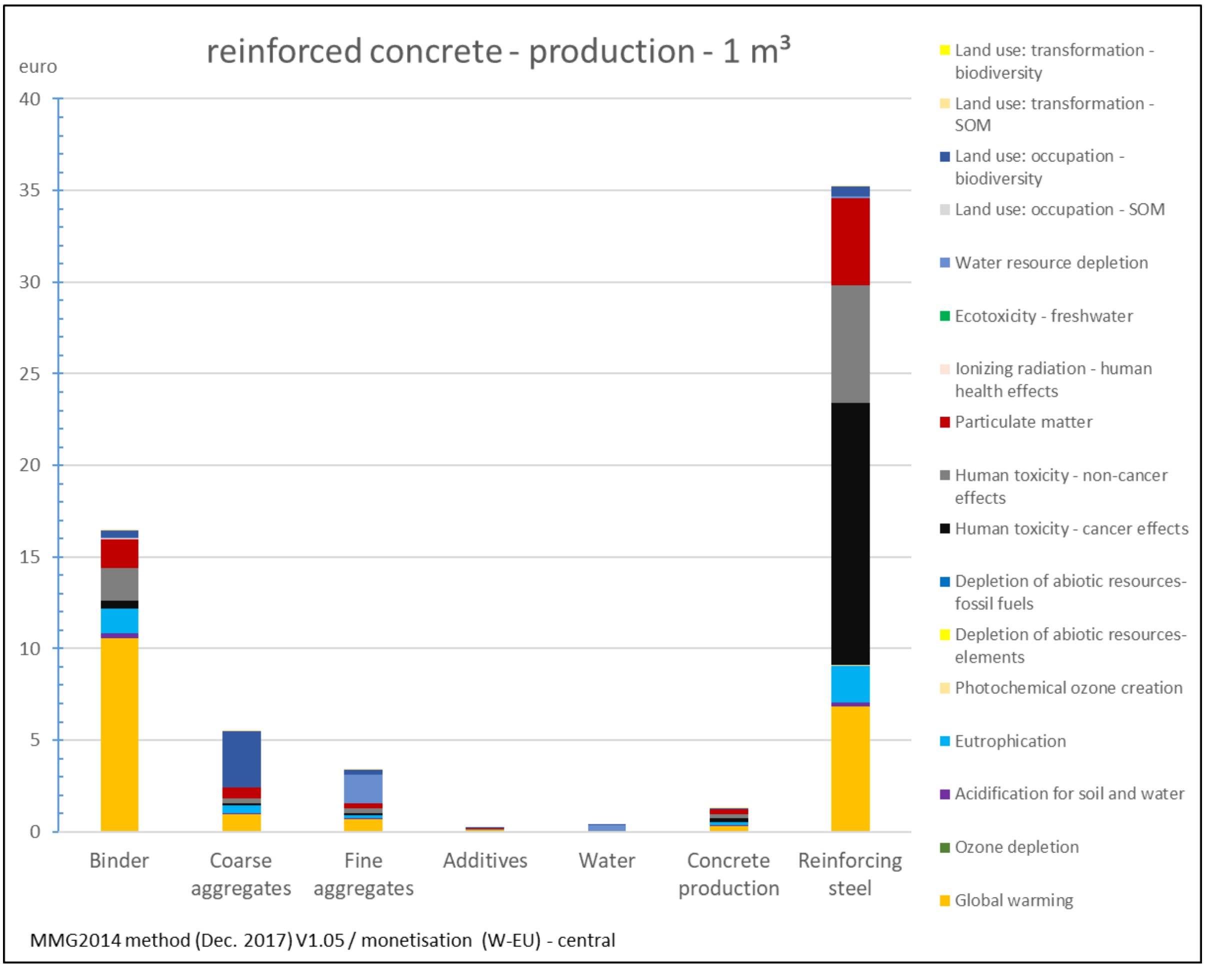

Figure 23: Environmental impact of the production of 1m³ of reinforced concrete for road pavements (modules A1-A3), per component and per indicator.

The highest impact is related to the production of the reinforcing steel, followed by the impact of the production of the binder. The reinforcing steel has a very large impact on the indicators 'human toxicity – cancer effects', 'human toxicity – non-cancer effects', 'global warming potential' and 'particulate matter'. The most important indicator for the binder production is 'global warming potential', for the production of the coarse aggregates 'land use' and for the fine aggregates 'water resource depletion'.

Asphalt sandwich layer (ABT asphalt)

As an asphalt sandwich layer (type ABT), the data from the APO-B asphalt sublayer from the reference bituminous road is used, as both differ very little. The environmental impact of this layer is given in Figure 16.

Cement-bounded broken limestone foundation

Figure 24 shows the environmental impact of the production phase (modules A1-A3) of 1 m³ of cement-bounded broken limestone foundation. Here, the impact of the cement production is most important. The latter has a significant impact on the indicators 'global warming potential', 'human toxicity', 'eutrophication' and 'particulate matter'. The most important indicators for the production of broken limestone are 'particulate matter', 'eutrophication', 'water resource depletion' and 'global warming potential'.

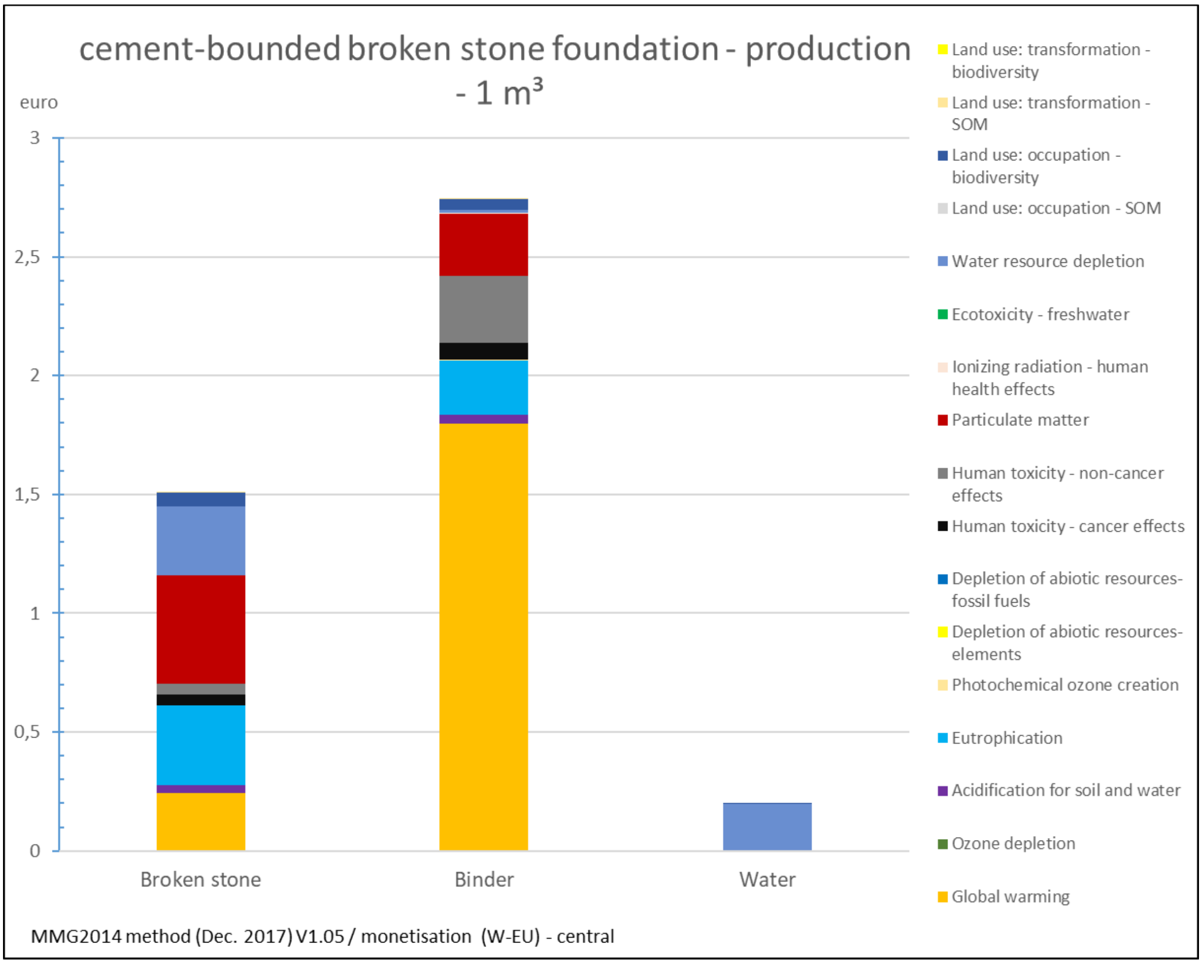

Figure 24: Environmental impact of the production of 1m³ of cement-bounded broken limestone foundation, per component and per indicator.

Complete road structure

When looking at the environmental impact of 1 m² of the reference concrete road over its entire lifecycle (30 years), it is clear that the impact of both the reinforcing steel and the concrete are most important, followed by the foundation and the asphalt sandwich layer (see Figure 25). As is already stated above, the reinforcing steel has an important impact on the indicators 'human toxicity – cancer effects' and 'human toxicity – non-cancer effects', while the concrete has the largest impact on the indicator 'global warming potential'.

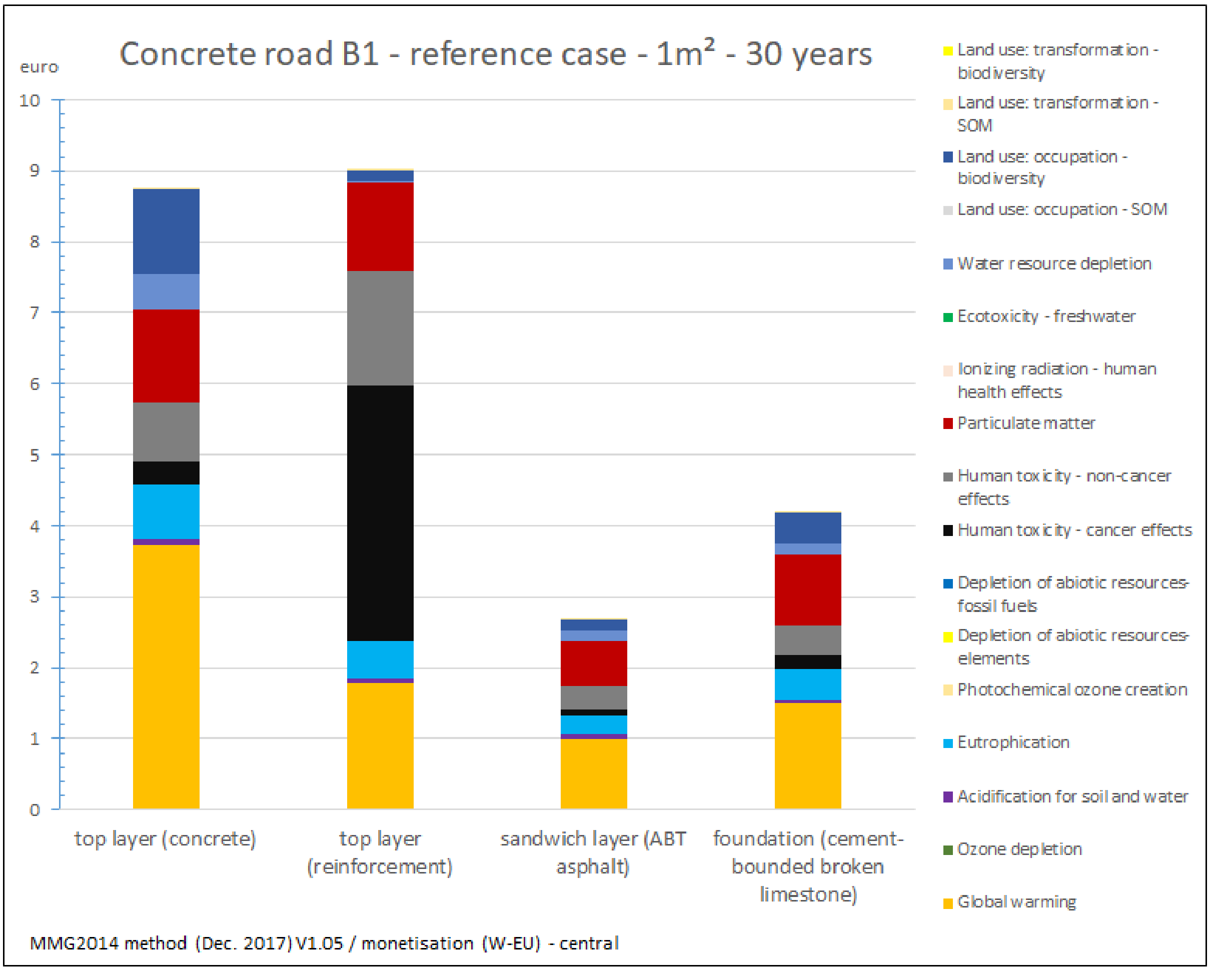

Figure 25: Environmental impact of 1 m² of the reference concrete road over 30 years, per layer and per indicator.