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OPTIMISING THE EVALUATION OF SUSTAINABLE PAVEMENTS: A LIFE-CYCLE ASSESSMENT APPROACH.

Doctoral Thesis with an International Mention

A Thesis Submitted in Partial Fulfilment of the Requirement for the degree of
Doctor of Philosophy in Civil Engineering from the Universidad de Granada

Thomas Mattinzioli

Supervisors:

Professor Germán Martínez Montes

Professor Miguel Del Sol Sánchez

Civil Engineering Doctoral Programme (B23.56.1)
Department of Construction Engineering and Engineering Projects
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PHD WITH AN INTERNATIONAL DOCTORATE MENTION

TÍTULO DE DOCTOR CON MENCIÓN INTERNACIONAL

The doctoral candidate hereby states that they successfully completed and accredited the requirements mentioned in Article 15 of Royal Decree 99/2011, of 28 January, on the "International Doctorate" Mention. The candidate undertook a research stay with the University of California at Davis, USA, from the 1 March 2021 to the 30 August 2021 under the supervision of Professor John Harvey. The stay was completed remotely due to the travel restrictions in place from the COVID-19 pandemic. The remote stay was fully approved by the University of Granada after careful consideration of the work plan.

Therefore, according to the requirements stated, the following was met:

a) During the training period, the doctoral student completed a mobility period of six months outside Spain conducting research at the University of California Pavement Research Center, USA.
b) The mobility period and activities were endorsed by the thesis supervisors, authorised by the Academic Committee and were incorporated into the doctoral student's activity document.
c) The doctoral thesis has been written and defended in English, one of the customary languages for scientific communication in the corresponding field of knowledge, different from any of the official languages in Spain.
d) This thesis has been peer-reviewed by at least two experts with doctoral degrees. Namely Prof Davide Lo Presti (University of Palermo, Italy) and Dr Ali Azhar Butt (University of California, USA).
e) An expert from a non-Spanish higher education institution, and doctoral degree holder, other than the person responsible for the mobility period from section a) was a member of the board of examiners for the thesis.

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TESIS COMO AGRUPACIÓN DE PUBLICACIONES

This doctoral thesis is based upon a collection of scientific articles, published by the doctoral candidate relevant to his knowledge area. To achieve this, the following required conditions were met:

a) This doctoral thesis consists of the regrouping of three research papers into a report, published by the doctoral student in high-impact journals relevant to their field of knowledge, as recommended by the Advisory Council for Doctoral Schools (CAED).
b) The articles were published after obtaining the undergraduate and master's degrees.
c) They have not been used in any previous thesis.
d) The co-authors of the presented publications declare they have not presented these articles in another thesis and will not do so in the future. The contribution of the doctoral student to the aforementioned works has also been indicated.
e) This doctoral thesis is composed of the aforementioned scientific articles integrated as chapters in the document.

The doctoral student has complied with all the intellectual property rights relating to the dissemination of the articles used in the doctoral thesis.

The scientific articles which were used for this thesis are summarised (along with their impact factor) below:

1. **Mattinzioli, T.**, Sol-Sánchez, M., Martínez, G., Rubio-Gámez, M. (2020). *A critical review of roadway sustainable rating systems*. Sustainable Cities and Society (**IF: 7.587**). Vol 63. https://doi.org/10.1016/j.scs.2020.102447
2. **Mattinzioli, T.**, Sol-Sánchez, M., Martínez, G., Rubio-Gámez, M.C. (2021). *A parametric study on the impact of open-source inventory variability and uncertainty for the life cycle assessment of road bituminous pavements*. The International Journal of Life Cycle Assessment (**IF: 4.141**). Vol 26. Pages 916–935. https://doi.org/10.1007/s11367-021-01878-1
3. **Mattinzioli, T.**, Sol-Sánchez, M., Jiménez del Barco Carrión, A., Moreno-Navarro, F., Rubio-Gámez M.C., and Martínez, G. (2021). *Analysis of the GHG Savings and Cost-Effectiveness of Asphalt Pavement Climate Mitigation Strategies*. Journal of Cleaner Production. (**IF: 9.297**). Vol 320. https://doi.org/10.1016/J.JCLEPRO.2021.128768.

Further supporting publications were also published in indexed journals and conference proceedings which helped with the training and development of the doctoral candidate:

1. Sol-Sánchez, M., Castillo-Mingorance,, J. M., Moreno-Navarro, F., **Mattinzioli, T.** and Rubio-Gámez, M. C. (2021). *Piezoelectric-Sensored Sustainable Pads for Smart Railway Traffic and Track State Monitoring: Full-Scale Laboratory Tests*. Construction and Building Materials (**IF: 6.141**). Vol. 301. https://doi.org/10.1016/J.CONBUILDMAT.2021.124324.
1. **Mattinzioli, T.**, Sol-Sánchez, M., Moreno, B., Alegre, J. and Martínez, G. (2020). *Sustainable Building Rating Systems: A Critical Review for Achieving a Common Consensus*. Critical Reviews in Environmental Science and Technology (**IF: 12.561**). https://doi.org/10.1080/10643389.2020.1732781.

2. **Mattinzioli, T.**, Moreno-Navarro, F., Rubio-Gámez, M. del C., Martínez, G. (2020). *LCA and Cost Comparative Analysis of Half-Warm Mix Asphalts with Varying Degrees of RAP*. Proceedings of the International Symposium on Pavement. Roadway, and Bridge Life Cycle Assessment 2020 (LCA 2020, Sacramento, CA, 3-6 June 2020). https://doi.org/10.1201/9781003092278
3. **Mattinzioli, T.**, Martínez Montes, G., Sol Sanchez, M, Rubio Gámez, M.C. (2019). *Sustainable Pavement Rating Systems: An International Critical Review*. Proceedings from the International Congress on Project Management and Engineering. CIDIP 2019 (Málaga). http://dspace.aeipro.com/xmlui/handle/123456789/2270
4. Martínez Montes, G., Alegre Bayo, J., Moreno Escobar, B., **Mattinzioli, T.**, and Álvarez Pinazo, M. J. (2021). *Sustainability Building Rating Systems. A Critical Review. Time for Change?* Proceedings of the Project Management and Engineering Research, AEIPRO XXII 2018. Part of the Lecture Notes in Management and Industrial Engineering book series (LNMIE). pp. 391–404. https://doi.org/10.1007/978-3-030-54410-2_28.

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Contents

List of Figures

List of Tables

List of Acronyms

AC	Asphalt Concrete
ACV	Análisis de Ciclo de Vida (ES)
CEEQUAL	Civil Engineering Environmental Quality Assessment and Award Scheme.
CMA	Cold-Mix Asphalt
CML	Centrum voor Milieukunde Leiden (NL) (Institute of Environmental Sciences, University of Leiden)
CR	Crumb Rubber
DU	Declared Unit
EC	European Commission
EP	Eutrophication Potential
EPD	Environmental Product Declaration
FHWA	Federal Highway Administration
FU	Functional Unit
GHG	Greenhouse Gases
GreenLITES	Green Leadership In Transportation and Environmental Sustainability
GWP	Global Warming Potential
HMA	Hot Mix Asphalt
HPD	Health Product Declaration
HWMA	Half-Warm Mix Asphalt
IC	Impact Category
I-LAST	Illinois - Livable and Sustainable Transportation
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Analysis
LCI	Life-Cycle Inventory
LCIA	Life-Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PCR	Product Category Declaration
PENRE	Primary Energy: Non-Renewable Energy
PMB	Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials
PMFP	Particulate Matter Formation Potential
POCP	Photochemical Ozone Creation Potential
RAP	Reclaimed Asphalt Pavement
RSL	Remaining Service Life
SDG	Sustainable Development Goal
SRS	Sustainability Rating System
TAP	Total Acidification Potential
WMA	Warm Mix Asphalt

ABSTRACT

The roadway sector is one of the largest players for the development of society and the economy. However, as it stands, the construction of road pavements uses large amounts of virgin materials (some of which are fossil-based) and consume quite a large amount of thermal energy with non-renewable fuels too. Considering the growing climate crisis, there is an urgent need for the cleaner production of these assets and for project managers and pavement practitioners to be able to make informed and reliable environmental decisions. In this regard, life-cycle assessment (LCA) has gained traction across various sectors, and has been recommended by the European Commission in its Communication on Integrated Product Policy as the most appropriate framework for assessing the environmental impacts of products.

Although pavement LCA was first conceived at the turn of the 21st century, it is not yet considered a part of project tenders and is primarily a voluntary exercise thus far. This can be related to a variety of factors, some of which are associated with the data needed (availability, uncertain reliability and high costs) and lack of result interpretation for non-experts. With this in mind, the limited adoption of LCA is understandable given that impact reporting requires the declaration of assessment results and data sources used, as well as their quality (according to standards such as EN 15978 and ISO 14040). The former is fundamental for reporting, yet practitioners lack support structures for interpreting the impacts found and how influential or beneficial an alternative, more sustainable replacement material or process may be. While the latter is key for understanding how precise and reliable a result is, it is not yet fully understood how data variability and uncertainty can affect the final results, or which processes contribute the most to them, especially in regards to open-source data. Therefore, as it stands, there is a current need for the improvement of environmental pavement LCA in these regards.

As a result, this doctoral thesis aims to optimise pavement LCA by quantifying the relative importance of its parameters on final results and to provide solutions to better interpret design alternatives. Through this aim, more intuitive, informed and reliable environmentally-friendly pavement designs can be made, and in turn facilitate faster environmentally-sustainable decisions. This was addressed via a three-step approach: 1) state-of-the-art on sustainability- and LCA-based requirements in sustainable roadway rating systems, 2) identification of the associated risks of using open-source data via a variability and uncertainty analysis, 3) analysis of the cost-effectiveness of pavement design climate change mitigation strategies considering alternative pavement materials and production methods at the product and life-cycle level.

Results of this thesis indicate that pavement LCA uncertainty could be reduced by the careful selection of material and mixture production data sources, given that these input parameters provided the largest uncertainties and influence on final results. Additionally, to environmentally optimise asphalt pavement design, replacing virgin aggregates with high amounts of reclaimed asphalt pavement (RAP) (beyond 30-50$_{wt}$%) was found to be the most cost-effective solution, considering residual binder and rejuvenators. At lower RAP amounts (0-30$_{wt}$%), the use of lower-temperature manufacturing or crumb rubber additives should be considered; the latter if a modified mixture is desired. Further greenhouse gas and cost savings were found from combining mitigation strategies for the case studies considered.

RESUMEN

El sector de la carretera es uno de los mayores protagonistas en el desarrollo de la sociedad y la economía. En la actualidad, en la construcción de pavimentos de carreteras se utilizan grandes cantidades de recursos naturales (algunos de ellos de origen fósil) y se consume gran cantidad de energía, cuyo origen no siempre es renovable. A la vista de la actual crisis climática, es necesario plantear modelos productivos de firmes más sostenibles y que los gestores de proyectos y los profesionales de los pavimentos sean capaces de tomar decisiones medioambientales en base a información contrastada y fiable. En este sentido, el análisis del ciclo de vida (ACV) ha ido ganando protagonismo en diversos sectores, y ha sido recomendado por la Comisión Europea en su Comunicación sobre la Política de Productos Integrada para el diseño ecológico de los productos.

Aunque la aplicación del ACV de pavimentos comenzó a principios del siglo XXI, todavía no se ha incluido de forma general en el diseño de los mismos y menos aún en los procesos de licitación pública, siendo su uso meramente voluntario. Ello puede deberse a distintos factores, algunos de los cuales están relacionados con los datos ambientales necesarios (disponibilidad, fiabilidad incierta y costes elevados) y la dificultad de interpretación de los resultados para los no expertos. Teniendo esto en cuenta, la limitada adopción del ACV es comprensible, dado que los informes de impactos requieren la declaración de los resultados de la evaluación y de las fuentes de datos utilizadas junto con su calidad (según las normas como la EN 15978 y la ISO 14040). Lo primero es fundamental para la aplicación de la metodología de ACV, y lo segundo es clave para entender lo preciso y fiable que es un resultado. A fecha de hoy no se conoce en profundidad cómo la variabilidad e incertidumbre de los datos afecta a los resultados finales, o qué procesos contribuyen más a ellos; especialmente en el caso de los datos de fuente abierta. Teniendo en cuenta estas dos circunstancias, es evidente la necesidad de mejorar el ACV de los pavimentos.

En consecuencia, el objetivo principal de esta tesis doctoral es de optimizar la aplicación del ACV en pavimentos cuantificando la importancia relativa de sus parámetros en los resultados finales y aportar soluciones para interpretar mejor las alternativas de diseño. De esta manera se podrán realizar diseños de firmes más alineados en la variable medioambiental y por ende más sostenibles. Para asegurar este objetivo principal se han planteado tres objetivos segundarios, que son: 1) la comprensión de los requisitos actuales de sostenibilidad y ACV a nivel de proyecto, mediante la revisión de los sistemas de calificación sostenible de carreteras y sus créditos basados en el ACV, 2) la identificación de los riesgos asociados al uso de datos de acceso libre y cuáles son los parámetros más influénciales a través de un análisis de variabilidad e incertidumbre, y 3) el análisis de la rentabilidad de las estrategias de mitigación del cambio climático para el diseño de pavimentos considerando materiales y métodos de producción alternativos a nivel del producto y el ciclo de vida.

Los resultados de esta tesis indican que la incertidumbre a la hora de aplicar el ACV a pavimentos se podría reducir mediante la selección adecuada de las fuentes de datos de producción de materiales y fabricación de mezclas, dado que sobre estas fases del análisis recaen las mayores incertidumbres e influencias en el impacto final. Adicionalmente, para optimizar medioambientalmente el diseño de las mezclas asfálticas utilizadas en los pavimentos, la sustitución de los áridos naturales por altas cantidades de RAP (más del 30-50%) resultó ser la solución más rentable, teniendo en cuenta el betún residual y los productos rejuvenecedores necesarios para su correcto diseño. Con cantidades inferiores de RAP (0-30%), deberían considerarse el uso de técnicas de fabricación a baja temperatura o el uso de polvo de caucho de neumáticos fuera de uso como aditivo (esto último si se desea una mezcla modificada). La combinación de las estrategias estudiadas mejoraría la reducción global de la emisión de gases de efecto invernadero, así como de los costes asociados.

CHAPTER 1. Introduction

1.1 The Need for Cleaner Pavement Production

The roadway sector is one of the largest players for the development of society and the economy. Roads accounted for 92.2% of passenger-kilometres travelled in Europe in 2018 for inland journeys (82.9% for cars and 9.3% for coaches, buses and trolley buses) (Eurostat, 2020) and 76.3% of total inland freight transport (per t-km) (Eurostat, 2021). Where in growing economies the increase in roadway freight traffic is also greatly increasing (e.g., China (+488%) and India (161%) from 2007-2017) (OECD, 2021). This transportation demand is causing great structural and economic stress on existing roadway networks (European Commission, 2019) and generating large budgets for new networks (global new infrastructure budget of US$90 trillion for the next 15 years (UN, 2016)). However, these investments will be partly futile by the expected increase in degradation caused by anthropogenic climate change.

At the turn of the century, global carbon dioxide (CO_2) emissions were roughly 23Gt (metric) per year, but by 2019 this reached a record high of 36.4Gt per year; primarily due to human activities. This increase in anthropogenic carbon emissions has led to an increase in CO_2 concentrations in the atmosphere (reaching its highest ever annual average concentration in the atmosphere of 412.5ppm in 2020) (IEA, 2021). As a result, the global surface temperature in the first two decades of the 21st century (2001-2020) was 0.99 [0.84-1.10] °C higher than 1850-1900 (IPCC, 2021). This has caused, and will continue to cause, a variety of adverse effects on the environment with very likely devastating effects to daily life (e.g., more frequent and more intense extreme weather events, like heatwaves and heavy precipitation events). In turn, these effects will also have large economic and social impacts too.

The escalating impacts of climate change is expected to cause an annual damage of €0.8 billion per year, reaching €11.9 billion per year (€5.4B–18.1B, +1496%) by the end of the century, according to a research study by the European Joint Research Centre (Forzieri et al., 2018). Similarly, in the USA pavement infrastructure costs from temperature increases are estimated to add approximately US$19.0 and US$21.8 billion to pavement costs (in the USA) by 2040 and 2070 under an intermediate atmospheric carbon concentration pathway (Underwood et al., 2017). As a result, this increase in global emissions has caused an international call for the cleaner production of products and practices in all sectors.

Therefore, a solution for the cleaner production of roadways, and more specifically their pavements, is required. This is especially true given that these assets are primarily constructed from virgin materials and asphalt (which constitutes the large majority of road pavements) is manufactured using non-renewable fuel sources (i.e., fuel oil and natural gas). In order to make reliable decision-making exercises for the reduction of energy usage and emissions output generated from roadway construction and maintenance, life-cycle assessment (LCA) can be used by pavement practitioners (Van Dam et al., 2015). Where this assessment technique was also concluded to be the most appropriate framework for assessing the environmental impacts of products by the European Commission (2003), in its Communication on Integrated Product Policy (COM (2003)302).

1.2 Life-Cycle Assessment for more Sustainable Pavements

In brief, life-cycle assessment (LCA) is a method that can be used for analysing and quantifying the environmental impacts of a product, system, or process. LCA is considered a comprehensive approach, given that it considers the inputs and outputs throughout the whole life-cycle, from raw material extraction to end-of-life. Through this systematic approach it is possible to identify the most influential impacts, where the most significant improvements can be made and also identify any potential trade-offs. Such a quantitative and systematic approach will be highly beneficial for the achievement of the Paris Agreement (UNFCCC, 2015) and various Sustainable Development Goals (SDG) (UN, 2020), such as SDG 9.4 for increased resource-efficient and cleaner and environmentally sound technologies and processes, SDG 12 for sustainable resource consumption and production, and SDGs 13.1-2 for strengthening resilience and integrating climate change measures into policies, strategies and planning. The rules for conducting LCA are defined within the family of the ISO 14040 standards (ISO, 2006a). Given that this standard is rather broad, more industry-specific rules have also been developed, to harmonise environmental results. Through these rules (i.e., Product Category Rules, PCRs), Environmental Product Declarations can be developed, which attest the environmental performance of products.

LCA for pavements may be considered to have started at the turn of the 21st century with the publication of several novel works (Häkkinen and Mäkelä, 1996; Stripple, 2001) and the first tool for pavements was also developed (Horvath, 2007). Later on, LCA was recommended assessing the sustainability of pavement systems in a Federal Highway Administration (FHWA) guidance document (Van Dam et al., 2015), and very soon after the first-pavement-orientated LCA guidance and framework document was also published (Harvey et al., 2016).

Additionally, while LCA is still a relatively new field of science and still evolving, it has been shown to provide real-world value in the last two decades for manufacturers, companies and governments, helping them to identify relevant environmental burdens and then to define actions to improve. Yet, its use for pavements, LCA still requires considerable work to define specific rules, common practices and how results should be used to measure and assess environmental (and social) impacts (Harvey et al., 2016).

One of the key barriers for sustainable pavement evaluation is the need for data availability and inventory collection (Azarijafari et al., 2016). In general, various open access reports have been published providing LCA data, and the industry is generally working towards creating specialised open-access local LCA tools in Europe (such as ECORCE (Jullien et al., 2015) and in North America (such as PavementLCA (Athena Sustainable Materials Institute, 2020) and PaLaTe (Horvath, 2007)). Where these sources have been used for decision-making, as shown by (Hamdar et al., 2020; Proust et al., 2014). However, there is a need to understand the influence of data variability on the results of an LCA, which is a trend currently taking place in other engineering specialisations (Hoxha et al., 2017; Pushkar, 2019; Sleep et al., 2020; van Grootel et al., 2020). Asphalt pavement impact uncertainty has been explored for individual projects, such as via the Monte Carlo method (AzariJafari et al., 2018; Noshadravan et al., 2013). Yet between sources, the final variabilities need to be better understood. In the studies by (dos Santos et al., 2017) and (Lo Presti and D'Angelo, 2017) both saw variability was present, and that this is a current need. Thus, the presence of variance between tool datasets supports the hypothesis that further variance will be found in the comparison and exploration of further data, from alternative sources such as published case studies and project reports. Therefore, the variance of data, especially open-source data, must be further explored.

Upon the understanding of the influence of data variability and uncertainty on LCA results, and the most impacting processes in pavement LCA, there is a need for assessing the effect of design parameters on the final impact results and also the viability of upcoming technologies for reducing the emissions of asphalt pavements. Thus, an assessment would be required for evaluating the viability of sustainable pavement climate mitigation strategies. This assessment would need to consider both the environmental burdens and the cost-effectiveness of such strategies. From previous LCA studies, it is apparent that to provide the largest environmental and cost savings in the production of asphalt pavements, the material extraction and mixture manufacture stages must be considered. For the material extraction phase, binders are a key impactor and so the use of waste materials can be explored; shown to be a viable mitigation strategy (L. L. Brasileiro et al., 2019; García-Travé et al., 2016; Jimenez Del Barco-Carrion et al., 2016). Additionally, within the vision of a post-fossil fuel society, the use of novel bio-binders can be explored, given their interest in both research and in practice (Blanc et al., 2019); with a pilot study already in place (EIFFAGE, 2018, n.d.). Regarding strategies for asphalt manufacture, the reduction of plant temperatures has also gained traction (M Carmen Rubio et al., 2012; Sol-Sánchez et al., 2016).

The use of an environmental-economic analysis regarding environmental savings for roads has had a somewhat limited application thus far. Harvey et al. (2020) carried out a cost-benefit comparison of including different amounts of RAP in mixtures, reported in terms of dollars per tonne of $CO_{2\text{-eq}}$ reduced, at different RAP quantities (25%, 40%, and 50%) within the mixture for the Caltrans network. Huang et al. (2021) used LCA and life-cycle cost analysis, along with multi-objective optimization, to determine a local model for optimised maintenance using an environmental damage cost unit. However, limited literature was found for assisting decision-makers on the environmental and economic benefits of asphalt mixtures using recycled or bio-based materials or reduced-temperature manufacturing.

CHAPTER 2. Motivation and Research Objectives

In view of the need for more optimised pavement LCA, this doctoral thesis aims to quantify the relative importance of LCA and design parameters on final results in accordance with the reporting needs of environmental sustainability assessment. In order to achieve this aim, and in light of the previous limitations found, the following objectives were defined:

1. Understand the current sustainability and LCA requirements at the project level, focusing on roadway sustainable rating systems and their LCA-based credits;
2. Identify the uncertainty and variability of the impacts of the materials and processes required for pavement LCA and how these are propagated to the final LCA results;
3. Investigate the cost-effectiveness of current climate change mitigation strategies for asphalt pavements with respect to their environmental saving potential, at both the cradle-to-laid and full LCA level.

CAPITULO 2. Motivación y Objetivos

La aplicación del ACV al diseño de firmes es fundamental para conseguir infraestructuras más sostenibles. Sin embargo, todavía existen limitaciones para su uso fiable y eficiente por todos los implicados en su diseño, proyecto y construcción. Esta tesis doctoral se enfoca en optimizar la aplicación del ACV de los pavimentos cuantificando la importancia relativa de cada uno de los parámetros utilizados, así como del propio diseño del mismo, todo ello de acuerdo con las normas y recomendaciones internacionales para la evaluación de la sostenibilidad ambiental. Para lograr este objetivo, y a la luz de las limitaciones anteriores definidas, se definieron los siguientes objetivos:

1. Comprender los requisitos actuales de sostenibilidad y ACV a nivel de proyecto, mediante la revisión de los sistemas de certificación sostenible de carreteras y sus créditos basados en el ACV;
2. Identificar la incertidumbre y la variabilidad de los impactos de los materiales y procesos necesarios para la aplicación del ACV de los pavimentos y cómo influyen en los resultados finales;
3. Analizar la rentabilidad de las actuales estrategias de mitigación del cambio climático para los pavimentos asfálticos al nivel del producto y a lo largo de todo su ciclo de vida.

CHAPTER 3. Methodology

Figure 3.1 shows the systematic approach taken to respond to the research objectives defined in this doctoral thesis. In order to achieve the thesis' objectives, two main research tasks were completed: 1) background on current LCA requirements in sustainable pavement projects; 2) evaluation of data and design parameters for pavement LCA. The scope of this work covers the cradle-to-laid stages for the asphalt pavement (A1-A5, EN 15804 (CEN, 2019)), as well as its maintenance (B2) and replacement (B4).

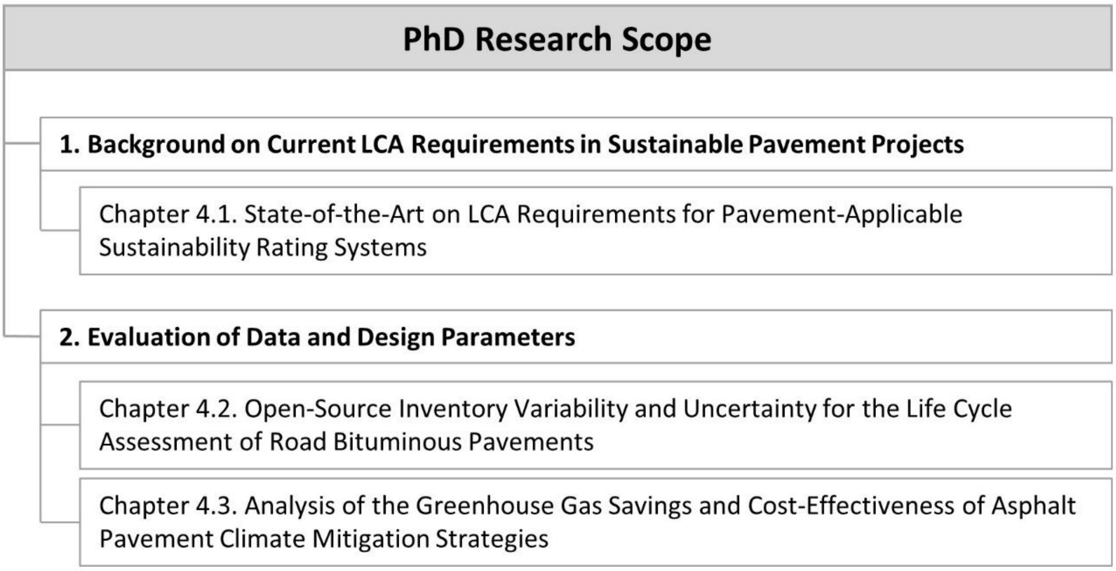

Figure 3.1. Scope of doctoral thesis.

The results are all presented in sub-sections in Chapter 4 and take the form of the published indexed scientific articles. Chapter 4.1 covers the introduction background, methodology, results, discussion and conclusions of the critical review undertaken on roadway sustainability rating systems. In this work, the SRS market was summarised and the seven globally-leading systems were selected to be analysed in-depth. This study assesses the key characteristics of these systems, their structures, common macro-categories, three pillars of sustainability and their asset management applicability. Within this last aspect, pavement applicable criteria are identified within these systems and their LCA- and EPD-related credits are reviewed.

Chapter 4.2 of this thesis focused on open-source LCA data variability and uncertainty. These were both studied at the constituent material level and how the variabilities would be propagated through to the final LCA results. To achieve this, 35 data sources were assessed, three data processing routes were defined according on source quality, and error propagation was explored analytically as a function of the variance.

Chapter 4.3 assesses the environmental benefits and the cost-effectiveness of three asphalt pavement climate mitigation strategies. Namely, the strategies considered were the 1) use of waste materials (reclaimed asphalt pavement, RAP, and crumb rubber, CR), 2) use of reduced temperature mixture manufacturing, and 3) use of bio-binders. Both the separate strategies were considered, as well as five case study mixtures which combined the aforementioned strategies. This was achieved via the development of a novel indicator, used to compare GWP and costs. The analysis was carried out for both the product and construction stages (stages A1-A5, EN 15804), along with a full LCA considering both structural and functional maintenance operations (stage B4, EN 15804).

Chapters 5 and 6 cover the general conclusions found from this doctoral thesis and future research topics, respectively.

CHAPTER 4. Results

4.1 A Critical Review of Roadway Sustainable Rating Systems[1]

4.1.1 Introduction

Roads are considered an essential part of modern daily life, and will have a key role in the development of smart cities too. The concept of the smart city consists of various characteristics, of which infrastructure sustainability can be considered one of them (Mohanty et al., 2016). In this context, the sustainable infrastructure characteristic would need to adhere to the triple bottom line, or the three pillars of sustainability (Silva et al., 2018), as originally defined by (Elkington, 1997). In response to this need, coupled with the current large energy (around 26% of Europe's total energy consumption (Eurostat, 2016)) and raw material use associated to roads, plus the need global need for US$90 trillion to be invested in new infrastructure over the next 15 years (UN, 2016), sustainable rating systems (SRS) for roads have grown in popularity.

These rating systems are composed of the current best-practices for road design, construction and maintenance and are recommended as one of the best-value procurement practices for sustainable highways for contractors and vendors (Muench et al., 2019). These system are therefore expected to assist in maximizing economic efficiency, improve social welfare, and help meet global sustainability targets (UN, 2019a; WHO, 2017). Where various case studies have supported their implementation. Such as, (Lew et al., 2016) who assessed 28 Greenroads projects and found a quantifiable improvement in performance compared to typical projects. And, in the experience of the Illinois Tollway, USA, a total of 22 projects pre- and post-Invest SRS were measured over 14 years, and found an increase in project sustainability over time (Illinois Tollway, 2015).

However, despite the fact that many sustainable choices outlined in these systems can measurably improve project sustainability with minimal or no impacts on cost (Anderson and Muench, 2013), there is still a limited amount of existing literature clarifying and explaining the differences between these systems (Simpson et al., 2014). Especially when a rating system, when used in the proper context, can provide a flexible approach to measure, manage, improve, and communicate sustainability at the project level (Muench et al., 2012). Key areas of uncertainty in past literature can be condensed to the need of clarification towards: (1) indicator weighting, (2) triple-bottom line adherence, and (3) whole life-cycle considerations. Where, (Clevenger et al., 2013) and (Simpson et al., 2014) found that while systems tend to share similar ideas with regards to what sustainability aspects to focus on, especially resources and energy use, they largely differ in their approach to defining the importance of these aspects in a rating system. In response, (Yang et al., 2018), (Rooshdi et al., 2014) and (Eisenman and Meyer, 2013) studied the adaptation of weightings to better suit local contextuality. Regarding the triple-bottom line, (Wu et al., 2015) stated that sustainable road projects provide a superior performance in terms of economic, social and environmental sustainability. However, (Flores et al., 2016) state that this is not always the case. (Diaz-Sarachaga et al., 2016) and (Peters, 2017) found that environmental considerations dominated SRS considerations, and (Furberg et al., 2015) and (Peters, 2017) found that social sustainability indicators should be better included. Concerning whole life-cycle considerations, (Flores et al., 2016) also state that some SRS do not cover all project life-cycle phases. This was reinforced by (Bueno et al., 2013) who identified that the life-

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[1] The work in this chapter is based upon the following publication: Mattinzioli, T., M. Sol-Sánchez, G. Martínez, and M. Rubio-Gámez. *A Critical Review of Roadway Sustainable Rating Systems*. Sustainable Cities and Society, Vol. 63, No. August, 2020. https://doi.org/10.1016/j.scs.2020.102447.

cycle considerations of SRS are limited mainly to the construction process. Similarly, (Alam and Kumar, 2013) found that certain high-impact considerations, usually modelled in life-cycle assessment (LCA), are lacking from SRS.

Therefore, considering the high impact potential of these systems, the current lack of clarity on the SRS market and the uncertainty associated to these systems, the aim of this review was to analyse the most prominent rating systems on the market to compare and contrast their functioning. Through this aim, it will be possible to gain clarity on these systems, identify the most suitable system, and understand any benefits or drawbacks associated to the current SRS market. This aim will be achieved by providing a general overview of the systems, and then a more specific analysis on the category and indicator weightings, three-pillar adherence and life-cycle considerations. This study will also focus on the most updated version of the SRS, given they have undergone various updates since their conception; potentially leading to changes in the aforementioned areas of uncertainty. Through these research focuses it will be possible to gain transparency on more environmentally and socially beneficial criteria for smarter roadways.

4.1.2 Background

First and foremost, roadway SRS are a form of decision support systems which function by evaluating a project against roadway and pavement sustainability “best practices”. These best practices are focused on covering the three pillars of sustainability (environmental, social and economic (Elkington, 1997)) and serve as the performance indicators within SRS. Within the SRS, the indicators are typically organised into categories depending on their common themes (i.e., energy use, resource use, pollution, land use and ecology, communities). Each performance indicator is measured according to a common metric, usually points, to enable their direct comparison (Maher et al., 2015; Van Dam et al., 2015). The number of points available per indicator is typically proportional to its importance and impact on achieving the system’s target optimal sustainability level. Upon completing the rating exercise, the total amount of points achieved is summed and a final score is awarded to the project. Where the award level score boundaries are defined per system.

Points can be awarded for outcome- or process-based results. For example, for the former they are awarded by obtaining certain levels of measurable improvements within the project (i.e., percentage reductions in energy use and emissions or tons of recycled material used). Whereas, for the latter, points can be awarded for the inclusion and consideration of certain practices too (i.e., perform a life-cycle cost analysis, demonstrate specific items are included in an asset management program).

Roadway SRS were found to have emerged from varying geographical regions (Figure 1), with different focuses and methods. This is associated with the fact that sustainability is a context-based solution, and varies depending upon local characteristics (Van Dam et al., 2015; Zietsman et al., 2011); therefore, a “one size fits all” solution would not be applicable. From literature review, and as mapped in Figure 1, North America, Canada, United Kingdom and Australia were found to be the key regions to have released sustainability rating systems. While further systems may exist, such as personalized SRS for internal applications as shown by (Clevenger et al., 2016), the ones displayed in Figure 1 were the most commonly referenced SRS in literature.

The regions of SRS release show a similar pattern to that found for building SRS (Doan et al., 2017). Where, in general, it is inferred that road SRS are acknowledged to have been influenced by building SRS, as discussed by (Barrella et al., 2017) that the leading transportation rating systems are modelled after the LEED building rating system (USGBC, 2020), and that roadway SRS gained traction long after building ones, in the early 2010’s (Figure 1), compared to the 1990s to 2000s, as shown by (Shan and

Hwang, 2018). This preceding sustainability awareness in the building sector can be linked to its already existing sustainable construction standards (ISO, 2011, 2008), while for their base network of roads no direct standards yet exist (Clevenger et al., 2013; Rooshdi et al., 2014); apart from general infrastructure standards (ISO, 2014).

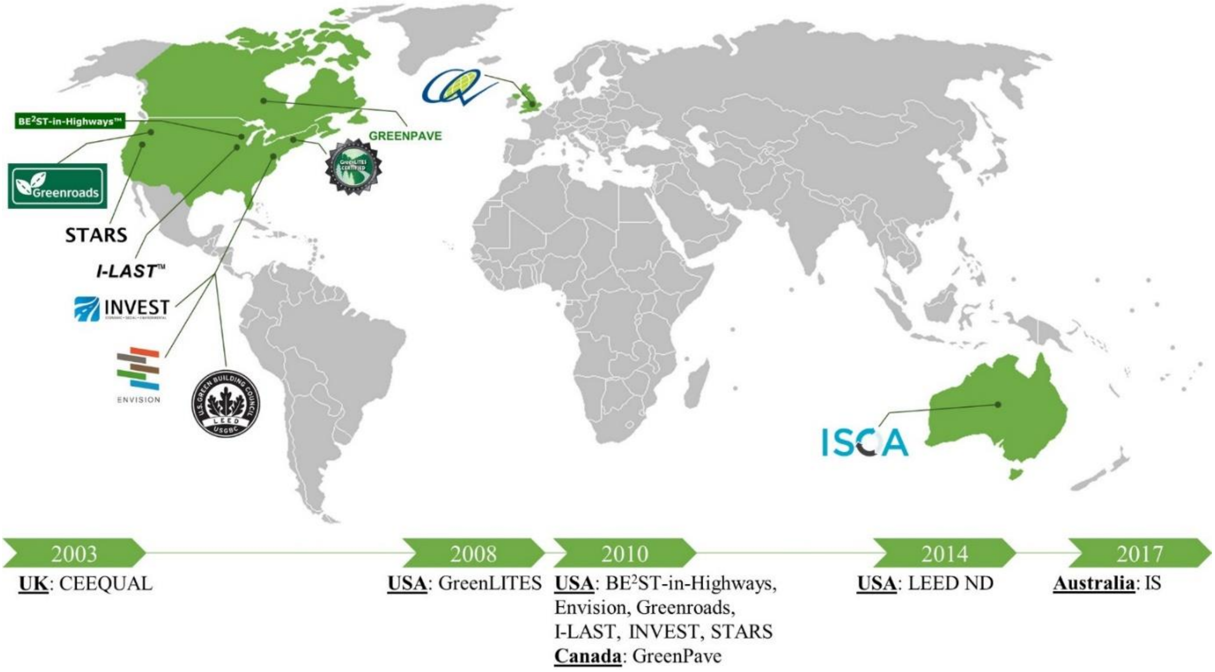

Figure 4.1. Origin map and release timeline of road-applicable RS.

4.1.3 Methodology

For the systematic objective review of roadway SRS, firstly the rating systems of most interest were selected, followed by a two-step analysis: (i) definition of the general characteristics and structure of the systems, followed by (ii) the analysis and interpretation of the system data collected.

4.1.3.1 System Selection

An extensive literature search was carried out to ascertain further information on the systems demonstrated in Figure 1. As a result, seven systems were selected for comparison. The systems selected all provided scientific interest (citations in Scopus and been included in a previous review study) and all had a consolidated development state with at least 10 years in service. Following these criteria, it was sensible to assume that these are the key systems pushing the market in enhancing sustainability assessment and recognition.

The seven selected systems were: CEEQUAL v6 (CEEQUAL, 2019), Envision v3 (ISI, 2018), BE^{2}ST-in-Highways (UWM, 2010), Greenroads v2 (Anderson et al., 2017), GreenLITES v2.1 (NYSDoT, 2010), Invest v1.3 (Reid et al., 2018), and GreenPave v2.1 (Lane et al., 2017). The systems selected are all for new projects (while the majority can be applied to rehabilitation and maintenance operations too).

The I-LAST, STARS and IS were excluded due to limited attention in literature and lack of transparency towards number of certified projects. LEED ND was excluded due to in nature being a neighbourhood development system and most of its scope being outside of the roadway.

4.1.3.2 System Review

As stated, the review of the systems underwent two steps. First, the evaluation of the data collected from the systems, involving the presentation of the systems' key characteristics and structure. Where, the key characteristics and structure were assessed to provide an insight into the systems assessed, which is a common starting point for the review of rating systems for engineered assets (Ameen et al., 2015; Doan et al., 2017).

Following the presentation of the data collected, the SRS underwent quantitative and qualitative review for their analysis and interpretation. For this stage, linking to the previously found areas of uncertainty, the following aspects were considered:

- Common macro-categories. Due to differing interpretations of sustainability, it is hard to directly compare the indicator weighting of rating systems, as they vary in their organisation. In consonance with (Mattoni et al., 2018) for building SRS, a normalisation procedure was implemented in order to obtain significant information on the systems and compare them.
- Three-pillar assessment. The assessment of rating systems according to the three-pillars of sustainability (environmental, social and economic, as first defined by (Elkington, 1997)), is important as sustainability is a multi-faceted problem and in order for a system to be fully sustainable it must consider all three aspects of sustainability (Analía Sánchez, 2015). Therefore, each selected system's indicators were assessed qualitatively in order to determine the interdependent nature of the pillars within the schemes; rating systems must be fully broken down in order to achieve this (Drexhage and Murphy, 2010, chap. 1). In this analysis, it was considered that some criteria will be applicable to more than one pillar, as found in the work of Park, Yoon, & Kim (2017) and Varma and Palaniappan (2019) reviewing building SRS.
- Asset management effectiveness. Life-cycle considerations are not only intrinsically imbedded into the original definition of sustainability (WCED, 1987), but are also especially important given that the majority of roadway projects nowadays involve the rehabilitation of a degraded surface (Bryce et al., 2017). Given the previous uncertainty expressed towards this aspect, the following asset management aspects were reviewed:
    - Life-cycle considerations. Necessary because as it stands a sectorial transition is required, where projects start to take a more comprehensive approach to evaluating the environmental burden of projects, and consider the whole life cycle (Harvey et al., 2016; UN, 2019b), not just initial costs. To analyse the life-cycle considerations, LCA credits were reviewed, as (Suprayoga et al., 2020) indicates LCA is one of the most appropriate tools for assessing project life-cycle sustainability performance with regards to efficient material and energy use. Similarly, life-cycle cost analysis considerations was considered, being the only economic indicator by the European Committee of Standardisation (CEN, 2016) for roadway sustainability. Finally, the inclusion of Environmental Product Declarations (EPD) was also reviewed, being an increasing requirement for the transparency of material selection in projects and providing harmonised data. Where, (Omer and Noguchi, 2020) found that building materials will play a key role in achieving several Sustainable Development Goals (SDG) and (Muench et al., 2019) states that they may become much more commonplace in the coming years;
    - Pavement applicable criteria. This aspect was reviewed as the pavement is considered as the most material intensive and one of the more complex sections of a roadway project,

and is the primary basis of maintenance operations in roadways. For the selection of the pavement applicable criteria, all aspects related to road side environment, road geometry, lighting, traffic control systems and access routes were considered outside of the pavement boundary (Van Dam et al., 2015, chap. 10).

4.1.4 Results and Discussion

From the data collected from the systems, it was possible to ascertain the systems' key characteristics (section 4.1.4.1) and structure (section 4.1.4.2). Meanwhile, from the quantitative and qualitative analysis and comparison of the reviewed SRS, it was possible to interpret their indicator focuses (section 4.1.4.3), three-pillar adherence (section 4.1.4.4) and asset management effectiveness (section 4.1.4.5).

4.1.4.1 Key Characteristics

The key characteristics of the roadway SRS are presented in Table 1. Within the Table, it is possible to visualise the organisation of each tool, its assessment scope, and certification scheme. These aspects have been organised in the following categories: SRS version and date; international applicability; project scope (infrastructure, roadways, and pavements); rating method; assessment type; rating classifications.

From the results, it was seen that the different SRS can be categorised depending on their scopes and assessment types. In the first case, three project scopes were identified according to project size, namely: infrastructure, roadway, and pavement. While, in the second, two assessment types can be seen: self-assessment and third-party rating. The assessment types of projects can be seen to have a notable influence on the rating result, as seen from (Lew et al., 2016) self-evaluations over-estimate final scores by an average of 15%.

A credit criteria rating method was most typically adopted by the rating systems, where CEEQUAL requires the completion of mandatory criteria (described in Section 4.1.4.2), and BE^{2}ST-in-Highways and Greenroads require the completion of a screening process. BE^{2}ST-in-Highways was the only system not found to function via credit criteria, but through the quantitative reductions of a project's impact compared to a "typical" highway project (i.e., with no incorporated sustainability concepts). Regarding the rating classifications, the levels varied across all systems, where the majority of systems adopted an Olympic-style rating approach (i.e., gold, silver, bronze). The Invest system was found to not use scoring boundaries, and states that it emphasises project outcomes and not scores.

The international flexibility of these systems was found to differ per system. From the review of the systems, only the CEEQUAL, Envision, Greenroads and Invest systems were found to have been used beyond the country of origin, hence their greater international applicability shown in Table 1. Regarding the two infrastructure systems, CEEQUAL has projects in Sweden, Hong Kong, Qatar, Norway, and USA (CEEQUAL, 2020) and Envision has projects in Canada, Italy, Israel and Saudi Arabia (ISI, 2020). Meanwhile, for roadway orientated systems, Greenroads was found to have been used for studies in Taiwan and India (Chang et al., 2018; Singh et al., 2011) and to have been also used Canada, New Zealand, Israel, South Africa, and United Arab Emirates (Greenroads, 2019). The Invest system has been used in Canada and Paraguay (FHWA, 2020). From literature it is suggested that for optimal long-term system use, the SRS should be reviewed and adapted to fit the requirements of local programmes, as was found to be the case for the Illinois Tollway (Illinois Tollway, 2015) and in other sectors (Sharifi, 2020; Sharifi and Murayama, 2015) to ensure SRS adherence to local targets and limitations.

Table 4.1. Key characteristics of the selected sustainability rating systems.

	Sustainability rating system						
	CEEQUAL	**Envision**	**BE^{2}ST-in-Highways**	**GreenLITES**	**Greenroads**	**Invest**	**GreenPave**
System Version & Year	v6 - 2019	v3 - 2018	v1 – 2010	v2.1 - 2010	v2 – 2017	v1.3 - 2018	v2.1 - 2017
Origin	UK & Ireland	USA	USA	USA	USA	USA	Canada
Applied Internationally	✓	✓	X	X	✓	✓	X
Project Typologies Scope	Infrastructure: airports, ports, railways, energy-related projects, water-related projects, electricity and gas supply-related projects and also information and communication system projects		Roadways: pavement, alignment, related structures, surrounding ecosystem. In most cases pedestrian and cycle routes too.				Pavement
Rating Method	Completion of mandatory criteria, and sum of awarded credits.	Sum of credit criteria.	Screening process, then quantitative assessment for percentage reductions.	Sum of credit criteria.	Completion of project requirements, then cumulative total of credits awarded.	Sum of credit criteria.	Sum of credit criteria.
Assessment Type	Third-Party	Third-Party	Self-Assessment	Self-Assessment	Third-Party	Self-Assessment	Self-Assessment
Rating Classifications	Pass (≥30%) Good (≥45%) Very Good (≥60%) Excellent (≥75%) Outstanding (≥90%)	Verified (≥20%) Silver (≥30%) Gold (≥40%) Platinum (≥50%)	Bronze (≥50%) Silver (≥75%) Gold (≥90%)	Certified (≥33%) Silver (≥67%) Gold (≥90%) Evergreen (>98%)	All PR + Bronze (40) Silver (50) Gold (60) Evergreen (80)	N.A. – describes goal as emphasizing outcomes over scores	Bronze (9-11) Silver (12-14) Gold (≥15) Trillium (yet to be defined)

4.1.4.2 System Structure

Table 2 summarises the criteria breakdown of the SRS in terms of their categories, indicators, mandatory indicators and achievable credits. Overall, it is seen that there are substantial differences between each system, across scope and application type, despite all systems sharing the same goal; as also found with sustainable building SRS (Zhang et al., 2019). As stated in Section 4.1.2, this can be associated to regional considerations, which are very important for sustainability assessment and render each project unique (Van Dam et al., 2015; Zietsman et al., 2011), where their omission is recognised as a limitation in sustainability evaluation activities (Bryce et al., 2017). While regional considerations were provided in all SRS, GreenLITES and BE^{2}ST-in-Highways were not found to offer specific criteria for road type (highway vs urban), although the latter system would include some in its LCA, LCCA and noise assessments.

The complexity of a system should be associated to its number of credits, rather than categories. For example, both CEEQUAL and BE^{2}ST-in-Highways offer eight categories, but the former only has 18 credits, while the latter has 5,010. Similarly, despite their differing scope, Envision and Greenroads have a similar number of indicators, yet Envision assigns close to over seven times more credits on average to indicators. GreenPave offers the least amount of performance measures and credits, due to its narrower pavement scope. Invest was found to have a unique methodology compared to the rest of the systems. Rather than presenting a series of categories depending on the project's different focuses, there are four categories organised per life-cycle stage, where each category includes a list of indicators relevant to the entire phase: planning (for states and regions), project development, and operations and maintenance phases.

Infrastructure system category indicators were also found to have a methodological workflow, which could be associated as to why they respectively have many more credits. For example, CEEQUAL's consultation and engagement sub-category starts with recording community comments (credit 3.1.7), followed by assessing community comments during design (credit 3.1.8), followed by assessing community comments during construction (credit 3.1.9). Similarly, Envision's CR2.5 for maximising resiliency, which is built upon CR2.3's risk evaluation and CR2.4's resilience goals and strategies.

A tactic which can be implemented by systems to ensure the inclusion of minimum sustainability requirements is the use of mandatory criteria (Sharifi and Murayama, 2013). Mandatory criteria refer to indicators within a rating system which must be achieved in order to obtain a certification. It was found that only three of the systems enforce mandatory criteria, where Greenroads and BE^{2}ST-in-Highways use them as rating pre-requisites. The Greenroads system dedicates 20% of its total performance indicators to its mandatory pre-requisite criteria, establishing a robust sustainability baseline for projects before carrying out rating. BE^{2}ST-in-Highways rating starts with a screening stage to ensure projects meet all local regulation requirements, while CEEQUAL requires all projects to check for invasive species, ensure sustainable timber is used, and ensure all waste is treated appropriately.

The lack of consensus and the notion of indicator pluralism, as described by (Ameen et al., 2015) for urban design SRS, demonstrated by the systems could therefore be associated to the current lack of confidence in SRS implementation. While the nature of the indicators is analysed in Section 4.1.4.3, the large difference purely in numbers could be preoccupying. For example, purely for roadway systems indicators can vary from 9 to 178, or 18 to 631 credits, for assessing the same roadway project. Similarly, overall, three of the seven systems were found to use mandatory criteria, so the holistic consideration of sustainability for most systems could be questioned.

Table 4.2. Structure of the selected sustainable rating systems.

System	Indicator Categories	Indicators	Mandatory	Credits
CEEQUAL v6	Management	29		550
	Resilience	16		600
	Communities & stakeholders	23		550
	Land use & ecology	38	2	600
	Landscape & historic environment	30		450
	Pollution	20		400
	Resources	73		1451
	Transport	19	4	400
	Innovation	2		500
	Total: 9	**250**		**5,050**
Envision v3	Quality of life	14		200
	Leadership	12		182
	Resource allocation	14		196
	Natural world	14		232
	Climate & resilience	10		190
	Total: 5	**64**		**1,000**
BE^{2}ST-in-Highways	Pre-Requisites	Indicators are same as categories.	1	
	Greenhouse gas emissions			2
	Energy use			2
	Waste reduction (Ex situ)			2
	Waste reduction (In situ)			2
	Water consumption			2
	Hazardous waste			2
	Life cycle cost			2
	Traffic noise			2
	Social carbon cost saving			2
	Total: 9 + screening			**18**
GreenLITES v2.1	Sustainable sites	55		93
	Water quality	12		19
	Materials & resources	39		65
	Energy & atmosphere	69		104
	Innovation/ Unlisted	3		17
	Total: 5	**178**		**281**
Greenroads v2	Project requirements	12	12	
	Environment & water	10		30
	Construction activities	11		20
	Materials & design	6		24
	Utilities & controls	8		20
	Access & liveability	10		21
	Creativity & effort	4		15
	Total: 7	**61**		**130**
Invest v1.3	System planning for states (planning)*	17		250
	Sustainable planning for regions (planning)*	17		250
	Project development	33		171
	Operations and maintenance	14		210
	*Only one to be selected for a project			
	Total: 3	**64**		**631**
GreenPave v2.1	Pavement Technologies	4		9
	Materials & Resources	4		11
	Energy & Atmosphere	4		8
	Innovation & Design Process	2		4
	Total: 4	**14**		**32**

4.1.4.3 Common Macro-Categories

Figure 2 demonstrates the analysis of the indicators of the SRS according to their key common categories, which were found to be: management; social aspects & community; environment & land use; energy use & atmosphere; resource use; innovation.

The results of the macro-category review suggest that the two primary focuses for roadway sustainability are resource use, and energy use with atmospheric considerations. The dominance of the resource use category can be associated to current targets for more sustainable resource use, such as New Circular Economy Action Plan as part of the European Green Deal (EC, 2020). Meanwhile, energy use interest can be associated to current global warming and CO_2 emission targets; such as SDG 13 (UN, 2019c). Relevant to SDGs 6 and 14, related to water's sustainable management and ecosystem integrity, all systems considered water and stormwater control methods. However, only the third-party systems (CEEQUAL, Envision and Greenroads) were found to consider potable water impacts.

Following resource use and energy use, social aspects and community related indicators followed as the most popular. Greenroads and BE^2ST-in-Highways were the two SRS which offered the highest consideration for this macro-category with 25% and 28% respectively. Social aspects are typically an aspect which is hard to quantify in sustainability and is further discussed in Section 4.1.4.4. The environment and land use macro-category were the fourth most popular and refers to the project considerations outside of the main structural boundary, such as the surrounding ecology, non-motorised access and cultural heritage preservation.

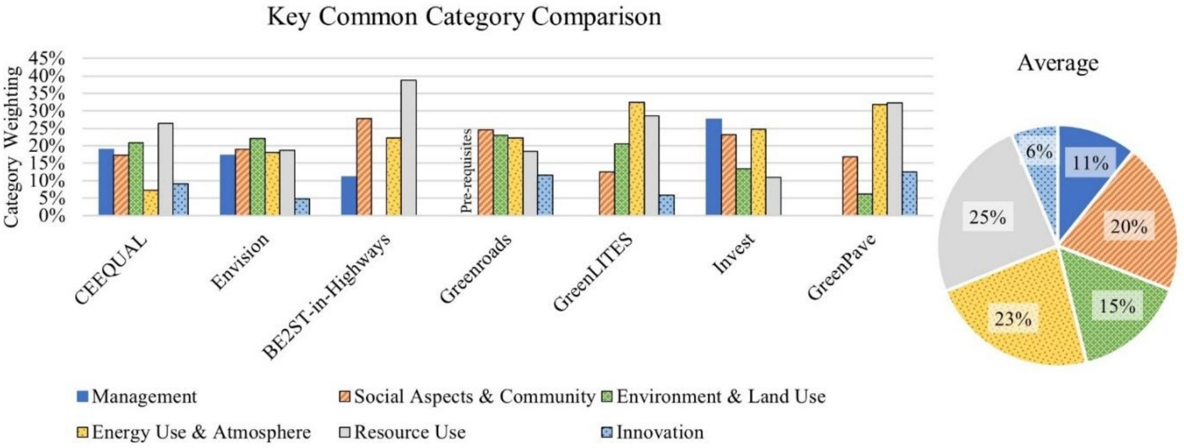

Figure 4.2. Breakdown of key common RS categories.

From reviewing the results of the indicator assessment, and linking to Section 4.1.4.2, the theme of lack of consensus on roadway sustainability assessment indicators and the optimal number of indicators is further suggested. While the key themes of the rating systems have been deduced, it could be inferred that the internal self-assessment systems are calibrated for the design stage of projects, hence why they display a lower consideration of the Management macro-area (typically the section which defines life cycle planning). Invest breaks this trend with the highest consideration of management issues across SRS (28%), and as seen in Figure 2, offers the most credits related to project planning. Alternatively, the third-party systems considered all macro-categories (unlike the self-assessment SRS) and provided a more homogeneous spread between the macro-categories identified; Greenroads does consider the Management macro-area, but in its pre-requisite category, which has no points, so does not appear in Figure 2.

Finally, in this assessment, many more performance indicators in the Project Management, Social & Community and Environment & Land Use macro-categories were present during the planning and design phase, than during the construction phase. Therefore, it could be interesting to consider the use of SRS early on in a project, in order to ensure that as many planning and design indicators as possible are considered and can be completed, to maximise the final score.

4.1.4.4 Indicator Three-Pillar Assessment

In this section, the results for the SRS indicators evaluated according to the three pillars of sustainability (environmental, social and economic) are presented in Figure 3. Overall, all systems were found to be led by their environmental considerations (average of 39%), except for BE^{2}ST-in-Highways which had the same distribution of credits for environmental and economic concerns. The dominance of the environmental pillar can also be seen from the results of the previous section. In the work of (Lew et al., 2016), the dominance of the environmental pillar was inferred to arise due to these aspects being the least represented in current practice, meanwhile in the developed countries where these systems originate from, social and economic policies may already be in effect in local regulations, hence less attention being applied to them.

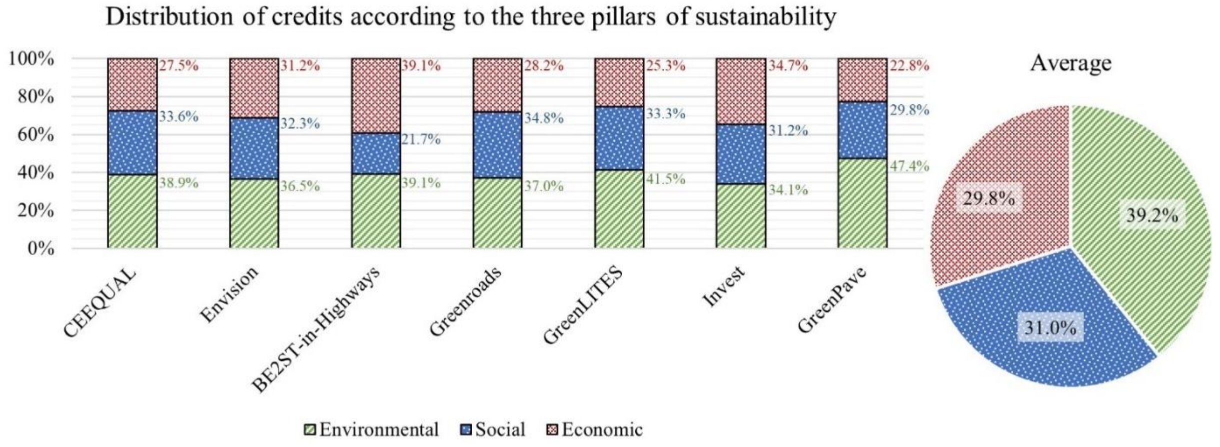

Figure 4.3. Analysis of the six RS against the three pillars of sustainability.

The majority of indicators were found to be multi-dimensional in terms of sustainability (average of 77% across systems), hence despite the large focus on environmental indicators in Section 4.1.4.3, the social and economic pillars were also well represented in Figure 3. The BE^{2}ST-in-Highways, Greenroads, Envision, and Invest systems best demonstrated this multi-dimensionalism with at least 80% of indicators all considering more than one pillar. The Greenroads' Project Requirements category has no points allocated to it; hence the results of this category were not included in the weighted analysis in Figure 3. However, in an un-weighted assessment, social considerations dominated the pre-requisites at 37.5%, followed by environmental at 33.3% and finally the economic considerations at 29.2%.

The noteworthy amount of social aspects considered, as seen in Figure 3, is especially significant given that social sustainability is a difficult aspect to quantify in roadway assessment (Abdel-Raheem and Ramsbottom, 2016; Lineburg, 2016; Sierra et al., 2018). Certain aspects such as reduced emissions in construction processes and improved traffic flow design are primarily environmental in nature, given that the emissions produced mainly affect global warming, but these reductions were found to also benefit society (reduced acidification potential, particulate matter etc.). As a matter of fact, it was found that 70% of the social indicators were also linked to the environmental pillar (i.e., hazardous waste reduction, reduced traffic delays, local material use, non-motorised vehicle access). This could infer that the social aspects found in rating systems are largely co-benefits of environmental project enhancements.

Of the social criteria which were independent to the environmental and economic pillars (21% of all social indicators), both process- and outcome-oriented indicators were found, with the latter being the most dominant, and the following key areas being assessed: noise reduction (traffic and construction), pedestrian safety and experience enhancement, community planning and public participation, site preservation (cultural and historic), and worker safety. The three third-party systems also were the only ones to include a social impact analysis. Unique social inclusions found in some SRS are BE^{2}ST-in-Highways' points for the social carbon cost of projects (links to how reducing CO_2 provides financial benefits by reallocating the resources to other purposes, i.e. creating new jobs) and Greenroads' MD-4 credit which requires the completion of a Health Product Declaration (HPD) (unseen in other SRS, but seen in building SRS (USGBC, 2018)).

4.1.4.5 Asset Management Effectiveness

4.1.4.5.1 Life-Cycle Considerations

Table 3 summarises the LCA, Environmental Product Declaration (EPD), LCCA and life-cycle considerations present in the SRSs'. As shown in Table 3, it is found that more tools stipulate the completion of a LCCA than LCA. BE^{2}ST-in-Highways is the only system which specifies which tools to use: PaLATE (Horvath, 2007) and RealCost (FHWA, 2004). GreenPave considers both LCA and LCCA under the *Exemplary Process* innovation category, but it states that PaLaTe can be used for both, unlike BE^{2}ST-in-Highways which requires two separate tools.

Regarding the use of LCA for life-cycle environmental impact quantification, only CEEQUAL, BE^{2}ST-in-Highways, Greenroads and GreenPave required the completion of an LCA, where BE^{2}ST-in-Highways was the only system to require a percentage saving to obtain credits. Meanwhile, the three third-party rating systems (CEEQUAL, Envision and Greenroads) implement LCA to encourage environmental reporting, rather than for alternative design selection. Therefore, in general it can be seen that the current use of LCA in rating systems is largely process-based. This could be associated to the fact that there are still challenges present for life-cycle inventory harmonisation (Mukherjee and Dylla, 2017).

Greenroads was the only system to require LCA (only energy and GWP impact categories for material and construction activities) and LCCA as a pre-requisite for carrying out a rating exercise. Meanwhile, in CEEQUAL v6 the LCA credit is by far the biggest, with 100 points, five times larger than the average credit weighting. Envision and GreenLITES do not require an LCA directly, but they do require reductions for certain environmental aspects under certain performance indicators: in Envision's *Climate and Resilience* (CR1.2) category requires percentage savings for embodied carbon and emissions, and GreenLITES does include reduced energy consumption and material usage themed credits in various categories (credit S-1d, M-1a, E-2 etc.), where an LCA could be the ideal tool for quantifying these savings.

GreenLITES was the only system to not require a LCCA, which was one of the most preoccupying results of this section, given that whole life costing is the only economic sustainability assessment requirement by the European Committee of Standardisation (CEN, 2016).

Environmental Product Declarations (EPDs) are currently gaining traction in the asphalt industry, where product category rules have been developed for both asphalt mixtures and roads (EAPA, 2016; NAPA, 2017; The International EPD System, 2019a, 2019b). EPDs provide transparency and harmonised environmental impacts, which can be used in a life-cycle inventory or be used to report the impacts of an LCA. As it stands, only the third-party rating systems (CEEQUAL, Envision, and Greenroads) consider them within their rating system. CEEQUAL's LCA credit must include the 10 most influential products used within the asset, where five of these must be justified via EPDs, where its institution (BRE) is also a provider of EPDs. As part of Envision's intention to promote to develop sustainable procurement policies, it accepts EPDs for the RA1.1 credit, along with but not limited to, ISO 14001 systems and third-party verified sustainability programs. To be awarded the MD-3 credit in Greenroads, all products must be listed and any with an EPD identified and its characteristics delineated. Greenroads was the only system to provide credits for Health Product Declarations, the same amount as for EPDs.

Table 4.3. LCA and LCCA considerations.

Rating System	Perform LCA	Present EPD	Perform LCCA	Considers all life-cycle stages
CEEQUAL	✓– section 7.3.1	✓– 7.3.2	✓– section 1.5.1	✓
Envision	X	✓– RA1.1	✓ – LD3.3	✓
BE^{2}ST-in-Highways	✓– *PaLATE* tool	X	✓– *RealCost* tool	✓
Greenroads	✓– prerequisite PR-2	✓– MD-3	✓– prerequisite PR-6	✓
GreenLITES	X	X	X	✓
Invest	X	X	✓– PD-02	✓
GreenPave	✓– I-2	X	✓– I-2	✓

4.1.4.5.2 Pavement Applicable Criteria

Figure 4 displays the results for pavement applicable indicators, following the indicator-applicability criteria stated in Section 4.1.3.2. From this analysis, the most appropriate systems for pavement sustainability assessment would be GreenPave, BE^{2}ST-in-Highways, Greenroads and Invest. Where GreenPave was designed purely for pavement projects, and BE^{2}ST-in-Highways' indicators were 100% applicable. Meanwhile, despite Greenroads' and Invest's indicators not being 100% applicable, they were deemed appropriate for pavements as Greenroads' online project directory shows that it has been used for pavement rehabilitation projects (Greenroads, 2019) and Invest's Project Development category has an option to only use paving-related indicators.

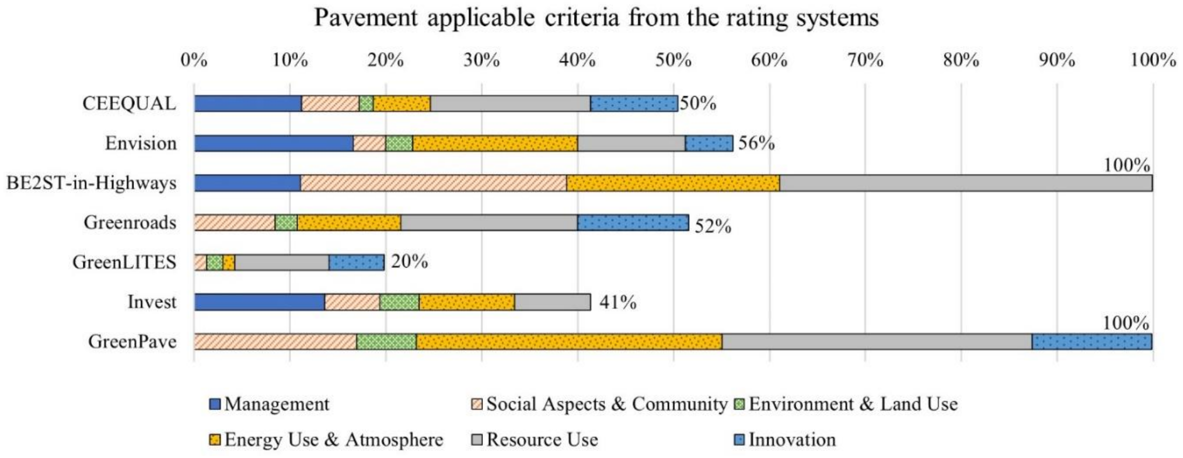

Figure 4.4. Pavement related criteria in roadway sustainable rating systems.

Whilst the infrastructure systems averaged more pavement-applicable indicators, their use would have to be revised given their broader project scope. The authors found that the credits in these systems could potentially be overly general (e.g., CEEQUAL's 1.2. and 2.3.1, and Envision's QL1.3 and

CR2.5), and limit ease of implementation. The theme of lack of specificity of infrastructure SRS indicators was also found by Beiler & Waksmunski (2015), when developing a rating system for non-motorised mobility paths.

Similar to Section 4.1.4.3, the resource use macro-category was the most common one found from the assessment of pavement applicable indicators (30%). This category was followed by management (22%) and energy use and atmosphere (19%). Where, the high consideration of resource use and energy use and atmosphere can be directly associated to the high impacts of the material processing phases in a pavement LCA (Thiel et al., 2014). The consideration of managerial aspects could also be considered to be larger than that stated, given that, similar to Section 4.1.4.3, Greenroads' pre-requisite section is unweighted, yet does contain pavement applicable managerial indicators. It is also worth noting that the social aspects macro-category was underrepresented (13%). Where many of the socially applicable criteria were again found to be co-benefits from enhanced environmental practices (i.e., waste management, pavement quality, reduced construction energy and work-site emissions).

However, with regards to the specific social indicators identified (i.e., community disturbance and noise control, worker health and safety, fair labour, local development (materials and labour), and heat island reduction), they were found to be outcome-based in nature, thus demonstrating that these best practices can be measured quantitatively. Which, judging from past literature, has not always been the case. For example, in recent proposed pavement management systems social aspects were not directly considered, where (Santos et al., 2017) did not consider social aspects, apart from perhaps those associated to LCA results, and (Torres-Machí et al., 2015) considered social aspects in economic terms via social carbon costing (EPA, 2013).

4.1.5 Conclusions

Roadway sustainable rating systems are currently growing in popularity globally as a tool for facilitating more responsible decisions, but are yet to become a trusted advisor for road projects. Where the practices recommended by these systems could greater benefit the creation of sustainable smart cities. Hence, this paper focused on critically reviewing the most prominent sustainable roadway rating systems on the market to compare and contrast their functioning. This was achieved by undertaking a thorough literature review on the selected systems' general characteristics and structures, followed by a more in-depth analysis of indicator weightings, three-pillar adherence and life-cycle considerations. From the results, it was found:

- SRS qualities can be greatly derived from organising them into two key categories: assessment type (self-assessment or third-party) and project size scope (infrastructure, roadway or pavement). Overall, third-party voluntary rating systems were found to provide a more balanced consideration of the three pillars of sustainability and the macro-categories identified. These systems were also found to be more internationally applicable (along with Invest). Meanwhile, self-assessment tools which offered a less equilateral implementation of sustainability, were found to be primarily focused on environmental aspects, and were focused on the design-stage of projects (except Invest). Regarding project size scope, generally the broader the scope, the more complex the system.
- With regards to the specific systems, the third-party roadway-dedicated Greenroads system was found to provide a holistic consideration of the three-pillars of sustainability and the key common areas identified, and fully considers the road life-cycle. The self-assessment BE^{2}ST-in-Highways system was the only for purely quantitative assessment, functioning via the use of LCA, LCCA and noise assessment tools. Invest has a unique structure which focuses on

whole the life-cycle and offers robust for project management guidance, although does not provide scoring boundaries defining itself as a guidance system. GreenLITES provided a lot of criteria for the road's surrounding ecology, and should be coupled with a LCCA tool to be sustainably viable. The GreenPave system is designed for pavement projects, especially for environmental project improvement. The CEEQUAL and Envision third-party infrastructure systems assessed were also very complete (macro-category, three-pillar considerations and life-cycle), but were comparatively much more complex and could lack specificity for pavement projects, so the systems should be revised to ensure their appropriateness.

- A potential leading benefit of rating systems could be their quantification of social aspects, especially considering its quantification difficulty in past roadway sustainability assessment studies in general. The results of this study found that the majority of the indicators which purely considered the social pillar were outcome based in nature, both for roadways and pavement indicators, suggesting they can be quantified. Meanwhile, a limitation of rating systems could be their process-based approach to the use of LCA, where points are generally awarded simply for reporting environmental impacts, rather than demonstrating the influence of them upon the project.

Therefore, based on the results of this work, further clarity has now been provided for the SRS market and system scopes, benefits and drawbacks better identified. These results can help establish a solid basis for SRS selection and sustainable smart road creation. Nonetheless, further research would be required to better understanding these systems. Future research lines should consider the implementation of systems in case study projects to better determine further implementation issues, especially for maintenance projects, and to quantify the overall net benefit of SRS in projects. This would ideally be carried out in a variety of regions to also understand the impact of regional contextuality on project scores and the potential for scoring boundary modifications (i.e., to adhere to local regulations).

Also, rating system structures varied greatly, while common indicator themes were able to be identified across all systems. Therefore, future research could also assess the effectiveness of multiple categories and indicators. This would therefore determine the whether a similar net result could be obtained from multiple indicators, compared to fewer.

Finally, the social indicators in SRS could also be assessed in further detail, considering the past difficulties found for their quantification and implementation. This could be included as a key objective in the case study assessment of the SRS.

4.1.6 References

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4.2 Open-Source Inventory Variability and Uncertainty for the Life Cycle Assessment of Road Bituminous Pavements[2]

4.2.1 Introduction

Around eighty two percent of the transportation sector's energy consumption is from road networks (Eurostat, 2016). While most emissions are related to vehicular transit, the road's pavement cannot be neglected given the current global new infrastructure budget of US$90 trillion for the next 15 years (UN, 2016) and given that these assets are primarily constructed from virgin materials. In order to make reliable decision-making exercises to reduce energy usage and emissions output, while exploring the increased use and benefits of recycled materials, life cycle assessment (LCA) can be used by pavement practitioners (Van Dam et al., 2015). Where LCA was concluded by the European Commission to be the most appropriate framework for assessing the environmental impacts of products (EC, 2019).

The interest and research in the use of LCA to validate the environmental burdens of pavements has increased exponentially from 2000 to 2019 in scientific literature. As seen in Figure 1, which demonstrates the results of a Scopus search considering the keywords LCA (or life cycle assessment) and pavement (Scopus, 2020). Furthermore, in recent years many regulatory developments have been made to ensure consistency in LCA results. Based on EN 15804 (CEN, 2014), globally Product Category Rules (PCR) have been defined for asphalt mixtures and pavements (EAPA, 2017; NAPA, 2017; The International EPD System, 2019c, 2019a). From this it is possible to create Environmental Product Declarations (EPD) and provide better understanding on the performance of the sector. However, there is currently still a limitation for LCA implementation due to data availability and inventory collection (Azarijafari et al., 2016).

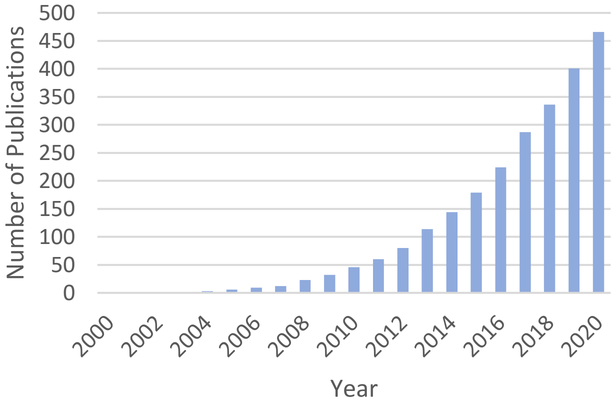

Figure 4.5. Cumulative total of documents on pavement LCA per year (Scopus, 2020).

The asphalt pavement industry is also generally working towards creating specialised open-access local LCA tools. Where several of these tools have been created both in Europe, such as ECORCE (Jullien et al., 2015), and North America, such as PavementLCA (Athena Sustainable Materials Institute, 2020) and PaLaTe (Horvath, 2007), and these tools have recently been used for LCA-based decision making exercises, as shown by (Hamdar et al., 2020; Proust et al., 2014). In turn, these tools also foster

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[2] The work in this chapter is based upon the following publication: Mattinzioli, T., M. Sol-Sánchez, G. Martínez, and M. Rubio-Gámez. *A Parametric Study on the Impact of Open-Source Inventory Variability and Uncertainty for the Life Cycle Assessment of Road Bituminous Pavements*. The International Journal of Life Cycle Assessment, Vol. 1, 2021, p. 3. https://doi.org/10.1007/s11367-021-01878-1.

life cycle inventory (LCI) availability and LCA implementation, especially considering commercial databases are not accessible to all parties, due to economic reasons (Arteaga, 2018). While tools are available, there are also many case studies and reports, which also provide open-source asphalt pavement LCI information, that have not yet been comparatively analysed, some dating back two decades (Stripple, 2001). Where the objective of creating open-access reliable LCI data also follows the goals of the European Commission and the USA (European Commission, 2020; LCA Commons, 2020).

Linked with the pending need for the comparison of this data, there is also a need for the assessment of the impact of variability on the results of an LCA. This is a current trend taking place in other engineering specialisations (Hoxha et al., 2017; Pushkar, 2019; Sleep et al., 2020; van Grootel et al., 2020), but yet to be more explored for open-source asphalt pavement data. Asphalt pavement LCI uncertainty and source variability has been primarily addressed by the assessment of the cumulative effects of parameter uncertainty due to data quality using commercial LCA software, and some US national databases, via the Monte Carlo method (AzariJafari et al., 2018; Noshadravan et al., 2013). (Torres-Machi et al., 2018) explored the environmental optimisation of maintenance operations under budgetary restrictions, and considered open-access databases, with the long-term effectiveness and greenhouse gas emissions as indicators. (dos Santos et al., 2017) and (Lo Presti and D'Angelo, 2017) both compared open source LCA tools, where the former also considered commercial tools, and have provided insight towards tool variability. These studies support the presence of variance between tool datasets, and thus support the hypothesis that further variance will be found in the comparison and exploration of further data, from alternative sources such as published case studies and project reports. Variability as a topic is considered to have been explored in limited depth in pavement LCA, as stated by (Santero et al., 2011), despite process variability having an impact on the resulting environmental impact of an LCA (van Grootel et al., 2020), and thus must be further explored and quantified.

Thus, in order to better explore the use of open-source data and examine its associated risk, this study aims to determine the variability and uncertainty of the various processes required for a cradle-to-gate with options (CEN, 2014), or cradle-to-laid (Butt et al., 2019), and their propagation through to the LCA results life cycle assessment of asphalt pavements. From this, the variability and uncertainty of each process can be determined and its influence on the final LCA results understood. As a result, more informed environmental and resource management decisions can be made and targets can be established for the creation of more reliable life-cycle inventories.

4.2.2 Methodology

In order to achieve the objective stated, the methodology applied in this study consisted of two main steps: (i) the creation of LCI data from the collection and processing of data from open-sources, following the recommendations of product category rules (PCR); (ii) assessment of the uncertainty and variability of the data through the LCA of three case study scenarios. A schematic summary of the methodology can be seen in Figure 2.

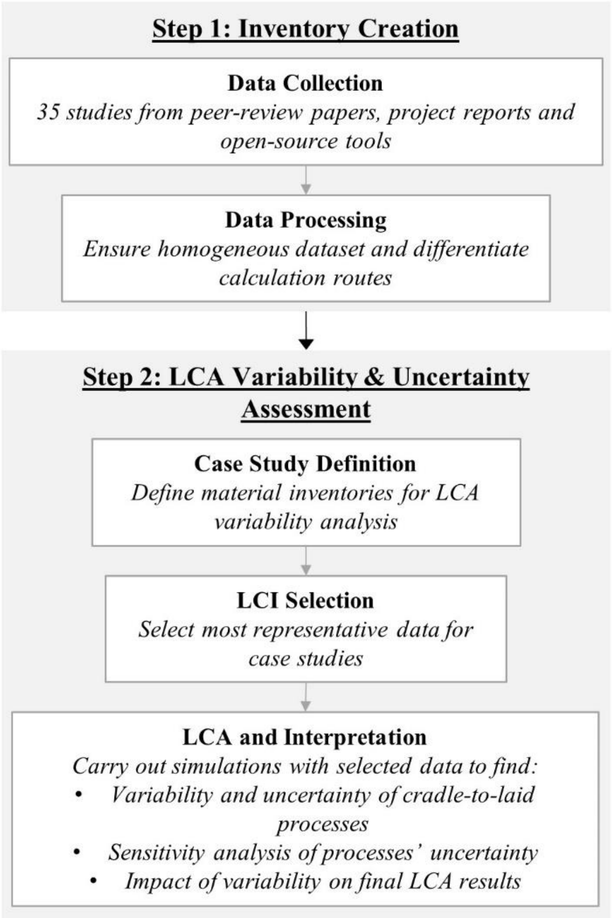


Figure 4.6. Methodology undertaken for LCA variability assessment.

4.2.2.1 Inventory Creation

4.2.2.1.1 Data collection

For the present study, literature was collected from peer-review published case-studies and project reports. The goal was to locate key open-source literature which had previously been used, or had the potential to be used, to carry out an LCA with cradle-to-gate with options (CEN, 2014) boundary conditions, or also referred to as a cradle-to-laid (Butt et al., 2019). Thus, the processes considered were: material extraction (A1), raw material transportation (A2), mixture production (A3), mixture transportation (A4), and paving (A5). Table 1 summarises the sources used in this study, according to the five process stages considered.

The boundary conditions of this study exclude impacts related to the sub-base, road markings, fences and railings, road signs, drainage and lighting as they are not within the scope of this study. The same type of truck was assumed to be used for transporting the materials to the plant and mixes to site, and the same paving and compaction machinery was also used on-site for the projects. In all sources collected, the boundary conditions for the processes were also ensured to be consistent to minimise process model uncertainty.

Within the system's boundary conditions the use phase is not considered. Given that this study is a first attempt for the data review for life cycle inventories, and limited data is available for the use phase of asphalt pavements, due to it still having problems in its calculation (Xu et al., 2019).

Table 4.4. Overview of selected sources according to process stages.

Source & year	Region	Route	Life-cycle stage					Source Type
			A1	A2	A3	A4	A5	
(Argonne National Laboratory, 2019)	USA	2		✓		✓		Inventory
(Bueche, 2009)	Europe	3			✓			Conference proceedings
(Casero, 2014)	Europe	3					✓	Thesis
(Caterpillar, 2019)	International	3					✓	Report
(D'Angelo et al., 2008)	Europe	3			✓			Report
(EC, 2010)	Europe	1	✓					Report
(Eurobitume, 2012)	Europe	2	✓					Report
(Eurobitume, 2019)	Europe	2	✓					Report
(Giani et al., 2015)	Europe	A2/4: 3; A3: 2; A5: 3		✓	✓	✓	✓	Peer-review study
(Gulotta et al., 2019)	Europe						✓	Peer-review study
(Horvath, 2007)	USA	A2/4: 3; A3: 2; A5: 3		✓	✓	✓	✓	Inventory
(Huang et al., 2009)	Europe	3		✓		✓	✓	Peer-review study
(Jullien et al., 2015)	Europe	1	✓	✓	✓	✓	✓	Inventory
(Larsen, 2001)	Europe	3			✓			Conference proceedings
(Lu et al., 2017)	China	A1: 1; A3: 3	✓		✓			Conference proceedings
(Marceau et al., 2006)	USA	2	✓					Report
(Marceau et al., 2007)	USA	A1: 1; A2: 3;	✓					Report
(MITECO, 2017)	Europe	2	✓					Report
(Mora Peris et al., 2017)	Europe	2	✓					Report
(Moral Quiza, 2016)	Europe	3			✓		✓	Thesis
(Ntziachristos and Samaras, 2018)	Europe	2		✓		✓		Report

(Pérez-Martínez et al., 2014)	Europe	3			✓			Peer-review study
(Rubio et al., 2013)	Europe	3			✓			Peer-review study
(Sampedro et al., 2012)	Europe	1	✓		✓		✓	Peer-review study
(SMAQMD and Ramboll, 2018)	USA	3					✓	Inventory
(Stripple, 2001)	Europe	2	✓	✓	✓	✓	✓	Report
(UK Government, 2018)	Europe	1		✓		✓		Inventory
(UNPG, 2011)	Europe	1	✓					Report
(US EPA, 1995a)	USA	2	✓					Report
(US EPA, 1995b)	USA	2	✓					Report
(Vaitkus et al., 2009)	Europe	3			✓			Peer-review study
(Ventura et al., 2009)	Europe	2			✓			Conference proceedings
(Vidal et al., 2013)	Europe	2			✓		✓	Peer-review study
(Wu and Qian, 2014)	China	1			✓			Conference proceedings
(Yang et al., 2014)	USA	1			✓			Conference proceedings

4.2.2.1.2 Data processing

After data collection, all source results were processed to ensure comparability. This required all inputs to be considered per the study’s functional unit (FU) and impact assessment methodology (Harvey et al., 2016; ISO, 2006a). Following the PCR recommendations of (CEN, 2014) and (EAPA, 2017) the FUs for the inventory in this study were one metric ton for the raw material extraction (A1), asphalt mixture production (A3), and the pavement construction (A5). Meanwhile, for the stockpile-to-plant (A2) and plant-to-site (A4) transportation, one metric ton kilometre was adopted. This FU was used for the construction stage (A5), despite the unit of 1m^2 typically being utilised, as at the inventory level the pavement’s geometric properties are unknown.

All environmental data from the sources were converted to the study’s impact categories (IC), using the CML baseline characterisation factors (Oers, 2016) (according to the original methodology defined by (Guinée, 2002)). The specific indicators considered are displayed in Table 2. All other IC, such as ozone and abiotic depletion, were not reported due to the lack of data for its calculation. Similarly, resource use was not reported due to data availability. From assessing the sources, all primary energy use reported was assumed to be non-renewable. The EC’s impact assessment guide (European Commission, 2013) also delineates respiratory inorganics as a class 1 recommended impact category, therefore the fine particulate matter formation impact category has been also included from ReCiPe 2016 (Huijbregts et al., 2016).

Table 4.5. Impact categories used.

Impact Category	Acronym	Unit
Non-renewable primary energy use	PENRE	MJ
Global warming potential	GWP	Kg CO_2-eq
Acidification potential	TAP	kg SO_2-eq
Eutrophication potential	EP	kg PO_4-eq
Photochemical ozone creation potential	POCP	kg ethylene-eq
Fine particulate matter formation	PMFP	kg $PM_{2.5}$

Table 3 summarises the three routes used for data processing, in order to achieve the harmonised LCI. The use of different routes for data processing were required due to fundamental differences in the data collected. It can be seen that, moving from route 1 to 3, more interaction is required to obtain the inventory values. This interaction could result in some added uncertainty on behalf of the authors into the calculations.

Table 4.6. Data processing routes taken depending on source quality.

Route	Requirement	Action
1	Data provided in impact categories of study.	No action required.
2	Emission data provided.	Characterisation factors applied.
3	Process productivity data provided (i.e., fuel consumption, material processes per hour).	1. Fuel quantity and machine type/productivity defined; 2. Emissions data obtained from (Ecoinvent, 2019), (EPA, 2016) or (SMAQMD and Ramboll, 2018) for processes; 3. Characterisation factors applied.

Uncertainty due to the choices made when performing LCA are unavoidable (Huijbregts, 1998). Therefore, it is fundamental that the choices made are fully justified to ensure the uncertainty due to choices, as defined by (Huijbregts, 1998), are reduced as much as possible. Route 1 and 2 provided minimal choice uncertainty, due to the former providing the data "ready-to-go" and the latter only requiring the application of the characterisation factors (harmonised due to the product category rules (EAPA, 2017)). For route 3 all sources underwent the same calculation steps to reduce possible calculation-related errors. Regardless, for the truck transportation related sources (stages A2 and A4), where only fuel consumption was reported, it was assumed that all trucks met the latest emission standards. Similarly, for construction machinery (stage A5), where the machine type and productivity were reported, it was assumed that all machinery met the latest emission standards. Following these steps, the calculation of the emissions was maintained as a strictly as possible to a methodology which would be followed from the collection of primary data.

In addition to calculation route 3, some processes required further external input. This included some assumptions required for transportation impacts and modifications in transport distance for the binder production processes. For dumper truck transportation, where fuel consumption was provided per ton of material, and speed was not provided, the truck speed was assumed to be 15 km/hr (Stripple, 2001). Finally, for the processes related to the bitumen binder, (Eurobitume, 2012) and (Eurobitume, 2019) do not indicate where in Europe the crude oil was transported, therefore the naval transport distance was re-calculated with a distance of 7602.5 km, as done by (Garraín and Lechón, 2019), with the emission factors from (Maurice et al., 2000). This returned around a 10% decrease in the transportation impacts found, and should thus be recommended for practitioners to carry out this check too. These transportation distances were used to replace all those for all binder sources, so ensure the equal comparison of the crude oil extraction, refining, and storage. It is also worth noting that (Eurobitume, 2019) does not cover emulsion and polymer modified bitumen, therefore the 2019 production values were calculated by adding the modern bitumen production values to the additional modified impacts seen in (Eurobitume, 2012).

4.2.2.2 LCA Uncertainty Assessment

From the data collection and processing stages, a database was thus created with all the impacts for the processes found per the sources used in Table 1. From this data, the mean, maximum, and minimum impacts could be ascertained, along with their standard deviation and coefficient of variation. With the data collected and processed, the results were assessed in terms of 1) variability and uncertainty per process, and 2) process uncertainty propagated through to the LCA results. For the LCA simulations, three case study scenarios were defined to explore both conventional and alternative asphalt mixtures. For the LCA case study scenarios, data was selected from the database to ensure representativity. Multiple LCA simulations were carried out to assess the variability between the selected, maximum and minimum data values. The methodology for the LCA is explained in detail in the following chapters.

4.2.2.2.1 Definition of case study scenarios

To assess the propagation of the process impacts on the final results of an LCA, three case study scenarios were assessed (Table 4). All asphalt mixtures considered are of type Asphalt Concrete (AC), under EN 13108-1:2016 (EN, 2016). It is assumed that the useful bitumen from the reclaimed asphalt pavement (RAP) is 50% (Mattinzioli et al., 2020). A hot mix asphalt (HMA) is used as a baseline mixture, while the half-warm mixtures (HWMA) were used to explore reduced temperature mixtures and recycled aggregates; current popular topics for reducing the environmental footprint of pavements (Mattinzioli et al., 2020).

The LCA case study scenarios were modelled as the paving of a surface layer, with a 5cm depth, 9m width and 1km in length. The same type of truck was assumed to be used for transporting the materials to the plant (40km), mixes to site (30km), and paving machinery to site (18km); where the same paving and compaction machinery was also used on-site for the projects, where these distances were used in a previous LCA case study by the authors (Mattinzioli et al., 2020). Given that only the A1-A5 processes are considered, the service life and traffic levels are considered to be constant, as these variables are not the subject of this assessment.

Table 4.7. Definition of LCA case study scenarios.

Material	*Scenario 1: HMA*	*Scenario 2: HWMA*	*Scenario 3: HWMA with 50% RAP*
Bitumen	*4.5%*	-	-
Emulsion	-	*6.5%*	*4.88%*
Cement Filler	*5.5%*	*5.5%*	*2.75%*
Sand	*30.0%*	*29.0%*	*15.00%*
Gravel	*60.0%*	*59.0%*	*30.00%*
RAP	-	-	*47.38%*

4.2.2.2.2 Inventory selection

For the representative LCA of the case study scenarios, the most representative data was selected for the case study region. In this study the region was taken to be the authors' country of origin, Spain. The most appropriate data was selected via the use of the Pedigree Matrix (Weidema and Wesnæs, 1996). This method was selected due to it being one of the most common approaches for identifying source data inaccuracy (epistemic basic uncertainty) and representativeness (additional uncertainty due to using imperfect data according to the scope) in a semi-automatic way (Huijbregts et al., 2001; Muller et al., 2016). The results of the pedigree matrix are provided in Annex A.1 and the LCI used in Annex A.2.

4.2.2.2.3 Life cycle assessment simulations, variability, and uncertainty calculation

This section first covers the methodology for the LCA impact calculation, followed by the calculation of the variabilities and uncertainties at for both the cradle-to-laid processes and the final LCA results.

4.2.2.2.4 Life cycle assessment impact calculation

The LCA impacts in this study were calculated in an Excel generated by the authors, where the calculation of the impacts is summarised in Equation 1 below:

$$I_{case,f} = \sum_{i=1}^{n} I_{case,f,i} \qquad (1)$$

Where $I_{case,f}$ is the environmental impact f of the case considered; n is the number of processes for the case; $I_{case,f,i}$ is the mean value for environmental impact f for process i of the case considered. Comma notation is used to separate the dependant variables.

For the calculation of the environmental impacts of $I_{case,i}$ Equation 2 was used:

$$I_{case,f,i} = m_{case,i} \times k_{f,i} \qquad (2)$$

Where $m_{case,i}$ is the material mass used per FU for the case study and process (i) considered, and $k_{f,i}$ is the environmental impact per FU.

4.2.2.2.5 Variability and uncertainty calculation

After establishing the LCI database and calculating the environmental impacts of the case study scenarios, the influence of the process variabilities and uncertainties was explored at two levels: a) for the constituent cradle-to-laid processes, and b) for the final LCA results.

The variability was found from the range of possible output values (i.e., from the maximum and minimum values). Thus, outputting upper and lower impact bounds for the cradle-to-laid process LCI outputs and the final LCA outputs. With regards to the final variability ranges of the final LCA results, nine LCAs were carried out: three for each case study scenario using the selected data, the maximum, and the minimum values.

Meanwhile, in analytical methods, uncertainties can be expressed in a number of ways, but in general they are expressed as a function of the variance (Morgan and Henrion, 1990). Therefore, at the process level the uncertainty was calculated using the coefficient of variance (ratio of the standard deviation to the mean), to show the level of dispersion around the mean, and at the LCA level using the propagation of the variance. Where, the uncertainty propagation of a product can be described via (Palmer, rule 4):

$$\frac{\delta q}{q} = \sqrt{\left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta z}{z}\right)^2} + \cdots \qquad (3)$$

Where q = x + y, and δq is the uncertainty for q, δx is the uncertainty for x, and δy the uncertainty for y.

Therefore, the calculation of the process uncertainty was made using the variance (σ - where the variance was calculated from the square of the standard deviation of the process' impacts) and the impact of the processes. Hence, the calculation of the uncertainty propagated to the final LCA results for case study *case*, impact category *f*, and process *i* can therefore be calculated as follows:

$$\sigma_{I_{case,f,i}} = I_{case,f,i} \times \sqrt{\left(\frac{\sigma_{m_{case,f,i}}}{m_{case,i}}\right)^2 + \left(\frac{\sigma_{k_{f,i}}}{k_{f,i}}\right)^2} \quad (4)$$

Where the variance of the mass and the total mass is considered negligible due to inventory mass uncertainties being outside the scope of this study. Thus, it would be excluded from equation 4. From calculating the uncertainty propagated per process, the total LCA uncertainty can be calculated through summation from (Palmer, rule 1). The resulting calculation for the propagated uncertainty on the LCA result, from process *i*, for case *case* and impact category *f* would be:

$$\sigma_{I_{case,f}} = \sum_{i=1}^{n} I_{case,f,i} \times \sqrt{\left(\frac{\sigma_{k_{f,i}}}{k_{f,i}}\right)^2} \quad (5)$$

4.2.3 Results

4.2.3.1 Data Collection and Processing

Figure 3 outlines the number of sources found per process modelled within the defined boundary conditions. In section A, the total number of sources used in this study are presented, along with how many of the sources provided data for calculating all of the indicators (i.e., complete sources). Whereas, section B demonstrates the routes (Table 3) required for impact category calculation per life-cycle stage.

It is visible that from section A, complete data could not be found for all sources. This was especially the case for the aggregate materials (stage A1) and the plant mixing processes (stage A3). Meanwhile, for binder production (stage A1) and construction machinery (stage A5), the majority of the indicators could be calculated.

From viewing section B, it is possible to see that while most of the stage A5 sources were complete, a larger number of assumptions were required to calculate the impact categories. This was due to mainly fuel consumption being reported. Meanwhile, stage A1 required the least amount of assumptions, and stage A3 a moderate amount (primarily due to WMA).

Overall, from the studies assessed, it was found that data completeness varied per LCA stage and not all sources provided all data for all the six impact categories considered. Furthermore, the PENRE and GWP impact categories were the most reported, where the popularity of the latter highlights the popularity of carbon footprinting exercises, especially for novel technologies. In the unique case of RAP, only one of the four sources found could provide TAP, EP and POCP impacts, and PMFP was not able to be quantified in this study. Meanwhile, it is possible to see HMA manufacturing separated by fuel source. This distinction was made due to a large number of sources found for this process, and sufficient (relative to the other processes) data was obtained to make the distinction. This distinction was also made in the ECORCE tool (Jullien et al., 2015). Meanwhile, the PaLaTe tool (Horvath, 2007), which differentiates mixtures per plant type (drum or batch), where it reports batch plants being 11% more energy intensive, and with higher CO, CO_2, NO_x and SO_2 emissions; where PM_{10} was lower. The other A3 manufacturing processes did not provide sufficient data quality for the separation of impacts per fuel source.

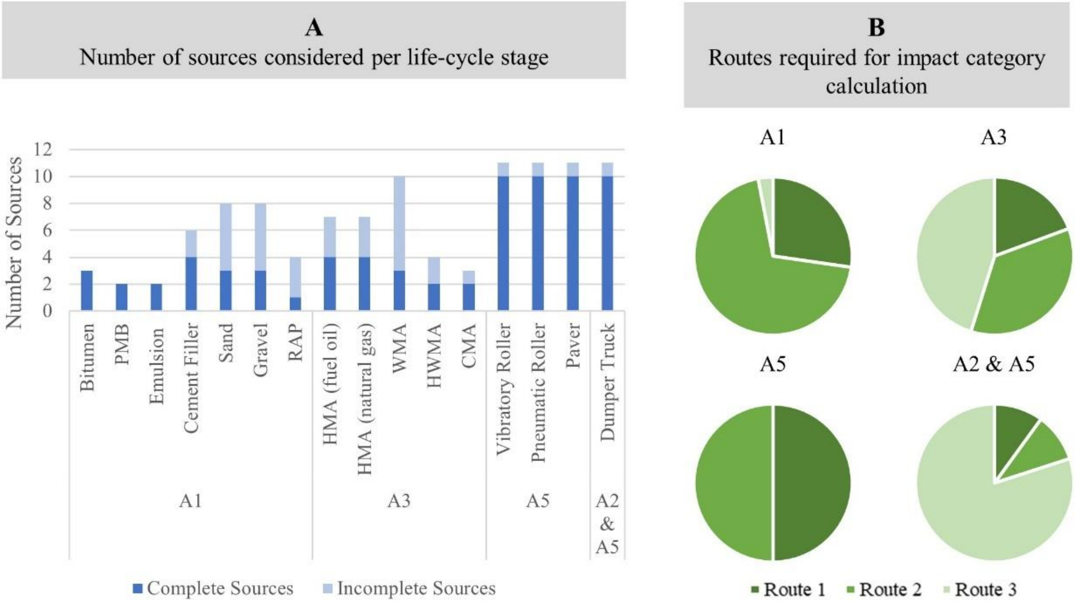


Figure 4.7. Number of sources per process considered, along with number of sources considering all impact categories (A). Breakdown of sources against calculation routes required (B).

4.2.3.2 Process Uncertainty

Following data collection and processing, the LCI was compiled and the variabilities of the processes quantified. Figures 4 and 5 show the results for the six impact categories considered for the raw material production (A1), mixture production (A3) and pavement construction (A5) stages per ton of material. Figure 6 shows the impacts for the dumper truck considered for the transportation stages (A2 and A4). Figures 4 and 5 are plotted on a logarithmic axis to better compare the processes, showing clearly the changes in magnitude of the processes, while Figure 6 is plotted on a standard axis. All figures show the number of sources and the coefficient of variation per process below the figures.

From the results, it is possible to see that the production of the fine aggregate (sand), WMA and the use of construction machinery have the largest variability. In the case of the sand, spanning one order of magnitude for the PENRE, TAP and EP impact categories, between 2-3 for GWP and POCP, and over three for PMFP. This variability could be attributed to the different processes for obtaining sand, where stone crushing has a higher impact than sourcing naturally occurring or dredging sand (Stripple, 2001). Care therefore must be taken to model the correct process for fine aggregates. Furthermore so, given that in some studies fine and coarse aggregate impacts are not differentiated despite being different processes (EC, 2010; Jullien et al., 2015; Lu et al., 2017). Additionally, the large variability found for the PMFP of sand was largely due to typical inventories reporting results due to fuel consumption, while the larger value found, by the US Environmental Protection Agency (US EPA, 1995a), directly measured fugitive dust during sand processing. In the case of WMA, differences can be associated with use of different fuels (fuel oil and natural gas) and the potential WMA technology implemented (i.e. foaming, organic and chemical additives (M. Carmen Rubio et al., 2012)). Insufficient data was found to determine these differences. With regards to the machinery for the construction process, the high variability was found associated with the large differences in fuel consumption reported. Therefore, both sand production and machinery use can be considered contextual to the assessment region.

On the other hand, while being one of the more impacting stages, the binder (raw, polymer modified and emulsion bitumen) production was found to have relatively lower magnitudes of variabilities across the impact categories. The polymer modified and emulsion binder's low variance can be associated with the limited sources found for their production, and that the same author was used for each (i.e., could infer low difference in methodology variability) with only the year of the study changing. However, the emulsion's low variance could be assumed valid comparing the results to those of (dos Santos et al., 2017). The bitumen production process is assumed to have changes due to the increase in its efficiency over time, where a 50% decrease in energy was found between the 2001 and 2019 references (Eurobitume, 2019; Stripple, 2001). Its variability could additionally differ depending on the naval and inland transportation required for an alternative study. On the other hand, regarding the cement filler, it provided a slightly larger variability (29% higher average increase/decrease compared to bitumen) across impact categories, especially for the PMFP impact category with a coefficient of variance of 141%. Where cement's large PMFP impact is associated with the fine particle size of the material, and its large variance can be associated with the multiple fugitive dust sources found both before and during the materials production process (US EPA, 1995b). In the study by (Santero et al., 2011) a much higher variability can be found for cement filler, compared to bitumen, too. Regarding the RAP, its variability was hard to quantify due to limited sources available. The reuse and recycling of asphalt is currently a target in Europe (EAPA, 2008), thus it is hoped that this variability may be better quantified in the near future.

With regards to the mixture production processes, HMA was the process with the most references found. HMA with heating via fuel oil was found to have on average a lower variability than with natural gas, mainly due to the latter's higher variance for PMFP. However, the use of natural gas is considered to be cleaner due to its decrease in sulphur and nitrous oxides, while providing a similar energy output per energy unit. Similar to the RAP, the CMA manufacturing process had few sources available. Thus, the variability precision would need to be updated in future studies.

Non-Renewable Primary Energy

	B	PMB	BE	CF	SFA	GCA	RAP	HMA.FO	HMA.NG	WMA	HWMA	CMA	VR	PR	P
N	3	2	2	4	7	7	4	6	6	8	4	3	11	11	11
CV (%)	33	14	27	20	51	53	37	23	28	40	51	63	80	80	83

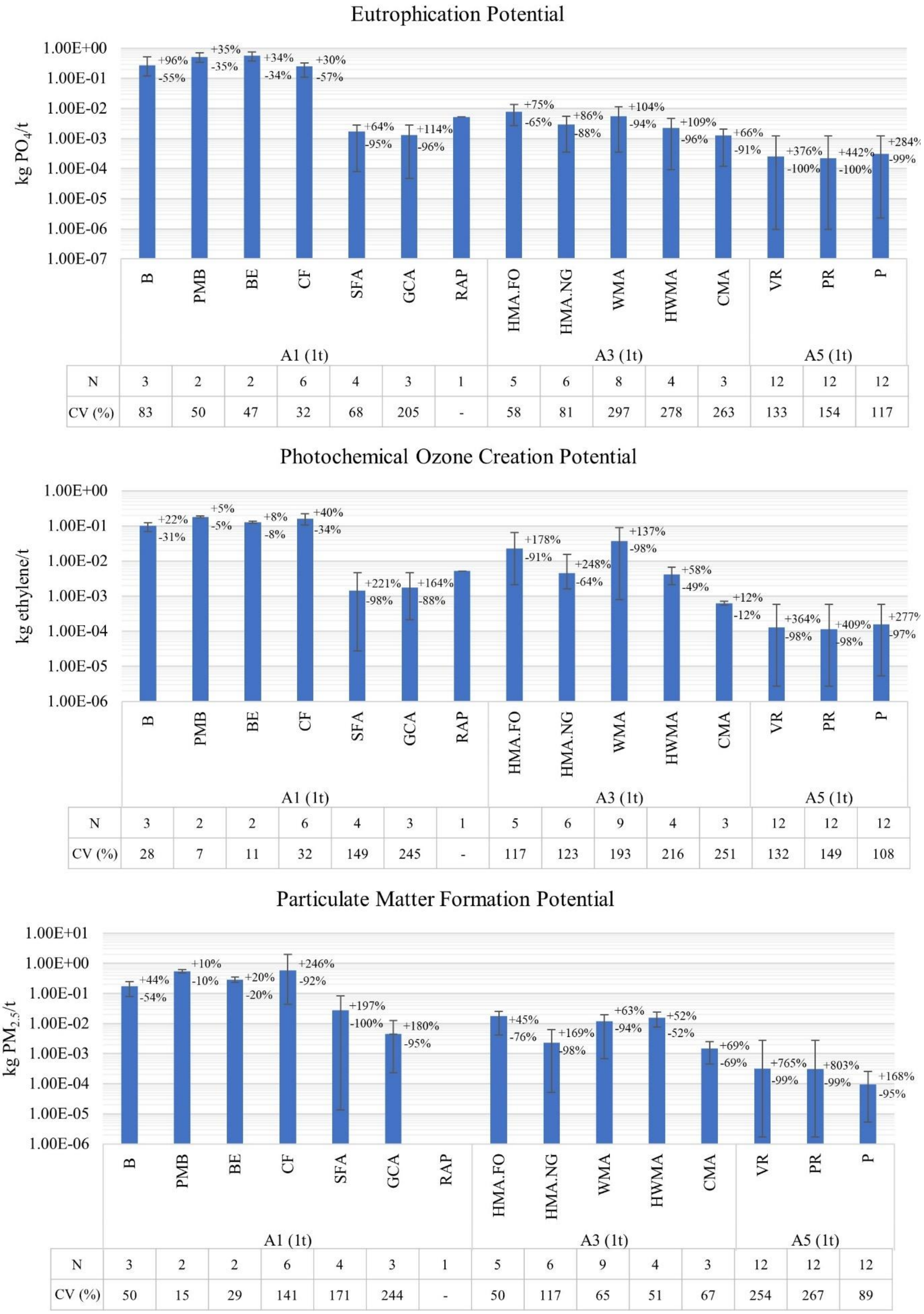
Global Warming Potential

	B	PMB	BE	CF	SFA	GCA	RAP	HMA.FO	HMA.NG	WMA	HWMA	CMA	VR	PR	P
N	3	2	2	5	7	6	4	6	6	11	4	3	11	11	11
CV (%)	10	7	10	35	120	66	23	19	30	41	55	54	84	87	100

Total Acidification Potential

	B	PMB	BE	CF	SFA	GCA	RAP	HMA.FO	HMA.NG	WMA	HWMA	CMA	VR	PR	P
N	3	2	2	6	4	3	1	6	6	10	4	3	11	11	11
CV (%)	28	7	13	60	65	181	-	51	65	180	249	254	318	321	313

Figure 4.8. Logarithmic plot of PENRE, GWP, and TAP impact categories for the A1-A5 stages analysed with upper and lower bounds.



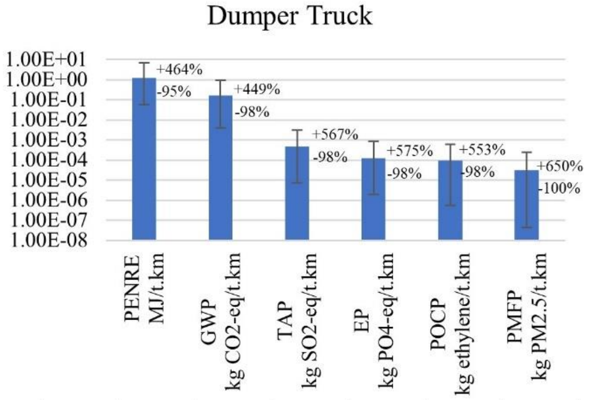
	B	PMB	BE	CF	SFA	GCA	RAP	HMA.FO	HMA.NG	WMA	HWMA	CMA	VR	PR	P
N	3	2	2	6	4	3	1	5	6	8	4	3	12	12	12
CV (%)	83	50	47	32	68	205	-	58	81	297	278	263	133	154	117

	B	PMB	BE	CF	SFA	GCA	RAP	HMA.FO	HMA.NG	WMA	HWMA	CMA	VR	PR	P
N	3	2	2	6	4	3	1	5	6	9	4	3	12	12	12
CV (%)	28	7	11	32	149	245	-	117	123	193	216	251	132	149	108

	B	PMB	BE	CF	SFA	GCA	RAP	HMA.FO	HMA.NG	WMA	HWMA	CMA	VR	PR	P
N	3	2	2	6	4	3	1	5	6	9	4	3	12	12	12
CV (%)	50	15	29	141	171	244	-	50	117	65	51	67	254	267	89

Figure 4.9. Logarithmic plot of EP, POCP, and PMFP impact categories for the A1-A5 stages analysed with upper and lower bounds.

Along with the stage A5 machinery, the dumper truck used for modelling stages A2 and A4 outputted the highest variabilities. These potentially large variabilities can be associated with the difference in fuel consumption and machinery productivity (i.e., material moved or paved per unit time) found between sources. Where, for example using ideal and up-to-date sources (i.e., machinery producer handbooks or the latest emission regulations) the fuel use will be much more efficient and emission reduction technologies will have been improved. Meanwhile, for older, and also for case studies with non-ideal terrains, the fuel consumption and emissions output could vary significantly. As an example, comparing the dumper truck impacts for the EMEP/EEA air pollutant emission guidebook (Ntziachristos and Samaras, 2018) and GREET (Argonne National Laboratory, 2019) to a commonly used case study published close to two decades ago (Stripple, 2001), the PENRE and GWP were found to have a difference of 138-140% and TAP, EP, POCP and PMFP around 192-195%. In comparison to the PaLaTe (Horvath, 2007) open source tool, also found to have been used in recent studies (Bloom et al., 2016; Hamdar et al., 2020; Mauro and Guerrieri, 2016), PENRE and GWP had a difference of around 144-147%, and TAP, EP, POCP and PMFP of around 199-200%. These differences highlight the importance of the correct modelling of these processes.



N	10	11	10	10	10	9
CV (%)	94	216	217	222	223	245

Figure 4.10. Standard plot of dumper truck for stages A2 and A4 with all impact categories.

4.2.3.3 LCA Results

4.2.3.3.1 Relative impact and uncertainty contributions

Figure 7 displays the relative uncertainty plotted against the relative impact for all processes and case study scenarios, on logarithmic axes to better identify low impact processes. A red dashed diagonal line is provided in the figure to better demonstrate the boundary between relative uncertainty and relative impact, while cut-off lines at 1, 5 and 10% are provided to better understand their contribution to the LCA results. 1 and 5% are defined cut-off limits mentioned by (EAPA, 2017), meanwhile 10% was used to identify processes with large relative impacts. The larger symbols with black contours represent the average results for the individual case study scenarios.

In general, from the uncertainty propagation it can be seen that the higher impacting processes were those to also predominantly contribute to the uncertainty. For example, for PENRE the plant manufacturing provided the most uncertainty (33.4% for HMA, and 26.8 and 33.6% for the HWMAs), followed by the cement filler (22.7%), followed by the binders (22.1% average for the emulsions, and 18.7% for the conventional bitumen). However, for the third scenario with HWMA and 50% RAP, the emulsion’s energy requirements surpassed those of the cement filler due to its reduced quantity. For GWP, and as also seen in Figure 4, cement filler provided the largest environmental impact and uncertainty across the case study scenarios (34.1% and 41.1%, respectively), followed by truck transportation (20.2% average for A2, and 14.7% for A4) due to the (Highways England, 2015) carbon reporting tool and ECORCE’s respectively high $CO_{2.eq}$ impact for dumper trucks. The TAP uncertainty was dominated by the HWMA plant manufacturing (56.3% average), followed by the cement filler (12.1% average) and the construction machinery (whole of stage A5 – 11.8% average). The contribution of the HWMA and stage A5 to the uncertainty is most notable for the TAP impact category, given that these processes contributed 6.4% and 1.8% on average to the impacts. Regarding, EP, the HWMA again was dominant, accounting for 92.2-93.8% for scenarios 2 and 3. Meanwhile, for scenario 1, the largest uncertainty was due to the conventional binder (33.0%), followed by the truck transportation (18.1% for stage A2 and 13.3% for stage A4). For POCP, plant manufacturing dominated the uncertainty results (84.6% average). Finally, for the PMFP, the uncertainty was dominated by the cement filler (53.0% average), followed by the sand production (16.4% average) and the plant manufacturing (14.7%). Where, the uncertainty due to the sand production is most notable, due to its impact contribution of 0.4%.

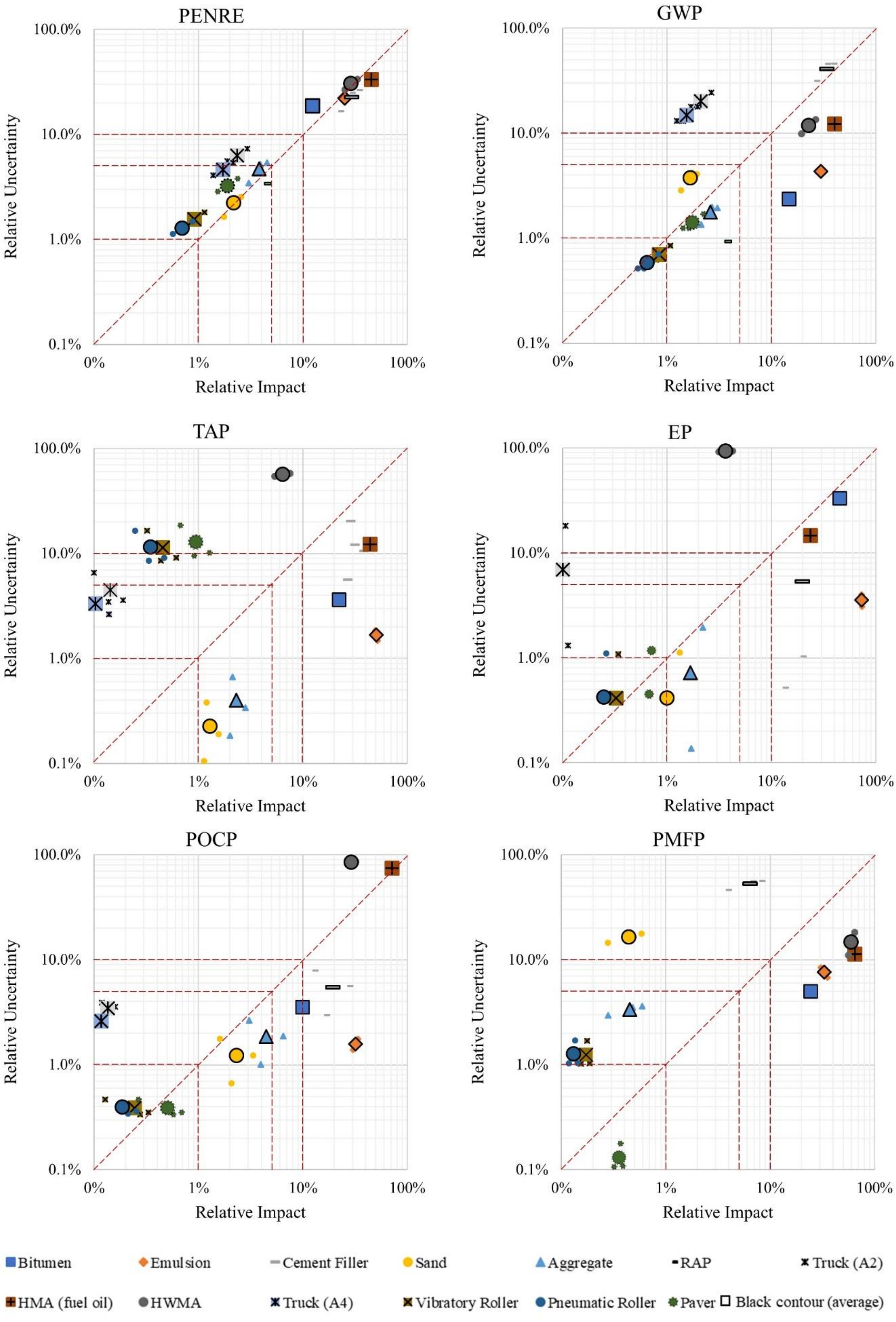


Figure 4.11. A1-A5 process impacts vs uncertainties for the six impact categories and the three case study scenarios considered.

Figure 8 summarises the process uncertainties found from the cradle-to-laid life-cycle assessment per impact category. Therefore, in summary, and as seen from the boundaries marked in Figure 7, it can be seen that the most impacting processes in the LCA results are typically the binders, cement filler and plant operations. As seen in Figures 4 and 5, these A1 processes were seen to be the most impacting per ton, while the A3 stage was applied to the whole FU of paving material hence also resulted in a high environmental output. However, as stated, care must be taken with the TAP, EP, POCP, and PMFP given that their uncertainty to impact distribution are must less linear than PENRE and GWP. For GWP and PMFP sand production was found to be one of the major uncertainty contributors. HWMA plant manufacturing and construction machinery was found to be the major contributors for TAP. Truck transportation was found to be a major contributor for GWP and EP. Thus, these processes should be those of largest concern for asphalt pavement LCA users. RAP on average contributes to 4% of the impacts across impact categories, however for POCP it contributed 13% (more than the virgin aggregates). However, due to data limitations its uncertainty was not possible to quantify for this impact category. This is also why RAP does not appear in Figure 7 and 8 for TAP, EP, POCP, and PMFP.

According to uncertainty propagation theory, a larger uncertainty input will often dominate in the output too (Palmer, n.d.). Therefore, the larger impacting processes with larger uncertainties, were found to dominate the LCA overall uncertainties. However, this trend was not the case for all products and processes. Specifically, the construction stage (A5) contributed significantly to TAP while only providing 1.8% of the LCA impacts. Similarly, HWMA production (A3) for EP and POCP (3.7% and 29.4% average impact respectively), and truck transportation (A2 and A4) for GWP (1.8% average impact). Furthermore, as previously stated, but significantly important in the results of this study, the dominance of the uncertainty from to sand production for PMFP (0.4% average impact).

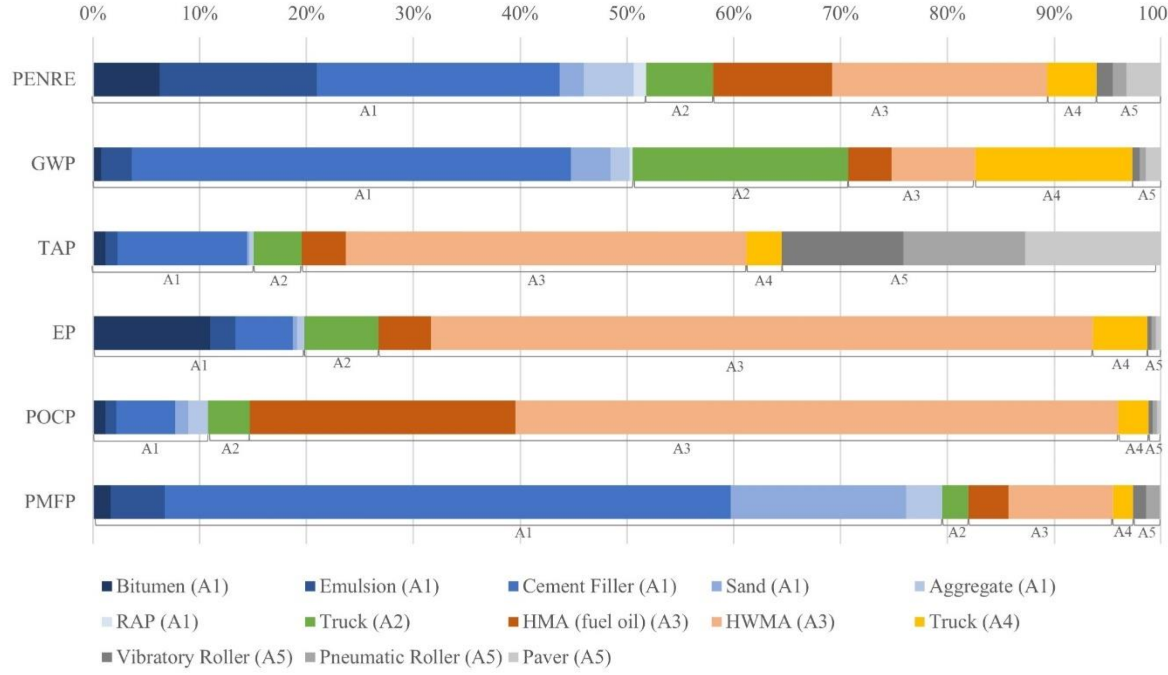


Figure 4.12. Summary of the origin of the uncertainties per life cycle stage and impact category.

4.2.3.3.2 Variability Effect on Final LCA Results

Following on from the assessment of uncertainty for the constituent processes, Figure 9 displays the final LCA results per impact category per FU of kilometre of paved highway for the selected data. Error bars are provided to show the variability (maximum and minimum) of the total impacts from the collected inventory. For each case study scenario, the impacts have been provided in terms of their constituent process stages (A1-A5).

The results found confirm the importance of the data quality when carrying out LCA, as seen previously for the impact and variability of results depending on the source of each process, bituminous and cementitious materials (stage A1) and mixture manufacturing (stage A3) showed to be the most influential processes in terms of both system impacts and variabilities. Overall, the TAP and PMFP impact categories displayed the largest potential increase in impacts, whilst EP the largest relative potential decrease in impacts. For TAP, this is largely attributed to the construction stage (A5), which was responsible for 35% of the variability despite its negligible contribution to the LCA impact (1-2%). This was largely attributed to the large difference in machinery fuel consumptions reported, as previously stated. Regarding PMFP, the large increase in potential variability was a result of the varying reported quantities for fugitive dust.

Regarding EP, the large potential savings may be misleading as the saving is provided largely by the binders used, however the larger impacts associated with the binders for EP is due to the updated Eurobitume LCI now reporting the chemical oxygen demand for crude oil extraction (Eurobitume, 2019). This was not previously reported, and as a result it should not be assumed that newer datasets will always provide environmental savings due to a more efficient technology level, as these datasets may now report previously unrecorded data too.

As a result of the variabilities, the HMA scenario has the largest potential both increasing and decreasing emissions for the TAP, EP, POCP, and PMFP impact categories. This could be associated to it having the largest impacts, and thus the largest variabilities. For the impact categories, the largest variabilities were typically found for the transportation stages (A2 and A4) and the construction stage (A5) for TAP, EP, POCP, and PMFP. However, given the smaller overall impact of these stages on the final LCA results, the variabilities were primarily a result of the material extraction (A1) and manufacturing (A3) stages; despite being significantly lower than the other stages.

Furthermore, the lowest variabilities for decreasing impacts were for the mixture production stage (A3) for all scenarios. Where the mixture production stages could be considered to be geographically variable. The Spanish sources used were considered fairly modern within the source stock found for PENRE and GWP, yet for the TAP and POCP they were at the mid-range, and for EP and PMFP are at the higher end of the spectrum. Geographic variability for mixture production was also found by (D'Angelo et al., 2008), who stated that aggregates in the USA aggregates have much higher water absorptions than in Europe; more heating energy is required during the mixture production process to dry the aggregates (Androjicánd et al., 2016).

The GWP, TAP and PMFP impact categories for the cement filler is seen to have a distinct influence on the variability potential of the LCA results. Regarding the GWP, the coefficient of variation for the production of cement filler is comparatively low (35% compared to GWP average of 63% across processes), however outputting so much CO_2, due to high clinker production temperatures and CO_2 also being a by-product of manufacture (accounting for 68% of total CO_2 (MITECO, 2017)), the magnitudes of the GWP variance are sufficient to largely influence the LCA results. The large potential increase for the TAP and PMFP impact categories was found to be temporally representative.

Therefore, it can be assumed that with time the fuel sulphur content and fugitive dust control measures, respectively, have become stricter and improved.

The use of RAP for the HWMA scenario, causing savings in bitumen emulsion (due to residual binder on the recycled aggregate), cement filler, and aggregates, provided an average environmental impact saving of 36% across all indicators for stage A1. This saving was especially pronounced for PENRE and GWP, with savings of 43% and 45%, respectively. However, it must be highlighted that for the TAP, EP and POCP the RAP does not influence the variability due to data limitations. Furthermore, the RAP impacts were not able to be quantified for the PMFP category. This is of immediate concern given that its dust is a major safety concern (Occupational Safety and Health Administration, 2017).

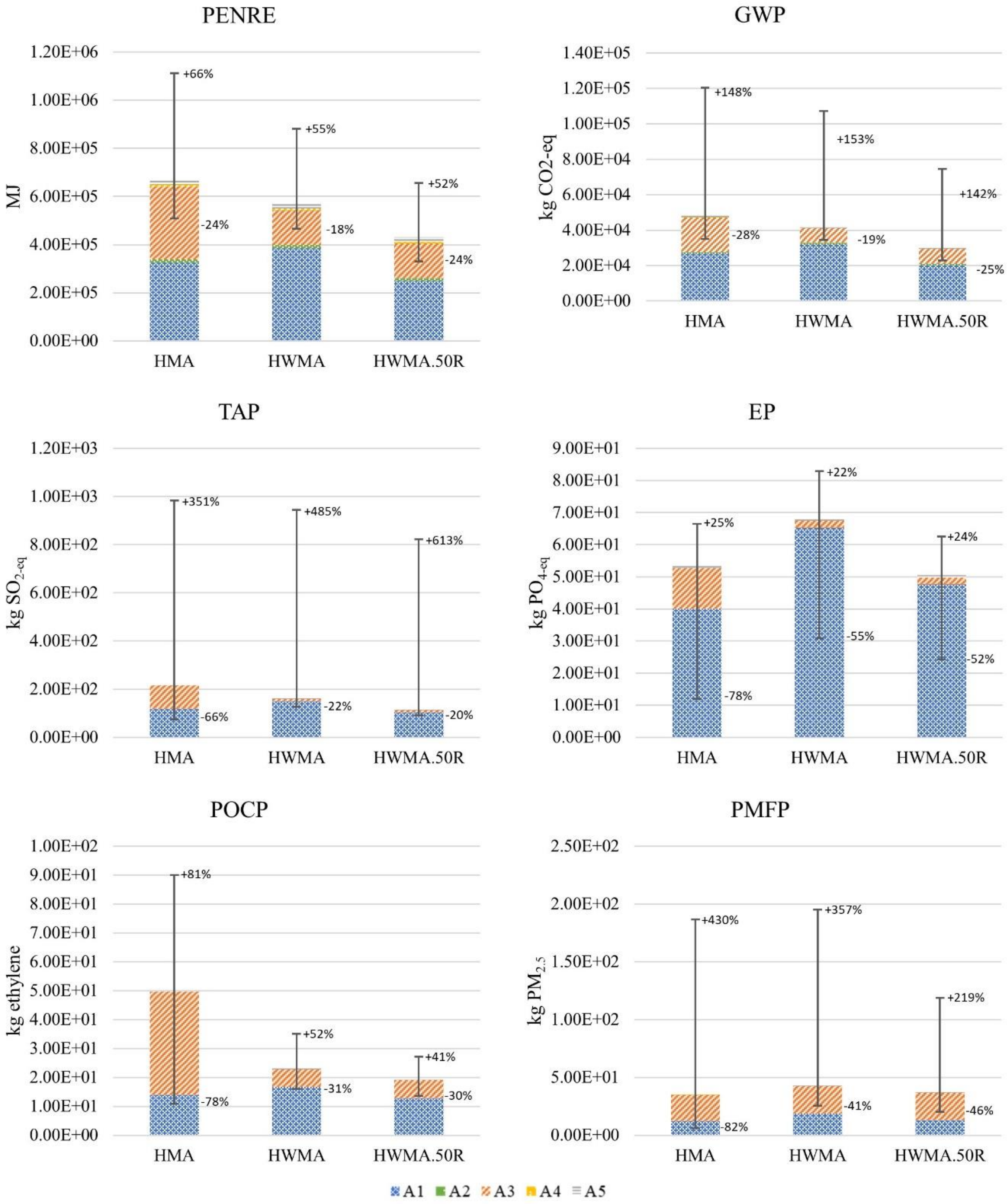


Figure 4.13. Total LCA impacts with variabilities of the scenarios assessed for all impact categories for one kilometre of paved highway.

4.2.4 Conclusions

The current study aimed to quantify the variability and uncertainties present in the use of open-source data for the cradle-to-laid LCA of asphalt pavements. To achieve this, various peer-published case studies and open source LCI material was reviewed. By compiling various sources together, it was possible to quantify their variabilities and uncertainties at both the process level, and on the final LCA results. From this, it was possible to provide users with recommendations for LCI creation and promote more accessible use for the environmental quantification of impacts for a cradle-to-laid study. From the assessment of the results, the following main conclusions were obtained:

- At the data collection level, the results of this study found that not all open data sources provide complete data for LCA and certain assumptions or further primary data collection would be required. Raw material production sources (stage A1) were found to be the most complete and required minimal impact calculation efforts, while the transportation (A2 & A4) and construction (A5) stages, despite having a large number of sources found, required more effort for impact category calculation. Furthermore, due to the lack of open-source data found for binder (both conventional and modified) and cleaner production technologies (lower temperature mixture production and recycled aggregates), their variabilities and uncertainties were hard to quantify.
- As a result of uncertainty propagation through to the LCA results, the most impacting processes were often accompanied by large uncertainties (binder and cement filler production, and plant operations). While the raw material production stage's uncertainty was primarily due to temporal variance, conventional mixture production was mainly due to geographical variance. Furthermore, the uncertainty found associated with stages A2, A4 and A5 were primarily due to fuel consumption reporting differences and differences in emission standards which have improved over time. The high impact – high uncertainty trend was not applicable to some low-impact processes, which were accompanied by large uncertainties, such as: i) sand production for GWP and PMFP, ii) truck transportation for GWP and EP, iii) HWMA manufacturing for TAP, EP and POCP, and iv) construction machinery for TAP.
- Regarding the final LCA results, the TAP and PMFP impact categories were the most vulnerable to increase in impact, whilst the EP was the most likely to decrease for all case study scenarios. For the non-conventional mixtures, the lower production temperatures were the main source of uncertainties for the TAP, EP, and POCP impact categories.
- Certain patterns were identified regarding data quality, such as material production (stage A1) was most influential for the uncertainty of the PENRE, GWP, and PMFP impact categories, whilst plant operation (stage A3) was most significant for TAP, POCP and PMFP in this study. Where construction (stage A5) was also a primary contributor to TAP too.

Therefore, based on the results of this study, open-source data could be used for the LCA of asphalt mixtures and pavements. Nonetheless, justified data sources should be used and users must be aware of the potential areas of uncertainty within the system, where this paper has aimed to contribute to the identification and understanding of these uncertainties in order to help minimise them. Through this understanding, more entities may be able to make more informed decisions using environmental reporting with open-source data or establish priorities for the development of local life-cycle inventories. Analysts must take care when assessing transportation and construction stages, given that fuel consumption reporting can vary considerably and emission standards have changed over time. These results are important for LCA practitioners, as the key areas of uncertainty have been highlighted and so where focus must be made to reduce error in future LCI creation, and for designers, to better interpret LCA outputs.

Limitations of the current study, at a data collection level, was the lack of open-source data for binder production (conventional and modified), lower temperature asphalt manufacturing, and the use of reclaimed asphalt pavement. In turn, this limited the capacity to quantify the variabilities and uncertainties associated with the processes to the same level of the rest of the processes. However, it is worth commenting, the sources selected for these processes (Annex 6.1) are representative of the either the whole of Europe or a neighbouring country of the case study region. Meanwhile, regarding the uncertainty due to the calculation routes undertaken, while minimal uncertainty was introduced from routes 1 and 2, route 3 did involve assumptions. The assumptions made were maintained as close as possible to the procedure followed to obtain emissions data from the collection of primary data of process fuel inputs, to minimise uncertainty.

Further research would be required to assess process impacts in further detail and the collection of primary data would reduce some of the large variabilities found. Furthermore, in future work the further exploration of variance between commercial tools and open data would be needed. In addition, the life-cycle use phase and the inclusion of further life-cycle stages (i.e., use, maintenance and rehabilitation, and end-of-life) would be required to identify the uncertainties for a complete LCA using open-source data. Finally, as a priority of open-source LCI, the PMFP should be quantified for RAP, given the importance of respiratory inorganics according to the European Commission's impact assessment guide.

4.2.5 References

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4.2.6 Appendix

In this section, the results of the pedigree matrix are provided, along with the life-cycle inventory used for the life-cycle assessment of the case study region.

4.2.6.1 Pedigree matrix results for locally representative data

Table 4.8 displays the representative sources selected following the methodology in Section 4.2.2.

Table 4.8. Pedigree matrix results for locally representative data.

Process	Source	Reliability	Source Completeness	Temporal Correlation	Geographical Correlation	Further technological correlation
Bitumen binder	(Eurobitume, 2019)	2	1	1	1	2
Emulsion	(Eurobitume, 2012)	2	1	3	1	2
PMB	(Eurobitume, 2012)	2	1	3	1	2
Cement	(MITECO, 2017)	1	1	1	1	1
	(Mora Peris et al., 2017)	1	1	1	1	1
Sand	(Jullien et al., 2015)	2	1	2	2	2
	(Stripple, 2001)	2	1	5	3	2
Gravel	(Jullien et al., 2015)	2	1	2	2	2
	(Stripple, 2001)	2	1	5	3	2
RAP	(UNPG, 2011)	1	1	3	2	2
	(Sampedro et al., 2012)	1	3	3	1	2
Truck transportation	(Ntziachristos and Samaras, 2018)	1	1	1	1	1
HMA	(Rubio et al., 2013)	1	3	3	1	2

	(Vidal et al., 2013)	2	4	3	1	2
	(Moral Quiza, 2016)	1	3	2	1	2
WMA	(Vidal et al., 2013)	2	4	3	1	2
	(Pérez-Martínez et al., 2014)	1	3	2	1	2
	(Jullien et al., 2015)	2	1	2	2	2
HWMA	(Rubio et al., 2013)	1	3	3	1	2
	(Jullien et al., 2015)	2	1	2	2	2
CMA	(D'Angelo et al., 2008)	1	1	4	2	2
	(Jullien et al., 2015)	2	1	2	2	2
Drum roller, vibratory roller & paver	(Sampedro et al., 2012)	1	3	3	1	2
	(Moral Quiza, 2016)	1	3	2	1	2
	(Vidal et al., 2013)	2	4	1	4	2

4.2.6.2 A.2 Life cycle inventory for representative data

Table 4.9 displays the life-cycle inventory used for the case study life-cycle assessment, according to the data selected in section 4.2.6.1.

Table 4.9. Life cycle inventory used for case study region.

		PENRE (MJ/t)	GWP, CML 2016 (kg CO2.eq/t)	TAP, CML 2016 (kg SO2.eq/t)	EP, CML 2016 (kg PO4.eq/t)	POCP, CML 2016 (kg ethylene.eq/t)	Fine Particulate Matter Formation, ReCiPe 2016 (kgPM2.5/t)
A1	**Bitumen**	1.81E+03	1.60E+02	1.07E+00	5.30E-01	1.10E-01	1.90E-01
	PMB	4.32E+03	2.97E+02	2.40E+00	6.99E-01	1.72E-01	4.92E-01
	Emulsion	2.18E+03	1.91E+02	1.21E+00	7.50E-01	1.18E-01	2.29E-01
	Cement Filler	3.59E+03	3.07E+02	1.12E+00	2.47E-01	1.18E-01	5.32E-02
	Sand	4.94E+01	2.80E+00	8.56E-03	2.32E-03	2.61E-03	6.79E-04
	Gravel	4.28E+01	2.17E+00	7.58E-03	1.93E-03	2.49E-03	3.43E-04
	RAP	3.86E+01	2.34E+00	1.79E-02	5.26E-03	5.22E-03	0.00E+00
A2	**Truck**	5.98E-01	3.95E-02	1.04E-05	2.68E-06	1.46E-06	1.85E-07
A3	**HMA (fuel oil)**	2.98E+02	1.94E+01	9.50E-02	1.25E-02	3.50E-02	2.25E-02
	HMA (natural gas)	2.84E+02	1.65E+01	2.88E-02	4.71E-03	1.78E-03	1.93E-03
	WMA	2.18E+02	1.56E+01	3.76E-02	5.78E-03	3.98E-02	1.95E-02
	HWMA	1.40E+02	8.15E+00	8.53E-03	2.10E-03	6.08E-03	2.35E-02
	CMA	2.08E+01	1.53E+00	7.82E-03	8.43E-04	6.68E-04	2.49E-03
A4	Truck	5.98E-01	3.95E-02	1.04E-05	2.68E-06	1.46E-06	1.85E-07
A5	Vib. Roller	4.86E+00	3.31E-01	6.95E-04	1.80E-04	6.29E-05	6.46E-05
	Pne. Roller	3.73E+00	2.53E-01	5.33E-04	1.38E-04	4.82E-05	4.95E-05
	Paver	1.01E+01	6.87E-01	1.45E-03	3.74E-04	1.31E-04	1.34E-04

4.3 Analysis of the Greenhouse Gas Savings and Cost-Effectiveness of Asphalt Pavement Climate Mitigation Strategies[3]

4.3.1 Introduction

Global green public procurement is a multi-faceted and large problem currently faced by the world. This is especially true for the pavement sector, which has limited budgets to follow, but is under great pressure from increasing traffic demands and adverse climatic events. While recent large developments have been made regarding the quantification of the environmental impacts of construction materials through environmental product declarations (EPD), and their use in life-cycle assessment (LCA) (Rangelov et al., 2020), progress is still required to help facilitate the incorporation of LCA results into pavement-based decisions. Furthermore, to fully justify possible cleaner technologies, the economic aspect of these solutions is a key determinator in their implementation and so must be studied in conjunction with the emissions.

From previous LCA studies, it is apparent that to provide the largest environmental and cost savings in the production of asphalt pavements, the material extraction and mixture manufacture stages must be considered (Mattinzioli et al., 2020). Regarding the former, large amounts of research has been undertaken for waste materials (L. L. Brasileiro et al., 2019; García-Travé et al., 2016; Jimenez Del Barco-Carrion et al., 2016), and it is now possible to see their incorporation into pavements; albeit in reduced quantities. The two most popular waste materials may be considered to be reclaimed asphalt pavement (RAP) and crumb rubber (CR), both produced in the end-of-life stage of asphalt pavements and tyres, respectively.

The increase in interest in RAP, as clearly demonstrable at a global level over the years (EAPA, 2019, 2014), given it being one of the most recycled materials in the USA (EAPA, 2019; NAPA, 2018); thus, indicating its inclusion within road corridors is becoming more and more viable. Further environmental benefits include the increase in circularity of the final pavement (Mantalovas and Mino, 2020). The use of such a waste material also offers significant economic benefits, given the relative reduction in need for quarrying and transportation required for virgin aggregates, and the savings associated with landfill fees; 34% higher per tonne than the cost of purchasing crushed virgin aggregates for asphalt (CEDEX, 2011; Ministerio de Fomento, 2016).

Regarding CR as a bitumen modifier, it acts similar to a virgin polymer-modifier, which improves the elastic properties of the binder. Throughout literature, CR is generally accepted to increase a pavement’s durability in both lab and field, thanks to its reduced oxidation, increased durability and increased resistance to reflective cracking (Lo Presti, 2013; Picado-Santos et al., 2020; Way et al., 2011; Zhou et al., 2014). Due to the need for processing the end-of-life-tyre (ELT), the cost and environmental burdens can be assumed to increase (Chiu et al., 2008; Farina et al., 2017), compared to a conventional un-modified binder, yet given studies also indicate that due to the increase in durability and technical viability (L. Brasileiro et al., 2019; Moreno et al., 2013), these impacts and costs could well be offset over the pavement life-cycle and provide an overall net benefit.

On top of CR as a modified binder, and within the vision of a post-fossil fuel society, the use of novel bio-binders are also gaining interest in both research and in practice (Blanc et al., 2019); with a pilot

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[3] The work in this chapter is based upon the following publication: Mattinzioli, T., M. Sol-Sánchez, A. Jiménez del Barco Carrión, F. Moreno-Navarro, M. del C. Rubio-Gámez, and G. Martínez. Analysis of the GHG Savings and Cost-Effectiveness of Asphalt Pavement Climate Mitigation Strategies. *Journal of Cleaner Production*, Vol. 320, 2021, p. 128768. https://doi.org/10.1016/J.JCLEPRO.2021.128768.

study already in place (EIFFAGE, 2018, n.d.). Bio-binders have already been characterised to be a viable replacement to fresh binder, and been shown appropriate for use with RAP (Barco Carrión et al., 2017). The use of such technology has already also been validated to reduce the environmental impact of mixtures across various impact categories (Mantalovas et al., 2020); especially for global warming potential when biogenic carbon is considered.

Regarding emission mitigation strategies for the manufacture of the asphalt product, rather than its raw constituent materials, the reduction of plant temperatures has also gained traction (Sol-Sánchez et al., 2016). The three main denominations for asphalt mixtures manufactured below conventional hot-mix (HMA) temperatures (150-190°C) are: Warm Mix Asphalt (WMA – 100-140°C); Half-Warm Mix Asphalt (HWMA – 60-100°C); and cold mix asphalt (CMA – 0-40°C) (M. Carmen Rubio et al., 2012). Where WMA and HWMA are typically produced in plant, and CMA in-situ; thus, the first two being most applicable for energy saving in-plant. The temperature reduction achieved by WMA is a result of recently developed technologies involving the use of organic additives, chemical additives, and water-based or water-containing foaming processes (M Carmen Rubio et al., 2012; Zaumanis, 2014). Meanwhile, HWMA is typically manufactured with the use of a bitumen emulsion as a binder. Overall, these technologies are found to provide reduced plant energy consumption, whose reduced fuel consumption generally results in overall cost savings also. However, this cannot always be assumed due to the need for additives in the mixture and mix design modifications.

As stated previously, while these strategies can be associated with environmental savings, to be included as cleaner and more sustainable technologies (where sustainability encompasses environmental, economic and social aspects (Elkington, 1997)), the economic viability of these technologies must also be explored and quantified to further reinforce their validity to different road stakeholders. The use of an environmental-economic analysis regarding environmental savings for roads has already been covered in literature, yet limited studies were found to combine the two to develop a more holistic indicator. For example, Huang et al. (2021) used LCA and life-cycle cost analysis, along with multi-objective optimization, to determine a local model for optimised maintenance using an environmental damage cost unit. This unit is based on the annual average value of carbon emissions. Li et al. (2019) carried out a review of LCA and LCCA studies for recycled solid waste materials in highway pavements. The findings of this study found that compared to LCA studies, corresponding LCCA studies were rare. (Santos et al., 2017) applied Multiple-Criteria Decision Analysis for the environmental and economic assessment of pavement construction and management practices. While perfectly applicable, the results of this study may not be comparable to other regions given the MCDA weightings are defined by multiple decision-makers with different agendas and biases towards their interests.

The two studies found to combine the LCA and LCCA results into a single indicator were Harvey et al. (2020) and (Yang et al., 2015). Where Harvey et al. (2020), carried out a cost-benefit comparison of including different amounts of RAP in mixtures, reported in terms of dollars per tonne of $CO_{2\text{-eq}}$ reduced, at different RAP quantities (25%, 40%, and 50%) within the mixture, at a network-wide level for decision-makers and planners. Meanwhile, (Yang et al., 2015) carried out an environmental and economic analyses of recycled asphalt concrete mixtures. In this study, the relative energy requirements, GWP and costs of RAP- and RAS-based mixtures were analysed. While the latter study provided the relative impacts of the results graphically, a potential improvement to the study could be the development of an indicator to combine the results and enhance interpretation. Furthermore, while these studies combined the LCA and LCCA results, they did only consider one climate change mitigation strategy and future work could cover the implementation of other solutions too (such as CR, reduced-temperature manufacturing and bio-based materials).

Therefore, this study aims to quantify the environmental-economic benefits or drawbacks of cleaner technologies to better interpret the benefits of these technologies. The three mitigation strategies considered were: 1) use of waste materials, 2) reduced-temperature production technologies, and 3) the use of novel bio-binders. To achieve this, both an LCA and LCCA was carried out to quantify the impacts for these strategies for an asphalt pavement product and across its life-cycle. The results of the analyses were quantitatively combined to enhance user interpretation of the results.

4.3.2 Methodology

To determine the economic and environmental viability of three mitigation strategies for the economically-efficient abatement of GHG emissions within the asphalt pavement construction sector, a two-step process was adopted: 1) analysis per functional unit (FU) of pavement (i.e., upfront climate burdens and costs), and 2) analysis across the service life of the pavement.

4.3.2.1 Mitigation strategies

The previously mentioned key mitigation strategies for climate abatement are summarised in Table 1 and further described in the following sections. All the mitigation strategies considered will be evaluated at the pavement product scale and across the whole life-cycle. Both are important for decision makers, as the former provides an understanding for the material supply and manufacturing stages (arguably two of the most impacting for asphalt pavements (Mattinzioli et al., 2020)), while the latter provides a better long-term understanding (Jimenéz del Barco Carrión et al., 2020).

Table 4.10. Definition of mitigation strategy scenarios.

Mitigation Strategy	Sub-Strategy	Variables Assessed
Waste materials I: RAP	Classified vs Un-Classified	• Classified • Un-Classified
	Residual Binder Content	• $2\%_{\text{RAP}}$ • $4\%_{\text{RAP}}$
	Rejuvenator Quantity (bio-based & fossil-based – assuming 2% residual binder)	• $3\%_{\text{RAP binder}}$ • $7\%_{\text{RAP binder}}$
	RAP Distance to Plant	• At plant (0km) • Same as other materials (30km) • Double other materials (60km)
Waste materials II: CR	Wet process	• $8\%_{\text{binder}}$ • $22\%_{\text{binder}}$
	Dry process	• $1\%_{\text{mixture}}$ • $2\%_{\text{mixture}}$
Reduced Manufacturing Temperature	Warm mix	• Chemical additive • Organic additive • Foaming
	Half-warm mix*	• Half-warm with emulsion
Novel materials: bio-binders	Bio-binders	• Bio-binder with SBS • Bio-binder without SBS

4.3.2.1.1 Waste materials I: RAP

For the benefit-cost analysis for reclaimed asphalt, four key sub-strategies were considered as seen previously in Table 1. The pathways were assessed for RAP contents of 15%, 30%, 50% and 100%. The first amount considered is the threshold, in the authors' region (Spain), for considering RAP as a standard aggregate to one where further design considerations must be made (Spanish Ministry of

Development, 2017). The following quantities were logical and viable (i.e., already seen in field) increments in RAP quantities. The four pathways considered were:

a) Classified vs un-classified RAP. As described by West (2015), “classified RAP”, is RAP from the local agency and assumed to be ready for use, whereas “un-classified” is that from a local stockpile which has mixed sources and would need to be processed before use.
b) Residual binder content. A conservative estimate of 2% residual binder and an ideal estimate of 4% binder (per RAP content) was modelled, based on the laboratory experience of the authors. The consideration of residual binder has been largely considered in previous experiences with RAP (Mattinzioli et al., 2020; Song et al., 2018; Van Winkle, 2014).
c) Rejuvenator content. Two rejuvenator contents were explored at 3% and 7% of the residual binder of the RAP (a conservative 2% for this study), to increase the amount of useful binder from the aged bitumen in the pavement (Tauste et al., 2018). For this assessment, two distinctly different rejuvenating agents were considered, one bio-oil (negative GWP, with biogenic carbon considerations) and the one tar-based agent with aromatic oils and solvents (RejuvaSeal, 2021).
d) Distance of RAP to plant. Three RAP-plant distances were considered, where the RAP was sourced at the plant (0km), the same average distance of all other sourced materials (30km), and at double the average distance of the sourced materials (60km). Through this, it was possible to identify the influence of haul distance on overall RAP inclusion environmental and cost benefit, for both site-sourced and off-site-sourced.

Finally, for the manufacture of RAP-based mixtures (stage A3 – EN 15804 (CEN, 2014)), fuel oil consumption requirements were assumed to increase respective to RAP quantity starting from 30% RAP (Sampedro et al. 2012 Vidal et al. 2013). From 30% RAP, the asphalt plant drum is required to be heated 20°C more (Sampedro et al., 2012) to consider the “superheating” process and conservatively accounts for the extra RAP energy requirements for processing RAP at the plant. A fuel oil plant was considered, as it was more representative of the authors’ local region.

4.3.2.1.2 Waste Materials II: Crumb Rubber

As part of this mitigation strategy, both the wet- and the dry-processes were considered (CEDEX, 2007; Farina et al., 2017; Wang et al., 2012). The considerations made for the analysis of these two processes can be summarised as follows:

a) Wet process: modification of binder before manufacture. The range of CR permitted for modifying a binder according to the standards in the authors’ region ranges from 8-22% of the binder content (CEDEX, 2007). For the blending of the CR with the binder, 18 litres of diesel were assumed, according to Bartolozzi et al. (2012).
b) Dry process: CR added as a dry aggregate during manufacture. CR is recommended be incorporated as a dry aggregate up to 2% of the weight of the asphalt mixture in the authors’ region (CEDEX, 2007). For this process, no further considerations were made for the CR incorporation.

4.3.2.1.3 Reduced temperature manufacturing

The following temperature classes were considered: 1) warm mix (WMA – 110-140°C), and 2) half-warm mix (HWMA – 70-95°C) (Rubio et al., 2013). Where the reduction of the manufacturing temperature corresponds to a reduction in fuel required for the heating of the materials. To implement these technologies in practice, several further complimentary considerations must also be made for technically viable mixtures. For the manufacture of WMA, additives are added to overcome the increased viscosity of the bitumen at reduced temperatures. Following the guidance of Rubio et al. (2012a), this can be achieved via three primary methods, as described as follows: 1) chemical additive, which is a combination of emulsification agents, surfactants, polymers, and additives, 2) organic additive, typically a wax-based material, and 3) bitumen foaming, which entails the addition of small amounts of water injected into the hot binder or directly into the mixing chamber.

Meanwhile, for the HWMA, additives were not considered, but an emulsion binder was considered (instead of a neat one with an additive). An additional consideration for the HWMA is its need for increased compaction during construction (observed to be around 50% more (Mattinzioli et al., 2020)).

4.3.2.1.4 Use of bio-materials

The final strategy considered the use of a novel alternative bio-material to replace the virgin bituminous binder. The bio-material modelled was considered to originate from waste material from paper industry. This bio-binder was considered neat and modified with SBS.

4.3.2.1.5 Case studies considering the mitigation strategies

On top of the considerations for the individual strategies, five final case study mixtures were compared to understand the influence of the combination of the mitigation strategies. The five case studies assessed were all from previous work by the authors and can be seen in Table 2. The measures adopted in these case studies were applied to the baseline mixture previously defined, rather than the mixtures considered in these studies; assumed to be valid given all were for the surface course. The baseline mixture was adapted, rather than taking the direct mix designs from the studies, to reduce further variables in the study; given that depending on the mixture typology used, the embodied impacts can vary (Mattinzioli et al., n.d.).

Table 4.11. Case study mixture designs, taken from previous work by the authors.

	Case 1: HMA CR$_{\text{wet}}$	**Case 2: WMA CR$_{\text{wet}}$**	**Case 3: HMA CR$_{\text{dry}}$**	**Case 4: HWMA 100RAP**	**Case 5: Bio 50RAP**
Binder modification	20%$_{\text{binder}}$ CR added via wet-process	20%$_{\text{binder}}$ CR added via wet-process	1.5%$_{\text{wt}}$ CR added as dry aggregate	-	Replaced with bio-binder (2.4%$_{\text{wt}}$ final)
Aggregate modification	-	-	-	Aggregate replaced with 100% RAP	Aggregate replaced with 50% RAP
Manufacturing temperature class	-	WMA	-	HWMA	-
Reference	(Sol-Sánchez et al., 2020)	(Sol-Sánchez et al., 2020)	(Moreno et al., 2012)	(Lizárraga et al., 2017)	(Mantalovas et al., 2020)

4.3.2.2 Methods

As mentioned previously, and as detailed in Figure 1, a two-step process was adopted to study the benefit-cost of the mitigation strategies: 1) comparison to reference mixtures per functional unit, and 2) comparison over the service-life of the pavement with durability considerations per functional unit. For the former, "cradle-to-gate, with options", according to the EN 15804 (CEN, 2014), or also as a "cradle-to-laid" (Butt et al., 2019) was considered. This considered the construction of the pavement (stages A1 to A5, according to the EN 15804:2012 (CEN, 2014)). Meanwhile, for the latter, a "mill and fill" rehabilitation strategy was modelled over a 40-year service-life for the mitigation strategies (stage B4 (CEN, 2014)), for the same surface courses modelled for step 1. The functional unit adopted was one lane-km of pavement. Only a surface course was considered for this study, given that it is the most commonly paved layer in the authors' region (Ministry of Transport, 2018). All emissions and cost data are provided in further detail in Appendix A.

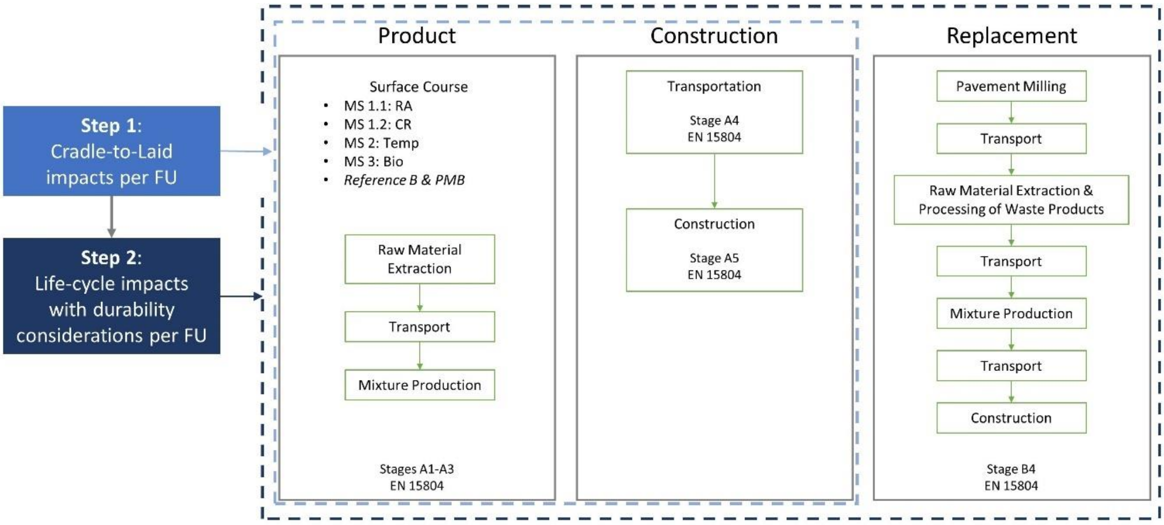

Figure 4.14. Steps undertaken for the benefit-cost analysis of the mitigation strategies.

4.3.2.2.1 *Step 1: Comparison of cradle-to-laid strategies per functional unit*

This section describes the LCA and LCCA methodology followed for the comparison of the cradle-to-laid benefit-cost impacts of the mitigation strategies. First, the baseline pavement is described, for which the mitigation strategies were applied, followed by the designs of five case studies combining the mitigation strategies considered.

4.3.2.2.1.1 Baseline pavement section

The baseline mixture selected was a densely-graded mixture (denominated Asphalt Concrete (AC)) with a maximum aggregate size of 16mm, binder content of 5.0% and cement filler content of 5.5%, over the weight of the mixture, designed according to local design standards (Spanish Ministry of Development, 2003). This mixture was selected given it is the most commonly used for surface courses in the authors' region (EAPA, 2019). The density of the mixture considered was 2.37 t/m^3, obtained from laboratory results. The thickness of the densely-graded pavement considered was 5cm. This led to a total need of 414.75 tonnes of asphalt mixture per FU.

For the RAP waste, temperature and non-SBS bio-binder strategies, the cases were compared with a mixture with a neat binder. Meanwhile, the CR waste and bio-binder with SBS cases were compared with a mixture with a polymer-modified binder (PMB, with 3.5% SBS), given these materials would provide enhanced binder properties. The reference mixtures were considered to have the same design, only the type of binder was changed.

According to the life-cycle assessment methodology defined by the ISO 14040 (ISO, 2006b), the goal of the present study is to quantify the environmental impacts of four alternative abatement strategies for an asphalt surface course. For the LCA of the baseline mixture, the Product Category Rules (PCRs) set by EAPA (EAPA, 2016), NAPA (NAPA, 2017), EPD Norge (EPD Norge, 2017a, 2017b) and the International EPD System (The International EPD System, 2019c) were consulted. Following these rules, it was ensured that the impacts were as transparent and comparable as possible. The intended application is to use these results to then define the cost-benefit potential per abatement strategy, in order to provide practical recommendations for interested stakeholders. Depending on their contribution, the mitigation strategies can then be seen to have either a greater environmental or economic saving, as seen in Figure 2 (developed by the authors).

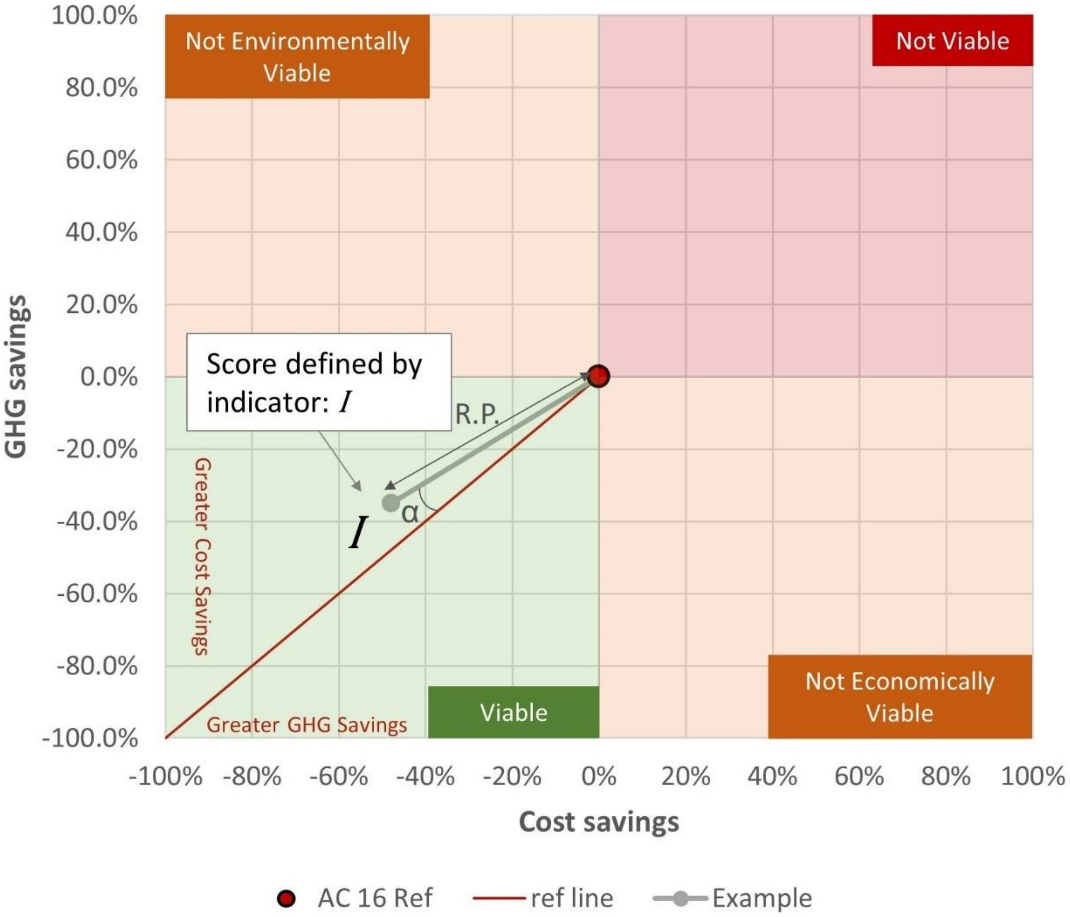

Figure 4.15. Comparison of GHG and cost savings of mitigation strategies.

As seen in Figure 2, each alternative will be assigned a final benefit-cost score to determine its viability according to its GHG and cost reduction potential (R.P., norm of the vector) and the relative environmental-cost benefit (α, angle of the vector from an equal GHG and cost saving, i.e., the red line shown in Figure 2). From combining these two, the viability of the strategy may be considered. According to the outputs in the format shown in Figure 2 and its geometrical properties, R.P. may be defined as:

$$R.P. = \sqrt{(GHG\ saved)^2 + (Costs\ saved)^2}$$

And, the relative environmental-cost benefit as:

$$\propto = \ tan^{-1}\left(\frac{GHG\ saved}{Costs\ saved}\right)$$

Where, α = 0 when the environmental and economic savings are equal (i.e., the red line shown in Figure 2). Thus, R.P. can be weighted by the relative environmental-cost benefit to output a single indicator:

$$I = R.P.\ cos(\propto)$$

Where *cos(α)* is utilised given that at α = 0 the best environmental-economic relationship is present and *cos(0)* equals 1, having equal environmental and economic savings and providing the most viable reduction potential.

The life cycle inventory for emissions used considers data which is publicly available and freely accessible to ensure transparency, as recommended by the PCRs followed. The majority of the emissions data for each of the unit processes was based on previous work by the authors (Mattinzioli et al., 2021), making it both applicable and validated for the authors' region. Further emissions data was also found for the unit processes not covered in the previous study. It was ensured that all data used was obtained from reliable sources; from certified institutions or peer-reviewed publications. The life-cycle inventory sources can be found in further detail in Appendix A.

The global warming impact category was calculated via the methodology stated by IPCC (2013). This is the same methodology used for EPDs within the International EPD system (The International EPD System, 2021) and NAPA (NAPA, 2020) directories and the EN 15804 standard (CEN, 2019).

Regarding the cost requirements for the pavement, the majority costs were obtained from the reference prices provided by the Government of Spain (Ministerio de Fomento, 2016), crumb rubber binders from de León Alonso et al. (2019), and crumb rubber from local contractors. RAP was not assigned a price per unit material, except that for its transportation and plant handling, given it is not a commercialised product.

4.3.2.2.2 Step 2: Influence across pavement service-life

In order to more accurately understand the influence of the environmental and economic requirements for the mixtures, the defined case studies (which consider the strategies in Section 4.3.2.1.5) were then compared over an analysis period of 40 years (EPD Norge, 2017b) and according to the boundary conditions shown in Figure 1. During which both superficial (i.e., operations for user experience) and structural (i.e., operations for the structural integrity of the pavement) operations were considered. Each case started with the initial construction of the surface, binder and base layers. Following which, two mill and fill operations to correct the surface roughness of the pavement (5cm) were required. For all operations, the surface course was considered to be the same per case study considered. For the LCA and LCCA analysis across the whole service life of the pavement, binder and base layers were also considered. The binder layer was a dense-grade AC 22 B 50/70 S 10cm thick, with 4% binder and 4.37% cement filler. The base layer was a dense-grade AC 32 B 50/70 G 15cm thick, with the same binder and filler contents as the binder layer, but only half of the filler content was cement and the rest was recuperated fines from aggregate crushing.

The durability of the surface course was assumed to have a service-life of 14 years, as that found from a European survey for densely-graded mixtures (EAPA, 2007). For all life-cycle analyses, the "remaining service life" (RSL) was considered (EPD Norge, 2017a; FHWA, 2002). The LCA impacts were obtained by following the guidelines provided by CEN (2019), Harvey et al. (2016) and FHWA (2002), where for the LCCA a deterministic approach was taken and a discount rate of 4% (default for RealCost software (FHWA, 2004)). The GHG and cost data can again be seen in Appendix A.

Additionally, a sensitivity analysis was undertaken to understand the GHG and costs impacts associated with changes in durability. This was undertaken given that the durability of the novel sustainable alternative mixtures is liable to change. This durability variance threshold was considered to be that found by the same study for the European average surface course densely-graded mixtures. This threshold was therefore defined as between -42.9% and +28.6%. Where with the decrease in durability, a full-depth replacement (30cm – according to local standards (Ministerio de Fomento, 2003)) was required to ensure the structural integrity of the pavement, plus another mill and fill. Based upon literature and the authors' experience, this threshold was deemed reasonable given that in the experience of (Picado-Santos et al., 2019) a CR-based mixture (dry-method, 1.87%mixture wt CR) had a minimum durability increase of 20% in durability for a two-lane Portuguese national road (low-medium traffic). This supports further literature which also states that CR is found to generally increase a mixture's service life (L. Brasileiro et al., 2019; Lo Presti, 2013; Moreno et al., 2013; Muench et al., 2019). Yet these benefits could change in regions high precipitation (Picado-Santos et al., 2020). Regarding RAP, it is difficult to ascertain its long-term effects, but as summarised by (Pouranian and Shishehbor, 2019) it can be found to negatively affect fatigue resistance and structure, yet improve rutting resistance. Regarding reduced temperature manufacturing, WMA fatigue resistance can be found to vary depending on the additive used (Ghabchi et al., 2015; Jamshidi et al., 2013; Notani et al., 2019), while rutting resistance was found to be similar to HMA (Jones et al., 2009). HWMA long-term effects are harder to quantify, but it has been in use in the authors' region for over a decade (Rubio et al., 2013). A further example for the use of the combination of the HWMA with 100% RAP was demonstrated in (SACYR, 2018), where full-scale accelerated pavement testing and in-situ test section in Madrid, Spain, was carried out and deemed technically feasible. Furthermore, in laboratory and in-situ tests HWMA with 70% and 100% RAP is comparable to HMA mixtures in terms of resistance to fatigue, water sensitivity, and permanent deformations (Lizárraga et al., 2018). The durability of bio-binders is largely unknown. They have been shown to have appropriate viscoelastic properties in laboratory (with the dynamic shear rheometer and two-point bending tests) (Barco Carrión et al., 2017), and is increasingly becoming marketed and has been used for a pilot study in France (EIFFAGE, 2018). It must be noted that all the above assumptions are based on adequate pavement design and construction.

4.3.3 Results and Discussion

This section reports and discusses the benefit-cost results found for the 1) individual mitigation strategies explored, 2) their respective comparison, and that with the defined case studies combining the strategies, and 3) the effect of the strategies on the life-cycle of the pavement.

4.3.3.1 Step 1: Comparison of cradle-to-laid impacts of mitigation strategies per functional unit

4.3.3.1.1 Strategy I: Incorporation of Waste Materials

The environmental-economic analysis results regarding the incorporation of the waste materials (i.e., RAP and CR) can be seen in Figures 3 and 4, for the GHG and cost indicators considered in this study. Figure 3 is separated into A to D to better highlight the differences between the sub-strategies (i.e., classified and un-classified, residual binder, rejuvenator (fossil- and bio-based), and RAP distance to plant). In Figure 3A, the markers represent the different quantities of RAP (15, 30, 50 and 100%, respectively moving away from the reference marker).

From Figure 3, it is possible to identify the benefits of adding RAP to asphalt through the different mitigation strategy pathways. Regarding the classification of the RAP (Figure 3A), it is possible to see that sourcing classified RAP, and avoiding its RAP processing as a result, would result in higher environmental savings (-11.8% savings compared to -5.5% for un-classified RAP at 100% recycling rate); as indicated by the resulting weighted reduction potential indicator. Meanwhile, minimal economic differences were seen for classifying RAP (0.8% difference). Considering the un-classified RAP case with residual binder (Figure 3B), both the 2% and 4% cases were seen to have a similar environmental-economic weighting, but the 4% residual binder case had a much larger reduction potential (-6.0% and -16.3% at 50% and 100% GHG savings, and -30.5% and 62.0% cost savings, for un-classified RAP rates). This sub-strategy also provided the largest saving potentials, thanks to the saving in raw bitumen; one of the most impacting constituent materials of an asphalt mixture (Mattinzioli et al., 2020; Santero et al., 2011).

When the use of a rejuvenator was considered for the 2% residual binder un-classified case (Figure 3C), the use of a bio-based rejuvenator resulted in a better reduction potential score. Furthermore, given the biogenic carbon of the bio-oil considered, a greater GHG reduction was found when it was incorporated at higher amounts (-12.9% on average, compared to -7.2% for fossil-based); an inverse pattern was found for the fossil-based rejuvenator. Finally, considering the RAP distance from the plant (Figure 3D), it was found that the need for superheating the aggregates (from 30% RAP) affected the viability of RAP at some aggregate percentages. Specifically, when the RAP was stored at the plant between 30-40% RAP resulted in an increase in GHG (0.2%-0.7%), and when the RAP was stored at double the average material source distance and exceeded 30% in quantity, it was not found to be environmentally viable (3.2% to 0.4% increase for 30% to 100% RAP). However, in all cases an economic saving was found in this study; always when RAP is not a commercialised product and viable (in the authors' region the price of landfilling is 34% more expensive than the cost of purchasing virgin crushed aggregates (CEDEX, 2011; Ministerio de Fomento, 2016)).

Comparing the four sub-strategies considered, at 15% RAP, the most viable sub-strategy with the highest *I* score would be that containing 4% residual binder. Up to this quantity of RAP, in the authors' region, RAP can be incorporated as a normal aggregate; where this will likely change depending on the study area (e.g. 25% in California (Harvey et al., 2020) and 30% in the Netherlands (Eliza et al., 2021)). Beyond this threshold, the use of residual binder would still be the best economically-efficient abatement strategy, but further considerations would probably need to be considered (i.e., RAP binder rejuvenation). For its rejuvenation, the use of a bio-oil should be used as it would provide greater GHG savings when biogenic carbon is considered. Where the use of higher RAP amounts would be subject to local availability and incorporation technology. With this said, the RAP distance to plant must also be considered, given the *I* score of this sub-strategy decreased as distance to plant increased (-47.4% when as far as the other raw materials on average, and -94.8% when this distance was doubled).

In this study, as mentioned previously, the RAP was not assigned a cost. Through the analysis of the results, it was found that to maintain an economically equivalent or viable pavement the cost of the RAP could not exceed the cost of the virgin aggregates.

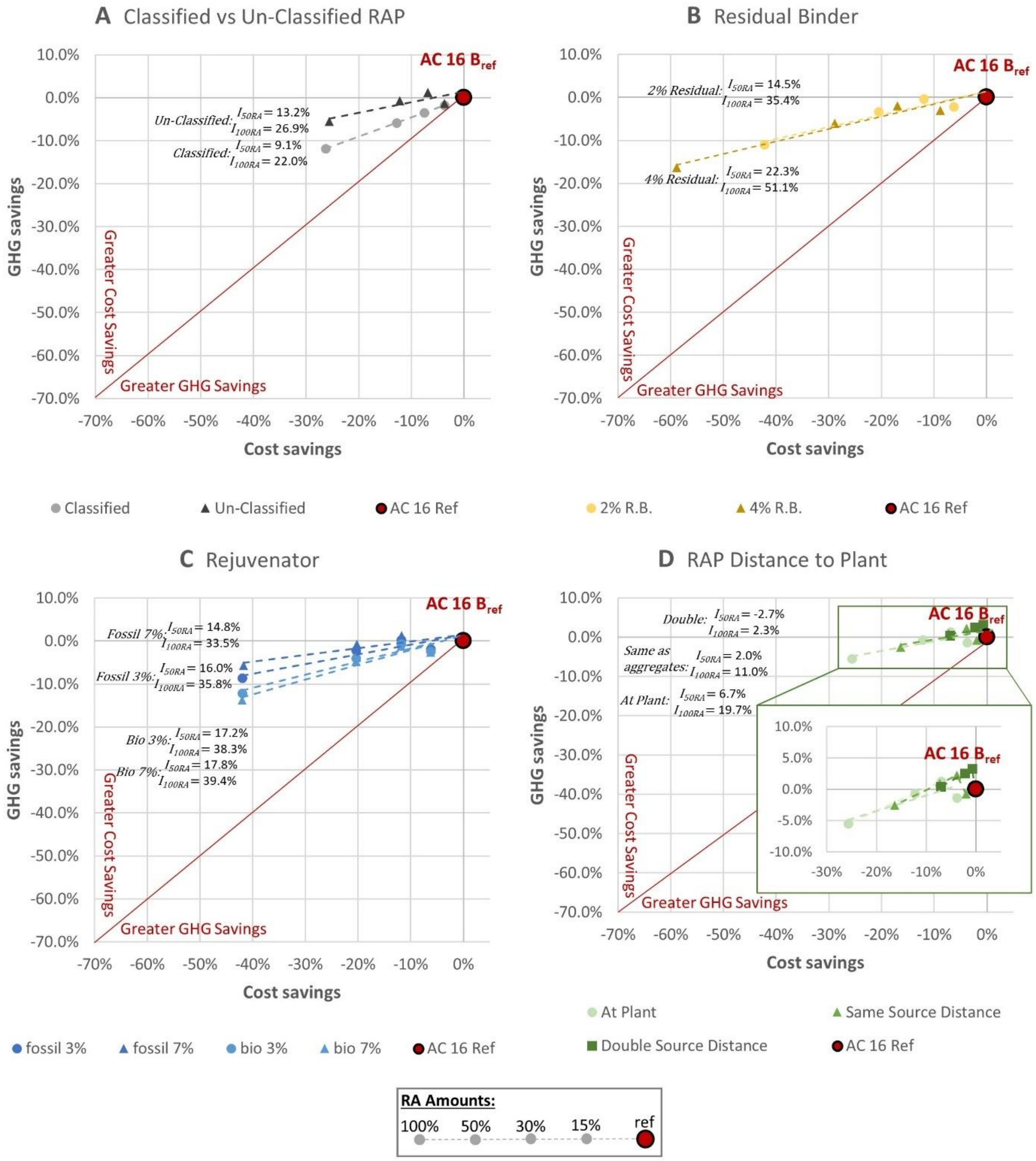

Figure 4.16. Cost-benefit analysis of using 100% RAP for an AC 16 (dense-grade) asphalt mixture.

Figure 4 shows the results for the addition of crumb rubber to the mixture, where these results are compared to a PMB; given that the CR both modifies the neat bitumen and increases a mixture's durability, as generally agreed upon in literature (Fazli and Rodrigue, 2020; Lo Presti, 2013; Moreno-Navarro et al., 2016).

From the environmental-economic results of the incorporation of crumb rubber, as seen in Figure 4, it is possible to see that the greater the addition of CR, the lower the environmental saving; while always polluting less than a PMB with SBS. Specifically, the order of GHG saving potential would be: dry 1%; wet 8% (CR 0.4% weight of the mixture); dry 2%; wet 22% (CR 1.1% weight of the mixture).

Here, the influence of weighting the indicator defined can be seen, given that the 1% dry case would provide an environmental saving of 8.8%, but this was reduced to 6.2% given its distance from the GHG-cost line.

Conversely, the cost results did not follow a similar trend, where the production of wet-process binders was found to be cheaper than the raw cost of CR. According to the data used in this study, this resulted in the wet-process binders being more economically viable, whereas the dry-process mixtures being equal or more expensive than the reference PMB mixture. This would depend on the provider of the CR (being a commercialised product). The content of the wet-process binders would also be dependent on the binder content, which varies per mixture.

Overall, the 8% wet-process was found to be the most viable according to the *I* indicator defined (-6.4% GHG and 14.0% cost saved, on average between field and terminal blend), followed by the 1% dry-process mixture (-8.8% GHG saved and 0.2% cost increase). However, durability considerations would also be required for the final implementation of this strategy, to ensure that all would be equivalent like in Figure 4, or adjust the analysis accordingly. Furthermore, this study considers the burdens (grinding, mixing etc.) to produce CR mixtures, yet it must also be kept in mind that as seen in (Farina et al., 2017), that when compared to landfilling the end-of-life tyres, the use of CR does generate an overall net environmental benefit of (in terms of MJ and GWP for the study considered); a similar observation to that made for RAP.

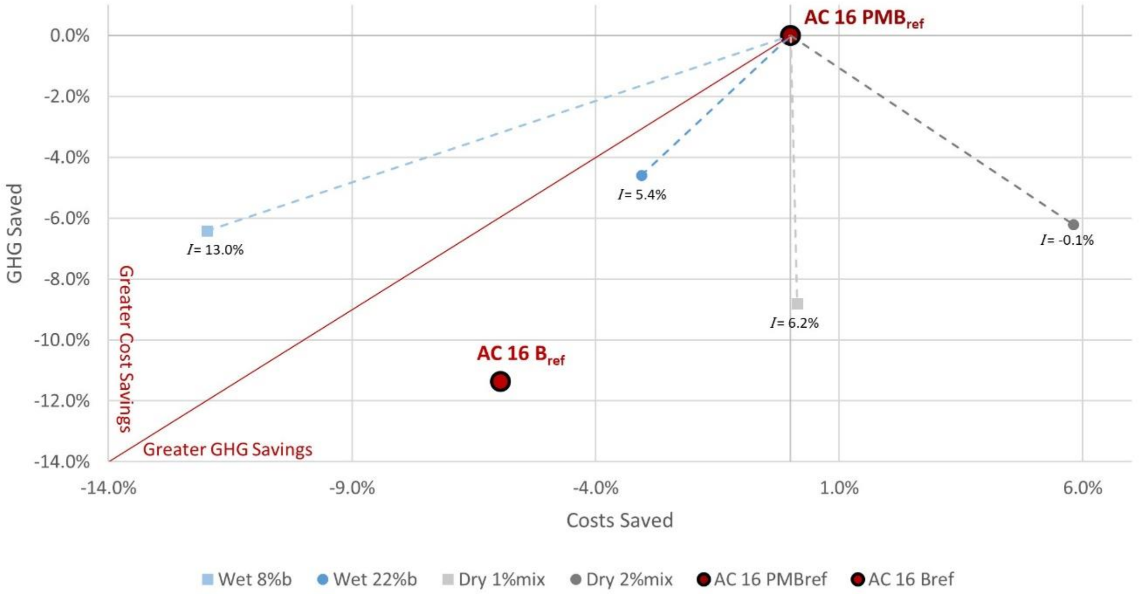

Figure 4.17. Cost-benefit analysis of using 8-22%$_{\text{binder}}$ RAP for an AC 16 (dense-grade) asphalt mixture.

4.3.3.1.2 Strategy II: Reduced temperature mixtures

Figure 5 demonstrates the results for the benefit-cost analysis of manufacturing mixtures at reduced temperatures. It is apparent that HWMA offers the largest environmental and cost savings, resulting in the best *I* score (21.7%). Despite the higher cost for the mixture's binder (i.e., emulsion, 42% higher per unit binder content at 60-40 binder-water content), its savings can be largely attributed to the energy savings from not having to surpass the latent heat of vaporization (as represented in (Rubio et al., 2013)). Meanwhile, the WMA being above 100°C, would have to. Thus, increasing the energy requirements significantly and in turn providing an average *I* score of 7.6%. With this said, the WMA was found to provide overall savings compared to the HMA (5.2% and 3.6% environmental and cost savings, respectively). The use of additives was seen to incur minimal further GHG emissions (coefficient of variation of $2.1e^{-3}$) and costs (CV of $1.1e^{-5}$) due to its very small overall content in the mixture. WMA could also offer similar durability performance to the HMA, regardless of the additive selected, in terms of fatigue cracking (Sol-Sánchez et al., 2018). However, additive environmental impact data was found to be limited, so further research into these agents would be required. Furthermore, a fuel oil plant was considered in this study given the author's region, yet it must also be acknowledged that a plant using natural gas as a heating fuel would provide significant GHG savings (Sampedro et al., 2012).

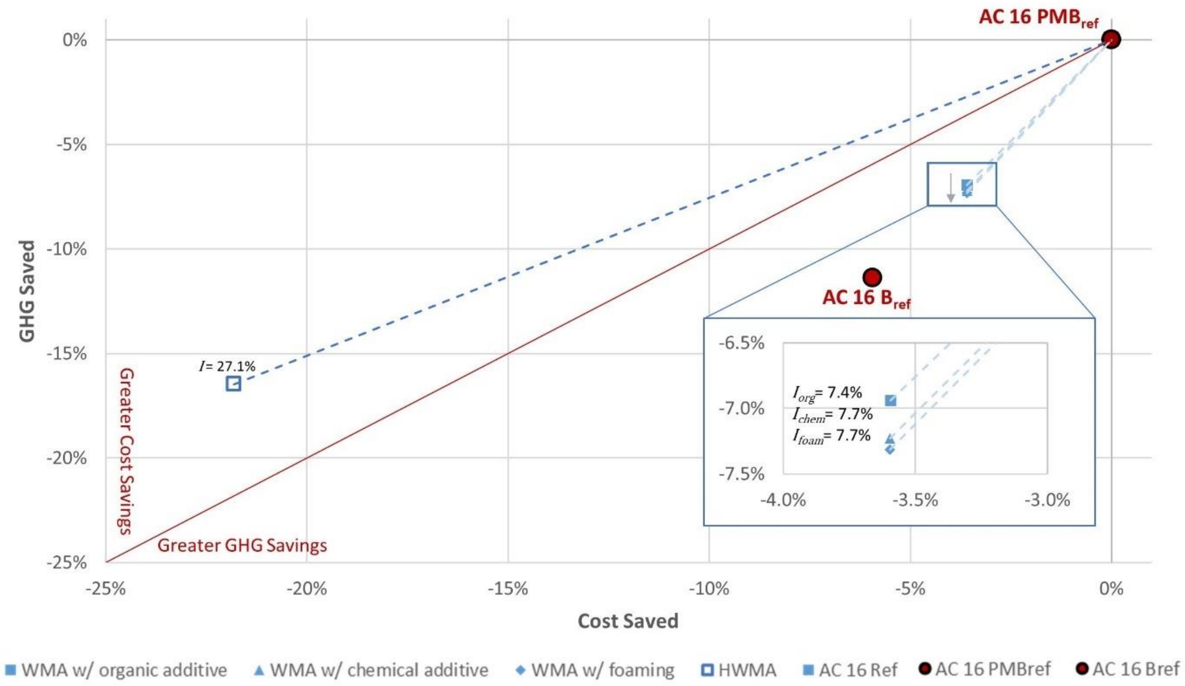

Figure 4.18. Cost-benefit analysis of reducing asphalt mixture temperatures.

4.3.3.1.3 Strategy III: Bio-binders

From the results of the binder replacement with bio-materials, as seen in Figure 6, this strategy would offer some of the largest overall GHG emissions reductions. This would be due to the consideration of biogenic carbon for the binder's production (i.e., bio-binder has a negative net GHG impact for its production). A bio-binder without SBS would offer a reduction of around 58.9% in GHG emissions per unit mixture, whereas with SBS a reduction of 43.3% could be found. On the other hand, regarding the costs for such a technology, given the bio-binder is not yet a commercialised product its costs would not make it yet viable (where its unit cost would be around double a PMB). However, with its further development (as it has been already included in pilot projects, as stated previously) its costs will be seen to gradually decrease over time, making its implementation more viable. With these considerations, both cases for this mitigation strategy received a negative final *I* score.

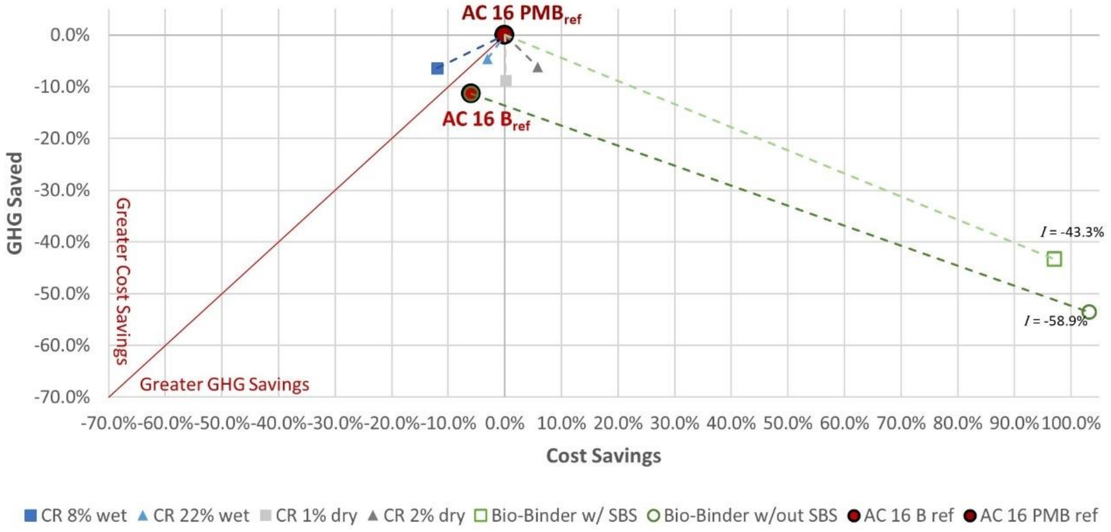

Figure 4.19. Benefit-cost results for the bio-binder mitigation strategy.

4.3.3.1.4 *Comparison of Strategies*

In order to gain a holistic vision of the mitigation strategies considered, the *I* score of the pathways previously considered are summarised in Figure 7. From these pathways it was possible to select the most environmentally and economically viable and the most unviable strategies. From these results, it was possible to understand the variance between the strategies.

From this figure, it is possible to see that manufacturing asphalt mixtures below 100°C and using high amounts of RAP with high residual binder (RAP sourced on-site) would provide the most viable solutions. At high RAP amounts, the use of a bio-oil rejuvenator should also be used, which would be more environmentally friendly when biogenic carbon is considered. However, if the RAP was to be sourced off-site, this could drastically affect the RAP benefits. Furthermore, as it stands, high amounts of RAP are not always available or are implemented in practice. With this consideration, the benefits of the CR can be highlighted. Where, the 8-22% wet-process and 1% dry-process CR-based mixtures had a higher or similar *I* score compared to the 15% RAP cases. Thus, by only modifying a small amount of the mixture with CR (compared to the 15% by weight of the mixture for the RAP-based mixtures), significant environmental and economic savings could be found; in turn, also probably having a positive effect on durability given that the properties of the binder influence the long-term performance of bituminous mixtures (Moreno-Navarro et al., 2017).

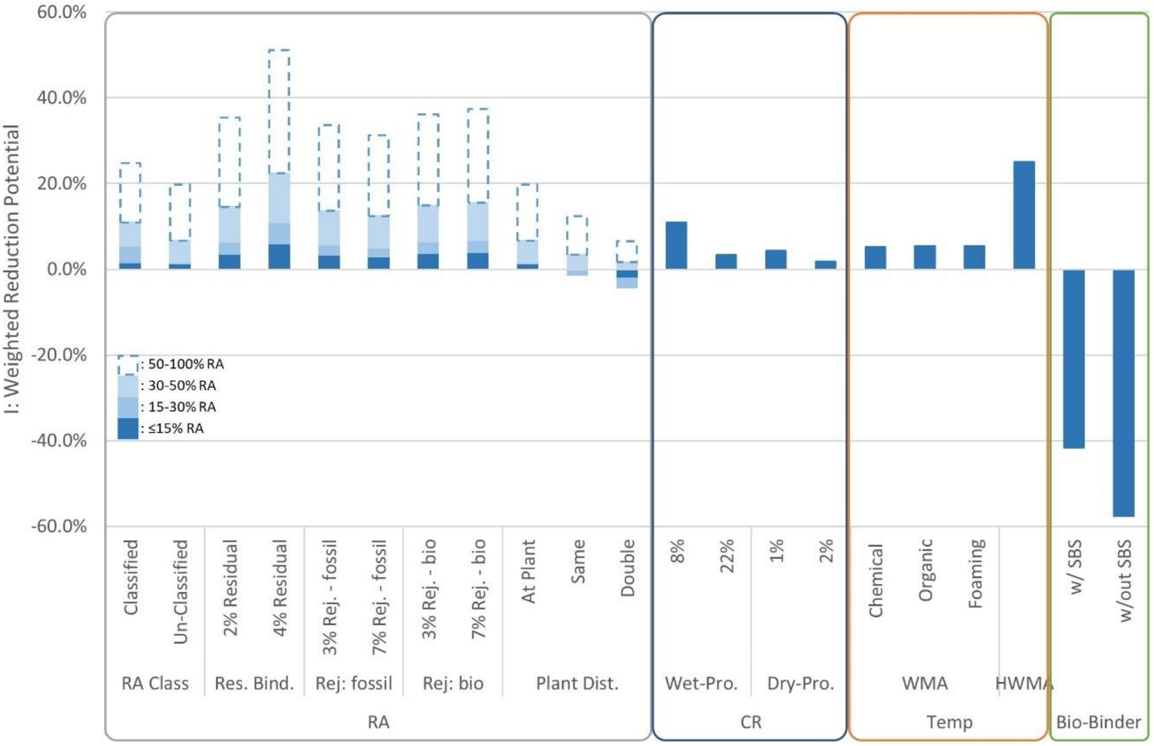

Figure 4.20. Comparison of weighted reduction potentials according to defined *I* indicator.

4.3.3.1.5 Comparison of Case Studies

Figure 8 shows the results for the asphalt mixture case studies considered from Section 4.3.2.1.5. They are represented on top of the results for the upper and lower RAP, and average CR, temperature and bio-binder individual strategies to better enable their comparison.

From Figure 8, it is possible to distinguish the environmental and economic benefits of the case study mixtures which consider the various mitigation strategies. The case study which provides the largest benefit, according to the defined scoring mechanism, is the HWMA with 100% RAP. This is apparent given the previous findings, where the HWMA and high RAP amounts were the two mitigation strategies with highest potential. However, the application of such a mixture could only be suitable for lower traffic roads, given the technology readiness level of high-RAP low-temperature mixtures.

Regarding the CR-based mixtures, it can be seen that both the use of the wet- and dry-processes provide a strong *I* score output. The most environmentally and economically viable of which was for the mixture also with a reduced temperature (i.e., WMA). The aforementioned cases all provided both GHG and cost savings, meanwhile the bio-HMA with 50% RAP provided the largest environmental benefit, but would incur an increase in costs compared to a reference modified mixture; due to the non-commercialised nature of this binder, as previously mentioned. However, this increase in cost was reduced, compared to the baseline bio-mixture with no RAP, given the presence of the residual binder on the RAP. Therefore, for the cost-efficient implementation of novel bio-binders, the use of RAP would be very worthy of consideration during the mix design stage.

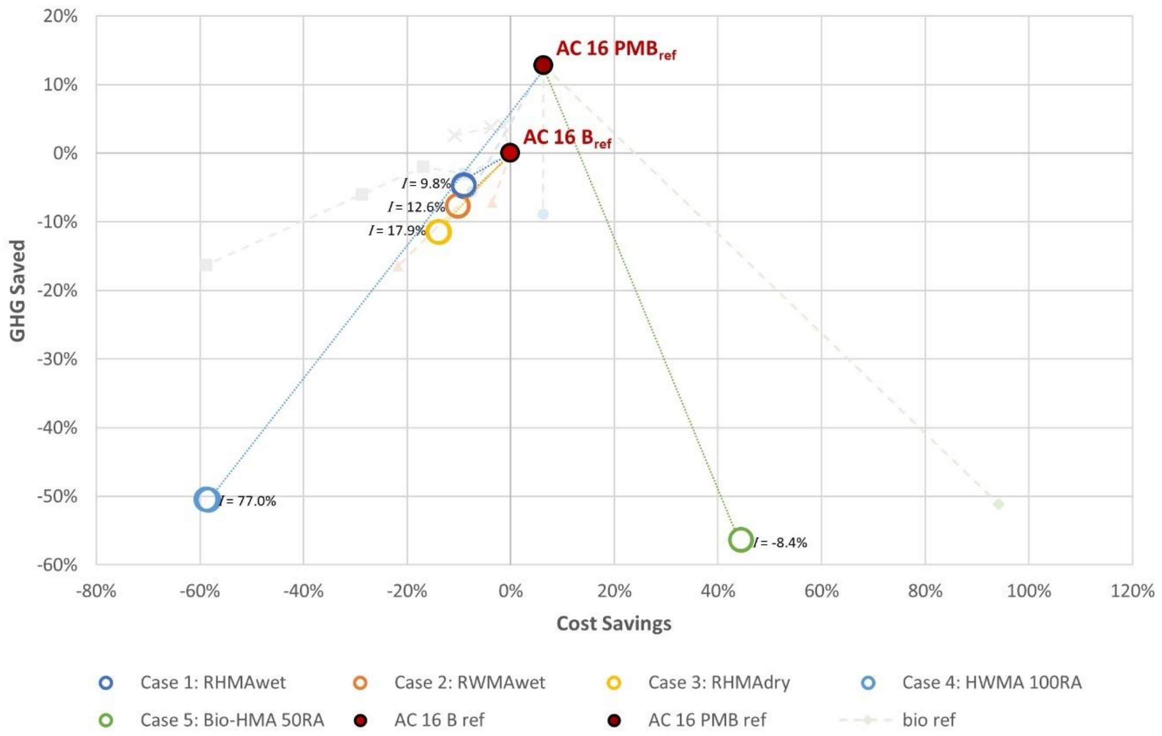

Figure 4.21. Comparison between case studies considered.

4.3.3.2 Step 2: Strategy Viability across the Life-Cycle

Figure 9 shows the environmental and economic life-cycle results for the case study alternatives considered. The error bars represent the +28.6% and -42.9% change in durability for the sensitivity analysis undertaken.

From the results of the life-cycle analyses considering pavement durability, it is possible to see that the HWMA 100RAP and bio-HMA 50RAP would provide a GHG reduction of over 19.2 and 19.3%, respectively, across their service life at the same durability as the reference mixture. This was also roughly applicable for the life-cycle cost of the HWMA (20.1%), yet the bio-HMA would require a longer service-life for it to be economically viable (11.6%); due to the reasons stated in the previous sections.

Regarding the CR mixtures, compared to the PMB reference mixtures, an overall environmental and cost benefit was found. Environmentally, the replacement of a PMB (3.5% SBS) with a CR-based binder would a binder with a GHG saving of 5.2% (1% over the conventional un-modified mixture). If this binder were also to be warm-mix, this mixture would be environmentally equivalent to the conventional mixture, yet would be using waste materials and the CR-based binder could increase the pavement's service-life. From the results of this study, the use of CR via the dry-process was found to be the most environmentally (-1.6%) and economically (-5.9%) viable technology; this could be associated to it not needing to be incorporated into the binder prior to mix production (which requires further energy inputs). The aforementioned CR-based mixture manufactured as a warm-mix would also provide a similar economic saving at (-4.8%).

Regarding the results of the durability sensitivity analysis, both environmentally and economically a similar increase in savings was found for the increase in surface course service-life (7.1% environmentally and 6.4% economically on average at 28.6% increase). For these case studies, the same number of operations were required over the 40-year analysis period as the baseline study (two mill and fill to correct surface roughness) and the increase in savings was found due to the increase service-life per operation (i.e., an increase in residual service-life). Alternatively, with a 50% higher decrease in durability (-42.9%) considered for the sensitivity analysis, a structural rehabilitation operation would be required. In turn, this greatly increased both the emissions and costs for case studies considered over the modelled analysis-period in this study (87.4% environmentally and 40.4% economically on average). The environmental increases witnessed were larger due to in LCA the "time value of money" is not included in the analysis (i.e., discount rate) (Harvey et al., 2016).

Previous studies have also commented on the use of CR increasing the initial environmental burdens of mixtures (16% and 11-14%, respectively (Chiu et al., 2008; Farina et al., 2017)), yet these impacts would typically be offset by the increase in durability found. Considering the results for the increase in durability found in this study, in all cases the use of a CR-based mixtures would be more environmentally and economically viable; more significantly for the CR-based HMA mixture, which originally emitted and cost more than the un-modified conventional mixture.

It must also be considered that the price of bitumen can fluctuate depending on the oil market. These fluctuations can be seen between the guideline prices provided for Spain (Ministerio de Fomento, 2016) and a study carried out in Spain a year later (de León Alonso et al., 2019). Therefore, pavement designers must also be conscientious of a post-fossil-based infrastructure, and that the use of alternative materials (e.g., bio-based materials) will have to become a reality. This, in turn, would also greatly benefit the GWP of bituminous mixtures.

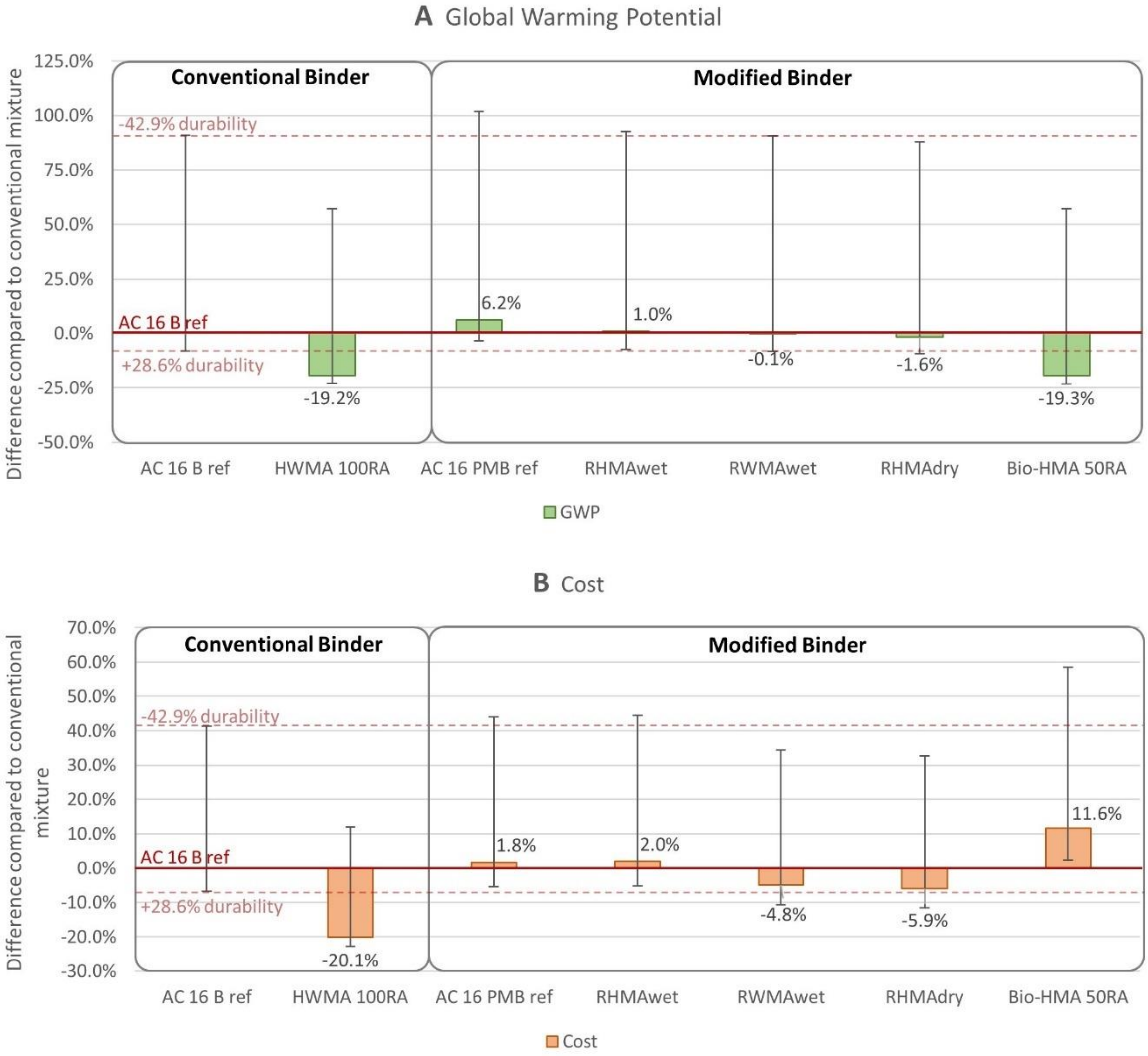

Figure 4.22. Permissible durability of the case study mixtures according to their 40-year service life emissions and costs.

4.3.4 Conclusions

This study assessed the viability of three climate abatement strategies for the design and construction of asphalt pavements, namely: 1) incorporation of waste materials, 2) reduced-temperature manufacturing, and 3) use of bio-materials. Their benefits and drawbacks were assessed both parametrically, combined through the use of case studies, and across their service-life with a 40-year analysis period. To ease their comparison, an environmental-economic indicator was also defined.

Overall, high quantities of RAP and producing mixtures below 100°C would provide the greatest environmental and cost benefits. However, the viability of RAP could greatly reduce when its haul distance is increased. Given that high RAP use would probably have high technical limitations (due to its technology readiness level), the use of CR coupled with reduced manufacturing temperatures (WMA) could be a more viable alternative to save both GHG emissions and costs. If just one strategy were to be selected, CR-based mixtures were found to be more or equally beneficial than the RAP at lower quantities (e.g., 15%). This benefit would be further pronounced if the pavement was found to have a higher durability (a case seen in practice and literature). Bio-based materials would provide a large GHG saving potential, when considering biogenic carbon, but they currently would need to be commercialised to be economically viable; where their high cost can be offset by the use of RAP with residual binder.

Comparing the case studies across a 40-year analysis period, to the un-modified and PMB reference mixtures, the two case studies considering large RAP amounts combined with another of the mitigation strategies (reduced production temperature in one case, and bio-binder in another) were found to have the lowest GHG emissions; yet would have a more uncertain technology readiness level. Regarding the CR-based mixtures, over the same analysis period, the dry-process CR-modified mixture case study was found to be the most environmentally and economically viable. The WMA wet-process case was the second-most economically viable, and the use of wet-process CR binders would offer savings compared to the PMB mixtures (to the magnitude of being equivalent to the un-modified mixture). If the CR-based mixtures were to have a higher durability than the conventional mixture, all the CR mixtures would provide an environmentally and economically more viable alternative to the conventional reference mixture with a non-modified binder.

The mitigation strategies defined are based on literature, primary data and the authors' experience. To further enhance the results of this study and provide more accurate results for local agencies, surveys would need to be undertaken to quantify specific case-study environmental and cost savings and the ease of implementation for the mitigation strategies on site. From these results it could also be possible to better understand permissible thresholds for the emissions and costs of the studied strategies in a more local context. Furthermore, further emission impact categories could be considered, depending on the local targets of the analysis area (i.e., smog creation or particulate matter for urban areas).

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4.3.6 Appendix

Table A1 provides details on the environmental and economic database used for the benefit-cost analysis.

Table A1. Environmental and economic inventory sources.

Related Stage	Unit	Material/ Process	Source	
			GWP	€
A1 – Material Extraction	t	Conventional bitumen	(Eurobitume, 2019)	(Ministerio de Fomento, 2016)
	t	Polymer-modified bitumen	(Eurobitume, 2019, 2012)	(Ministerio de Fomento, 2016)
	t	Cement filler	(MITECO, 2017)	(Ministerio de Fomento, 2016)
	t	Fine aggregate	(UEPG, 2015)	(Ministerio de Fomento, 2016)
	t	Coarse aggregate	(UEPG, 2015)	(Ministerio de Fomento, 2016)
	t	Classified RA	(Sampedro et al., 2012), verified with (Mukherjee, 2016)	Non-commercialised material
	t	Un-classified RA	(Sampedro et al., 2012), verified with (Mukherjee, 2016)	Non-commercialised material
	t	Crumb rubber	(Ecopneus, 2013) kWh, for Spain's electrical grid using (RED Eléctrica de España, 2019) and (Ecoinvent, 2019)	Supplier
	t	Crumb rubber-modified binder	(Bartolozzi et al., 2012)	(de León Alonso et al., 2019)
	t	Bio-binder with SBS	Supplier	Supplier estimate
	t	Bio-binder without SBS	Supplier	Supplier estimate
	t	Rejuvenator: tar-based	Ecoinvent: treatment of coal tar, in industrial furnace 1MW, GLO	Assumed equal to bio-based
	t	Rejuvenator: bio-based	Supplier	Market value for palm-based bio-oil
	t	WMA additive: chemical	(Ingevity, 2020)	Supplier

	t	WMA additive: organic	Ecoinvent: non-ionic surfactant production, fatty acid derivate	Supplier
A2 – Transport	t-km	Truck transportation	EcoInvent: transport, freight, lorry >32 metric ton, EURO6, GLO	(Ministerio de Fomento, 2016)
A3 – Mixture Production	t	Hot-mix	(Vidal et al., 2013)	(Ministerio de Fomento, 2016)
	t	Warm-mix	(Vidal et al., 2013)	Extrapolated from (Ministerio de Fomento, 2016)
	t	Half-warm-mix	(Rubio et al., 2013)	Extrapolated from (Ministerio de Fomento, 2016)
A4 – Transport	t-km	Truck transportation	EcoInvent: transport, freight, lorry >32 metric ton, EURO6, GLO	(Ministerio de Fomento, 2016)
A5 – Construction	m^2	Vibratory roller	(Moral Quiza, 2016)	(Ministerio de Fomento, 2016)
	m^2	Pneumatic roller	(Moral Quiza, 2016)	(Ministerio de Fomento, 2016)
	m^2	Paver	(Moral Quiza, 2016)	(Ministerio de Fomento, 2016)
B4 – Replacement	m^2	Miller	(Moral Quiza, 2016)	(Ministerio de Fomento, 2016)

CHAPTER 5. Conclusions

This doctoral thesis focused on optimising pavement life-cycle assessment (LCA) by quantifying the relative importance of data quality and design parameters on final results and improving result interpretation in accordance with the reporting needs of environmental sustainability assessment. Specifically, the influence of data variability and uncertainty on final LCA results was reviewed, along with the cost-effectiveness of pavement climate mitigation strategies according to the most influential processes within pavement LCA. Through this aim, pavement LCA users and decision makers will be able to make more reliable and informed, and in turn, more efficient decisions. The general conclusions of this thesis can be summarised as follows:

- From the literature review, considering current voluntary environmental assessment reporting, LCA was found to mainly be a process-based task, rather than an output-based one. This means that LCA-based credits are primarily awarded for reporting, but not providing an alternative cleaner design or implementing the results found. However, the need for LCA has been recognised given its high credit weighting within the seven leading systems studied.
- At the data collection level, not all open-access data sources provided all energy and emissions data in the final impact categories. Raw material extraction sources (stage A1, EN 15804) were found to be the most complete in this study and required minimal impact calculation efforts. The transportation (A2 and A4) and construction (A5) stages were found to require more intermediary steps for impact category calculation, which could incur further error in the results.
- Raw material extraction (A1) impact variability was found to be primarily due to temporal variance, where emissions reduced over time, due to technological advancements over time. A 17.3% increase in bitumen transportation (A2) global warming potential (GWP) was also found from re-calculating the naval transportation for the authors' region, compared to the European source; translating to a 2.5% increase in binder emissions. Conventional mixture production (A3) variability was observed to be mainly due to geographical variance considering the data collected, although many sources did not report temperature and plant type, only mix temperature category. The transportation (A2 & A4) and construction (A5) stage variabilities were largely due to variations in fuel consumption reporting.
- LCA results indicate that the most impacting input parameters contributed the largest to final result uncertainty. This was found for binder and cement filler production (33, 23% impacts and 12, 31% uncertainty, average across impact categories) and plant operations (32% impacts and 21% uncertainty, average across impact categories). However, some low impact processes could also largely influence final result uncertainty, such as sand production, truck transportation, half-warm manufacturing and construction machinery; affecting impact categories differently too).
- Material production (stage A1) input parameters were found to be most influential for the non-renewable energy, GWP and particulate matter formation impact category uncertainties, whilst plant operation (stage A3, using fuel oil) was most significant for acidification potential, photochemical ozone creation and again particulate matter formation in this study. As well as the material production stage, the transportation stages (A2 & A4) largely influenced GWP uncertainty too.
- Comparing the cost-effectiveness of the climate change mitigation case studies, the GWP-cost indicator developed was successfully used for strategy comparison, both for asphalt products and across a 40-year analysis period.
- Considering single climate change mitigation strategies, mixtures replacing virgin aggregates with high amounts of reclaimed asphalt pavement (RAP, beyond 30-50$_{wt}$%) were found to be most

environmentally and economically viable (with residual binder and rejuvenator considerations). Meanwhile, the use of a crumb rubber (CR) additive (8-22$_{bin}$% wet- or 1-2$_{wt}$% dry-process) was found to be more or equally beneficial than aggregate replacement at lower RAP quantities (0-15$_{wt}$%), when compared to a polymer-modified binder mixture. This suggests that for RAP to have a viable impact on GWP reduction, its benefit threshold should be determined. RAP viability was also found to greatly reduce if its haul distance is increased.

- A positive correlation was found between decreasing mix production temperature and GWP-cost viability, regardless of warm-mix additive. Warm-mix production (135°C) was found to have a similar reduction potential to lower-RAP and CR additive mixtures, while half-warm (<100°C) production to higher RAP amounts.
- Across a 40-year analysis period, the two case studies considering large RAP amounts combined with another of the mitigation strategies (<100°C production with 100% RAP in one case, and bio-binder with 50% RAP in another) were found to have the lowest GWP, compared to a conventional reference mixture. The use of bio-binder, despite its large GWP savings, was not found to be economically viable yet.

Based on the results of this thesis, pavement LCA uncertainty could be reduced by paying special attention to the acquisition of environmental impact data for materials and manufacturing parameters, given they were found to provide the largest result uncertainty and highest influence on LCA results. Thus, being most susceptible for causing inaccurate or misleading LCA results. Additionally, when aiming to optimise environmental pavement design via LCA, the replacement of virgin aggregates with high amounts of RAP was found to be one of the most cost-effective methods. At lower amounts of RAP, the use of lower production temperatures should be considered, or a CR-based additive if a modified-binder mixture is desired, given these two strategies were the second most influential.

CAPITULO 5. Conclusiones

La presente tesis doctoral se centró en la optimización del análisis del ciclo de vida (ACV) de los pavimentos mediante la cuantificación de la importancia relativa de la calidad de los datos y los parámetros de diseño en los resultados finales, y mejorar la interpretación de los mismos, de acuerdo con las necesidades de las normas de la evaluación de la sostenibilidad medioambiental. En concreto, se revisó la influencia de la variabilidad e incertidumbre de los datos en los resultados finales del ACV, así como la rentabilidad de las estrategias de mitigación climática de los pavimentos según los procesos más influyentes dentro del ACV. De esta forma, con el uso del ACV se podrán tomar decisiones más fiables y a la vez más eficientes desde el punto de vista de la totalidad del ciclo de vida de los pavimentos.

Las principales conclusiones de esta tesis son las siguientes:

- A partir de la revisión de los sistemas de certificación ambientales para carreteras, se encontró que el ACV es principalmente una tarea basada en el proceso, más que en el resultado. Es decir, que los créditos basados en el ACV se conceden principalmente por informar, pero no por aplicar los resultados a la hora de llevar a cabo un diseño alternativo más limpio. No obstante, la presencia de la metodología de ACV en todos los sistemas estudiados indica la idoneidad de la herramienta.
- A nivel de recopilación de datos, no todas las fuentes de datos de acceso libre proporcionaron los datos de energía y emisiones en las categorías de impacto finales. Las fuentes de extracción de materias primas (etapa A1, EN 15804) resultaron ser las más completas en este estudio, requiriendo un menor esfuerzo de recuperación. Las etapas de transporte (A2 y A4) y de construcción (A5) requirieron más pasos intermedios para el cálculo de las categorías de impacto, lo que podría dar lugar a más errores en los resultados.
- La variabilidad del impacto de la extracción de materias primas (A1) se debió principalmente a una variación temporal, ya que las emisiones se redujeron con el tiempo. Se encontró un aumento del 17,3% en los impactos del transporte del betún al recalcular el transporte naval para la región de los autores, España, en comparación con la fuente europea; lo que se tradujo en un aumento del 2,5% en las emisiones del ligante. Se observó que la variabilidad de la producción de la mezcla convencional (A3) se debía principalmente a la variación geográfica teniendo en cuenta los datos recogidos, aunque muchas fuentes no informaban de la temperatura y el tipo de planta, sino sólo de la categoría de la temperatura de la mezcla. Las variabilidades de las etapas de transporte (A2 y A4) y construcción (A5) se debieron en gran medida a los distintos consumos de combustible.
- Los resultados del ACV indican que los parámetros de entrada con mayor impacto contribuyeron a las mayores incertidumbres en los resultados finales, estos son: la producción de betún y cemento (33, 23% impactos and 12, 31% incertidumbre, valores medios de todas las categorías de impacto) y las operaciones de la planta (32% impactos and 21% incertidumbre, valor medio de todas las categorías de impacto). Sin embargo, algunos procesos de bajo impacto también podrían influir en la incertidumbre de los resultados finales (afectando de forma diferente a las distintas categorías de impacto), como la producción de áridos, el transporte por camión, la fabricación de mezclas templadas y la maquinaria de construcción.
- Los parámetros de entrada de la producción de materiales (etapa A1) resultaron ser los más influyentes para las incertidumbres de la categoría de impacto de energía no renovable, potencial de calentamiento global (GWP) y potencial formación de partículas ($PM_{2.5}$), mientras que el funcionamiento de la planta (etapa A3, que utiliza fuel) fue el más significativo para el potencial de acidificación del suelo y de los recursos de agua, la formación de ozono troposférico y otra vez

la formación de partículas. Además de la etapa de producción de materiales, las etapas de transporte (A2 y A4) también influyeron en gran medida en la incertidumbre del GWP.

- Al comparar la rentabilidad de los estudios de caso de las estrategias de mitigación del cambio climático, el indicador de GWP-coste desarrollado se utilizó con éxito para análisis de las estrategias en donde se utilizan productos asfálticos (considerado un periodo de ciclo de vida de 40 años).
- Considerando las estrategias individuales de mitigación del cambio climático, las mezclas que sustituyen a los áridos naturales por altas cantidades de RAP (más allá del 30-50% por unidad de peso) resultaron ser las más viables desde el punto de vista medioambiental y económico (incluido el efecto derivado del ligante residual y de los rejuvenecedores) Mientras tanto, el uso de un aditivo de polvo de neumáticos fuera de uso (CR, 8-22% por peso ligante para el proceso húmedo, o 1-2% por peso mezcla para el proceso seco) resultó ser más o igual de beneficioso que la sustitución de los áridos en cantidades más bajas de RAP (0-15% por peso de mezcla), en comparación con una mezcla con ligante modificada con polímeros. Esto sugiere que para que el RAP tenga un impacto viable en la reducción del GWP, debe utilizarse en proporciones altas. También se comprobó que la viabilidad del RAP se redujo en gran medida si se aumentaba su distancia de transporte.
- Se encontró una correlación positiva entre la disminución de la temperatura de producción de la mezcla y la viabilidad del coste del GWP, independientemente del aditivo elegido. Se comprobó que la producción de mezcla semicalientes (135°C) tenía un potencial de reducción similar al de las mezclas con menor cantidad de RAP y aditivo CR, mientras que la producción templada (<100°C) a cantidades mayores de RAP.
- A lo largo de un periodo de análisis de 40 años, los dos casos de estudio que consideraban grandes cantidades de RAP combinadas con otra de las estrategias de mitigación (producción a <100°C con 100% de RAP en un caso, y bio-ligante con 50% de RAP en otro) resultaron tener el menor GWP, en comparación con una mezcla convencional de referencia. El uso del bio-ligante, a pesar de su gran potencial de ahorro de GWP, no resultó económicamente viable.

Basándose en los resultados de esta tesis, la incertidumbre de los resultados a aplicar el ACV en el pavimento podría reducirse prestando especial atención a la adquisición de datos de impacto ambiental para los materiales y los parámetros de fabricación, ya que se ha demostrado que son la fuente más importante de la incertidumbre de resultados y la mayor influencia en los resultados del ACV. Por lo tanto, serían los más susceptibles de causar resultados de ACV inexactos o engañosos. Además, cuando se pretende optimizar el diseño del pavimento desde el punto de vista ambiental utilizando ACV, la sustitución de los áridos naturales por altas cantidades de RAP resultó ser una de las formas más rentables. Con cantidades más bajas de RAP, debería considerarse el uso de temperaturas de producción más bajas, o un aditivo basado en CR si se desea una mezcla de aglutinante modificado, dado que estas dos estrategias fueron las segundas más influyentes.

CHAPTER 6. Future Research

From the development of the work in this doctoral thesis, several areas of future research lines were identified to have the potential for being explored in further detail. Firstly, regarding sustainability rating systems (SRS), future work should consider the implementation of systems in case study projects to better determine possible LCA application issues, especially for pavement maintenance projects, and to quantify the overall net benefit of LCA use on SRS in projects. This would ideally be carried out in a variety of regions to also understand the impact of regional contextuality on project scores and the potential for scoring boundary modifications (i.e., to adhere to local regulations). Additionally, as the LCA science develops and becomes more harmonised, it must be seen how LCA outcomes are to be incorporated into the credits; transitioning away from the current process-based LCA use (i.e., to just report, and not act upon). This could also be supplemented by reviewing other rating systems in other sectors, and provide recommendations for pavement-applicable LCA systems.

Secondly, while this study has provided understanding on the variabilities and uncertainties of open-source data and generated a reliable database with less risk, there is a much-needed push for policy makers to enforce environmental reporting. As a result, more primary data can be collected and used, thus lowering uncertainties. Additionally, future work should focus on better understanding the variance between open-source and commercial tools and the exploration of further life-cycle stages (i.e., use, maintenance and rehabilitation, and end-of-life). As a priority of open-source LCI, the particulate matter formation potential impact category needs to be better explored for reclaimed asphalt pavement (RAP), given the importance of respiratory inorganics according to the European Commission’s impact assessment guide and the material’s popularity.

Finally, while the mitigation strategies defined are based on literature, primary data and the authors’ experience, surveys would need to be undertaken with local agencies to quantify specific case-study environmental and cost savings and the ease of implementation for the mitigation strategies on site. Through this, it would be possible to better understand the permissible thresholds for the emissions and costs of the studied strategies in a more local context. Furthermore, further emission impact categories could be considered, depending on the local targets of the analysis area (i.e., photochemical ozone creation potential (or smog creation) or particulate matter formation potential for urban areas). To improve the understanding of impact thresholds, standard durabilities for mixture classes should be ascertained and mechanistic-empirical pavement design outputs assessed; likely requiring the use of probalistic methods.

CAPITULO 6. Líneas Futuras de Investigación

A partir del desarrollo del trabajo en esta tesis doctoral, se identificaron varias áreas de líneas de investigación futuras que podrían ser estudiadas con mayor profundidad.

En primer lugar, en lo que respecta a los sistemas de certificación, los trabajos futuros deberían considerar su utilización en la fase de proyecto. Un estudio generalizado y extendido a varias regiones permitiría conocer la influencia de la ubicación del proyecto en los resultados previsibles a la hora de aplicar el ACV.

En segundo lugar, aunque este estudio ha permitido comprender las variabilidades e incertidumbres de los datos de fuente abierta y ha generado una base de datos fiable con menos riesgos, el acceso a bases de datos comerciales, de aplicación en el sector, se lleva a cabo de una forma ciega, sin apenas conocimiento de la naturaleza y procedencia de los datos utilizados. La armonización de ambos tipos de bases de datos se antoja esencial para la mejora del análisis y de la fiabilidad de los resultados obtenidos.

Por último, aunque las estrategias de mitigación definidas se basan en la bibliografía, los datos primarios y la experiencia de los autores, sería necesario realizar encuestas con los organismos locales para cuantificar los ahorros medioambientales y de costes específicos de los estudios de caso y la facilidad de aplicación de las estrategias de mitigación de forma local. De este modo, sería posible comprender mejor los umbrales admisibles para las emisiones y los costes de las estrategias estudiadas en cada uno de los contextos estudiados. Además, podrían considerarse otras categorías de impacto de las emisiones, en función de los objetivos locales de la zona de análisis (es decir, la creación de smog o el potencial de formación de partículas para las zonas urbanas). Para mejorar la comprensión de los umbrales de impacto, deberían determinarse las durabilidades estándar de las clases de mezcla y evaluarse los resultados del diseño mecanicista-empírico de los pavimentos, lo que probablemente requiera el uso de métodos probalísticos.

CHAPTER 7. References

This section lists the references used in Chapter 1 Introduction. The references and bibliography used in each of the papers that make up the compendium of publications are attached at the end of each of the corresponding chapters.

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