Università degli Studi di Palermo

SCUOLA POLITECNINA

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Strutture e Infrastrutture

S.S.D: ICAR/04 - Strade, ferrovie ed aeroporti

A thesis submitted to the Department of Engineering and the committee on graduate studies of the University of Palermo in fulfilment of the requirements for the degree of the European Doctor of Philosophy

Increasing the Circularity of asphalt mixtures: Integrated Sustainability and Circularity Assessment as a progress monitoring tool towards more Circular and Sustainable asphalt pavements

Ph.D. Candidate

Konstantinos Mantalovas

Advisors

Prof. Gaetano Di Mino, Prof. Orazio Giuffre

PhD Coordinator

Prof.ssa Antonina Pirrotta

Cycle XXIII A.A. 2020/2021

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IL DOTTORE

Konstantinos Mantalovas

IL SUPERVISORE

Prof. Gaetano Di Mino

IL COORDINATORE

Prof.ssa Antonina Pirrotta

Prof. Giuffre Orazio

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SMARTI ETN

Sustainable, Multifunctional, Automated, Resilient Transportation Infrastructure European Training Network (SMARTI ETN) is part of the Marie Curie Skłodowska actions for Research, Technological Development and Demonstration, and funded by H2020-EU.1.3.1, under grant n.721493. It is a four years project that started at the beginning of October 2016 and has offered training-through-research for 15 young researchers with a consortium of universities, research centres and companies/industries from different EU countries (UK, Italy, France, Ireland, Denmark, and Spain). The world's surface transport network has developed over thousands of years; emerging from the need of allowing more comfortable trips to roman soldiers to the modern infrastructure enabling modern vehicles to travel at high speed. However, in the last two decades, the world is changing very fast in terms of population growth, mobility and business trades creating greater traffic volumes and demand for minimal disruption to users, but also challenges such as climate change and more extreme weather events. At the same time, developments in digitalisation, vehicle design, mobile and wireless communications and sensor technologies continue apace. It is within this environment and in close consultation with key stakeholders, that this consortium considers of paramount importance the shift to SMARTI [Sustainable, Multi-Functional, Automated, Resilient Transport Infrastructures].

SUSTAINABLE

Designed by using improved decision frameworks aimed at improving durability, maximise recycling and minimising environmental, economic and social impacts

MULTIFUNCTIONAL

Conceived not for transport purposes only and towards optimisation of land use by adding energy harvesting capabilities

AUTOMATED

Equipped with low-cost, wireless sensors to allow pro-active communication towards a more intuitive use and a simplified management

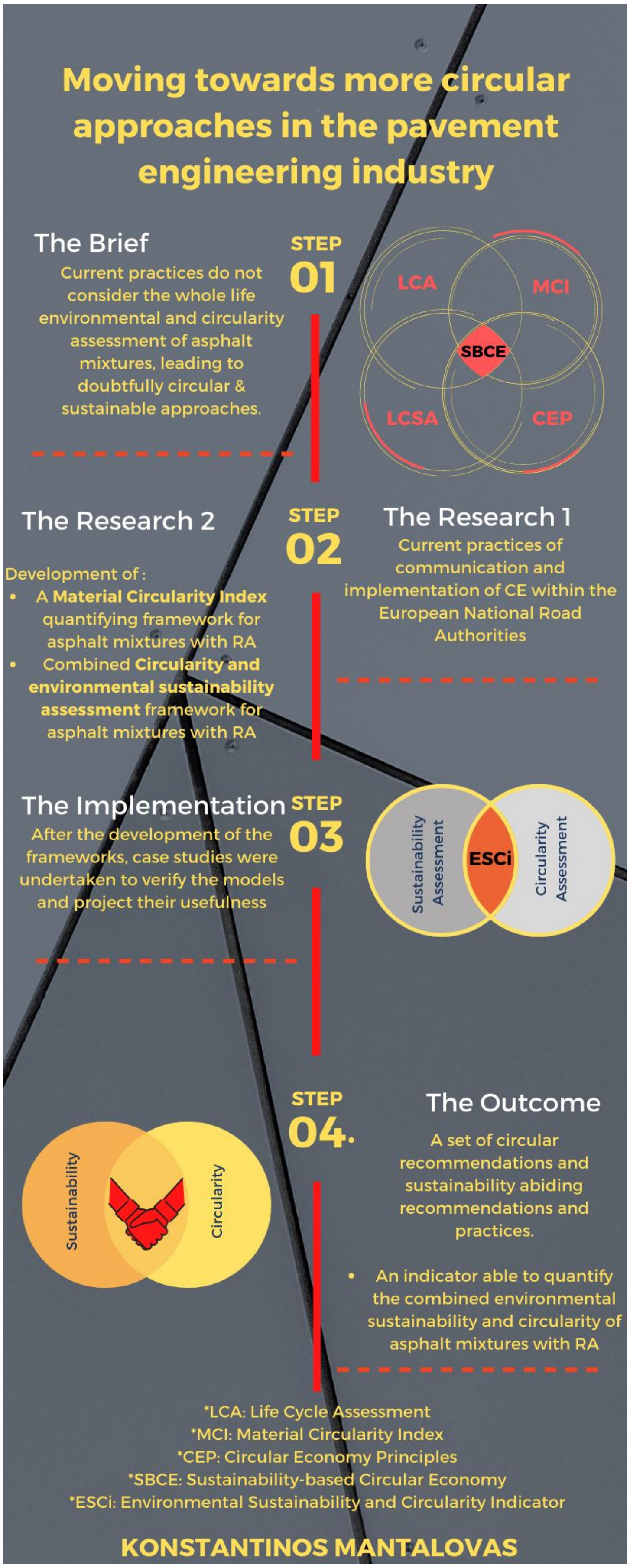
RESILIENT

Conceived to self-repair and be adaptable to changes due to natural and anthropogenic hazards

Preface

Sustainability and Circular Economy (CE) are two concepts that lately have been profoundly linked to each other. The road engineering industry has gradually been adapting practices that are considered both circular and sustainable. However, not all of these practices entirely consider the whole life environmental and circularity assessment and implications of asphalt mixtures.; which in turn leads to doubtfully circular and sustainable approaches. For this reason in this thesis, after analysing the ways that National Road Authorities implement and communicate CE through questionnaires and web searches, a Material Circularity Index quantifying framework, based on the proposed methodology of the Ellen MacArthur Foundation, for asphalt mixtures was developed to assess their circularity. Within this framework, aspects relevant to the mechanical performance of the asphalt mixtures have also been incorporated. Furthermore, in order to also include the aspect of sustainability, a combined circularity and environmental sustainability assessment framework and indicator for asphalt mixtures with reclaimed asphalt was developed; by utilising the Material Circularity index methodology and the well-established framework of Life Cycle Assessment. The development of the frameworks was followed by case studies that verified the models and projected their usefulness towards more informed decisions when it comes to more circular and sustainable asphalt mixtures. Results of this thesis highlight that National Road Authorities are still facing a plethora of challenges towards the implementation and communication of CE, along with lack of knowledge and incentives. They do implement CE principles such as recycling and preventive maintenance, but they do not utilise metrics to assess their performance. By utilising the proposed indicator and frameworks circular and sustainable recommendations could be drawn along with a knowledge development map for the involved stakeholders. Most importantly, it was deduced that practices that are considered sustainable and highly circular, after the combined sustainability and circularity assessment , were actually found not to be what believed so far. Thus, when it comes to asphalt mixtures and their life cycles, during the decision-making process, each CE-related action must be thoroughly investigated case by case.

Graphical Abstract



Publications included in the current thesis

All the Chapters of this thesis have been published as parts or slightly modified parts of the following international publications:

- **"European National Road Authorities and Circular Economy: An insight into their Approaches"** *published in the international Open Access journal "Sustainability" of MDPI under an open access Creative Commons CCBY 4.0 license and has thus, been reproduced here with the mission of the copyright holder[https://doi.org/10.3390/su12177160]*
- **"The Sustainability of Reclaimed Asphalt as a Resource for Road Pavement Management through a Circular Economic Model"** *published in the international Open Access journal "Sustainability" of MDPI under an open access Creative Commons CCBY 4.0 license and has thus, been reproduced here with the permission of the copyright holder [https://doi.org/10.3390/su11082234]*
- *"**Integrating Circularity in the Sustainability Assessment of Asphalt Mixtures**" published in the international Open Access journal "Sustainability" of MDPI. The article is licensed under an open access Creative Commons CCBY 4.0 license and has thus, been reproduced here with the permission of the copyright holder. [https://doi.org/10.3390/su12020594]*

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List of Abbreviations

LCA: *Life Cycle Assessment*
LCSA: *Life Cycle Sustainability Assessment*
LCCA: *Life Cycle Cost Analysis*
S-LCA: *Social Life Cycle Assessment*
CE: *Circular Economy*
NRA: *National Road Authority*
EU: *European Union*
EC: *European Commission*
RA: *Reclaimed Asphalt*
UNEP: *United Nations Environmental Program*
WWF: *Worldwide Wildlife Fund*
IUCN: *International Union for the Conservation of the Nature*
WCS: *World Conservation Strategy*
WCED: *World Commission on Environment and Development*
UNCED: *United Nations Conference on Environment and Development*
SDS: *Sustainable Development Strategy*
EMS: *Environmental Management System*
EMAS: *Eco-Management and Audit Scheme*
EPD: *Environmental Product Declaration*
PCR: *Product Category Rules*
EAPA: *European Asphalt Pavement Association*
NAPA: *National Asphalt Pavement Association*
MRA: *Mixture with Reclaimed Asphalt*
CEM: *Circular Economic Model*
HWMA: *Hot and Warm Mix Asphalt*
RAP: *Reclaimed Asphalt Pavement*
ANAS: *Azienda Nazionale Autonoma delle Strade*
EMF: *Ellen MacArthur Foundation*
WTM: *Wheel Tracking Machine*
IRI: *International Roughness Index*
MPD: *Mean Profile Depth*
VOC: *Volatile Organic Compound*
CMU: *Circular Material Use*

List of symbols

ΔU ≡ F_{RA}: *RA placed rate*
QF[a]: *RA available factor*
QF[p]: *RA placed quantity factor*
RA[p]: *rate with which RA is utilised*
RA[a]: *rate with which RA becomes available*
G_{MRA}: *mass of the end product (asphalt mixture with RA)*
G: *mass of the dismantled pavement*
V: *mass of virgin feedstock used*
G_{RA}: *mass of the RA collected after dismantling*
P_{RA}: *Fraction of feedstock deriving from recycled sources*
E_T: *Efficiency of the recycling process during treatment phase*
E_P: *Efficiency of the recycling process during production phase*
W_{EOL}: *Amount of waste going to landfill or energy recovery*
W_T: *Quantity of waste produced during the recycling process*
W_P: *Quantity of waste produced during the production of any recycled content to be used as feedstock*
W: *Overall amount of unrecoverable waste*
LFI: *Linear Flow Index*
X: *Utility*
F[X]: *Utility factor built as a function to the utility of an end product*
MCI^*_{MRA}: *Material Circularity Indicator for asphalt mixtures with RA*
MCI_{MRA}: *Material Circularity Index for asphalt mixtures with RA*
L_{MRA}: *the actual average lifetime of the end-product*
M_{MRA}: *the average number of loading cycles before failure in terms of fatigue or rutting achieved by the end-product*
L_{av}: *the actual average lifetime of an industry average product*
N_{av}: *he equivalent number of loading cycles of an industry-average product of a similar type*
ESC_i: *Environmental Sustainability and Circularity Indicator*
LCA_T: *Aggregated, normalised, and weighted LCA results*
P_F: *Utility factor's performance fatigue parameter*
F: *average number of loading cycles before fatigue failure of the asphalt mixture*
F_{av}: *the actual average lifetime of an industry average asphalt mixture*
P_{PD}: *Utility factor's performance permanent deformation parameter*
P_D: *the average number of loading cycles before achieving a specific rutting depth value*
P_{Dav}: *is the equivalent number of loading cycles of an industry-average asphalt mixture before reaching the very same value of rutting depth*
$\prod_{i=1}^{n}[P_i]$: *Productor of all the quantified performances (fatigue & permanent deformation)*

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1.1 Sustainability and the environment

Sustainability based principles are increasingly been adapted by a plethora of companies, agencies, institutes, policy makers and governing bodies, within their vigorous efforts to "do business" and manage their activities in a more sustainable way. Key environmental, social and economic factors are being addressed and incorporated into their decision-making processes, by the adaptation of sustainability principles. However, this is not something completely novel. Sustainability-based considerations were not absent even in the past, being taken under consideration though, indirectly or informally. The last years, it can be observed that significant efforts are being made in order for the sustainability effects to be quantified and properly addressed. In addition, these efforts include several organised attempts for the sustainability to be actually incorporated into the decision-making process of transportation infrastructures and specifically in asphalt pavements [1].

As also emphasized by Kidd [2], [3] the concept of sustainability is not something that just emerged lately. It has a long history and it has actually been evolving through the passage of time. Different schools of thought have influenced sustainability and made it what it is today. Following the concept of "strong sustainability", which supports the idea of irreplaceable functions of the natural environment; sustainability frequently is translated to strictly environmental issues [4]. In detail, during the 1970s, the term sustainability started to be generally utilized in correlation to natural issues [2], [5]. In light of this and indirectly, the United Nations were pushed towards addressing environmental issues, related to the industrial pollution and in a broader sense, global environmental problems that were characterized as "barriers to development" [2]. For this very reason the United Nations held the conference on Human Environment in Stockholm, which took place in 1972. A significant outcome of this conference was the development of 26 principles, able to address timely environmental concerns by projecting the concept of Earth's carrying capacity [3], [6], [7]. One of the principles developed in the conference stated: "the capacity of the Earth to produce vital renewable resources must be maintained and, wherever practicable, restored or improved"[8]. Hence, the conference can be characterized as the stepping-stone for the UN to launch the United Nations Environmental Program (UNEP) and the development of a plethora of environmental agencies with the purpose of fulfilling the 26 defined principles throughout all the industrial sectors. Moreover, UNEP was at the time a firm supporter of the eco-development that was accordingly defined by them as "the yield of renewable resources and the simultaneous monitoring of the depletion of non-renewables"[9], [10]. After that, and in 1980, the UNEP along with the International Union for Conservation of Nature (IUCN) and the World Wildlife Fund (WWF) launched the World Conservation Strategy (WCS). It described "sustainable development" in the context of the conservation of natural resources combined with the improvements in human life and thus, its purpose was to support sustainable development via the detection of priority conservation issues [3], [4]. According to this strategy, conservation expresses the "management of human use of biosphere so that it may yield the greatest sustainable benefit to present generations while maintaining its potential to meet the needs and aspirations of future generations"[11]. Furthermore, in 1987 the well-known and widely accepted final report of the World Commission on Environment and Development (WCED) was presented. It was entitled "Our Common Future" and it provided a detailed overview of the current then, state of the environment along with the most acknowledged definition of sustainable development that is still used until today: "*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*"[12]. The WCED report was the spark that triggered the 1992 Rio Summit [4]. More importantly, during the 1992 UN Conference on Environment and Development (UNCED), that is also referred to as the "Rio Earth Summit", a global action plan was developed in order for global sustainable development to be achieved. What came out of the conference, were the Rio Declaration, the Commission on Sustainable Development, and Agenda 21. The latter was specifically focusing on available and potential best practices that could lead to the achievement of sustainable development, focusing though on environmental issues [4].

However, with a decrease in the momentum of sustainable development, during the Kyoto Conference on Climate Change in 1997, the failure of complying with the best practices proposed by Agenda 21 was highlighted. Multinational companies and corporations followed through and also tried to project a "reactive" way of operating when faced with environmental issues [13]. During the 1980s, given the developing guidelines on ecological protection, large organizations constrained their endeavours to comply with laws and prerequisites. In the 1990s partnerships started to receive an increasingly 'proactive' approach, through which they begun to attempt to envision the ecological impacts of their tasks and to acquire a business advantage from the administration of ecological execution. Since that point, companies had step by step endeavoured to insert natural concerns into their business rationale through developing the Environmental Management Systems (EMSs) [3]. They were "*systems and databases that integrate procedures and processes for training of personnel, monitoring, summarizing, and reporting of specialized environmental performance information to internal and external stakeholders of a firm*" [14]. EMSs are considered valuable tools that can help stakeholders to comply with the set regulations and prerequisites regarding their industrial activities and their levels of environmental pollution and waste production.

The European Commission also developed in 1993 the EMAS. It stands for Eco-Management and Audit Scheme (EMAS) and proposes a wide spectrum of indicators relevant to energy and material efficiency, emissions, biodiversity, water consumption and waste production. In 1997, sustainable development became a fundamental objective of the EU when it was included in the Treaty of Amsterdam as an overarching objective of EU policies. At the Gothenburg Summit in June 2001, EU leaders launched the first EU sustainable development strategy, based on a proposal from the European Commission. This strategy was composed of two main parts. The first proposed objectives and policy measures to tackle several unsustainable key-trends while the second part, arguably more ambitious, called for a new approach to policy-making that ensures the EU's economic, social and environmental policies mutually reinforce each other. The central instrument developed for this purpose was the obligation for the Commission to submit each new major policy proposal to an Impact Assessment. After a broad public consultation from August till October 2004, in February 2005 the European Commission issued a Communication with initial stock-taking and future orientations for the review. Subsequently in June 2005 the European Council adopted a set of guiding principles for sustainable development. In December 2005 the Commission presented a proposal for a reviewed strategy and platform for further action. The Commission's proposal was built based upon the 2001 strategy and advocated a shift in focus to take account of progress made, tackle shortcomings and take account of new challenges. The result was a renewed strategy for an enlarged EU, adopted by Heads of State and Governments at the European Council as of 15-16 June 2006. Moreover, the European

Commission adopted in October 2007 the first progress report on the Sustainable Development Strategy (complemented by a detailed staff working paper). According to the report, there have been significant policy developments in some of the seven key priorities identified in the revised SDS (Sustainable Development Strategy) of 2006 - including climate and energy - but progress on policy had not yet translated into substantial concrete action. Eurostat in 2007 published a monitoring report based on an extended set of sustainable development indicators. This report was one of the inputs for the first progress report on the Sustainable Development Strategy. Finally, in 2015, countries adopted the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals defined by the United Nations (UNs) [15]. This definition is focused on the concept of "needs not wants" and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs. The 17 Sustainable Development Goals are the blueprint to achieve a better and more sustainable future for all. They address the global challenges that the world faces, including those related to poverty, inequality, climate, environmental degradation, prosperity, and peace and justice. The 17 goals are:

- **Goal 1:** End poverty in all its forms everywhere
- **Goal 2:** End hunger, achieve food security and improved nutrition and promote sustainable agriculture
- **Goal 3:** Ensure healthy lives and promote well-being for all at all ages
- **Goal 4:** Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
- **Goal 5:** Achieve gender equality and empower all women and girls
- **Goal 6:** Ensure availability and sustainable management of water and sanitation for all
- **Goal 7:** Ensure access to affordable, reliable, sustainable and modern energy for all
- **Goal 8:** Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
- **Goal 9:** Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
- **Goal 10:** Reduce inequality within and among countries

- **Goal 11:** Make cities and human settlements inclusive, safe, resilient and sustainable
- **Goal 12:** Ensure sustainable consumption and production patterns
- **Goal 13:** Take urgent action to combat climate change and its impacts
- **Goal 14:** Conserve and sustainably use the oceans, seas and marine resources for sustainable development
- **Goal 15:** Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
- **Goal 16:** Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
- **Goal 17:** Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

1.2 Sustainability and the society

While the environmental aspect of sustainability was emerging within the sustainable development argument, social aspects were not ignored. For instance, the WCED's definition of Sustainable Development [12] addresses also the settlement of the needs of present and future generations. Dempsey et al. [16] state that the focus given to inter-generational equity by the WCED definition stresses social aspects, and particularly the key determinants of social equity, such as social justice, distributive justice and equality of conditions. [3], [17]. Under these circumstances, prohibition from participating in the social, monetary and political existence of a network was viewed as at the centre of the idea of social equity, since it could prompt prejudice and segregation [17]. Moreover, the social aspects of sustainable development could also be detected in the spectrum of corporations and has been specifically correlated to the term of social responsibility. By 1953 Howard Bowen's Social Responsibilities of the Businessman addressed the social responsibility of businessmen as "the obligations of businessmen to pursue those policies, to make those decisions, or to follow those lines of action which are desirable in terms of the objectives and values of our society" [18]. Bowmen's social responsibility constituted the steppingstone for the definition of Corporate Social Sustainability (CSR) during the 1960s [19]

.CSR refers to “businessmen’s decisions and actions taken for reasons at least partially beyond the firm’s direct economic or technical interest” [19]. It has also been suggested that a plethora of ”socially-responsible” decisions could be partly vindicated by the long-run economic gains of the firm; [20] while “social responsibility” in the final analysis implies a public posture toward society’s economic an human resources, as a willingness to see that those resources are used for broad social ends and not simply for the narrowly circumscribed interests of private persons and firms” [20]. Later on, around the 1980s and 1990s, different approaches to CSR emerged, such as stakeholder theory corporate citizenship [21] and business ethics [3], [22], [23].

According to the point of view of the United Nations and after the 1997 Kyoto Conference on Climate change, an essential aspect in order for the social concerns to be addressed was the development of the “Millennium Development Goals” (MDGs) established in 2000 for the period 2000–2015. The goals focused on a wide array of rights and needs, including aspects such as health, discrimination, equality and poverty. The summit that followed in 2002 in Johannesburg, on Sustainable Development (WSSD) exhibited a significant alteration in the momentum of sustainable development. A shift could be detected towards the social and economic development apart from the environment-related sustainable development that was prevailing [4]. Thus, a significantly beneficial change by focusing considerably more attention on social development issues had been achieved [3], [4]. Afterwards, in 2012, in Rio de Janeiro the United Nations Conference on Sustainable Development (UNCSD) took place. The Conference is also known as Rio+20. Within Rio +20 the UN agreed on the need for Sustainable Development Goals (SDGs) by emphasizing the importance of both social and environmental concerns and the need for a more comprehensive definition of the role of business for sustainable development.

1.3 Sustainability and the economy

The third pillar that has experienced development and belongs to the wider sphere of sustainability is the economy; or else the bidirectional relationship between industrial corporations and the hodgepodge of social and environmental dimensions of sustainability. Through their operational patterns and their activities, corporations and multinational companies significantly contribute to the depletion of natural resources, the production of wastes and emissions and in general the degradation of the natural ecosystems. This can be quite successfully be described by Gray [24]: "Capitalism and its destructive tendencies are manifest through its greatest creation—the corporation". However, corporations should instead move towards operation patterns that will allow them to use and consume resources at rates below the natural reproduction or at rates below the development of substitutes. Moreover, as Dyllick and Hockerts [25] suggest, companies should not engage in operations that could degrade ecosystems but instead they should produce emissions and waste at rates that would allow them to be absorbed and assimilated by the planet's natural sinks. In this way not only eco-efficiency, but also eco-effectiveness could be achieved [25]–[29]. If someone was to "stare" at sustainability from a business perspective, they would probably witness glimpses of productivity, financial prosperity, environmental and social asset management, and a tendency for time-lasting business models. In other words sustainability from a businessman perspective can be characterized as "the business of staying in business" [30]. Others have also attempted to define sustainability separately for the business sphere as: "meeting the needs of a firm's direct and indirect stakeholders without compromising its ability to meet the needs of future stakeholders as well" [3], [25]. It can thus, be seen that in this respect, an intrinsic paradox between sustainability and corporations has emerged [24], [31]. Powerful corporations are considered by the governmental bodies as inevitable means of sustainability implementation through their power over society and their control of large-scale innovation production. However, they are constantly -and probably correctly- accused of having the largest part of the pie when it comes to the depletion of natural resources, pollution, waste production and social inequalities creation. This paradox is still a proof that social, environmental and economic aspects integrated into the sphere of sustainability must furtherly be analysed and their intertwined relationship should be more clearly defined; although that would require vast amounts of philosophical and ethical debates.

1.4 Sustainability and the transport engineering sector

Now, transport is one of the main pillars of societies to guarantee their consistent development and, within transport infrastructures, roads are one the most impactful aspect, in terms of environmental, social, and economic impacts. Thus, it can easily be deduced that the transport engineering sector has the potential of impacting the sustainability levels of societies in a regional or even a global way in terms of social, economic, and environmental aspects. According to the European Asphalt Pavement Association (EAPA), in EU, more than 80% of motorized inland passenger transport and 70% of all inland freight transport use roads [32]. Ensuring the correct performance of roads while dealing with their environmental, social, and economic impacts in a sustainable way is the most important target nowadays in pavement engineering, as an integral part of the road network. Pavements should provide a smooth and durable surface that benefits a range of vehicles (cars, trucks, buses, bicycles) and users (commuters, commercial motor carriers, delivery and service providers, local users, leisure travellers), as well as a resilient structure able to resist traffic loads and climate conditions. Given their key role and widespread use, there is a unique opportunity to improve the sustainability of pavement structures with the potential to deliver tremendous environmental, social, and economic benefits. Regarding these components, listed below are just a few examples of how pavements can impact sustainability:

- **Environment:** energy consumption; Green House Gas (GHG) emissions; noise; air quality; stormwater treatment.
- **Society:** safety; smoothness; vehicle operating costs; GHG emissions; access, mobility; noise; aesthetics.
- **Economy:** construction, maintenance, and rehabilitation costs; vehicle operating costs; accident costs.

An ever-growing number of agencies, companies, organizations, institutes, and governing bodies, including transportation and highways authorities, are embracing principles of sustainability in managing their activities and conducting business. This approach focuses on the overarching goal of emphasizing key environmental, social, and economic factors in the decision-making process. "Sustainability," in the context of pavements, refers to system characteristics that encompass a pavement's ability to [1]:

- Achieve the engineering goals for which it was constructed.
- Preserve and (ideally) enhance surrounding ecosystem.
- Use financial, human, and environmental resources economically.
- Meet basic human needs such as health, safety, equity, employment, comfort, and happiness.

1.5 Ways of "measuring" Sustainability

For the sustainability to be addressed, it firstly must be evaluated and/or measured in some way. This is the cornerstone of assessing progress and establishing gauges. To do so, several tools and methods have been developed over the years, with which it becomes possible for the sustainability of pavements to be assessed. The most widely used and relevant tools are described below. It is worth mentioning that these tools can either be utilised individually or in several combinations [1]:

Performance Assessment: evaluates the performance of a pavement, relating it to the function for which it has been constructed. Performance is usually addressed in relation to that of the current standard practice. In detail, if the currently established standard surfacing of an asphalt pavement is approximately expected to last 10 years, the value of a different pavement surfacing will be based on the projected life of the considered alternative to the 10-year service life of the standard asphalt pavement surfacing. It could also be expressed in the context of physical attributes and the link of them with the performance that is expected from this pavement to be delivered [1].

Life-Cycle Cost Analysis (LCCA): is an analysis method, which utilises financial investigation to assess the aggregate cost of a venture alternative in monetary value, referring to a specified analysis period, which usually is the total life cycle of the project under investigation. LCCA does not address social or environmental impacts of potential projects. It only focuses on the total life cycle costs of different alternatives. However, if environmental or social impacts have been expressed in monetary values and they are about to be included in an LCCA, significant attention has to paid in order for double counting (when LCCA and LCA are both utilised as a composite decision-making tool) and unrealistic monetarisation of environmental and societal issues to be avoided [1].

Sustainability Rating System: is basically a list of practices or characteristics that affect sustainability, merged into a common unit of evaluation (usually a point system) that allocates values to the relative impacts. Thus, it becomes possible for the negative effects/impacts of the aforementioned practices and characteristics to be addressed and compared under a common unit, usually referred to as rating points. The practices and the characteristics may as well include ecosystem connectivity, tons of recycled materials utilised, value of art, delays imposed to road users, health and safety of road users, changes in pavement design life, total energy consumed originating from renewable/non-renewable sources etc.). Hence, in detail, sustainability ranking systems are able to rank the "level of sustainability implemented" in a project and in every alternative of it, making the decision making more sustainable. Nowadays, many sustainability rating systems relevant to pavements are available for utilisation. Some of them are: Greenroads, BEST, Invest, Envision, SUP&R ITN) [1].

Life-Cycle Assessment (LCA): is a technique utilised in order for the environmental aspects and potential environmental impacts to be addressed and quantified throughout a pavement's life cycle; starting from raw material acquisition and including production, use, end of life treatment, final disposal or recycling. The utilisation of this approach can reveal where the most diverse impacts occur and which exactly, they are, making thus possible the environmental improvement of pavements and the identification of possible trade-offs. LCA is dating way back approximately to '60s, but due to its significant contribution to the sustainability of products and services, it has lately been standardised, according to ISO 14000 series. 14040 and 14044 ISO standards [33], [34], describe step by step how an LCA should be conducted and establish a flexible framework, in order to be followed by LCA practitioners. These standards are quite broad and do not refer to pavements directly. Hence, each company, organisation, institute, industry or even government must adjust to the standards and calibrate them to their specific needs. LCA is a scientific field that is still evolving. It has been proved that the utilisation of LCA as a decision-making tool can further improve the sustainability of products and limit the diverse impacts imposed in the environment. Companies are also, investing in creating Environmental Product Declarations (EPDs) and to address the environmental impacts of their products that can be used by the paving industry [1].

Each one of the decision-making tools described above has its own benefits and drawbacks. It is worth reiterating that these tools can either be utilised individually or in several combinations. Performance assessment for instance can provide an accurate engineering evaluation of the pavement performance, which can easily be compared with the widely accepted standards. Utilisation of the LCCA, which is well established by now, can provide and overall assessment of the total cost impacts of a pavement or of a broader transportation infrastructure scheme. Sustainability Rating systems are user friendly, since their interface is not mainly based in quantification of environmental impacts, making them thus, widely accepted and used worldwide in pavement related decision-making circumstances. LCA is an evolving methodology which can be utilised for assessing the environmental impacts of pavements. Indeed, is being widely used and guidelines (ISO 14040, 14044) have been well established for its implementation. However, further R&D and work is required in order for a universal and harmonised consensus to be established for when used in the context of pavements. A deeper understanding of where the most adverse environmental impacts in the life cycle of a pavement occurring and how different alternatives may improve them have to be established. Finally, the best possible pavement engineering practices relevant to materials, design, construction, use, maintenance and end of life techniques, have to be adopted in order for the overall life cycle sustainability of pavements to be achieved.

1.6 Circular Economy

The overall life cycle sustainability is a concept that has been around for a long time. One of the first publications that successfully managed to raise awareness about the issue of overloading earth's natural sinks and overexploiting non-regenerative resources, was the report of Meadows et al. (1972), "The Limits to growth", for the Club of Rome. The broader public was confronted with the thought that only limited growth is possible on a finite planet with finite resources [35]. The proposed model of Meadows and colleagues studied the intertwined interactions between pollution, population, non-renewable resources, food and industrial output. According to their scenario, the system "failure" occurs due to pollution, even though -supposedly- society would have been able to effectively manage to conserve non-renewable resources [8], [35]. However, B. Lomborg, questioned the objectivity and accuracy of the Meadows model, arguing that the human ingenuity and the strength of innovations were not taken under consideration in the described model [36]. A philosophy or concept that encompasses in its' core innovation and innovative business models as well, is the Circular Economy. It is a concept that made its first appearance as a proactive policy goal for numerous businesses and in political agendas in the late 1970s, mainly due to climate change and the acute concern of rising resource prices, raised by R. Carson and K. Boulding [37]–[41]. The Circular Economic concept encompasses the principles of multiple schools of thought, such as "industrial ecology and symbiosis", "performance economy", "biomimicry", "cradle to cradle", "blue economy", "regenerative design", "cleaner production", and "natural capitalism" [42], [43]. Although there is not a consensual and definitive definition of CE, one of the most widely accepted definitions is that of the Ellen MacArthur Foundation (EMF): "economy that is restorative and regenerative by design, and which aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles" [44]. Two different types of products can be identified; products that after their lifecycle can either return into the technical cycle (durables), or into the biological cycle (consumables) [42]. This definition is based on three principles [45], [46]:

- **Design out waste and pollution:** This includes the detection and exclusion of the negative externalities of economic activities, which can cause damage to human health and ecosystems, by minimizing the emission of toxic substances, greenhouse gases, and eliminating water, air, and land pollution.
- **Keep products, components, and materials at their highest value and in use**: Adapting the design process to support the reuse, the remanufacturing, and the recycling of components and materials, biological or technical, in order to keep them in circulation within the same or another product system. In circular systems, it is possible to maximize the use and the value of various components that have been designed in such a way by cascading them into different applications or product systems [45].
- **Regenerate natural systems:** CE is able to support the flow of nutrients or technical materials within the same system, generating ideal conditions for regeneration, and thus, the enhancement of natural capital [45], [47].

Moreover, following this definition, Ellen MacArthur foundation supports the norm of thinking in systems and cascades. This comes as a natural continuity of the second principle. Adopting a systemic thinking and a cascade approach, end-products, components and even materials can be repurposed, reutilised, recycled or have their service life extended while keeping their highest values. Another aspect that consists a core pillar of circular economy, is the utilization of renewable resources for the operation of production systems [44], [45], [47], [48]. Moreover, the concept of CE has as an end target of providing a "marketable set of products and services capable of jointly fulfilling a user's needs" and not just end products to be solely sold to consumers [49], [50]. That would mean that retailers and manufacturers can maintain the ownership of their products and become their "service providers" [47], [51]. This is something that would be sensible, and it would be significantly beneficial if implemented to asphalt pavements and their holistic life-cycle management. The manufacturer of the road would also have to manage their asset in addition to just constructing it [37]. **Figure 1.1** summarises the main schools of thought that have contributed into shaping the philosophy of CE as known today.

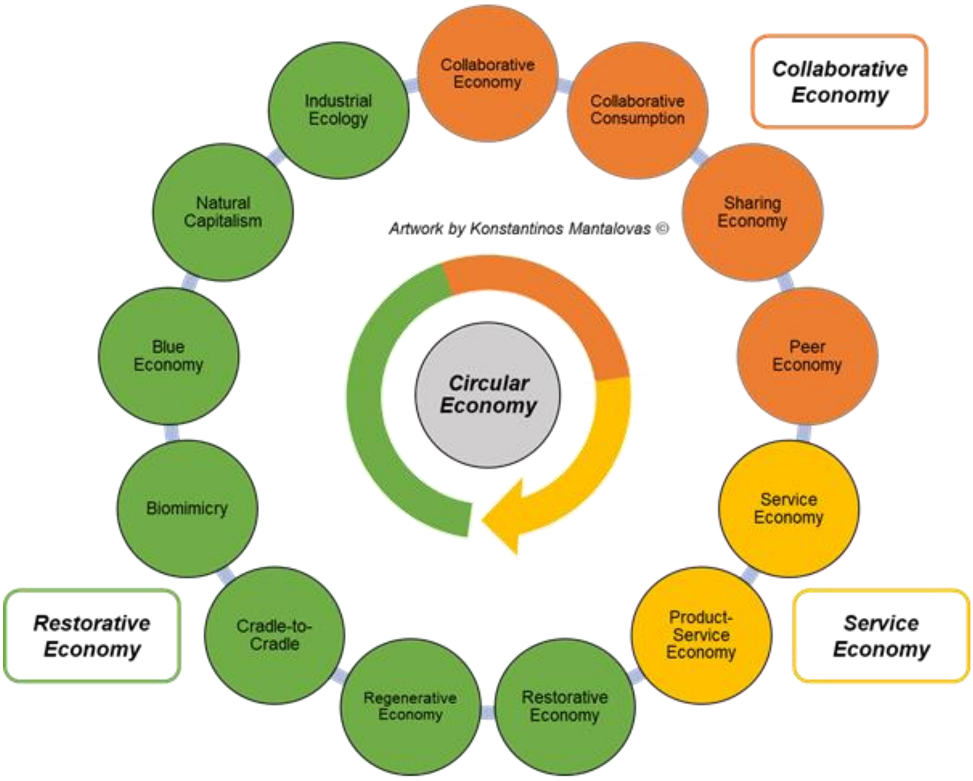

Figure 1.1*.Schools of thought and economic approaches that have assisted in moulding the CE*

Circular economy is a type of economy that integrates principles and approaches originating from all the different type of philosophies/approaches seen in **Figure 1.1**. Some of these proposals date back to 1970 and the constant evolution of different, but with a similar end goal, approaches have been developed since. CE was firstly mentioned in 1990 by Pearce and Turner who also modelled it [52]. After that, various researchers and economic approaches have helped CE to shape its principles and values as they are known today. In particular in **Figure 1.2**, the aforementioned schools of thought are being allocated to the three principles of CE defined and adopted for the asphalt pavements.

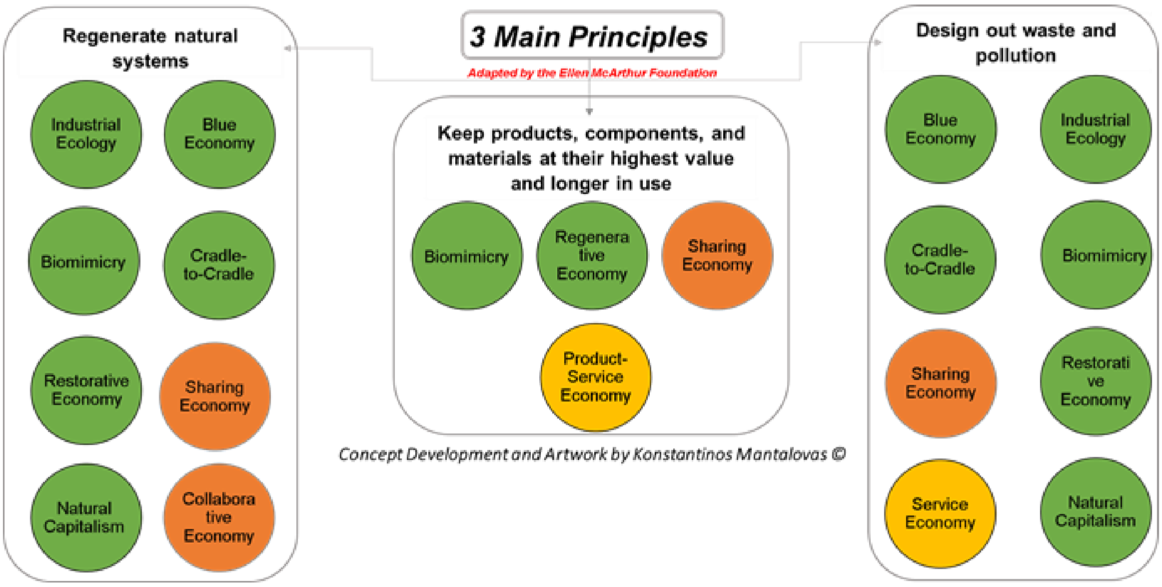

Figure 1.2.*Schools of thoughts within the CE and how they can be allocated in help of defining the 3 main principles of CE for the context of asphalt pavements*

Collaborative economy is a type of economy that has been decentralized and contains networks of individuals and communities instead of institutions. This type of economy aims to change the way of current production, consumption, finance and education [46], [53]. Different expressions that could describe this type of economy is "sharing economy/peer economy" or even "collaborative consumption". In the context of this type of economies, inventors and investors are brought together in order to compile the full procedure of sharing, selecting, producing and distributing new products. Moreover, the utilization of products through redistribution or shared access is a representative paradigm of this type of economies. Thus, the three main aspects of a collaborative economy can be described as:

- A shift of power away from institutions towards networks of individual actors.
- Main drivers are technological innovation, shifting values, economic realities and environmental pressure.
- Innovative and efficient product utilization [44], [46], [53].

Restorative Economy or "regenerative economy" represents the need for a new type of relationship to be created between the industrial systems and the ecosystems. This type of economy should be able to successfully and efficiently copy the natural mechanisms/practices of nature in order to restore the natural environment instead of degrading it. Products in the context of this economy should be accordingly designed so as to be able to be reused as material inputs to another system's lifecycle or to be easily deconstructed and reused or maintained with an ultimate goal of increasing biodiversity and not the opposite [46], [54]. Other similar approaches that have also been inspired by nature are: "cradle to cradle", "biomimicry", "blue economy", "industrial ecology" and "natural capitalism" [29], [31], [55]–[62]. The circular economy contains aspects of all three alternative economic models mentioned above. However, the concept distinguishes itself by focusing on the circularity of resources and the avoidance of waste.

Service economy supports the transition of procurement patterns from product purchasing to service purchasing. The consumer becomes a user, who pays for using a specific product instead of owning it. The term refers to an economic model where the importance is placed on services and the majority of jobs are in service activities. By changing this economic pattern, the service provider not only has an incentive to cut down the resource expenditure but also to reduce the energy consumption in the production process [46], [62].

1.6.1 Circular Economy and the benefits arising via its implementation

CE lays in the centre of attention of numerous governments, institutions, businesses and researchers. It is a concept that is currently being promoted by the European Union and by various governments individually, including Japan, the United Kingdom, China, France, Canada, Sweden, The Netherlands and Finland [63], [64]. The reason behind this, is that numerous advantages could be exploited by the implementation of a holistic circular economic approach. According to recent publications, the European Commission estimated that the EU manufacturing sector alone could potentially have a benefit of 600 billion euros annual economic growth, if a transition to CE was to be achieved [48], [65], [66]. Finland's annual economy is estimated to experience growth of 2.5 billion euros, while when it comes to the global annual economy, the magnitude of the numbers significantly increases and estimates reach values of 1000 billion US dollars per year [67]–[69]. Furthermore, China is recognised as the first country worldwide to actually have implemented circular economy-related legislations [66]. In other words, lately, the consensus seems to be that CE could be utilized as a means of economic growth that complies with the definition of sustainable development [37], [44], [45], [48], [66], [70]. The currently dominating linear economic patterns of "make-use-dispose", seem to be agreeably unsustainable [71], [72].

On the contrary, CE is able to provide alternative energy and materials flow-models, within the economic system; flow-models that are circular and opt to minimise waste production and maximise the service life of each and every material, service or product within a system [48], [73], [74]. The increasing demands for raw materials, the dependence on other countries, the increasing population and energy demand, and the impact on the planet, consist the most crucial factors leading to the belief that shifting towards such an economic approach can have great advantages. They are not just limited in environmental gains, but instead, the adoption of CE seems able to deliver economic benefits as well, according to L. Frodermann [46]. According to Su et al. [71] and Geng et al. [75], the adoption of CE can lead to improved competitiveness of enterprises, more efficient use of materials and energy, increased competitive advantage, revenues from "waste" sales, and reduced environmental penalties. Park et al. [76] and Preston et al. [77] state that the implementation of CE can lead to more direct relationships with the consumers through collaborative consumption, while reducing the costs through the usage of recycled materials, the utilization of centralized waste management plans and the resale of used products, projecting a more positive corporate image. Sinkin et al. identified the benefits of CE as reduced costs through fewer waste inefficiencies, and increased firm value. Kienbaum Management Consulting [78] published a report identifying the contribution of CE implementation as reduced costs through less waste pollution, reduced material and energy costs and competitive advantage. Additional income streams from the selling of refurbished products, reduced labour costs, enhanced customer value and differentiation, are the most important benefits of the CE according to Accenture [79].

Finally, through multiple publications of the Ellen MacArthur foundation (EMF), namely, "Towards the Circular Economy"[48], "Towards a Circular Economy: Business Rationale for an Accelerated Transition"[44] and "Towards the Circular Economy Vol.3: Accelerating the scale-up across global supply chains"[47], the potential benefits of a transition to a CE in Europe are described as annual net material cost savings in the European economy; reduced labour and energy costs, and costs for carbon emissions, along with improved customer interaction and dependency on resource prices. Finally, reduced product complexity and simpler lifecycles with reduced warranty risks and improved product design could be achieved. It thus, becomes apparent that the transition to CE is essential and stakeholders along with governmental bodies should aim towards the support and acceleration of this transition.

1.6.2 Circular Economy and its limitations

1.6.2.1 Macroeconomic implications of the CE

Having reported the potential benefits of the implementation of the CE in an economic and environmental perspective, it becomes essential to also highlight some of the most important limitations that could be encountered towards the way of its implementation. There has been a controversial discussion about the immediately applicable and long-term impacts of the CE implementation in a macroeconomic level. Generally, there is a strong and coherent link between economic efficiency and negative environmental impacts, raw material and energy consumption, and greenhouse gas emissions. Fast and increased production growth, low unemployment, and price stability, none of which has to necessarily clash with environmental protection, are usually the most common economic goals. By implementing the CE, economic growth and GDP growth while preserving the environment and reducing the consumption of natural resources can be achieved [80]–[82].

However, various studies have shown that when modelling the macroeconomic implications of a CE implementation, three aspects are exhibiting the most favourable changes: resource taxes, technology changes, and adapting costumer patterns [80]–[83]. A widespread proposed approach that has been identified in the literature is that a circular transition requires, even at a degree, policy interventions that can incrementally generate macroeconomic and social benefits, and environmental benefits that can be considerable, as well [81]. Thus, more research seems to be required when it comes to the modelling of case-to-case CE scenarios. Moreover, alternative circular practices can entail different trade-offs. These trade-offs should be transparently identified in terms of economy, environment, and regionality [81], [82]. Increased attention should be paid as well, to the decoupling between material use and economic output at both a sectoral and macro level.

Finally, though, a plethora of studies suggests that a transition to CE that entails reduction in resource extraction and waste production could have an insignificant or even positive impact on aggregated macroeconomic impacts, especially when the interactions between sectors and regions is taken under consideration [82].

1.6.2.2 *Spatial and temporal boundary limitations*

Global economic systems are mostly linear. Around 75% of global energy production is based on non-renewable energy resources [63]. Non-renewable resources are extracted from nature, processed, used, exploited and then are dumped again back into nature in a harmful form [63]. Along these lines, although sustainable development is a worldwide objective, CE-type initiatives that have been executed and/or will be realized in the not so distant future, will consistently be local or regional at most. Moreover, there is not a global administrative instrument. Be that as it may, gradually -and obviously- step by step, the future could be shaped towards a change, projecting a global improvement aligned with the principles of CE and sustainability [63], [84].

1.6.2.3 *Lack of the social sustainability aspect*

Strongly rooted in environmental sustainability, the CE framework lacks an elaborated description of the social dimension of sustainability (e.g. the fulfilment of human needs, territorial implications). Its principles are primarily based upon a business perspective and strive equally for environmental and economic benefits. Social benefits are often omitted. Stahel has shown that additional manufacturing processes in a Circular Economy – e.g. refurbishing or recycling, demand more human labour, as these processes cannot often be standardized [62], [69]. Even if this can create employment opportunities, it is not sure that the jobs are created locally. Moreover, people's basic needs at a global level may still be further undermined by abuses of power, unhealthy or unfair labour and living conditions or a disrespect of human rights. As such, the circular economy framework does not necessarily fulfil all the dimensions of sustainability [63]. To achieve thus, a compatible fit, CE initiatives must be analysed via means of global sustainability net gains and in the long-term, before being implemented.

1.6.2.4 *Path dependencies and market lock ins*

When the market patterns and their revolving clusters, networks, stakeholders, and the financial investments are directed towards CE, the resulting innovations will have many difficulties to break through in the market. This would happen even if they were economically, ecologically and socially superior to the prevailing technologies. In other words, the recycling market, just like any other market, has operational patterns, has cultures and structures that have already been well-established. CE-based, high-value product reuse, remanufacturing and refurbishment, will have to compete with the aforementioned aspects, plus the managerial aspect of these actions. The economics and business logic of path dependency may prevent many of the emerging CE innovations from penetrating alternative markets [63].

1.6.2.5 Interorganisational strategies

The material and energy flows extracted from nature, travel via many different non-interconnected parts within the economic production-distribution-consumption system before ending up as wastes and emissions within ecosystems. These flows do not necessarily respect pre-defined administrative, geographic, sectoral or organizational borders and/or system boundaries. Innovative business models including designing for multiple life cycles, functional economy and product-service systems have been proposed for the implementation of the CE. However, these have as a prerequisite interorganizational sustainability management. Cooperation is required between the supplier firm and the customer firm and between the producer and consumer [47], [63], [67], [85].

1.7 Sustainability Assessment and Circular Economy

Assessing the sustainability of a product or a service is not yet corelated with assessing its circularity. Specifically, for the transportation engineering industry, and in detail, the asphalt production processes, aspects that are relevant to either if the asphalt mixture has been produced and managed by following the principles of circular economy or not are not taken under consideration. Moreover, the effort of the pavement engineering industry towards more circular products has not yet been assessed in terms of its environmental impacts. In other words, as aforementioned, CE-related initiatives should be carefully examined case-by-case; and in the context of asphalt mixtures, a composite approach that can identify and evaluate the impacts of the asphalt mixtures' increased circularity in the environment, needs to be adopted. An approach towards the integration of circularity within the framework of Life Cycle Sustainability Assessment has to be followed and supported. Circularity indicators are already integrated into various life cycle management tactics but not into their environmental sustainability assessment. For example, Germany's resource efficiency plan (ProGress) that supports the quantification of the recycling rates of reclaimed materials, along with material flow mapping. The Netherlands are now starting to follow the circularity indicator characterized as material circularity index within the building assets, which can be extended to pavement applications (CB'23 Platform)[86]. Another key parameter leading the research community towards this direction is that the framework of LCA is not taking under consideration the circularity of the end-product, and the frameworks of circularity assessment do not consider the environmental impacts of the corresponding production process. Thus, it appears necessary for an approach that merges both aspects to be adopted. No previous attempts of the integration of circularity assessment within the sustainability assessment of asphalt mixtures have been recorded. Thus, naturally, the first step towards this integration is the combined assessment of the environmental impacts of the life cycle of asphalt mixtures along with their levels of circularity. The usefulness of such an assessment is inextricably correlated with the understanding of the underlying importance of the sustainability and circularity assessment coupling and the ability of National Road Authorities (NRAs) and stakeholders to assess the sustainability of their CE implementation altogether. In other words, NRAs that are eager to become more circular would be in this way able to assess if they are simultaneously sustainable as well circular and vice a versa. In some cases, and under specific circumstances, a CE-related initiative could be unsustainable. The implementation of such methodology to asphalt mixtures can lead to increased awareness of national road authorities and stakeholders belonging to the sphere of road engineering and the management sector, about the level of their businesses' circularity and environmental sustainability and could eventually constitute a tool for the involved decision-makers for evaluating how environmentally sustainable their circular practices and choices are. Hence, the integrated quantification of asphalt mixtures' circularity and their environmental sustainability seems to be the cornerstone for simultaneously circular and sustainable asphalt mixtures.

1.8 Scope and Objectives of the Thesis

Having identified the importance of the steadily decreasing available non-renewable resources along with the potential benefits emerging from the implementation of sustainability as a best practice in combination with the principles of CE, this thesis has a specific scope and targeted objectives. The scope of this thesis is to present the current situation within the European National Road Authorities in terms of sustainability and CE implementation and communication, analyse what is being implemented and how and what could be further done in order for the road and pavement engineering industry to shift towards more sustainable but simultaneously, and vice versa, more circular operational patterns and approaches. For this reason , the objectives identified that can fulfil the predefined scope for the context of this thesis are:

- The development of background knowledge on the topics of sustainability and circular economy and how it can be fitted in the context of asphalt mixtures.
- The identification of sustainable and circular practices within the transportation engineering sector, through the review of published CE road maps, from regional and/or national authorities; along with the recommendation of targeted knowledge development areas that could assist to the transition to CE.
- The identification of sustainable and circular practices in the pavement engineering sector. Namely the assimilation of the ways the NRAs communicate and implement principles of the CE in the pavement engineering sector, through questionnaires sent and thus, the development of suggestions and recommendations for strategies towards the implementation of CE.
- The development of a framework and methodology able to quantify the Material Circularity Index of asphalt mixtures with reclaimed asphalt as end products.
- The development of a methodology and a framework accompanied by an indicator able to integrate the circularity within the sustainability assessment of asphalt mixtures with reclaimed asphalt as end products.

In this way, all of the involved stakeholders and National Road authorities will be able with the utilisation of the novel indicator and framework, to rank the available asphalt mixture alternatives in terms of combined environmental sustainability and circularity, shifting their business models towards more sustainable and circular ones that will be able not only to increase their firm values but also to protect and enhance the quality of the environment.

1.9 Structure of the thesis

After the introduction presented above, the scope and the specific objectives of this thesis, the structure and the composition of the thesis can be found here. In **Chapter II**: "Sustainable and Circular approaches in the transportation engineering sector", the literature review of the most relevant road maps towards CE that have been published within the European Commission's website are critically reviewed. Existing practices that help improve the sustainability and circularity of transportation infrastructures are listed and analysed. In this way a roadmap towards knowledge development from which the NRAs and the governmental bodies can receive direct recommendations is developed.

In **Chapter III:** "Sustainable and Circular approaches in the pavement engineering sector", the focus is given on the sustainable and circular approaches adopted by specific administrative bodies such as NRAs. In other words, there is an analysis of what involved stakeholders and NRAs are implementing towards a more sustainable and circular future. In order to do so, a questionnaire has been sent to a plethora of NRAs across the EU and the results are findings are analysed. Moreover, an online search has been conducted in the websites of the selected European NRAs to identify implementation and communication channels utilised for the CE.

After having identified the lack of sustainability and circularity metrics and operational approaches; in **Chapter IV:** "Measuring the circularity of asphalt mixtures", a methodology for quantifying the circularity of asphalt mixtures containing RA is developed in detail. It is a methodology based on the circularity indicator proposed by the Ellen MacArthur Foundation but specifically tailored for the context of asphalt mixtures. Moreover, a case study is presented for the validation and the easier comprehension of the indicator.

In **Chapter V:** "Measuring the environmental sustainability of asphalt mixtures", there is a further step taken towards the sustainability of asphalt mixtures. A methodology with which NRAs and stakeholders can quantify the environmental sustainability in combination with the circularity of asphalt mixtures with RA is developed and presented. A novel indicator has been developed that is able to vigorously discriminate between alternative asphalt mixtures, based on both their environmental impacts and circularity. A validating case study is also presented within the chapter for the importance and usability of the indicator and methodology to be projected.

Finally, the last chapter is entitled **Chapter VI:** "Conclusions and Future Perspectives" and entails the analysis of the results obtained after the implementation of the developed methodologies. In the end, the conclusions that can be drawn by the research conducted for this thesis are presented along with the future perspectives and knowledge gaps that in future could potentially be hotspots worth investigating.

2 **Chapter II:** Sustainable and Circular approaches in the transportation engineering sector

2.1 Scope and Objectives of the Chapter

Sustainable and circular practices are lately emerging in various industrial sectors. The civil engineering sector is one of them. However, more specifically, for the pavement engineering sector there is not available literature, investigating the CE practices adopted by different governmental bodies or policy making officials. In this chapter, an attempt to allocate the meaning of CE to the context of transportation infrastructures and asphalt pavements is being made, along with a critical review of published Road Maps/Route Maps of governmental bodies, national and/or regional authorities towards a CE in the European CE Stakeholder Platform (https://circulareconomy.europa.eu/platform/). The Road Maps are not specifically developed for the pavement engineering sector and thus, the review is focusing on identifying which of their aspects can be of contribution in the sector. After the identification of gaps in knowledge through the literature review conducted, a map of targeted knowledge development is presented for national and/or regional road authorities, and stakeholders that can assist them with their unavoidable and incipient transition to more circular practices and managerial approaches.

2.2 Circular Economy and the asphalt pavements

So far, the most common practices that can be potentially highly beneficial in terms of environmental and economic impacts, and would also be in line with the principles of circular economy are:

- the recycling of asphalt,
- the adaptation of pavement design towards the utilisation of lower amounts of materials,
- the extension of the pavements' service life (preventive maintenance),
- the utilization of wastes in the production of asphalt mixtures,
- the utilisation of secondary materials and by-products in the design and production of asphalt mixtures,
- the increase of the allowed percentage of recycled materials inside the asphalt mixtures,
- the prioritization of regenerative energy sources.

Sometimes however, some of these practices are actually implemented not because they serve the principles of circular economy and are beneficial in terms of sustainability, but just because they are economically profitable and by the rule of thumb are considered as best practices. Again, nothing has been published in terms of asphalt pavements when it comes to legislative guidelines towards more circular pavements. This has not stopped though some individual stakeholders moving towards this direction. KRATON for example has moved forward by producing SYLVAROADTM RP1000; it is an additive derived from Crude Tall Oil (CTO), a renewable raw material, characterized as a by-product of the paper industry and developed by. It is able to increase the levels of RA incorporated into the asphalt mixtures while avoiding significant environmental burdens [37], [87]. Another noteworthy attempt towards more circular products has been made by Tarpaper Recycling, along with Super Asfalt, which have proposed the production of REC100. It is a mobile asphalt plant that ensures 100% utilization of the resources in roofing felt and asphalt waste, in order to produce asphalt mixtures incorporating 100% recycled resources. Unfortunately, though, the effort of the pavement engineering industry towards more circular and sustainable products can merely be characterized as adequate. More attempts thus, should be made towards this direction.

2.3 Current situation: Analysis of the Roadmaps produced by national/regional authorities towards Circular Economy

Policies that encourage the implementation of the principles of CE have already been introduced in some cases. The European Commission following the increasing pressures on natural resources launched the European Resource Efficiency Platform (EREP) in 2012 [88]. The target was to move towards a harmonized and controlled transition from linear economic patterns to circular ones. After the foundation of the aforementioned platform, which is composed by practitioners and politicians, guidelines have been publicly provided, in order for the implementation of "circular economy(-friendly)" approaches and frameworks to be widely adopted and finally implemented [88], [89]. Moreover, the United Kingdom acting as a pioneer in this context was the first ex-European country to publish standards about the implementation of CE in 2017 [42]. France followed with the development of voluntary standards called XP X30, published by ANFOR in 2018. The title is "Circular economy - Circular economy project management system - Requirements and guidelines –" and the standards propose a common understanding grid, laying out the terms, principles, and practices relevant to CE. The development of the aforementioned standards led to the creation of a technical committee within the International Organization for Standardization (ISO TC 323) which is working on enriching and developing international standards for the field of circular economy. Moreover, in July 2019, Platform CB'23 from the Netherlands has published a framework for circular construction, focusing on the building works. The requirements for a uniform measurement method of circularity are emphasized and a circularity quantifying approach is proposed accordingly [86].

Finally, the European Union understanding the necessity of CE had officially adopted an action plan in 2015 to help accelerate Europe's transition towards a circular economy, boost global competitiveness, promote sustainable economic growth and generate new jobs and in 2019 the Circular Economy Action Plan has been fully completed [90]. However, when it comes to transport infrastructures and asphalt pavements specifically, it becomes difficult to encompass and conceptualize all these principles in their life cycles. Indeed, there is a plethora of roadmaps towards circular economy that have been published attempting to pave the way towards achieving circularity in national levels but not a lot of effort has been put to specifically address the sector of road engineering. In **Table 2.1**, all the national plans and/or roadmaps published online through the European CE Stakeholder Platform can be found, along with the unique roadmap related directly with national road authorities.

Table 2.1. *National plans and/or roadmaps published online through the European CE Stakeholder Platform (circulareconomy.europa.eu)*

A. The Danube goes Circular – Transnational Strategy to Accelerate Transition Towards a Circular Economy in the Danube Region (ENGLISH)	Austria, Bulgaria, Croatia, Czech Republic, Germany, Hungary, Romania, Slovak Republic, Slovenia, Ukraine, Moldova, Serbia, Montenegro, Bosnia and Herzegovina
B. Circular Flanders kick-off statement (ENGLISH)	Belgium
C. Leading the cycle – Finnish road map to a circular economy 2016–2025 (ENGLISH)	Finland
D. 50 Measures for a 100% Circular Economy (ENGLISH)	France
E. German Resource Efficiency Programme II (ENGLISH)	Germany
F. National Action Plan on Circular Economy (ENGLISH)	Greece
G. Towards a Model of Circular Economy for Italy – Overview and Strategic Framework (ENGLISH)	Italy
H. Leading the transition: a circular economy action plan for Portugal (ENGLISH)	Portugal
I. Roadmap towards the Circular Economy in Slovenia (ENGLISH)	Slovenia
J. A Circular Economy in the Netherlands by 2050 (ENGLISH)	The Netherlands
K. Kernmethode voor het meten van circulariteit in de bouw (DUTCH)	The Netherlands
L. Making Things Last: a circular economy for Scotland (ENGLISH)	United Kingdom
M. Circular Economy Approach and Routemap* (ENGLISH)	United Kingdom

*The only National Road Authority that has published a publicly available roadmap towards circular economy is Highways England in collaboration with AECOM and ATKINS.

A: The Danube goes Circular – Transnational Strategy to Accelerate Transition Towards a Circular Economy in the Danube Region [91]**.** It is a strategic document prepared on the basis of studies, reports and analyses made by national and/or European organisations, with the purpose of setting the objectives to improve the framework conditions and policy instruments for eco-innovation and the transition to a circular economy [91]. The reference period is from 2019 until 2030 and the target groups that the document is aiming towards are National, regional and local public authorities, business support organisations, higher education and research organisations, private and public business entities [91]. In this strategic document a framework methodology for measuring circular performance of Danube region is explained. Few of the selected indicators refer to the quantification of the percentage of materials that have been reused (such as Circular material use (CMU) rate) and the framework can be linked to the built environment indeed, but not directly to road pavements. Furthermore, the key challenges were identified with regard to the transition of the Danube Region towards a circular economy are identified and strategic objectives and sets of recommendations are proposed, stressing the need for new circular business models [91].

B: Circular Flanders kick-off statement [92]**.** This kick-off statement was published by Vlaanderen Circulair and refers to the Flanders region. The document emphasizes the need for transition from a linear economy to a circular economy, outlining the benefits that the latter can provide. Their transition action plan is analysed, and it is based on three main principles: circular purchasing, circular cities and circular business. It is worth mentioning that the pillar of circular cities also includes built environment and thus transportation infrastructures, but without any further details relevant to road pavements [92].

C: Leading the cycle – Finnish road map to a circular economy 2016–2025 [68]. Published by SITRA in 2016, this roadmap covers the strategic action plan of Finland towards a circular economy from 2016 to 2025. Emphasis is given to the fact that for an actual transition to circular economy, systematic change is needed. The action plan is described and analysed and the circular economy targets for the economy, the society and the environment are defined. Moreover, the roadmap separates the actions needed into five main sectors: food systems, forest-based loops, technical loops, transportation and logistics, and common actions. Practices to implement CE within the built environment and transportation infrastructures are explained and promoted, without specific reference to road pavements [68].

D: 50 Measures for a 100% Circular Economy [93]. The roadmap was published by the French Ministry for an Ecological and Solidary Transition and Ministry for the Economy and Finance in 2018. It analyses the reasons behind the need for transition to a circular economy and provide the objectives of the published framework. The roadmap is divided in four major action areas (better production, better consumption, better management of wastes and mobilization of all the actors). Detailed description of the hey objectives of each are is being provided along with the key measures and the targeted audience. The roadmap includes the built environment and infrastructures, without direct mention to road pavements. However a plethora of the measures can be directly implemented to the latter [93].

E: German Resource Efficiency Programme II, Programme for the sustainable use and conservation of natural resources [94]. It is the second resource efficiency published by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB). The first one was published in 2012 paving the road for resource efficiency from 2012 to 2015. However, the second resource efficiency program of Germany refers to energy efficiency as well. It emphasizes and describes the inclusion and interaction of other resources such as water, soil, air, living organisms, land and resources as food and feedstuff. Analytic indicators are presented in the document along with the desirable targets and the action areas under focus. It is worth mentioning that the specific resource efficiency programme takes under consideration the built environment, the transportation infrastructures and there are targeted mentions directly to asphalt recycling and re-circulation [94].

F: National Action Plan on Circular Economy [95]. The Greek national action plan on Circular Economy was published in the end of 2018 and analyses the compatibility of CE with the recently adopted development plan. In the document the policy axes to achieve a CE are described along with the main strategies and goals to be followed in the future. Finally, the operational and governance action plan with its regulatory and legislative reforms is presented. The specific action plan also refers to urban development and the built environment setting targets relevant to the construction sector, without being specific about road pavements though. It is worth mentioning that in 2017 the Greek government adopted a set of laws relevant to waste management and materials efficiency that supports in a legislative way the implementation of CE principles [95], [96].

G: Towards a Model of Circular Economy for Italy – Overview and Strategic Framework [97]. The Italian roadmap towards circular economy was published in 2017 by the "Ministero dell'Ambiente e della Tutela del Territorio e del Mare and the "Ministero dello Sviluppo Economico". It describes the current situation in Europe and specifically in Italy while stressing that for an effective transition to CE, the companies, the consumers and also the fiscal and economic instruments have to walk towards the same direction. In order for this transition to be ensured, indicators measuring circularity are analysed along with emphasis given in the importance of the traceability of the resources and the production chains and the promotion of sustainable production and consumption models. The roadmap includes recommendations for the construction sector, but nothing specifically addressed to transportation infrastructures and/or road pavements.

H: Leading the transition: a circular economy action plan for Portugal [98]. It is an action plan published in 2017 that presents a constitute proposal for action towards the implementation of CE. Within the published action plan the importance of a CE is emphasized and the approach of achieving a CE is analysed. The aim is to introduce CE principles in three levels: macro, meso and micro. It is worth mentioning that according to the action plan, guidelines for the most important and environmentally relevant sectors will be developed and detailed goals and complementary indicators will be present, monitoring the progress. Guidelines will be developed also specifically for the built infrastructures and roads, covered by the complementary indicators [98].

I: Roadmap towards the Circular Economy in Slovenia [99]. This roadmap was published in 2018 and it is a part of Slovenia's strategic development priorities. It emphasizes that the transition to CE is not a trend but a civilizational necessity instead. It defines and analyses the circular triangle, which is based on Circular Culture (citizens as the core), Circular Change (public sector as the core) and Circular Economy (companies as the core). Moreover, all the areas in which the transition should be prioritized are recognized and the potentials occurring due to CE within these areas are analysed. One of the strategic areas is "mobility"; within this area transportation infrastructures are included, and recommendations are given towards more circular practices. However, no direct mention exists about road pavements specifically [99].

J: A Circular Economy in the Netherlands by 2050 [100]. It is more in reality a government-wide programme for the transition of the Netherlands to a CE, published in 2016. In the document the promising prospects of the implementation of CE are analysed along with the necessity for the transition towards such an economy. Moreover, the economic opportunities of reusing materials are described and the vision along with the goals of the programmed are mentioned. Generic and specific policies for change for each sector and/or value chain are provided and an attempt towards fostering legislations and removing obstacles is made. In the document the prioritized sectors of biomass and food, plastics, the manufacturing industry, consumer good and construction sector, are explained along with the action plan for each one of them. It is worth mentioning that within the construction sector, asphalt pavements and the reuse and/or the recycling of asphalt are mentioned and promoted, supported by best practices paradigms and finally the anticipated strategic goals [100].

K: Kernmethode voor het meten van circulariteit in de bouw [86]. It is worth mentioning that the specific document was not found in the European CE Stakeholder Platform, but instead was published by Platform CB'23. It was reviewed since it consists one of the most analytic and comprehensive approaches towards the implementation of CE within the construction sector holistically; meaning that every time of built infrastructure could benefit by following the proposed approach and methodology. It focuses on the material aspects of circularity in an attempt to promote the integral sustainability that The Netherlands is already pursuing as already declared in "A CE in the Netherlands by 2050" [100]. It is focusing in the built environment, referring thus to the transportation infrastructure as well. To do so, within this report, it is described how to develop "passports for construction" that represent a digital representation of a construction work and it depends on the life phase of the work itself and the value that than can be created with this data. Life Cycle Assessment is coupled with the creation of a passport and the metrics of alternative passports are compared. Moreover, an approach to quantify the circularity of construction works is defined and direct mentions exist about transportation infrastructures and asphalt based material [86].

L: Making Things Last: a circular economy for Scotland [101]. It was published in 2016 by the Scottish government and it is a strategy that sets Scotland's priorities for moving towards a more circular economy. It builds on Scotland's progress in the zero waste and resource efficiency agendas. In the document the environmental, economic and societal benefits emerging through the implementation of CE are analysed. Moreover, it is explained that in order for the transition to CE to be achieved priority should be given to the following aspects: waste prevention, design, reuse, repair, remanufacture, recycling, producer responsibility for reuse and recycling, recovering value from biological resources, energy recovery, and landfilling. In addition, the built environment along with the construction sector and transportation infrastructures are mentioned but without focus on road pavements. Finally, targets are being set and metrics such as waste reduction, recycling rates and re-use rates are set as indicators [101].

M: Circular Economy Approach and Route map* [102]. This route map is the only one published by a national road authority. It was published in 2016 by Highways England in collaboration with AECOM and ATKINS. Its' objectives are described as: the development of a corporate circular economy strategy within the context of the Highways England Sustainable Development strategy; the definition of what circularity means for Highways England; the shift towards a fully optimised resource use on Highways England's projects and operations and to deliver a plan to embed a culture of resource efficiency across the organisation and Highways England's supply chain. It is separated in 4 core components: governance, procurement, monitoring and reporting, tools and guidance. Resource efficiency, utilisation of waste and minimisation of resources exploitation are the cores of the proposed actions of this report. It is worth mentioning that direct mention to transportation infrastructures in general and to asphalt pavements in specific can be found, stating that the wastes originating from the life cycle management of roads should be exploited with utmost efficiency. However, specific indicators and metrics have not been developed for the quantification of the circularity, but instead key performance-based indicators are mentioned.

2.3.1 Circular Economy roadmaps: Analysis and discussion of the reviewed documents

Reviewing the documents collected from the European Circular Economy Stakeholder Platform, it becomes obvious that the principles of CE within the transportation sector are not well established yet. It is worth mentioning that only one of the reviewed documents has officially been published by a national road authority i.e. Highways England, while the rest of them have been published by governmental bodies, ministries, companies and/or groups and platforms formed to promote circular thinking. Not all of them however are analytical and comprehensive delivering a specific set of strategic actions and indicators, metrics or desirable targets to be reached. Some of the most detailed publications are providing specified action plans for each sector to be followed and targets that need to be fulfilled under specific timetables in order for the transition to a CE to be actually realised. The most common points that can be found in the documents are initiatives such as more effective waste management and waste minimisation, utilisation of waste as resources to parallel industries, minimisation of CO_2 emissions under predefined time horizon and resource and energy efficiency. In detail, the most common elements of the aforementioned road maps, which include aspects of the pavement engineering industry can be seen in **Table 2.2**.

***Table 2.2** Summary of the approaches, strategies, and indicators directly applicable to asphalt pavements originating from the analysed documents.*

Highways England (UK)	• A detailed plan is deployed until 2025, including the aspects of governance, procurement, monitoring and reporting and the development of tools and guidelines. • Potential indicators: material use/km of road built, material use in schemes, financial performance, savings, and the content of materials purchased, used and recycled. • Significant weight given to communication, monitoring and reporting.
Platform CB23 (The Netherlands)	• One of the most analytical and comprehensive approaches towards the implementation of CE within the construction sector. • Describes "passports for construction", a digital representation of construction works and the value that than can be created with these data. Life Cycle Assessment is coupled with the creation of a passport and the metrics of alternative passports are compared. • Approach to quantify the material circularity index of construction materials and processes. Quantity of materials used, available for next cycle, lost. Influence on the quality of the environment. • Quantity of existing value used, value available for next cycle, existing value lost.
German Resource Efficiency Programme II	• Utilization of secondary materials for asphalt and concrete pavements. • Calculation of the reclaimed asphalt percentage that is used in paving activities, and the percentage of recycled aggregate used as concrete aggregate relative to total volume of recycled construction materials. • Minimization of the cumulative raw material consumption and cumulative energy expenditure in roadbuilding by maximizing the recycling rates of asphalt. • Raw material productivity (Economic indicator): Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all via resource conservation and using resources economically and efficiently (total raw material productivity = (GDP+ imports)/raw material input).
50 Measures for a 100% Circular Economy (France)	• Key objectives and measures for better production, consumption, waste management, mobilization of all sectors. • Increased use of secondary materials and uptake of product-service systems. • Adaptation of waste regulations to support CE. • Allocation of dedicated funding towards the support of CE implementation.
Luxembourg as a knowledge capital and testing ground for the Circular Economy	• Establishment of a materials within infrastructures inventory. • Innovate designs and usage models with higher material productivity and recyclability • Improve residual value of materials and components. • Material passports and/or material banking. • Modular designs and equipment leasing

2.4 Suggestions and recommendations for knowledge development targeted knowledge development of NRAs

Having identified the most commonly accepted definition of the CE, it shall thus mean that it would be time to attempt and translate it in the context of asphalt mixtures. As mentioned, the three main principles of the CE are:

- Design out waste and pollution.
- Keep products, components, and materials at their highest value and in use.
- Regenerate natural systems.

Hence, practical recommendations for the national/regional authorities would have to be focusing on translating actions and approaches into an eligible hodgepodge of measurable outputs towards the implementation of the aforementioned principles. The combination of these pieces of information while keeping the sustainability assessment of asphalt mixtures in mind are inevitably leading towards identifying areas of knowledge that if developed, could lead to a better understanding of CE and a more informed implementation of its principles in the context of asphalt mixtures. The lack of guidelines for the circular and sustainable development of the pavement engineering sector that has been identified via the critical review of the analysed Road Maps emphasizes the gaps of knowledge that exists in the managerial aspect of the sector. In other words, national and regional authorities and private stakeholders in some cases should expand their knowledge in CE and sustainability topics, in order for a successfully holistic transition towards CE to be achieved. The areas for knowledge development that have been identified by the author and could potentially improve the understanding and the implementation of circular economy by governments and national/regional road authorities are presented in **Table 2.3**, along with the pre-defined principles of CE that they fulfil.

Table 2.3. Areas proposed to the regional/national authorities and private stakeholders for knowledge development and the CE principles they can fulfil

Knowledge Development Areas	*CE principles*
Alternative energy sources	1, 3
Technical feasibility	1, 2, 3
Circular procurement	1, 2, 3
End of life strategies	1
Lifecycle extension	1, 2
Circularity + Environmental metrics	1
Supply chain management	2
Material flows	1, 2, 3
Waste Management	1, 3
Sustainable Development Goals	1, 2, 3
Innovation	1, 2, 3

Where: **(1)** Design out waste and pollution; **(2)** Keep products, components, and materials at their highest value and in use; **(3)** Regenerate natural systems

In a more analytic perspective and considering that regional/national authorities can usually be in collaboration with different stakeholders relevant to the production of asphalt mixtures and the maintenance of asphalt pavements. In other words, assuming that most authorities represent the area of a "Cluster", even if by themselves develop the knowledge in the suggested areas, for a holistic life cycle approach, various other stakeholders will have to be a committed part of the equation -as well- in order to collectively progress towards a systemic regional circular economy. Therefore, it is worth reiterating that communication, transparent supply chains and stakeholders' engagement are key components towards a CE.

2.5 Summary and Conclusions

Within the perspective of a post-fossil fuel road engineering industry, based upon the principles of sustainability and circular economy, asphalt pavements and the way they are constructed and managed, play a key role in achieving so. Sustainable and circular practices are lately increasingly implemented by various authorities. This is achieved either by complying to existing legislations, or via trying to promote a more sustainable way of doing business out of environmental, social or mostly economic concerns. As seen in **Chapter 1**, CE is not something new, but the natural evolution of concepts that attempt to lead humanity into achieving a more sustainable living and development within the boundaries of the planet earth. Different schools of thought have emerged through time, all finally leading to the latest definition of such a sustainable economic model, the CE. When it comes to asphalt mixtures however, not a lot of attention and weight has been given. As it can be concluded from the analysed roadmaps in, only a few have taken under consideration the potential of CE in asphalt pavements and thus, asphalt mixtures. Most of these documents recognize the potential CE benefits in a larger scale, i.e. the built environment without direct focus on asphalt pavements. Thus, it can be said that, in general, governments so far have not adequately invested into producing roadmaps towards the implementation of CE. This is happening due to lack of budget, lack of experts in CE within the national road authorities and due to the uncertainty of the successful implementation of CE, which also incorporates the lack of well-structured and comprehensive circular business models and incentives for the stakeholders associated with the market of asphalt pavements. This could lead to the conclusion that more people with specialization in CE should be operating within the administrative and governing bodies, providing higher accuracy, more insights and knowledge in terms of CE implementation.

Finally, more and more national/regional authorities should allocate percentages of their budgets towards the development of circularity metrics and roadmaps/strategies towards the implementation of CE and the assessment of the levels of this implementation. This could help to monitor and evaluate the progress that is being made and finally develop a feasible and spherical framework of how they should actually be implementing CE in asphalt pavements in the best way possible. The implementation of CE is not a simple and instant process. In order for circularity to be achieved within an organisation or an authority in this case, knowledge development has to occur in different layers of stakeholders and not just the organisational territory itself.

3 **Chapter III:** Sustainable and Circular approaches in the pavement engineering sector

3.1 Scope and Objectives of the Chapter

In this chapter, an in-depth analysis of the approaches that National Road Authorities are adopting for their transition to more sustainable and circular operational patterns is made, in order to identify best practices and/or the lack thereof. The objective is to identify if and how NRAs communicate CE, if and how they implement CE and improve both aspects by introducing circular recommendations. Firstly, a survey was undertaken online by researching in the official websites of European National Road Authorities the words "circular economy" and "sustainability", in both English and their local languages, in order to identify the ways that NRAs communicate CE and their potential commitment to it. Moreover, in order to acquire a more spherical perspective of the topic, questionnaires were sent to the same NRAs, relevant to CE, its principles and its implementation, in an attempt to identify the levels of knowledge these authorities have on CE and the levels of implementation they are currently exhibiting. Finally, having in mind as an objective the motivation of NRAs towards the uptake of CE, a set of circular recommendations is proposed. Recommendations have been drawn through reviewing published reports from the EU and through an extensive literature review on relevant topics and sectors.

3.2 Asphalt pavements: economic relevance and environmental aspects

To start with, a pavement is a set of superimposed layers of imported materials (selected, processed unbound and bound materials) that are placed on the natural soil or on an artificial structure for the creation of a road [103]. A pavement can be considered a complex structure developed to accommodate numerous functions. The fundamental structural function of a pavement is to support traffic loads while transferring them to the subgrade. The structure of a pavement should be able to allow for the surface of the subgrade, receiving these stresses, to exhibit merely minimal damages and deformations. Moreover, the upper layers should be able to be as impermeable as possible in order for water damage in the lower layers of the pavement and the subgrade to be avoided. The surface layer of a pavement has to be able to provide adequate skid resistance, to be even in order to smoothly accommodate traffic and to endure the polishing action imposed to it by the vehicle tires [103]. Vehicle based traffic and the severe environmental pollution that imposes are still a significant environmental concern, as it has been for decades. With approximately 1.6 billion vehicles in operation today and more on the way, Earth's atmosphere continues to absorb massive amounts of harmful emissions from a billion internal combustion engines on a daily basis [104]. Parking lots and roads, and in general civil engineering assets that require the use of bituminous bonded materials, are continuously expanding in order to fulfil the increasing demands for traffic accommodation. This is something that furtherly creates problems. Raw materials are required, thus through drilling, mining, and generally extracting non-renewable resources from the ecosystems, severely impacts the sphere of the environment. The production of asphalt mixtures, the construction of asphalt pavements and their management through maintenance throughout their whole life cycle can be significantly intensive processes in terms of materials and energy consumption. Road construction companies have developed ways to reuse existing asphalt by remixing it with virgin materials [103], [104]. Furthermore, asphalt is a high-VOC (volatile organic compound) substance. As the product is converted to asphalt, significant quantities of harmful gases are released into the atmosphere. Additionally, some areas still use high-VOC paints for striping roads and parking lots, adding another unsustainable element to the process of road and parking lot construction. Finally, a significant amount of wastes is produced during the material acquisition of the materials required for the production of the asphalt mixtures, during the construction of the asphalt pavements and during their end of life, where reclaimed materials could end up in landfills [105], [106].

On the other hand, transport and mobility are tremendously important for the social and economic development. Hence, most of the developed countries have allocated remarkable resources and budget in order to be able to develop and manage high-quality transport networks. Present approaches for the construction of pavements unavoidably lead to noteworthy maintenance requirements that can be immediately relatable to high costs. The continued growth in road traffic and axle loads and the pressure to restrain government spending put growing pressures on road authorities to come up with new solutions [107]. Simultaneously, congestion and disruption during the phases of road maintenance on roads that accommodate high volumes of traffic have severe impacts to economies. Thus, the need for long-life transportation and more specifically, road infrastructure, that require minimal amounts of maintenance actions, is apparent. The road infrastructure of a country translates to a tremendous capital worth, which can be considered the outcome of vast investments through several generations. The financial estimation of this asset is commonly the current deteriorated substitution cost of the development of the whole system-network. Running expenses incorporate the expenses of keeping up, restoring and broadening the system at a level that fulfils the requirements of the present society [107].

Now, the most common denominator that is able to scale down both the environmental and economic impacts during the whole life cycle of an asphalt pavement, is the utilisation of Reclaimed asphalt [108]–[114]. However, other practices can be detected as well. Different types of additives can be introduced in an asphalt mixture in order to prolong its durability; rubber asphalt is also utilised in order to achieve environmental and economic benefits; polymers, anti-stripping agents; and a plethora of other applications. Still, the use of RA is the most common practice that has been exploited for decades, in order for economic and environmental benefits to be achieved during the construction and management of assets such as asphalt pavements. By using RA, non-renewable resources are preserved, less virgin materials are utilised and significant economic benefits are achieved, since a material considered waste, or else a secondary material, can be actually used as the main material for the production of the asphalt mixtures that are going to compose an asphalt pavement. This is the reason why, in this research, the main focus for the development of the aforementioned methodologies, has be given to asphalt mixtures that incorporate Reclaimed Asphalt.

3.3 CE communication of National Road Authorities

In this chapter, the ways that various NRAs are communicating their circular practices and their commitment to CE are researched and analysed, since communication of an organization's values can often have a significantly positive impact and value. Hence, in order to identify the ways that NRAs communicate CE, an online search was undertaken specified under a textual web search query. The search was conducted online in English and also in the corresponding local language of every investigated NRA, respectively. The official websites of the NRAs that participated in the survey were identified and afterwards, in their "search" function, the words "circular economy" and "sustainability" were searched in English and in their local language.

The key words were selected in a way that could cover a wide spectrum of CE. Results such as reports and initiatives were reviewed with an end goal to clearly identify how the aforementioned NRAs are trying to communicate to the broader public their commitment to the CE, and what they are doing to integrate circular practices in their operational approaches. The results of the search have been tabulated in **Table 3.1**.

Table 3.1. *Ways that NRAs are communicating CE*

National Road Authority per Country	*CE Implementation Plan and communication*
Austria [ASFiNAG]	Sustainability strategies and reports / nothing related to CE
Belgium [Agency for roads and traffic / Wallonia General Direction for roads and traffic]	Sustainability related research and reporting / nothing related to CE
Denmark [Danish Road Directorate - Vejdirektoratet]	Environmental Assessment reports, Sustainability related research and reporting / nothing related to CE
Germany [Federal Ministry of Transport, Building and Urban Development - Bundesministerium für Verkehr und digitale Infrastruktur]	Climate Action Program 2030 / CE related: preservation of resources, maximization of resource efficiency, resource cycle management/bio economy
United Kingdom [Highways England, Transport Scotland, Welsh Government, Roads Service	Circular Economy Approach and Route map
Lithuania [Lithuanian Road Administration and family of road engineers]	Nothing related to CE
Norway [Norwegian Public Roads Administration -NPRA]	Sustainability related research and reporting / nothing related to CE
Slovenia [Slovenian Roads & Infrastructure Agency]	Conferences organized, JRC collaborations for circular economy implementation / Slovenian development days to promote CE
Sweden [Swedish Transport Administration-Trafikverket]	Sustainability related research and reporting / nothing related to CE
Netherlands [Rijkswaterstaat, State advisors for urban development & infrastructure]	Circular Public Procurement / Resource Efficient business models / National Waste management Plan

As it can be observed, the majority of the NRAs are not thoroughly investing into communicating the ways that CE principles can be projected through their operational patterns. The only NRA that has published an "Approach and Route Map" towards circular economy is the Highways England. In which future visions and plans that are aligned with the implementation of CE are described. Moreover, Germany's NRA seems to be in a similar path since it has developed a plan called Climate Action Program 2030, which contributes towards the implementation of more circular and sustainable practices. In addition to that, practices relevant to the preservation of resources, maximization of resource efficiency, resource cycle management and bio economy are strongly supported and communicated. It can be seen however that the majority of the investigated NRAs is publishing sustainability reports and communicating their plans in terms of sustainability, but CE is still not a matter that seems to be under their attention.

3.4 CE implementation of National Road Authorities

Furthermore, in order to focus the research on the field of pavement and road engineering, agencies such as National Road Authorities were under the focal point. The NRAs of different European countries were contacted in order to identify if they are familiar with CE and how they are implementing it. Consequently, a questionnaire was formulated mostly relevant to their sustainability assessment approaches, since they were part of the Pavement LCM project (https://www.pavementlcm.eu/), funded by the Conference of European Directors of Roads (CEDR) and focusing on the life cycle management and sustainability assessment approaches that NRAs could adopt. However, the survey was structured in a manner which was able to provide a qualitative analysis through the questions that can be found in Appendix A, which are relevant to the CE and were also included to the questionnaire for a more spherical overview. A plethora of European NRAs is in partnership with the funding body, CEDR; thus, most of these NRAs were contacted through email and the ones interested in participating replied. The data and results presented in this chapter, include all the NRAs that have filled in the questionnaire. It was filled openly by up to 2 persons working within the corresponding NRAs in positions closely related to sustainability and/or sustainability development and assessment. The countries and their corresponding national road authorities, along with the replies in the questionnaires can be seen below, in **Table 3.2** to **Table 3.11** Moreover, the detailed questionnaire can be found in Appendix A. The investigated NRAs are:

- Austria [ASFiNAG]
- Denmark [Danish Road Directorate - Vejdirektoratet]
- Germany [Federal Ministry of Transport, Building and Urban Development - Bundesministerium für Verkehr und digitale Infrastruktur]

- United Kingdom [Highways England, Transport Scotland, Welsh Government, Roads Service]
- Lithuania [Lithuanian Road Administration and family of road engineers]
- Norway [Norwegian Public Roads Administration -NPRA]
- Slovenia [Slovenian Roads & Infrastructure Agency]
- Sweden [Swedish Transport Administration Trafikverket]
- Netherlands [Rijkswaterstaat, State advisors for urban development & infrastructure]

Table 3.2 *Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of Austria*

COUNTRY	**Austria**
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	*-Design out/minimise waste* *-Use waste as resource* *-Prioritize regenerative resources* *-Preserve and what is already made*
Implemented CE principles	*-Design out/minimise waste* *-Use waste as recourse* *-Prioritize regenerative resources* *-Preserve and what is already made*
CE practices	*-Specifications in guidelines and internal planning manuals*
Challenges of implementing CE	*-Reasons for non-implementation is when a certain lifetime or required requirements cannot be achieved*
Use of CE indicators	*YES*
CE indicators/metrics	*-End of life recycling input rate* *-Resource efficiency*
Challenges of developing indicators/metrics	-
Existing Roadmap towards CE	*YES (Sustainability Strategy)*
Public availability	https://www.asfinag.at/media/3077/asfinag-nachhaltigkeitsbericht_2017.pdf
Challenges of developing a detailed Roadmap towards CE	-

Table 3.3 *Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of Belgium*

COUNTRY	Belgium
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	-
Implemented CE principles	-
CE practices	*-Lifetime Enhancing Maintenance (incipient)*
Challenges of implementing CE	-
Use of CE indicators	*NO*
CE indicators/metrics	-
Challenges of developing indicators/metrics	*-Budget restrictions*
Existing Roadmap towards CE	*YES (Not published by an NRA)*
Public availability	*https://vlaanderen-circulair.be/en*
Challenges of developing a detailed Roadmap towards CE	-

Table 3.4 *Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of Denmark*

COUNTRY	Denmark
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	*-Preserve and what is already made*
Implemented CE principles	*-Preserve and what is already made (preventive maintenance)*
CE practices	*-Preserve the road condition to extend the lifetime using proper maintenance strategies.*
Challenges of implementing CE	-
Use of CE indicators	*NO*
CE indicators/metrics	-
Challenges of developing indicators/metrics	-
Existing Roadmap towards CE	*NO*
Public availability	-
Challenges of developing a detailed Roadmap towards CE	*-The change in policy and lack of common point of view which does allow to combine efforts*

Table 3.5 *Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of Germany*

COUNTRY	**Germany**
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	*-Design out/minimise waste* *-Use waste as resource*
Implemented CE principles	*-Use waste as recourse*
CE practices	*-Circular economy is largely based on waste legislation (Kreislaufwirtschaftsgesetz national law of EU directive 2008/98/EG)*
Challenges of implementing CE	-
Use of CE indicators	*YES*
CE indicators/metrics	*-Quota of reuse of RAP in hot mix asphalt*
Challenges of developing indicators/metrics	-
Existing Roadmap towards CE	*NO*
Public availability	-
Challenges of developing a detailed Roadmap towards CE	*-The incentive for reuse is industry driven*

***Table 3.6** Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of United Kingdom*

COUNTRY	**United Kingdom**
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	*-Design out/minimise waste* *-Use waste as resource* *-Preserve and what is already made*
Implemented CE principles	*-Design out/minimise waste* *-Use waste as recourse* *-Preserve and what is already made (preventive maintenance)*
CE practices	*-Use waste as recourse* *-Preserve and what is already made (preventive maintenance)*
Challenges of implementing CE	-
Use of CE indicators	*NO*
CE indicators/metrics	-
Challenges of developing indicators/metrics	*-This would be led by others within Highways England, rather than the Pavements Team specifically.*
Existing Roadmap towards CE	*YES*
Public availability	*https://s3.eu-west-2.amazonaws.com/assets.highwaysengland.co.uk/specialist-information/knowledge-compendium/Circular+Economy+-+Approach+and+Routemap.pdf*
Challenges of developing a detailed Roadmap towards CE	*-The above is not specific to pavements – interpretation of what the circular economy means specifically for road pavements would be useful*

***Table 3.7** Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of Lithuania*

COUNTRY	**Lithuania**
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	*-Design out/minimise waste* *-Use waste as resource*
Implemented CE principles	-
CE practices	*-Trying out and testing materials from waste in trial sections to find out their potential use and limitations in road structures. Existing materials are being evaluated during design phase to maximize their second use and minimize waste*
Challenges of implementing CE	*-In some cases, there are technology limitations. A limiting factor is that LRA is administration body and its rights are regulated very strictly*
Use of CE indicators	*NO*
CE indicators/metrics	-
Challenges of developing indicators/metrics	*-Unclear rules and legislations*
Existing Roadmap towards CE	*NO*
Public availability	-
Challenges of developing a detailed Roadmap towards CE	*-The above is not specific to pavements – interpretation of what the circular economy means specifically for road pavements would be useful*

***Table 3.8** Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of Norway*

COUNTRY	**Norway**
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	*-Design out/minimise waste* *-Preserve and what is already made*
Implemented CE principles	-
CE practices	-
Challenges of implementing CE	-
Use of CE indicators	*NO*
CE indicators/metrics	-
Challenges of developing indicators/metrics	-
Existing Roadmap towards CE	NO
Public availability	-
Challenges of developing a detailed Roadmap towards CE	-

__Table 3.9__ Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of Slovenia

COUNTRY	**Slovenia**
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	*-Design out/minimise waste* *-Use waste as resource*
Implemented CE principles	*-Use waste as recourse*
CE practices	*-Recycling and reusing of asphalt*
Challenges of implementing CE	-
Use of CE indicators	-
CE indicators/metrics	-
Challenges of developing indicators/metrics	-
Existing Roadmap towards CE	-
Public availability	-
Challenges of developing a detailed Roadmap towards CE	-

__Table 3.10__ Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of Sweden

COUNTRY	**Sweden**
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	*-Efficient use of existing and renewable resources with recirculated material flows* *-Use waste as resource*
Implemented CE principles	*-Preserve and what is already made (preventive maintenance*
CE practices	*-Removing restrictions on asphalt recycling*
Challenges of implementing CE	*-Difficult to avoid downgrading*
Use of CE indicators	*NO*
CE indicators/metrics	-
Challenges of developing indicators/metrics	-
Existing Roadmap towards CE	-
Public availability	-
Challenges of developing a detailed Roadmap towards CE	-

Table 3.11 *Summarized results of the replies relevant to CE, provided for the questionnaire by the contacted national road authority of the Netherlands*

COUNTRY	**Netherlands**
Awareness about CE	*YES*
Principles of CE that the NRA is familiar with	*-Design out/minimise waste* *-Use waste as resource* *-Prioritize regenerative resources* *-Preserve and what is already made*
Implemented CE principles	*-Use waste as recourse* *-Preserve and what is already made*
CE practices	*-Incorporation of recycled material in asphalt mixtures (foundation layers as well as pavement layers), periodic maintenance to repair aged spots of the pavement and preventive maintenance with the use of rejuvenators*
Challenges of implementing CE	*-The durability of recycled materials or bio-based is a challenge. Shorter durability is undesirable as it will cause cost, environmental impact and nuisance for the road user. other test methods are needed*
Use of CE indicators	*NO*
CE indicators/metrics	-
Challenges of developing indicators/metrics	-
Existing Roadmap towards CE	*YES*
Public availability	*https://platformcb23.nl/leidraden (referring to Construction works)*
Challenges of developing a detailed Roadmap towards CE	-

3.4.1 Analysis of the questionnaire findings

Following **Table 3.2** to **Table 3.11**, it can be seen that all the NRAs contacted are aware of the concept of CE and have at least minimum knowledge about what it is that it represents. All the NRAs seem to be familiar with the most commonly known and easily applicable principles of the CE, apart from the NRA that represents Belgium. Austria's and the Netherlands' NRAs seem to be the most informed in terms of CE knowledge, exhibiting the higher number of CE principles that they are familiar with. Among all the NRAs to which the questionnaire was sent, the most commonly known principles of CE are:

- Design out/minimize waste.
- Use waste as resource.
- Preserve and extend what is already made; usually translated as "preventive maintenance".

When the NRAs were asked about which principles of the CE are implementing, Belgium, Norway and Lithuania replied that none of them is currently being implemented. However, among the remaining NRAs the most common answers that were received in terms of implemented CE principles are:

- Preserve and extend what is already made
- Design out/minimize waste

In the question about which are the applied practices that indicate the implementation of some of the CE principles, Austria's NRA replied with specifications in guidelines and internal planning manuals, similarly to Germany's NRA which is following the waste legislation (Kreislaufwirtschaftsgesetz national law of EU directive 2008/98/EG), Belgium's, United Kingdom's and Denmark's NRAs stated that are preserving the road condition and extending its service life. Lithuania is trying to test waste materials in trial sections in order to promote the use of waste as a resource, while Slovenia and Slovakia are marching towards removing restrictions on asphalt recycling and keep recycling and reusing asphalt. Finally, the Netherlands are incorporating recycled materials in asphalt mixtures and extensively perform periodic preventive maintenance to extend the lifecycle of the asphalt pavements. Thus, the most commonly applied practices that indicate the implementation of some of the aforementioned principles are:

- Removing restrictions on asphalt recycling
- Extending the service life of the asphalt pavements, usually by preventive maintenance
- Testing waste materials for potential utilization as resources on asphalt pavements

At this point it is worth mentioning that although the concept of CE is not totally new as already analysed and hence, some of its characteristics have already been practiced for years by National Road Authorities. Aspects such as recycling, resource efficiency and utilization of waste materials in foundation layers are not new topics and have been implemented by NRAs for years now. Indeed, these practices that have been adopted for a long time now are in line with the principles of CE and yet some of the NRAs do not project them as "supporting the CE". In other words, although some NRAs might have stated that no specific principles of the CE are being implemented, they still recycle and trying to use their resources efficiently while extending the service life of their assets. This turns out to be a matter of definitions. Some country might do nothing about sustainability or CE but do have legislation or targets for using waste in foundations and are thus, although they do not use the word itself, practicing CE. Moving on, the challenges of implementing CE practices that the NRAs stated exist are the inadequate technical and mechanical performance of recycled materials, technological and administrative limitations and the difficulty laying upon the downgrading of recyclable materials. When it comes to CE indicators and/or metrics, only the NRAs of Austria and Germany are implementing some of them. In detail, Austria's NRA is utilizing the end of life recycling input, while Germany's the quota of reuse of Reclaimed asphalt pavement in the production of hot mix asphalt.

The rest of the NRAs state that the challenges encountered towards developing or implementing circularity metrics are the budget restrictions along with the lack of clear rules/legislations to support this effort. Finally, the only NRA that has officially published a roadmap or a strategy towards the implementation of CE is the one of United Kingdom's. However, Austria's NRA is following the national sustainability strategy, Belgium's has adopted the circular roadmap published by the "Circular Flanders", and the Netherlands' is following the guidelines towards circularity, recently published by Platform CB'23. The challenges of doing so as well, that most of the remaining NRAs are encountering are the changes in policy and lack of common points of view which does allow to combine efforts, the lack of incentives and the fact that the existing incentives foe the reuse of asphalt is mostly industry driven.

3.5 Suggestions and recommendations for strategies towards the implementation of CE principles

3.5.1 Green Public Procurement for road design, construction and maintenance

The European commission has invested into CE and sustainability in every sector. For the pavement engineering and road construction and maintenance sectors, a technical report has been published in 2016 [115], detailing the practices that NRAs and involved stakeholders should be implementing for more sustainable and circular approaches. Moreover, a set of criteria has been developed, that can help stakeholders act immediately even without having a deep knowledge of CE and sustainability. EU commission has identified some of the most impactful stages and aspects of a road's lifecycle that when modified accordingly can be significantly beneficial for the environment and the economy, based on the principles of green procurement and CE. The stages/aspects identified are:

- **Pavement vehicle interaction (Mean Profile Depth [MPD], [International Roughness Index [IRI]:** higher fuel consumption has been detected with higher values of these two indicators and thus, lowest possible and acceptable values are suggested.
- **Resource efficient construction:** Implementation of Life cycle assessment for every stage of the road construction and maintenance phases, along with increased attention to the embodied impacts of the transportation distances of the materials.
- **Recycled content:** Materials that able to be recycled within a closed loop perspective seem to be crucially beneficial for the environment. In this regard, it is suggested that high percentages of materials are recycled into the asphalt pavements while, however, complying with the performance requirements for the road pavement. It is highlighted that the transportation distance of the recycled materials should be assessed in order not to end up transporting materials to be recycled in such distances that in the end will impact the environment in a higher degree.
- **Materials transportation:** Significant focus is being given to the total transportation of the materials whether they are virgin or recycled. Transport distance can impose a significant environmental burden when an environmental assessment has not been undertaken. It is suggested that NRAs should adopt an indicator that is able to express the CO_2eq per tonne of transported materials and thus can optimise the location of the plants and quarries in order to minimise the environmental impacts originating from the energy consumption during the transportation of the materials.
- **Excavated materials, soil and wastes management:** It is highly recommended that excavated materials such as soils and wastes that are not labelled as hazardous are reused on site. Moreover, it is proposed that tracking of the waste production is undertaken and recorded.
- **Water and habitat conservation:** It is suggested that SUDS (Sustainable Urban Drainage Systems) are promoted and utilized in the asphalt pavements, while the addition of drainage components assisting the removal of sediment and solid particles is supported.

- **Noise:** Although both low-noise road surfaces and noise barriers contribute positively to the reduction of noise levels in targeted areas, whether one type of approach or the other, or a combination of both is the optimum solution, will depend very much upon. It is thus suggested that noise emissions are monitored during the construction, use and maintenance phases and desirable thresholds should be set (ISO/DIS 11819-2). Namely:
  - 87 dB(A) at 50 kph, and/or
  - 92 dB(A) at 70 kph, and/or
  - 95 dB(A) at 90 kph.
- **Congestion:** For extra potential environmental impacts due to congestion, fuel usage and lack planning to be avoided, traffic mitigation plans are suggested to be developed, not only during the construction stage of and asphalt road but also during its use and maintenance.
- **Maintenance and rehabilitation strategies:** The design team or the Design and Build tenderer or the Design Build and Operate tenderer shall include a Maintenance & Rehabilitation Plan, that follows all the suggestions, in the detailed design. For each section of road specifically characterised by specific construction methods, materials, environmental conditions, meteorological conditions and use, the M&R Plan shall, as a minimum:
  - Include routine, preventive and rehabilitation actions;
  - Optimise the cost-benefit ratio of the maintenance works;
  - Declare the environmental performance of any routine, preventive and rehabilitation action/strategy
  - Include the cost, expected intervals between maintenance activities, the Traffic Congestion Mitigation Plan and the Demolition Waste Management Plan for each action.

All the suggestions and recommendations relevant to different stages and/or aspects of the construction, use and maintenance of a road can be seen summarized in Figure 3.1.

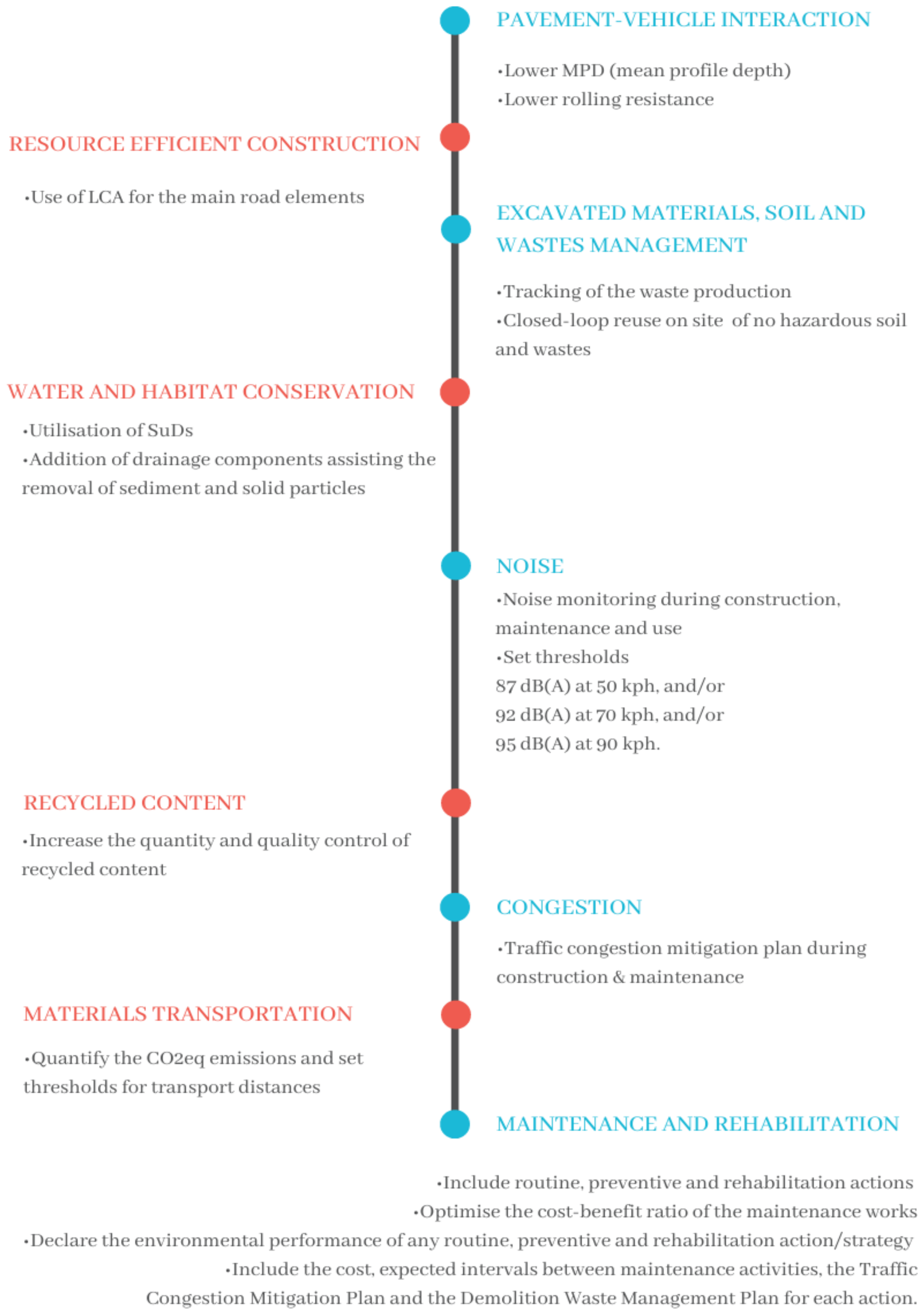

Figure 3.1. *Suggestions and criteria to be fulfilled for the construction, use and maintenance of a road for a more sustainable and circular approach according to the European commission* [115]

3.5.2 Circular Economy: Principles for Buildings Design

Moreover, the European Commission has also published a document entitled "Circular Economy: Principles for Buildings Design" [116] and details the general principles that should be implemented if a more circular approach is to be adopted in the building sector. The document is specifically focused on buildings, but the main defined principles are presented here due to the fact that a lot of similarities exist between buildings and roads and these principles are immediately transferable to the road engineering domain:

- Design principles of circular economy and sustainable buildings are applicable to all actors along the value chain.
- Sustainable choices must consider total life cycle costs, financial and non-financial return on investments.
- Principles need to be applied considering proportionality - benefits should outweigh the costs.
- Better knowledge is needed about construction techniques to facilitate deconstruction and to enhance durability and adaptability of a building.
- Durability of buildings depends on better design, improved performance of construction products and information sharing.
- Prevent premature building demolishment by developing a new design culture.
- Design products and systems so that they can be easily reused, repaired, recycled or recovered.

As aforementioned these principles are referring to buildings, but the majority of them can easily and immediately be transferred into the road sector and.

3.5.3 Map of Circular recommendations & practices

The purpose of this map is to allow NRAs to detect their internal opportunities that could be exploited towards the transition to a more circular way of operating. As mentioned above, the three principles of the CE that can be projected in the context of asphalt pavements are presented in green colour within **Figure 3.2** It is worth mentioning though, that for an organisation or an NRA in this case the first 4 steps that can in a way be considered as prerequisites are the stakeholder's engagement, the transparent and safe communication with the supply chain, the corporal social responsibility reporting and finally the push towards regional, circular procurement policies. The map starts with the 3 principles of CE defined (green boxes). Further on, the blue boxes represent some of the practices that can assist on fulfilling the CE principle that are related to. After that, the grey boxes are different alternative processes -that do not recant each other- which can be implemented and lead towards increased circularity. Hence, some of the most immediately applicable recommendations that can be given to NRAs towards the implementation of CE are:

- Establish compulsory and regulated end of life strategies.
- Optimise pavement design standards towards thinner layers.
- Optimise preventive maintenance strategies by implementing a holistic sustainable pavement management system.
- Use material flows and material passports to track the life cycles of materials.
- Use of biomaterials as main paving materials through reusing and recycling.
- Maximise the use of Reclaimed asphalt and increase the reuse of secondary materials.
- Use of lower percentages of virgin materials should be established as the norm.
- Target setting towards the exploitation of all the available Reclaimed Asphalt.
- Use of renewable energy sources.
- Change utilisation patters (sharing models, product as service).
- Minimise the construction of new road networks by optimising the layouts of existing ones.

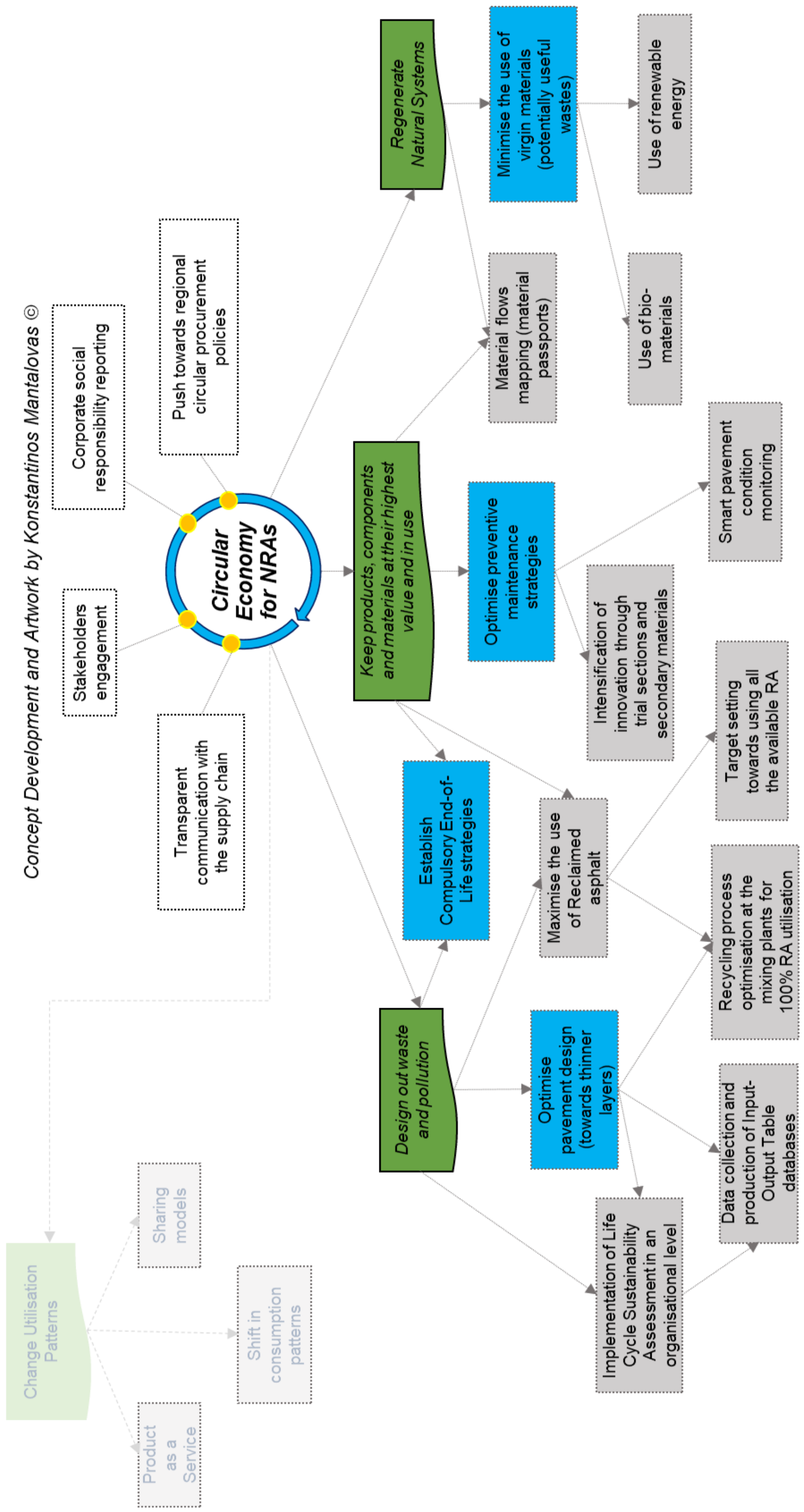

Figure 3.2. *Circular Map of recommendations for the implementation of CE by NRAs*

3.6 Summary and conclusions

As it can be concluded from the analysed roadmaps in **Chapter 3**, only a few have taken under consideration the potential of CE in asphalt pavements. Most of these documents recognize the potential CE benefits in a larger scale, i.e. the built environment without direct focus on asphalt pavements. Thus, it can be said that, in general, NRAs so far have not adequately invested into producing roadmaps towards the implementation of CE. This is happening due to lack of budget, lack of experts in CE within the national road authorities and due to the uncertainty of the successful implementation of CE, which also incorporates the lack of well-structured and comprehensive circular business models and incentives for the stakeholders associated with the market of asphalt pavements. In addition, several national road authorities have been contacted. Through the questionnaires that have been sent to them and as analysed in **Chapter 4**, it seems that all the NRAs are familiar with the concept of CE and most of them are also familiar with most of the principles it represents, but their majority is not implementing them thoroughly. Most of the NRAs replied that are:

- Prioritizing the "designing out" of the waste of their products.
- Prolonging the life of their assets by conducting preventive maintenance.

Some of the NRAs stated that they are not implementing such circular practices, but however, they do recycle, they do implement preventive maintenance regimes and they do sometimes utilize waste materials as resources within the asphalt pavements that they construct and manage. This proves that all of the NRAs that have filled the questionnaire with one or another way, do implement practices that are aligned with the principles of CE. This could lead to the conclusion that more people with specialization in CE should be operating within the NRAs providing higher accuracy, more insights and knowledge in terms of CE implementation. Recommendations and best practices that would be able to provide NRAs a more sustainable and circular operating angle have been presented in **Chapter 3**. The most immediate actions that NRAs could undertake in order to move towards this direction are:

- The rethinking of their designs, minimising the use of materials and improving the durability of the asphalt pavements.
- The utilisation of end of life materials such as biomaterials, reclaimed asphalt and by

products in general that are considered wastes.

- The utilisation of life cycle assessment within the design phase of their assets, quantifying the potential environmental impacts and thus proceeding with the most preferable options.
- The investment in research and development of alternative, more environmentally friendly construction methods
- Design products and systems so that they can be easily reused, repaired, recycled or recovered.
- Communication and transparent relations with the whole value and supply chain
- Development of circular business models that will benefit both the NRAs and the stakeholders along with the users.
- The utilization of material flow mapping, along with the utilization of soil and wastes during the construction and maintenance phases as useful materials.
- Development of methodised end of life strategies, focusing on the possibility of closed loop approaches and/or upcycling.

Finally, more and more NRAs should allocate percentages of their budgets towards the development of circularity metrics and roadmaps/strategies towards the implementation of CE and the assessment of the levels of this implementation. This could help to monitor and evaluate the progress that is being made and finally develop a feasible and spherical framework of how they should actually be implementing CE in asphalt pavements in the best way possible. This way could be complimented by following the recommendations for knowledge development and the "Map of Circular Recommendations" deployed in previous chapters, in order for a Sustainable & Circular Life Cycle Management approach to be achieved.

4 **Chapter IV:** Measuring the circularity of asphalt mixtures

4.1 Introduction

4.1.1 Circular Economy and Reclaimed Asphalt

Towards the attempt of the road engineering industry to promote the circular economy (CE) and its principles, while reducing the use of large amounts of energy and materials [117], Reclaimed Asphalt (RA) exhibits a high potential for exploitation. By definition, CE is restorative and regenerative and aims to keep products, components, and materials at their highest utility and value at all times , i.e., it supports the "re-circulation" of materials and energy within the same (closed loop process) or alternative product systems (open loop process), and thus the elimination of avoidable wastes [118]. Hence, RA is perceived as an ideal material that can re-enter the cycle of asphalt mixture production [119]. Although the concept of CE is not new, it still has not been widely and formally implemented in transportation infrastructure projects and specifically in asphalt pavements. The concept of CE made its first appearance as a proactive policy goal for numerous businesses and in political agendas in the late 1970s, mainly due to climate change and the acute concern of rising resource prices, raised by R. Carson and K. Boulding [38]–[41], and as aforementioned, it encompasses the principles of multiple schools of thought, such as industrial ecology and symbiosis, performance economy, biomimicry, cradle to cradle, blue economy, regenerative design, cleaner production, and natural capitalism [42], [43]. However, when it comes to transport infrastructures, and more specifically asphalt pavements and RA, it becomes complex to encompass all the principles of CE in their life cycles, and thus no record of studies and approaches relevant to the quantification of their circularity have been recorded. Highways England, London's Waste and Recycling Board (LWARB), Ellen MacArthur Foundation, and Opportunity Peterborough are some of the institutions and companies that are driving towards introducing CE and its metrics within their agenda, hoping to influence a wider decision-making audience. Highways England, in collaboration with two of the most reputable construction companies worldwide, published an "Approach and Routemap" detailing how the implementation of CE can be achieved through their incipient strategies [102]. Moreover, LWARB has recently published the London's CE Route Map, in an attempt to accelerate the growth and development of CE across London, whilst setting out an ambitious plan of action, including the built environment and transportation infrastructure [120]. "Cities in the Circular Economy: An initial exploration" is a report published by the Ellen MacArthur Foundation. It highlights the challenges of the linear economy and promotes the advantages of implementing CE on an urban scale, and within the built environment [45]. Opportunity Peterborough published the "Circular City Roadmap" in 2018. It is a resourceful plan and performance monitoring framework towards 2021, which sheds light upon the next steps to be followed for the realization of circular infrastructure, with the ultimate target being a "circular city" [121]. Some attempts have also been made by companies trying to specifically implement the principles of CE into the production of asphalt mixtures as mentioned in **Chapter 2.2**. Tarpaper Recycling, along with Super Asfalt, have proposed the production of REC100. In addition, SYLVAROAD™ RP1000 is an additive derived from Crude Tall Oil (CTO) that can increase the levels of RA incorporated into the asphalt mixtures.

4.1.2 Reclaimed Asphalt

Site-won asphalt comprises asphalt taken by milling of asphalt road layers, slabs ripped up from asphalt pavements and asphalt from reject and surplus production. The processing of site-won asphalt results in RA, suitable and ready to be used as constituent material for asphalt, after being tested, assessed and classified [122]. Reclaimed asphalt may be used as a constituent material for bituminous mixtures manufactured in an asphalt plant, in accordance with the specifications for those mixtures. Thus, Reclaimed Asphalt can be defined as existing asphalt pavement materials that have been removed during the resurfacing, rehabilitation, or reconstruction operations of asphalt pavements and accordingly processed [108], [109]. All of the motorways within the EU member-countries consist of asphalt pavements, which—as anticipated—suffer from various types of distresses [123]. Their maintenance and rehabilitation are significantly impactful processes in an environmental, economic, and social context. In order to minimize the impacts of these processes and move towards a more sustainable and circular approach, recycling of RA is nowadays a widespread practice within the road engineering industry [123]–[127]. For the first time, asphalt recycling took place in 1915 [106], [128]. However, it properly started gaining popularity and a sustained approach of use during the 1970s in the United States. This occurred during the period of the Arab oil embargo, due to the significantly increasing cost of crude oil. Afterwards, the construction practices started to systematically change in an attempt to utilise higher proportions of RA. This led to an extensive study about the incorporation of high percentages of RA in bituminous pavements. In 1979, a field demonstration project by the Federal Highway Administration of the United States was carried out in New Jersey, where they incorporated around 50% RA into asphalt pavements [128], [129]. The use of RA became popular in State transport departments by the time the Superior Performing Asphalt Pavements (Superpave®) mixture design method was developed in late 1990s [128]. The lack of guidance for the use of reclaimed asphalt in the production of Hot Mix Asphalt by the Strategic Highway Research Program, led to the halt of high RA utilisation by many departments [108]. However, by the end of the 20th century, guidelines for the utilisation of RA within the Superpave® method had been developed; and thus, allowing again the recycling of asphalt pavements to become well-established. In the United States, asphalt exhibits the highest recycling rates than any other material, helping in this way to lower overall material costs, allowing road owners to achieve more roadway maintenance and construction activities within limited budgets [130], [131]. Moreover, lately, and mainly due to the advancement of asphalt mixing plants, it has become possible to utilise higher proportions of RA during the asphalt production process. According to a survey that took place in 2017 the European countries, Belgium, Finland, Great Britain, Hungary and Slovakia were recycling more than the 90% of the available RAP in hot and warm mix asphalt production for surface layers [128], [132]. The annual average quantity of available RA within Europe reaches approximately 45.5 Megatonnes, while the average annual proportion that is actually being utilized in asphalt production is only 23.2 Megatonnes [132]–[143].

The main techniques with which RA can be utilized are in hot in-plant recycling, hot in-place recycling, full depth reclamation, cold in-plant recycling, and cold in-place recycling [124], [144]. The percentage of RA incorporated in road pavements is usually limited between 10% and 30%, despite the advantages that its use might imply and the increased levels of RA incorporation that can be achieved with the utilisation of rejuvenators. This is mainly occurring due to legislation limitations and technical issues, such as the variability of the RA properties, the lack of certainty about the performance of the mixture in absence of experimental results on full scale conditions, and the lack of complete understanding of the mechanisms taking place during the asphalt mixture production [145], [146]. For example, in Italy, the maximum allowed percentages of RA utilisation are 30%, 25%, 20%, for the base courses, binder courses, and surface courses, respectively [147], [148]. In Germany, the maximum allowed percentage of RA that can be incorporated into different layers depends upon different characteristics of the RA itself and has to be calculated. The maximum values are 100% for base courses and 50% for binder and surface courses [149]. In Denmark the allowed percentages of RA incorporation range from 15% to 40% for base and binder courses, depending upon the type of the asphalt and the asphalt mixing plant; while for surface courses this percentage is significantly lower, ranging from 0% to 5% depending on the type of the surface course [150]. Moreover, according to the technical regulations of Poland, the maximum allowed RA percentage for the surface courses is 0%, and for binder and base courses between 20% and 30% depending of the recycling method [151]. The indicative RA limits for the four aforementioned countries are summarised below, in **Figure 4.1**.

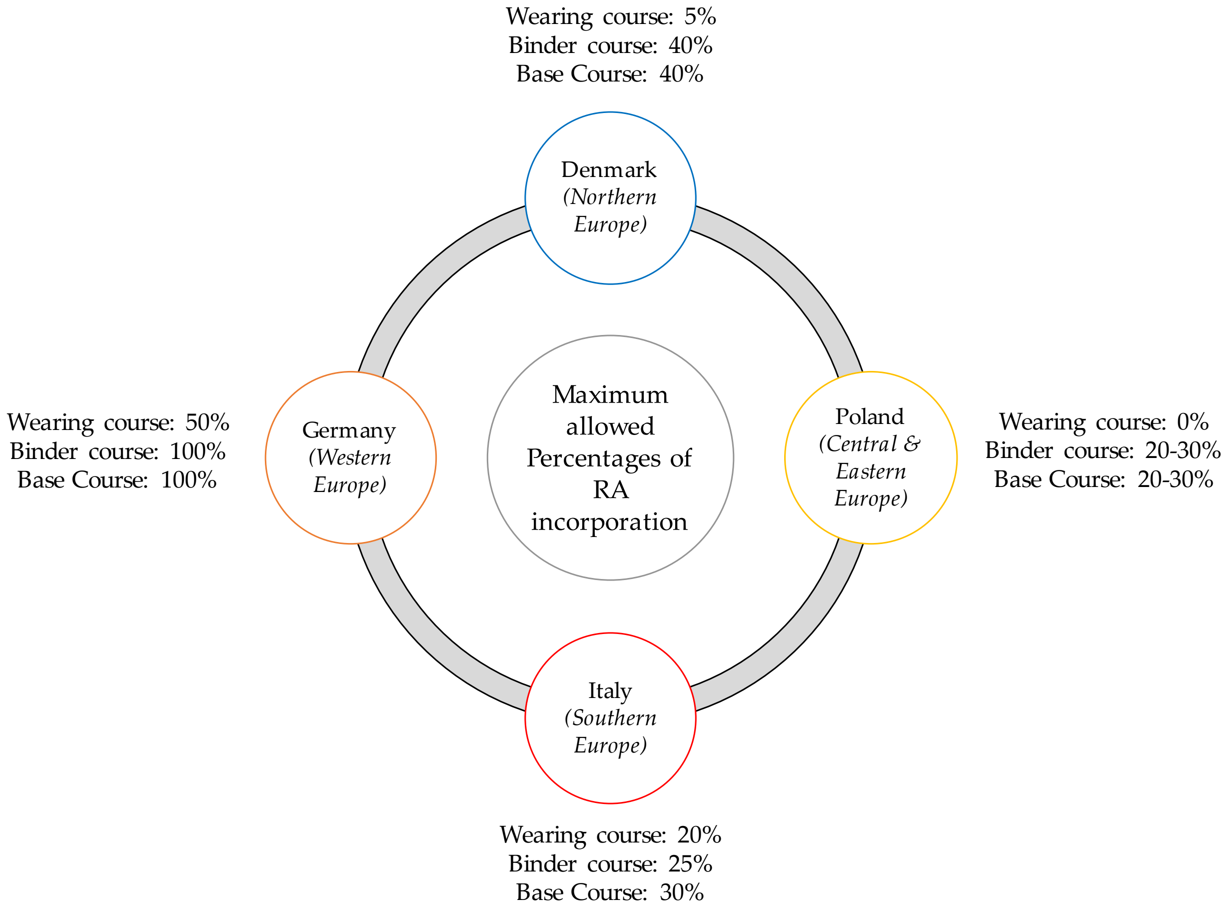

Figure 4.1 *Allowed RA percentage per layer for four different European countries, each one from a different major EU region*

It can thus be deduced, that RA is a brilliant example of material re-circulation within a product system. It has the potential to be 100% circular and existing within a closed loop system. However, although RA exhibits a significantly valuable opportunity for the integration of CE practices in the road engineering sector, as can be indicatively seen by the allowed RA percentages from **Figure 4.1**, regulations and technical standards still halt its full exploitation. Several studies have attempted to pave the way towards higher utilization of RA in asphalt pavements. The main conclusion of these studies is that higher utilization of RA is possible when attention is paid to the mixture design and the RA's properties, so that a consensus between the laboratory mix design and the full-scale realization of the asphalt pavement can be achieved [152]–[157].

4.2 Scope and Objectives of the Chapter

As it is theoretically possible to incorporate up to 100% of RA in the production of asphalt mixtures, a question that arises is "how can we quantify the circularity of asphalt mixtures incorporating RA?" This chapter attempts to answer this question and provide the missing link between the concept of CE and the utilization of RA under the umbrella of a Circular Economic approach. Hence, a thorough market analysis of the current recycling rates and trends of RA exhibited in EU member-countries is imperative. Moreover, the introduction of new parameters (RA Placed rate (ΔU), RA Available Quantity Factor (QF[a]) and RA Placed Quantity Factor (QF[p]) that help interpret the availability and the actual exploitation of RA is considered essential. Furthermore, a case study for the quantification of the Product Material Circularity Index (MCI_{MRA}) of asphalt pavements could enlighten the potential hotspots within the life cycle of a pavement, as can be seen in **Figure 4.2**, and potentially it could help stakeholders and asphalt mixture producers to optimize their production approaches environmentally and economically.

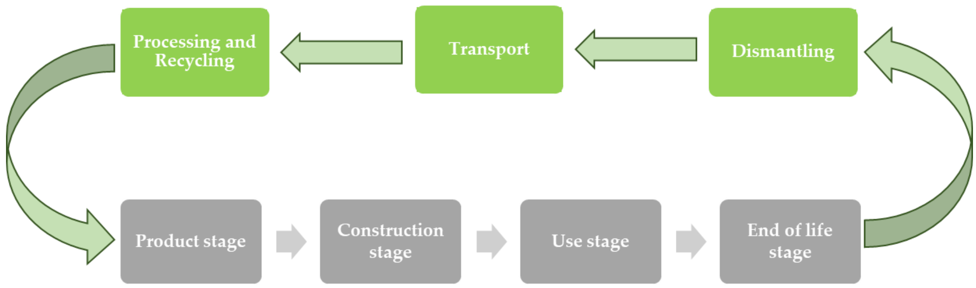

***Figure 4.2**. Graphic representation of the life cycle of asphalt pavements according to the European Asphalt Pavement Association and a potential Circular Model* [158]

To achieve a sustainable production process, this process must also be based on a circular economic model [51], [70], [72]. The purpose of this chapter is, thus, to quantify and evaluate the circularity potential of RA in the Hot and Warm Mix Asphalt (HWMA) production market through an analytical top-down process. Following this approach, three main objectives can be identified. The first objective is to provide a complete and up-to-date overview of the aforementioned market at a European scale; the second is to implement a Circular Economic Model (CEM) for the asphalt mixtures with RA (MRA), in accordance with the methodology proposed by the Ellen MacArthur Foundation [159], a foundation recognized as a preeminent institution for CE matters. Finally, the third objective is to quantify and evaluate the circularity potential of the asphalt mixtures with RA, within a specific scenario referred to hereafter as "Case Study". To do so, a Material Circularity Index quantifying framework, specifically tailored for asphalt pavements, has been developed. The usefulness of this quantification is inextricably correlated with the understanding of how far along the road engineering industry is in its transition from a linear way of operating to a circular one. The implementation of this methodology to asphalt pavements would lead to increased awareness of stakeholders about the level of their business' circularity and could potentially detect hotspots relevant to specific processes or products, which when tackled could achieve a holistic system improvement.

4.3 Methodology

4.3.1 Analysis of the Reclaimed Asphalt market in Europe: First objective

In this chapter, in order to effectively assess the capacity of RA recycling on a European scale, reputable sources of data were utilized. All of the data needed for the realization of this part of the work was collected from the European Asphalt and Pavement Association (EAPA), through its annual reports, entitled "Asphalt in Figures" [132]–[143]. The analysis has been performed from 2006 to 2017. However, in order to make the results more cohesive and consistent, Europe was divided into four major regions, increasing the homogeneity and the geographical representation of the data. The division was performed according to Eurovoc, and thus, the European Union's guidelines, and it can be seen in **Figure 4.3** and it is further analysed in **Table 4.1**.

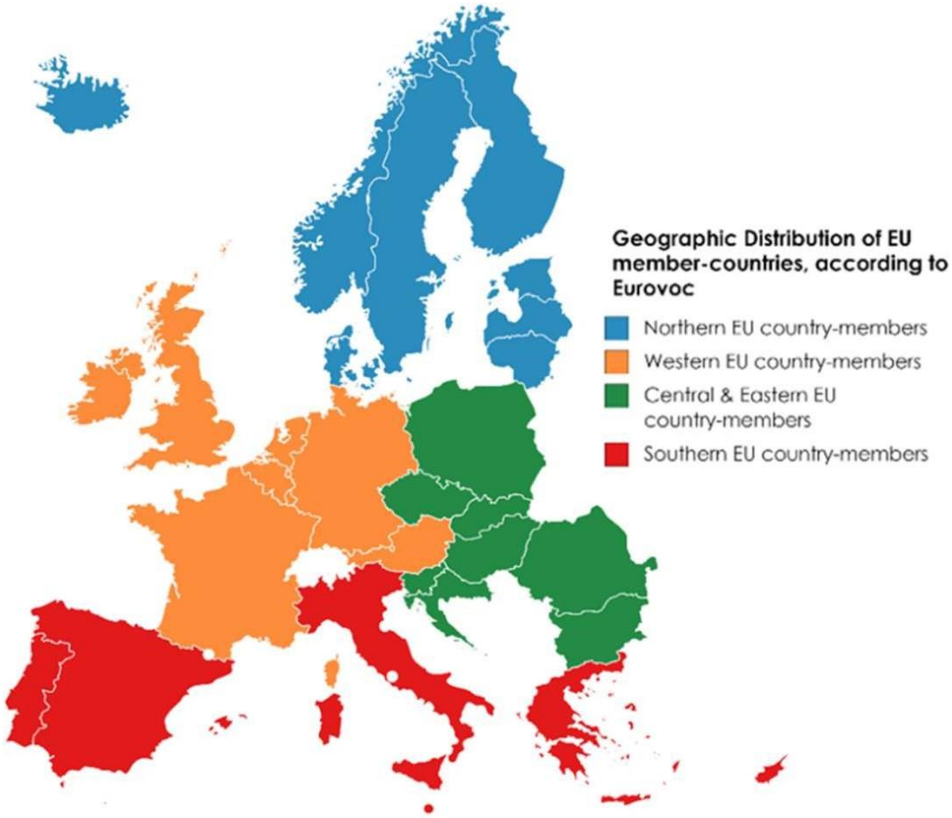

Figure 4.3. *Distribution of the EU member-countries into four major regions.*

Table 4.1. *Members-countries included in each major EU region.*

Northern EU members	**Central and Eastern Eu members**	**Western EU members**	**Southern EU members**
Denmark	Bulgaria	Austria	Cyprus
Estonia	Croatia	Belgium	Greece
Finland	Czech Republic	France	Italy
Latvia	Hungary	Germany	Malta
Lithuania	Poland	Ireland	Spain
Sweden	Romania	Luxemburg	Portugal
	Slovakia	Netherlands	
	Slovenia	United Kingdom	

After the distribution of the EU member-countries in the four major regions, all the data relevant for each country was acquired from EAPA and grouped in correspondence with the regions. The data relevant to the total annual HWMA production per EU region is the primary focus. Moreover, data that represents the main applications of HWMA production was collected.

Hence, it became possible to classify the average percentage distribution of HWMA uses per pavement layer, namely, surface, binder, and base courses, and per EU region from 2006 to 2017. Moreover, an indicator characterized as the "RA Placed rate" (ΔU), was quantified, along with the introduction of two new parameters: "RA Available Quantity Factor" (QF[a]) and "RA Placed Quantity Factor (QF[p]). The Formulae (1)–(3) of the defined parameters can be found below. These parameters were introduced for the interpretation of the results to be relevant to the magnitude of actual RA utilized in conjunction with the availability of RA. Furthermore, ΔU describes the rate with which RA is being utilized (RA[p]), in relation to the total available RA (RA[a]), or the current balance between RA demand and supply in the road pavement construction market. The values of ΔU can vary between 0 and 1, measuring the current RA ability to be introduced into a circular production process, namely, the RA transition level from being perceived as a waste (ΔU = 0) to being utilized as a resource (ΔU =1).

$$\Delta U = \frac{RA_{placed}}{RA_{available}}$$ *Equation 1*

QF[a] and QF[p] represent the incidence of RA[a] compared to the total asphalt production, which is the sum of recycled and virgin asphalt (RA[a] + HWMA), and the incidence of RA[p] compared to the total asphalt production already defined, respectively. Under the assumption of an active road construction market and by considering the values of QF[a] varying from 0 (no RA utilized as material source) to 100 (no demand of virgin materials for asphalt mixture production), the QF[a] measures the potential ability of the RA to meet the demand for asphalt mixture production. The values of QF[p] vary from 0 (no RA utilized as material source) to 100 (total recycling of RA) and represent the actual ability of RA to meet the demand for asphalt mixture production.

$$QF[a] = \frac{RA_{available}}{RA_{available}+HWMA} * 100$$ *Equation 2*

$$QF[\boldsymbol{p}] = \frac{RA_{placed}}{RA_{available}+HWMA} * 100$$ *Equation 3*

It is worth mentioning that the values of QF[p] tend to be equal to the values of QF[a] when ΔU tends to 1. This is when a fully restorative flow of RA is achieved.

4.3.2 Developing a Circular Economic Model for Asphalt Mixtures with Reclaimed Asphalt: Second Objective

The typical feed materials for asphalt mixture, i.e., bituminous binder and natural aggregates, are obtained by extracting non-renewable resources, and their management requires a CEM, aligned with the goals of sustainable development. Therefore, according to the whole-life product approach [47], [159], the CEM developed in this thesis considers the "technical cycles", in which the products, asphalt mixtures with RA, are evaluated by considering the re-circulation of the RA into the road construction process through recycling. The material flows, going for recycling, originate from the dismantling of the asphalt pavements at the end of their service life. The CEM is based on just one life-cycle, as depicted in **Figure 4.4**, where the conventional linear economic model is also illustrated to highlight the difference between the processes. It is worth stressing that after the dismantling of the pavement, the first step towards the asphalt mixture production is the treatment of the RA, by crushing and sieving the Reclaimed Asphalt Pavement (RAP), at the recycling plant. When RA is about to be introduced in the asphalt mixing process, it is usually treated as an aggregate (black rock) and its overall mass percentage characterizes both the mechanical performance and the durability of the end-product. The final asphalt mixture consists of both virgin and recycled feedstock and it can be assumed that the end-product is in the transition from being "linear" to becoming "circular".

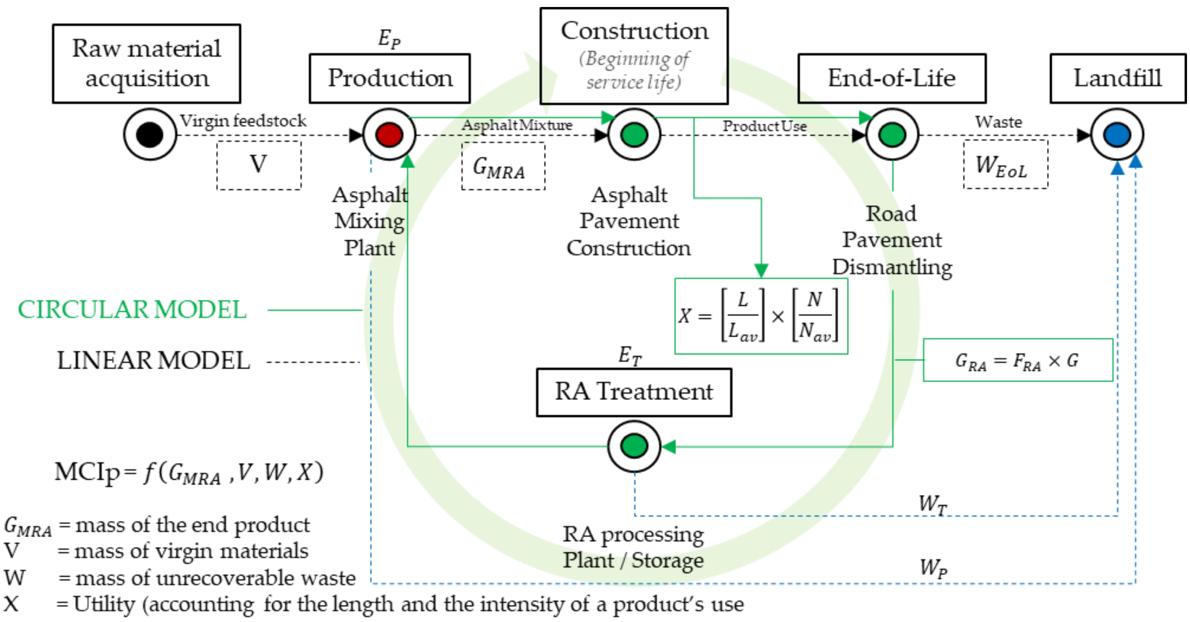

Figure 4.4. *Depiction of the defined Circular Economic Model compared with the traditionally linear economic*

model

With the aim of assessing the circularity of the end-product, a tailored and analytical method has been developed, whose steps are illustrated in **Figure 4.5**, according to the framework developed by the Ellen MacArthur Foundation [159]. The input data has been acquired by calculating the mass of the end-product [G_{MRA}], which is equal to the mass of the dismantled pavement [G], along with the required virgin feedstock [V] and the mass of the reclaimed asphalt collected after dismantling [G_{RA}]. Further inputs are the fraction of the recycled material expressed as a mass ratio between the end-product and the RA [P_{RA}], the fraction of the product collected for recycling at the end of service-life [F_{RA}], the efficiency of the recycling process at stage 1, the treatment of the RA [E_T] and the efficiency of the recycling process at stage 2, and the production of the asphalt mixture [E_P]. Finally, the amount of waste produced at the End-of-Life of the pavement [W_{EoL}], along with the amount of waste produced from the treatment of the RA [W_T] and the amount of waste originating from the production of the asphalt mixture [W_P], are required. The total amount of waste [W] is also taken under consideration for the calculation of the Linear Flow Index (LFI), which measures the potential linearity of the end-product. LFI, along with the Utility [X] of MRA's, defines both the Product Material Circularity Indicator (MCI^*_{MRA}) and the Product Material Circularity Index (MCI_{MRA}).

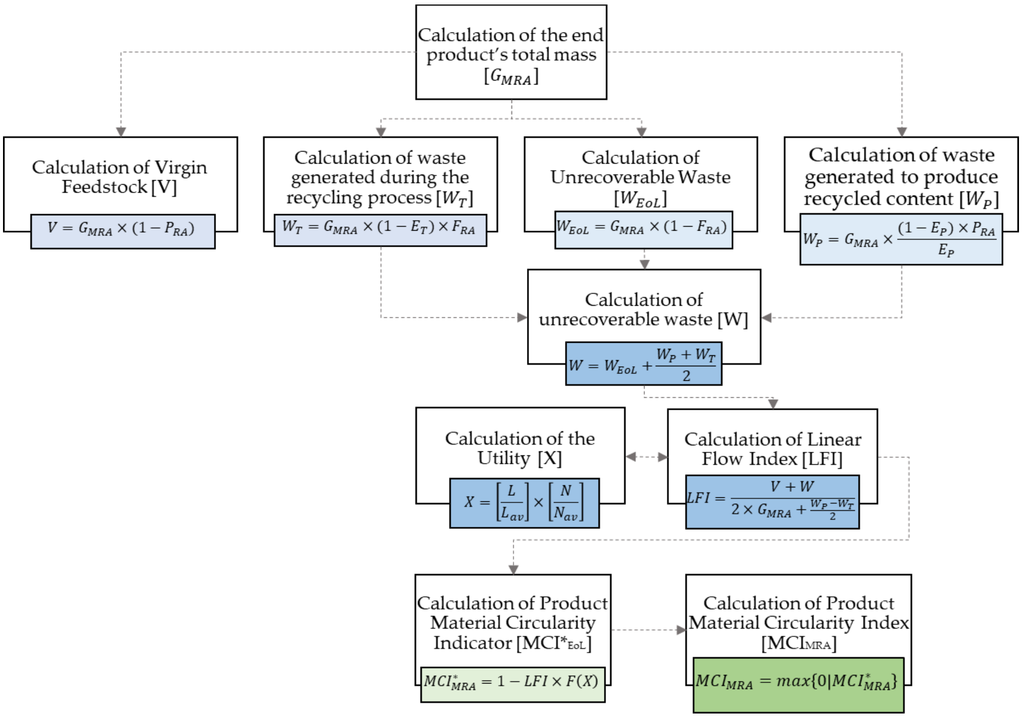

Figure 4.5*. Definition of the inputs required for the calculation workflow of the proposed framework.*

A critical aspect of the process of acquiring and utilizing the required data is the definition of the Utility factor [X]. It is a function of the actual average lifetime of the end-product (L_{MRA}), the actual average lifetime of an industry average product (L_{av}), the average number of loading cycles before failure (N_{MRA}) in terms of fatigue or rutting achieved by the end-product (N_{MRA}) during laboratory testing, and the equivalent number of loading cycles of an industry-average product of a similar type (N_{av}).

$$X = \frac{L_{MRA}}{L_{av}} * \frac{N_{MRA}}{N_{av}} \qquad \textit{Equation 4}$$

Regarding the second part of the Equation 4, N_{MRA}/N_{av}, and according to the results of experimental campaigns that have been conducted by the Illinois Centre for Transportation and the University of Tennessee [160], [161] about the impact of RA content on the performance of asphalt mixtures, the influence of different levels of RA incorporated into asphalt mixtures was identified [162]. Sheng Zhao et al. [163], Ibrahim Sonmez et al. [164], Taleb Al-Rousan et al. [165], Tabakovic et al. [166], [167], and W. Bankowski [168] have also performed similar studies identifying the influence of the RA percentage on the mechanical behaviour of different layers composing asphalt pavements. This was achieved by testing representative specimens for fatigue and rutting resistance. The studies concluded that different levels of RA percentages incorporated into asphalt mixtures could lead to different performance levels. These studies showed that for surface courses containing RA, the resistance to rutting increases with increasing RA content, while the resistance to fatigue for binder and base courses with RA increases with increased RA content after the threshold of 20% and 30%, respectively. Thus, it became possible to establish the average number of loading cycles before failure (N_{MRA}) in terms of rutting (surface course) and fatigue (binder and base courses) achieved by the end-product (N_{MRA}) during laboratory testing and the equivalent number of loading cycles of an industry-average product of a similar type (N_{av}). It is worth mentioning that the fraction L_{MRA}/L_{av}, defined within the EMF's methodology was assumed to be equal to 1. The underlying reason behind this specific assumption is that it would be unrealistic to assume a value for the actual average lifetime of the end-product (L_{MRA}) and the actual average lifetime of an industry average product (L_{av}). Hence, as stated in the very same methodology, if it is not possible to provide a good estimate of the aforementioned fraction, it is conservatively suggested for the average lifetime to be deemed equal to $L_{MRA}/L_{av} = 1$ [74]. Finally, the MCI^*_{MRA}, as a measure of the circular flow of the end-product, is calculated through the following equation:

$$MCI^{*}_{MRA} = 1 - LFI \; x \; F[X]$$ *Equation 5*

Where the parameter F[X] is an equilateral hyperbolic function of the Utility factor with constant K equal to 0.9. In order to avoid a negative value of circularity potential of the end-product, the MCI_{MRA} is established by comparing and choosing the highest value between 0 and MCI^{*}_{MRA}. This value is the final measure of the circularity potential of the end-product and it represents the impact of the MRA's on the road market construction in terms of innovation and sustainability.

4.4 Quantifying the MCI_{MRA} of the Italian motorways: A case study: Third Objective

Having defined the availability and the recycling rates of RA within the EU, the data concerning Italy was isolated and utilized in order for the case study to be structured and undertaken. However, it is worth mentioning that the applicability of the proposed Circular Economic Model along with the Material Circularity Index quantification method is not restricted in terms of regionality, at least within Europe. The chain of asphalt mixture production is similar or in some cases identical in most countries, and thus the inputs for the MCI_{MRA} quantification are region independent. The goal of the calculation is to assess the circularity of the mixtures with RA originating from the dismantling of the asphalt pavements, constituting Italy's motorway network. The final assumed road pavement structure that was considered for this case study is depicted in **Figure 4.6**.

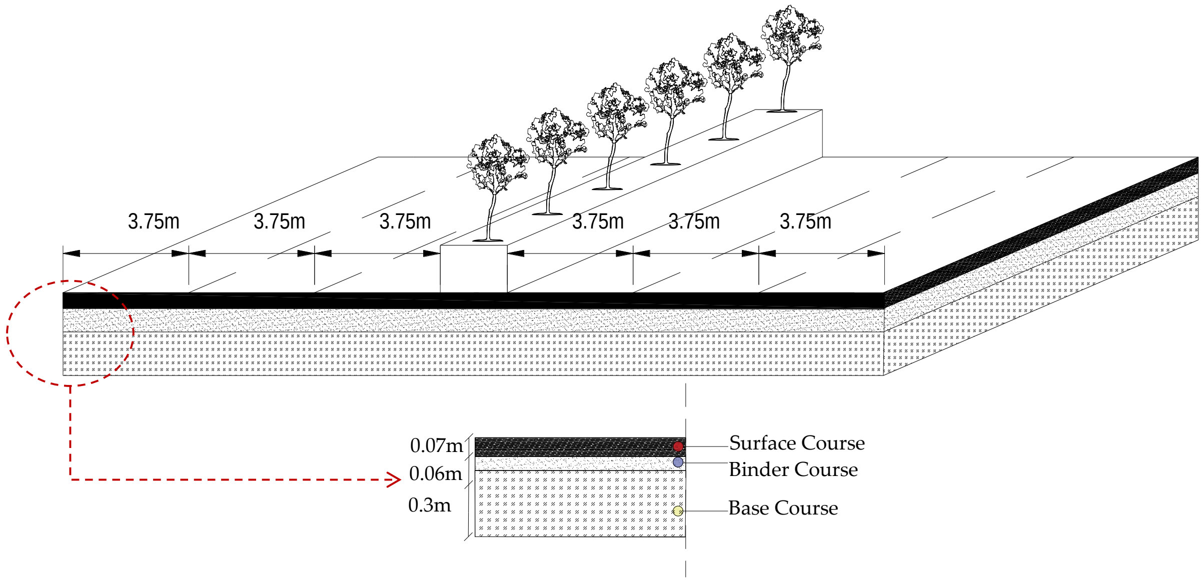

Figure 4.6. *Cross section of the asphalt pavement structure under study.*

First, data relevant to the total length of the Italian motorways was collected from the official website of the EU and data concerning the availability and exploitation rates of RA was collected from EAPA, as mentioned before. According to the Italian road design standards [147], [169], the average thickness of the pavements was determined, as well as the average number of lanes along with their width. The motorway pavements were sub-divided into three layers, namely, surface, binder, and base course, due to the fact that different percentages of RA are incorporated in each layer, according to the Italian road design standards [147], [169] and different levels of RA utilization were detected in each layer according to the analysis performed on the state of the HWMA production and RA utilization within the EU. For transparency reasons, all the essential data collected and, of course, the assumptions made in order for this case study to be undertaken, have been summarized and presented in **Table 4.2**.

Table 4.2. Data collected, and assumptions made for the completion of the study.

Average road dimensions	Total Length of motorways (km)	6.83×10^{3}
	Number of lanes per direction	3
	Average width of lanes (m)	3.75
Average Layer Thicknesses	Surface course (m)	0.06
	Binder course (m)	0.07
	Base course (m)	0.3
Allowed % of RA incorporation within the pavement layers	Surface course	20%
	Binder course	25%
	Base course	30%
Quantities of Hot and Warm Mix Asphalt Production and Reclaimed Asphalt	Total Available RA (tonnes)	1.02×10^{7}
	Total Placed RA (tonnes)	1.70×10^{6}
	Total HWMA production (tonnes)	2.83×10^{7}
Total average mass of pavement layers as final products	Surface course (tonnes)	2.17×10^{7}
	Binder course (tonnes)	2.53×10^{7}
	Base course (tonnes)	1.08×10^{8}
Total average use of the total HWMA production per pavement layer	Surface course (tonnes)	7.37×10^{6}
	Binder course (tonnes)	8.22×10^{6}
	Base course (tonnes)	7.37×10^{6}

Utilizing the data collected and reported in **Table 4.2**, the MCI_{MRA} of surface, binder and base courses of the Italian motorways was quantified, following the proposed framework. The focus has been given to the "technical circle" of RA re-circulation within the product system. This is because no biomaterials have been used to produce the asphalt mixtures that would have contributed to the restoration of the biosphere during their End-of-Life. In detail, since different layers incorporate different levels of RA, the analysis is carried out by considering three mixtures with different RA content in order to provide results with higher accuracy and actual representativeness, compared to undertaking the study considering the asphalt pavements as complete end-products. The efficiency of the recycling process (RA treatment) is assumed E_T = 100%, as usually the entire amount of the milled RA, after appropriate crushing and screening, is utilizable [170]. The efficiency of the recycling process to produce MRA's is assumed to be E_P = 98%. In the majority of the situations, when HWMA production is involved, RA has to be appropriately screened, crushed, and processed, in order for the required gradation and aggregate specifications to be fulfilled [170]. The mass of the virgin and recycled feedstock was calculated by the data acquired from EAPA [28]-[38] and the mass of the finished products was calculated by using the average layers thicknesses' for each layer, according to the Italian Road specifications [147], [171] and assuming the bulk density of the asphalt mixture constituting the pavement layers, $G_{mb} = 2.35$ Mg/m^3. The fraction of the mass collected for recycling at the End-of-Life of the pavements was extrapolated based upon the quantities of the available RA and the percentages of hot mix asphalt utilization in different layers. The amount of waste going to landfill, or energy recovery and the quantity of waste generated during the two stages of the recycling process were calculated according to the proposed model. The outcomes of the experimental campaigns conducted by the Illinois Center for Transportation and the University of Tennessee [160], [161]; along with the results of the studies undertaken by Sheng Zhao et.al. [163], Ibrahim Sonmez et.al. [164], Taleb Al-Rousan et.al.[165], and Tabakovic et.al. [166], [167], were utilized to calculate the resistance to rutting and fatigue of surface, binder, and bases courses with varying percentages of incorporated RA. Hence, it became possible to calculate the Utility factor [X], required as an input for the completion of the case study and the quantification of the MCI_{MRA} of Italy's motorway network for surface, binder, and base courses. In **Table 4.3**, the inputs required, are presented for transparency and reproducibility reasons.

Table 4.3. Inputs and calculation required for the quantification of the MCIMRA of surface, binder and base courses

MCI_{MRA} of pavement layers in Italian motorways (INPUTS)		**Surface Course**	**Binder Course**	**Base Course**
DEFINITION	***SYMBOL***	***VALUE***	***VALUE***	***VALUE***
Mass of Virgin Feedstock used	V (tonnes)	2.07x10^7	2.28 x10^7	9.15x10^7
Fraction of feedstock derived from recycled sources	P_{RA}	0.043	0.097	0.156
Mass of the finished product	G_{MRA} (tonnes)	2.17 x10^7	2.53 x10^7	1.08 x10^8
Fraction of the mass of the product collected for recycling at the End-of-Life	$F_{RA} = \Delta U$	0.2130	0.2130	0.2130
Amount of waste going to landfill or energy recovery	W_{EoL} (tonnes)	1.71 x10^7	1.99 x10^7	8.53 x10^7
Quantity of waste generated in the recycling process	W_T (tonnes)	9.23 x10^4	1.08 x10^5	4.62 x10^5
Quantity of waste generated to produce any recycled content used as feedstock	W_P (tonnes)	0.00	0.00	0.00
Efficiency of recycling process as treatment	E_T	98%		
Efficiency of the recycling process as production	E_P	100%		
Overall amount of unrecoverable waste	W (tonnes)	1.71 x10^7	2.00 x10^7	8.55 x10^7
Linear flow index (LFI)	LFI	0.87	0.85	0.82
Utility	X	1.00	1.00	1.00
Utility factor built as a function of the utility factor X of a product	F[X]	0.90	0.90	0.90

4.5 Results and Discussion

4.5.1 Hot and Warm Mix Asphalt Production and its utilisation trends per layer

Following the data acquisition described in the previous sections, in **Figure 4.7**, **Figure 4.8**, and **Figure 4.9** the total annual HWMA production per European region, the total utilization of this production in surface, binder, and base courses, and its average percentage distribution in these layers are illustrated, respectively.

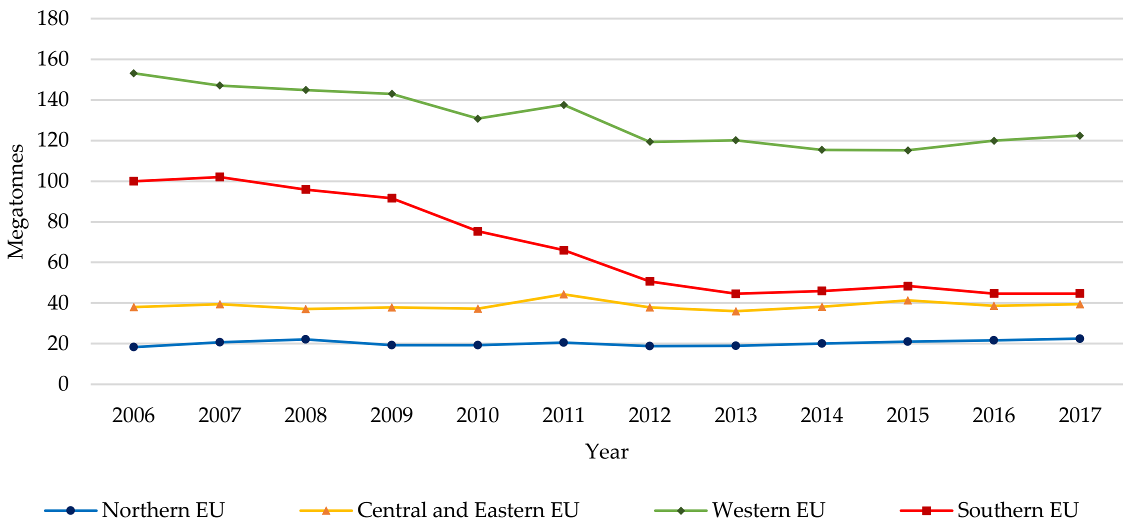

Figure 4.7. *Total Hot and Warm Mix asphalt mixture production per European section per year (2006-2017)*

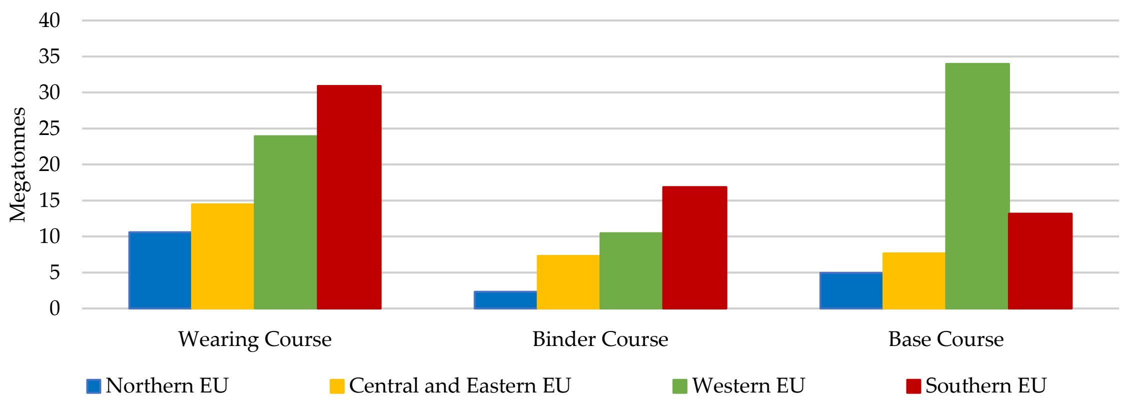

Figure 4.8. *Total production of HWMA in Megatonnes and its utilization per European area and layer (2006-2017)*

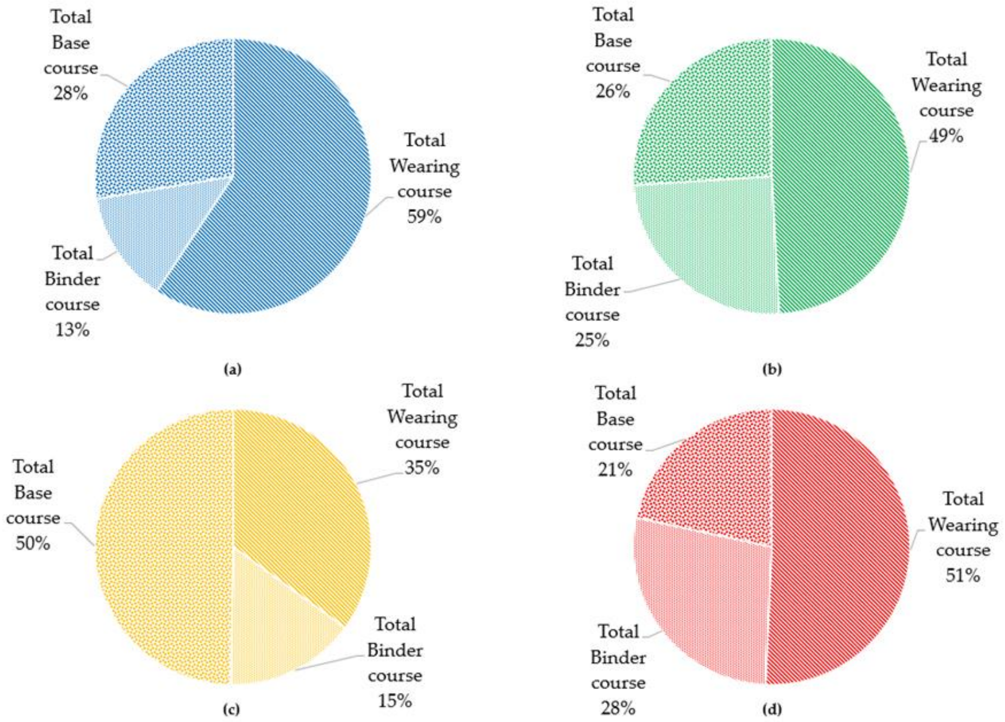

Figure 4.9**. Average Percentage Distribution of Hot and Warm Mix Asphalt uses per pavement layer in:* ***(a) *Northern EU (2006-2017);* ***(b)*** *Western EU (2006-2017);* ***(c)*** *Central and Eastern EU (2006-2017);* ***(d)*** *Southern EU (2006-2017)*

Hence, it can be safely deduced that the annual HWMA production for the Northern EU, has remained almost static from 2006 to 2017, accounting for approximately 20 Megatonnes per year. The situation for Central and Eastern EU is quite similar in terms of its trend over the years but, with a higher average annual production, reaching about 40 Megatonnes. In the Western EU the HWMA production has decreased over the years starting from approximately 155 Megatonnes in 2006 and dropping to 120 Megatonnes in 2017, experiencing a decline of 23%. Moreover, in Southern EU the HWMA production in 2006 accounted for almost 100 Megatonnes and experienced a significant decrease of 50% by 2017 when approximately 50 Megatonnes of HWMA mixtures were produced. In terms of the average utilization of these mixtures, from **Figure 4.7**, it becomes obvious that the main pavement component that they are utilized in is the surface course, followed by the base course and finally the binder course. This fact emphasizes the high demand of asphalt mixture production addressed to surface courses, indicating that surface layers are the largest "end-users" of asphalt mixtures and that most of the established rehabilitation regimes including resurfacing or interventions are focused on the surface courses.

In detail, especially in the Southern EU, where Italy is allocated to, more than 51% of the total HWMA production is intended for use in surface courses; and also according to the Italian regulations [147], [171], surface course is the layer that experiences the lower allowed margin in terms of RA quantity, accounting for merely 20%.

4.5.2 Outcomes of the Reclaimed Asphalt market in Europe analysis

Quantifying now, the RA recycling rate, along with the parameters QF[a] and QF[p], defined before, through the aforementioned formulae (1), (2) and (3), **Table 4.4** illustrates the annual fluctuation of these parameters.

Table 4.4. *Annual fluctuation of ΔU, QF[a] and QF[p], per European section*

	Northern EU						Central and Eastern EU					
Year	HWMA (Mt)	RA Available	RA Placed	ΔU	QF[a]	QF[p]	HWMA (Mt)	RA Available	RA Placed	ΔU	QF[a]	QF[p]
2006	18.300	0.900	0.500	0.581	4.69%	2.60%	38.000	1.600	0.232	0.143	4.04%	0.59%
2007	20.700	1.400	0.800	0.590	6.33%	3.62%	39.500	0.700	0.347	0.503	1.74%	0.86%
2008	22.100	1.900	0.900	0.467	7.92%	3.75%	37.100	2.700	0.450	0.168	6.78%	1.13%
2009	19.300	1.800	0.900	0.508	8.53%	4.27%	37.900	2.600	0.369	0.140	6.42%	0.91%
2010	19.300	2.500	1.000	0.394	11.47%	4.59%	37.200	1.900	0.284	0.146	4.86%	0.73%
2011	20.600	2.700	1.300	0.463	11.59%	5.58%	44.300	1.700	0.287	0.169	3.70%	0.62%
2012	18.800	2.600	1.200	0.464	12.15%	5.61%	37.900	1.700	0.441	0.265	4.29%	1.11%
2013	18.900	2.600	1.400	0.539	12.09%	6.51%	36.000	1.600	0.366	0.227	4.26%	0.97%
2014	20.100	3.500	2.700	0.761	14.83%	11.44%	38.100	1.900	0.366	0.197	4.75%	0.91%
2015	21.100	4.100	3.200	0.783	16.27%	12.70%	41.400	2.300	0.565	0.247	5.26%	1.29%
2016	21.600	3.900	3.200	0.831	15.29%	12.55%	38.700	2.100	0.521	0.248	5.15%	1.28%
2017	22.500	2.365	1.969	0.833	9.51%	7.92%	39.500	2.854	0.542	0.191	6.74%	1.28%
	Western EU						Southern EU					
Year	HWMA (Mt)	RA Available	RA Placed	ΔU	QF[a]	QF[p]	HWMA (Mt)	RA Available	RA Placed	ΔU	QF[a]	QF[p]
2006	153.100	31.048	15.953	0.514	16.86%	8.66%	100.000	14.690	2.727	0.186	12.81%	2.38%
2007	147.100	31.015	16.439	0.530	17.41%	9.23%	102.000	15.650	3.603	0.230	13.30%	3.06%
2008	144.900	29.930	16.717	0.559	17.12%	9.56%	95.900	14.150	0.552	0.039	12.86%	0.50%
2009	143.000	31.353	18.813	0.600	17.98%	10.79%	91.600	13.850	3.362	0.243	13.13%	3.19%
2010	130.800	31.380	18.607	0.593	19.35%	11.47%	75.300	12.611	3.094	0.245	14.35%	3.52%
2011	137.550	31.920	19.957	0.625	18.84%	11.78%	66.000	12.352	3.187	0.258	15.76%	4.07%
2012	119.310	29.110	19.067	0.655	19.61%	12.85%	50.700	10.368	2.243	0.216	16.98%	3.67%
2013	120.100	28.750	19.260	0.670	19.31%	12.94%	44.600	10.205	2.174	0.213	18.62%	3.97%
2014	115.400	24.985	18.287	0.732	17.80%	13.03%	45.900	*Data N/A*	*Data N/A*	*Data N/A*	*Data N/A*	*Data N/A*
2015	115.200	29.104	22.567	0.775	20.17%	15.64%	48.400	9.410	2.185	0.232	16.28%	3.78%
2016	119.900	28.691	22.197	0.774	19.31%	14.94%	44.700	9.490	2.128	0.224	17.51%	3.93%
2017	122.400	28.950	22.650	0.782	19.13%	14.97%	44.700	9.494	2.480	0.261	17.52%	4.58%

From the results presented, it can be seen that there is a significant deviation between the available RA and the RA that is actually been utilized in HWMA production, indicating an inadequate process of managing and exploiting the RA produced. This leads to an inefficiently circular approach of asphalt mixture production. The availability and the actual exploitation of RA have slowly and steadily increased in Northern and Western EU sections from 2006 to 2017, while for the Southern and Central & Eastern EU, the actual utilization of RA in HWMA production is almost the same over time. Moreover, in **Figure 4.10**, the total HWMA production per year and EU major region are being compared to the total RA availability.

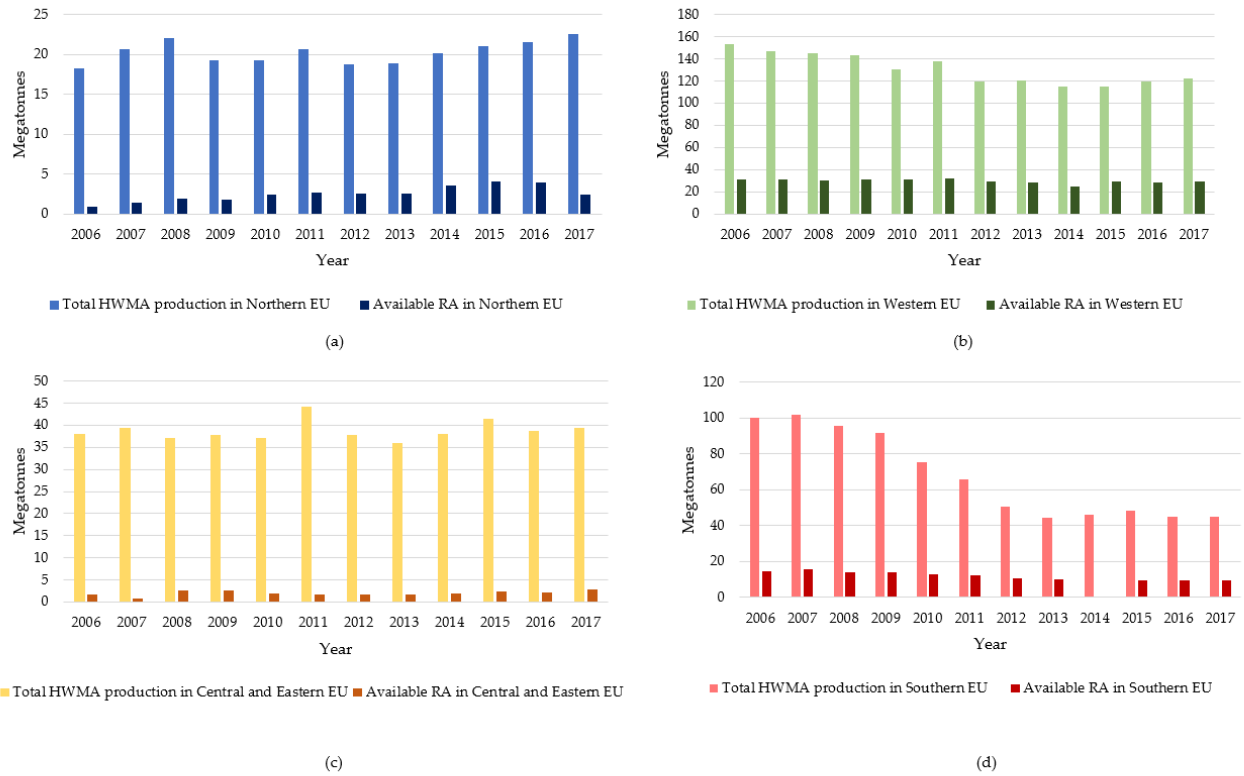

Figure 4.10. *Comparison between the total HWMA production per year and EU major section and the available RA in the corresponding section*

It can be deduced from this analysis that the production of RA is far from satisfying the market's demand for HWMA production in all the EU sections. It is also worth mentioning, that according to the values of QF[a] and QF[p], it seems that the goal of 100% recycling, is far from being achieved. In an even broader consideration, it could be said that the sustainability of the whole process of the re-circulation of RA in the product system of asphalt pavements is significantly weak. For comparative reasons, after having calculated the total annual HWMA production, the total available RA and the RA utilized in HWMA production in EU, **Table 4.5** has been created. The annual levels of possible decrease in HWMA production in the EU can be seen, considering the case that all the available RA is being utilized, namely if ΔU accounted for 1.

Table 4.5. *Percentages of a possible decrease in HWMA production in the EU, when full utilization of available RA is occurring*

Year	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Northern EU	5.1%	7.1%	9.5%	10.3%	14.5%	15.1%	15.9%	15.6%	21.1%	24.0%	22.0%	11.7%
Central & Eastern EU	4.5%	1.8%	7.8%	7.5%	5.5%	4.0%	4.6%	4.7%	5.2%	5.9%	5.7%	7.8%
Western EU	25.4%	26.7%	26.0%	28.1%	31.6%	30.2%	32.3%	31.5%	27.6%	33.8%	31.5%	31.0%
Southern EU	17.2%	18.1%	17.3%	17.8%	20.1%	23.0%	25.7%	29.7%	N/A	24.1%	27.0%	27.0%

Finally, a heatmap illustrating the potential percentage reduction on HWMA production per year and EU section, after the implementation of the proposed CEM, has been created and presented in **Figure 4.11**.

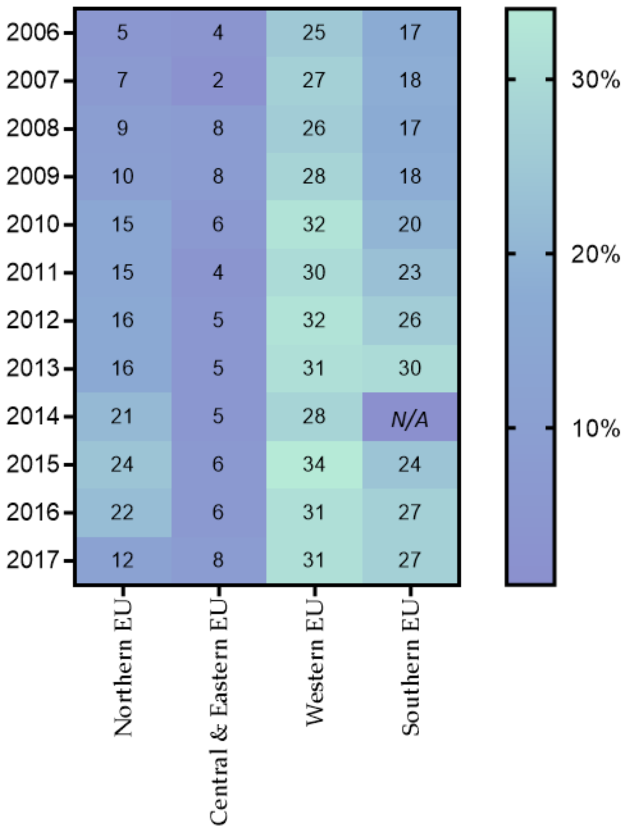

Figure 4.11. *Heatmap of the potential reduction on HWMA production per year and EU section, after the implementation of the CEM*

4.5.3 Product Material Circularity Index of Italian motorways per layer

Having identified the weakness in terms of circularity and sustainability, of the re-circulation process of RA into new asphalt pavements' product systems, naturally, the next step was to quantify the levels of circularity of asphalt pavements themselves. To do so, the MCI_{MRA} of the three basic bituminous layers of the asphalt pavements, namely surface, binder and base course, constituting the motorway network of Italy was quantified. For the quantification of the circularity levels of the pavements, the tailored Material Circularity Index Methodology, defined was utilized. Finally, in **Table 4.6**, the final outputs of the calculation can be found, and are presented in **Figure 4.12**.

Table 4.6. Calculation of the product material circularity index according to EMF, per pavement layer

MCI_{MRA} of pavement layers in Italian motorways (OUTPUT)	**Surface Course**	**Binder Course**	**Base Course**
Material circularity indicator per pavement layer MCI_{MRA}	0.213	0.2377	0.2643

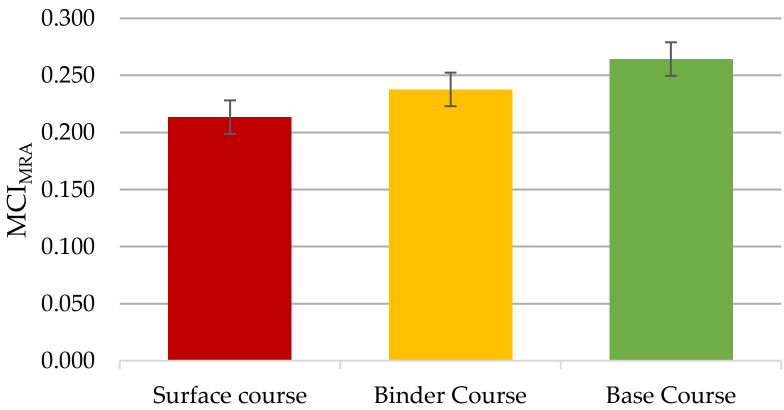

***Figure 4.12**. Product Material Circularity Index per pavement layer for the Italian motorways*

From the results of the calculation, the layer that exhibits the highest levels of circularity, is the base course, which raises a controversy, since only 21% of the total HWMA production is intended for utilization in base courses. However, the percentage of RA incorporation in the base layers is significantly higher compared to the corresponding level in the upper layers, usually restricted to 10%-30% in Italy, and the total mass of the mixtures required for the construction of the base courses is significantly increased (higher layer thickness). To improve the levels of circularity of every pavement layer, following a "back-calculating" process of the MCI_{MRA}, the following recommendations could be provided:

- Optimize the Utility [X], by extending the actual average lifetime of asphalt pavements and thus the functional units achieved through their life cycle, by introducing more systematic and effective maintenance regimes.
- Minimize the Linear Index flow (LFI), by reducing the utilization of virgin feedstock and increasing the feedstock originating from recycled sources; or in other words, maximize the potential of RA recycling.

It becomes obvious that in order to increase the circularity and sustainability of asphalt pavements, it is imperative for the technical viability of the layers that contain significantly high proportions of RA to be demonstrated and validated; for the decision-makers and stakeholders to be finally able to alter technical standards and specifications towards the successful transition of the currently linear road engineering industry to a circular way of conducting business.

4.6 Summary and Conclusions

For a policy focused on effectively achieving the goals of sustainable development, innovative processes and product models must be developed so that economic, technical and environmental advantages could simultaneously be achieved. An approach supplemented by the principles of the CE seems aligned with this purpose, since it supports the reduction of the exploitation of non-renewable resources and the minimization of polluting emissions on critical resources such as air, water, and soil. The circular economic models are therefore based on production chains built on technical cycles that are systematically able to provide maintenance, reuse, refurbishment and recycling of products and materials. To obtain meaningful results, capable of positively altering the state of problems such as climate change and the price of non-renewable raw materials, circular economic models must be applicable and generalizable on an extended geographical scale and on industrial processes that intensively involve large amounts of resources. Among these processes lies the construction of asphalt road pavements for new infrastructures as well as their maintenance and management. These processes involve intensive consumption of non-renewable raw materials, i.e. aggregates, and secondary materials, such as bitumen, and a resulting environmental impact in terms of air, soil, and water pollution. The end-product is the asphalt mixture whose market has been analysed, in an updated historical series, on a European scale, disaggregating the data by distinct geographical areas and by type of mixture according to the final layer within the road pavement. Together with this analysis, the production of the reclaimed asphalt has also been investigated by defining three parameters (ΔU, QF[a], QF[p])] to evaluate both the actual and the potential influence of RA exploitation on the asphalt mixture production market. Such an analysis has led to several considerations. The HWMA production market, although still being characterized by a high value of produced quantities, around 230 Megatonnes in 2017, shows a substantially constant or slightly decreasing trend in supply. Consequently, the historical trend reveals a mature market for such a product. The supply of RA shows a similar trend, with a lower rate of production equal to approximately 44 Megatonnes in 2017, even with different demand allocated to the sub-divided major EU regions. The highest values are detected in Northern and Western EU (in average countries economically more advanced), and the lowest ones in Southern and Central EU.

On the base of the market analysis, a CEM for asphalt mixtures with RA as end-products seems to be the optimal way to evaluate their actual rate of circularity to identify both the strengths and weaknesses of the production process and to highlight the sensitive points to be discussed. The developed model, according to the general framework proposed by the Ellen MacArthur Foundation, is based on the philosophy of closed loop and adopts the whole product approach within the product level methodology. Such a model provides a rigorous quantification of the product's circularity, expressed as Product Material Circularity Index (MCI_{MRA}). In this index, the Utility function, expressed as ratio between the mechanical resistance of the end-product and the current or reference product, is the most relevant in order to drive the transition from a linear product to a circular one. In this case, it appeared conceptually sound to measure the Utility function in terms of rutting for the surface course, while in terms of fatigue for the remaining bituminous layers, since these phenomena are the main drivers of expected design life of the asphalt layers. In addition, it is worth noting that the proposed model refers to a single cycle, but it may be easily extended over more cycles.

The Italian motorway network has been chosen, as a representative scenario, since this country belongs to an EU region where a large part of demand, up to around 30%, might be met by fully exploiting the available RA. The results in terms of MCI_{MRA} can be considered unsatisfactory. In other words, the end-product is linear for two main reasons: the very low production rate of recycled feedstock and the significantly low allowed limits of incorporating RA into the mixtures that compose the different pavement layers. It is worth considering that the RA production rate depends on the technical specification limits. Something that is accurate only to a certain extent. If QF[p] was equal to QF[a], i.e. ΔU=1, the MCI_{MRA} of the surface course, for instance, would reach the value of 0.458, which would suggest an 115% improvement. Under the assumption of also increasing the regulatory limits of the allowed RA to be incorporated up to the values tested by different authors, the aforementioned MCI_{MRA} would reach the value of 0.567, which is 166% higher value than the first one. The same trend, but with a higher magnitude, for the binder and base courses can be observed in **Figure 4.13**.

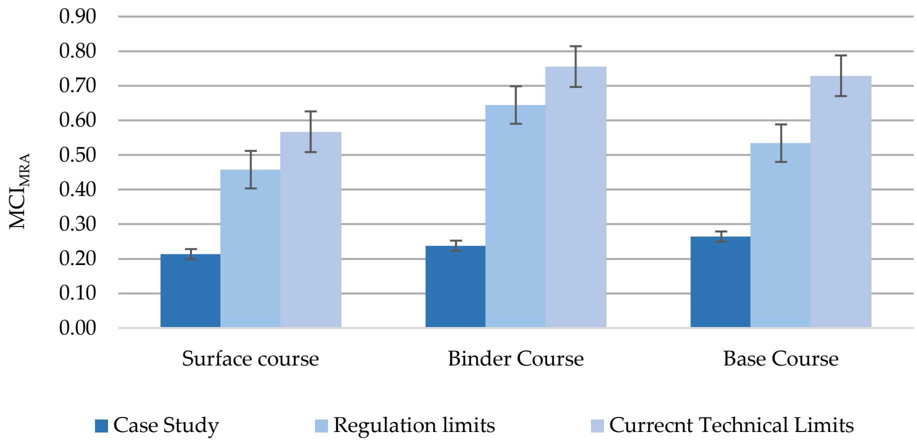

Figure 4.13. *Fluctuation of MCIMRA under different scenario analyses, per pavement layer*

Therefore, pursuing an effective policy aimed at implementing the principles of sustainability and CE, a strong cooperation between stakeholders should be considered, focused on optimizing:

- **ΔU**, by encouraging waste recycling techniques, while at the same time discouraging landfilling through incentives, bonuses and penalties.
- **P_{RA}**, by increasing the allowed limits of RA incorporation in the asphalt mixtures, following the current direction of scientific research.
- **X**, by increasing the utility factor through an appropriate and specifically tailored mix design addressed to RA.
- **F[X]**, by further analysing and fully defining the parameter of utility function according to "ad hoc" structure for the end product.
- **Capability and Efficiency**, by accordingly adapting and strengthening the asphalt

production chain, with particular reference to the structure and equipment of the treatment and mixing plants.

5 **Chapter V:** Measuring the combined circularity and environmental sustainability of asphalt mixtures

5.1 Introduction

The effort of the pavement engineering industry towards more circular products has not yet been assessed in terms of its environmental impacts. In other words, as aforementioned, CE-related initiatives should be carefully examined case-by-case; and in the context of asphalt mixtures, a composite approach that can identify and evaluate the impacts of the asphalt mixtures' increased circularity in the environment, needs to be adopted. An approach towards the integration of circularity within the framework of Life Cycle Sustainability Assessment must be followed and supported. Hence, an integrated framework of environmental sustainability and circularity assessment of asphalt mixtures is developed in this thesis. A methodology of quantifying the combined environmental sustainability and circularity of asphalt mixtures, towards an increased uptake of the latter, is presented. Moreover, a case study, implementing the aforementioned framework has been orchestrated and undertaken. A brief representation of the concept developed and presented in this work can be seen in **Figure 5.1** Schematic presentation of the components constituting the assessment methodology and composite indicator developed.

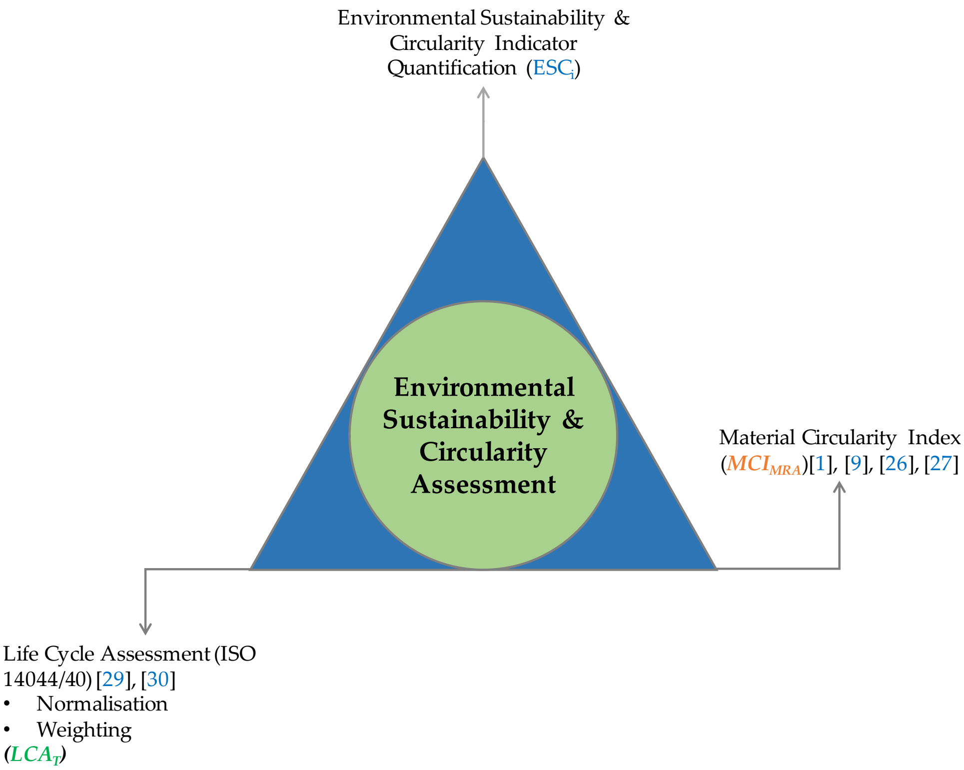

Figure 5.1. *Schematic presentation of the components constituting the assessment methodology and composite indicator developed*

5.2 Scope and Objectives of the Chapter

The purpose of this chapter is, thus, to provide a methodological approach able to quantify and evaluate the combined environmental sustainability and circularity of asphalt mixtures that incorporate reclaimed asphalt (RA), through the development of an analytical approach. It is worth highlighting at this point that the scope of this work, is limited in the assessment of the circularity and the environmental pillar of sustainability of the life cycles of asphalt mixtures. No previous attempts of the integration of circularity assessment within the sustainability assessment of asphalt mixtures have been recorded. Thus, naturally, the first step towards this integration is the combined assessment of the environmental impacts of the life cycle of asphalt mixtures along with their levels of circularity. However, the CE economy, or better, CE-related initiatives in the context of asphalt mixtures, seem to be significantly more influential on the environmental pillar of sustainability than the social or economic pillars [63]. Therefore, the first attempt for the aforementioned integration, was decided to be the development of a parameter that is able to address the change in environmental impacts of asphalt mixtures while their levels of circularity are fluctuating; addressing in this way the environmental pillar of sustainability. In detail, perceivably, the results of the Life Cycle Assessment (LCA) study of the production of an asphalt mixture can project the environmental relevance of the production process of the mixture itself, while on the other hand the Material Circularity Index (MCI_{MRA}) is able to provide an end-product label that characterizes the final product itself. Hence, when combined, LCA and MCI_{MRA} are able to provide a holistic assessment on both the final product and the process through which it was produced. To do so, while simultaneously validating their feasibility and usefulness, a case study has been developed and undertaken in order to shed light on the underlying processes of developing this indicator. Firstly, the environmental impacts of four different asphalt mixtures that contain 0%, 30%, 60%, and 90% RA, respectively, were quantified, via the utilization of the LCA framework. Secondly, the product MCI of the very same asphalt mixtures was quantified, by using the methodology developed by the EMF [159] and specifically tailored for the context of asphalt mixtures by Mantalovas and Di Mino in **Chapter 4** [37].

Finally, the composite indicator of environmental sustainability and circularity that has been developed, was implemented in order to rank the four different alternatives. The usefulness of this assessment is inextricably correlated with the understanding of the underlying importance of the sustainability and circularity assessment coupling. As mentioned above, in some cases and under specific circumstances, a CE-related initiative could be unsustainable. The implementation of this methodology to asphalt mixtures could lead to increased awareness of national road authorities and stakeholders belonging to the sphere of road engineering and the management sector, about the level of their businesses' circularity and environmental sustainability and could eventually constitute a tool for the involved decision-makers for evaluating how environmentally sustainable their circular practices and choices are. Finally, this methodology, along with the indicator developed is not geographically restricted and is widely applicable even on an extended geographical scale.

5.3 Methodology

5.3.1 Life Cycle Assessment of Asphalt Mixtures with Reclaimed Asphalt

Firstly, in order to quantify the environmental impacts of the production of the asphalt mixtures with reclaimed asphalt, under study, which is defined in **Chapter 5.4**, the framework of LCA was utilized. LCA is a potent tool, able to provide an insight into the environmental impacts of a product, service or process during its whole life. It is widely utilized as a decision-making support tool amongst national road authorities and it is able to provide a comparative ranking between different designs or material alternatives. It is a framework that has been standardized [33], [172] and there are also Environmental Product Declarations (EPDs) and Product Category Rules (PCRs) when it comes to asphalt mixtures [158], [173]. The approach adopted for the LCA exercise was cradle-to-gate, since the analysis is focusing on asphalt mixtures as end-products. A cradle-to-gate analysis considers only some of the life cycle stages of the whole life of an asphalt mixture. Considering as the main stages of the life cycle of an asphalt mixture the product stage, the construction stage, the use stage, and the End-of-Life and Recycling stages; a cradle-to-gate analysis includes only the product stage. In **Figure 5.2** a more analytical depiction of the life cycle stages of an asphalt mixture, along with the most common LCA approaches is presented.

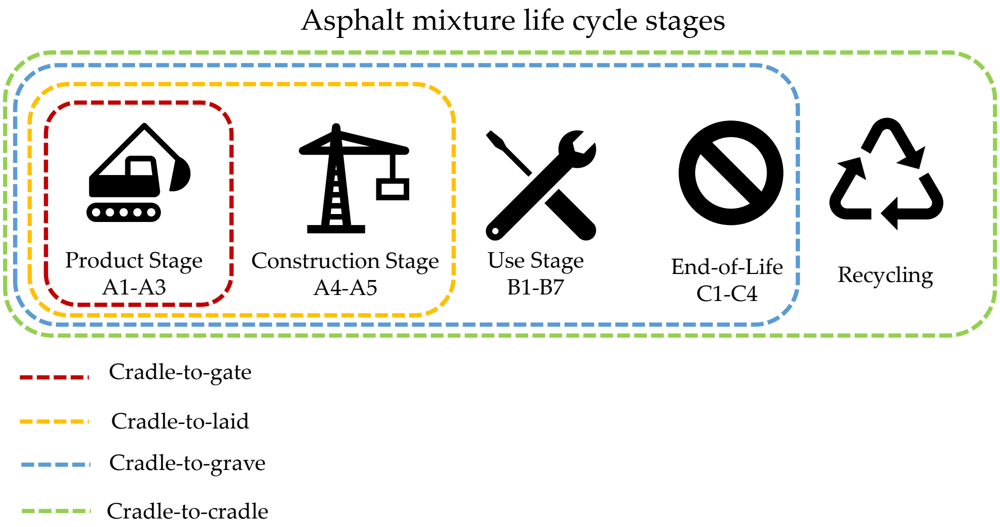

***Figure 5.2** Life cycle stages of an asphalt mixture's life cycle and the most commonly used assessment approaches*

Moreover, a declared unit was defined instead of a functional unit since asphalt mixtures agreeably do not exhibit a function during their cradle-to-gate life cycle stage, according to EN 15804 and the PCRs for asphalt pavements and mixtures of the European Asphalt Pavement

Association (EAPA) and the National Asphalt Pavement Association (NAPA), respectively [158], [174], [175].

5.3.2 Product Material Circularity Index of Asphalt Mixtures with Reclaimed Asphalt

Secondly, the quantification of the product level Material Circularity Index of the examined asphalt mixtures with RA became possible with the utilization of the methodology developed by the EMF and adjusted for asphalt mixtures with RA by Mantalovas and Di Mino [37], [159]. The basis of the methodology can be seen in **Chapter 4**. Moreover, the definitions of the parameters/inputs required for the quantification of the Material Circularity Index, presented in **Figure 5.3**, can be found in **Table 4.3**, in **Chapter 4.4**.

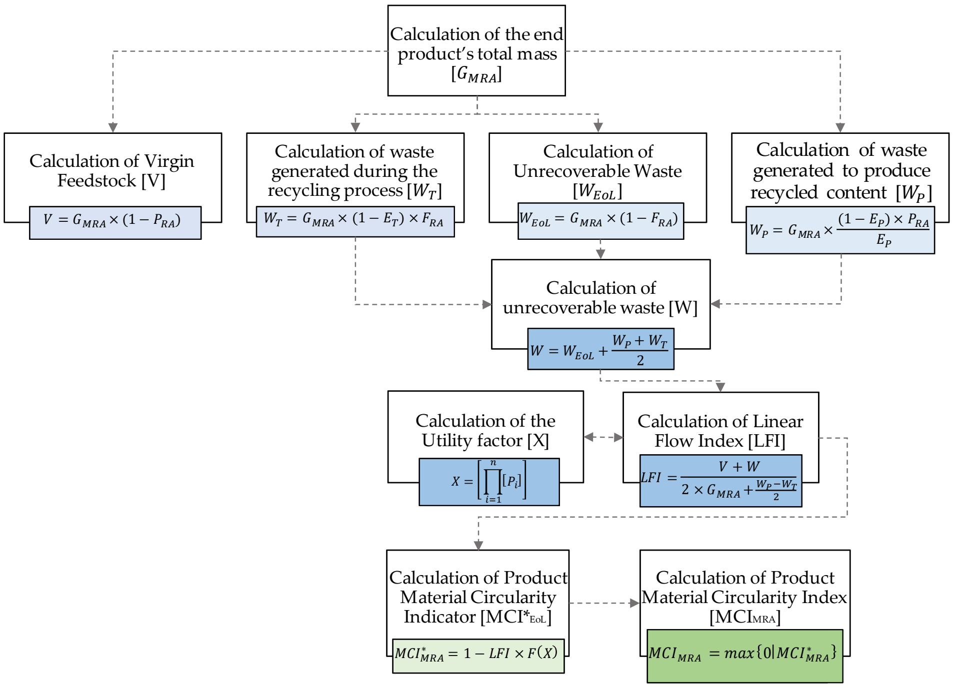

Figure 5.3. *Workflow followed for the quantification of the product level Material Circularity Index (after Mantalovas and Di Mino, 2019* [37]*)*

Compared to the original methodology based on the EMF framework and the methodology developed and presented in **Chapter 4.3.2**, the quantification of the utility factor [X] now incorporates two types of mechanical performances of the end-products, namely, the asphalt mixtures. These are the resistance to fatigue and the resistance to permanent deformation. By considering both of the aforementioned performances, widely accepted as key drivers for the design of asphalt mixtures, the utility factor is capable of comprehensively describing the behaviour of the asphalt mixtures during their service life [176]. Thus, the product level Material Circularity Index of asphalt mixtures with RA (MCI_{MRA}) is also taking under consideration technical aspects of the mixtures. In order to do so, laboratory tests were conducted to assess the behaviour of the investigated asphalt mixtures in terms of fatigue and permanent deformation resistance; the test themselves and their results are described in **Chapter 5.4.3.1**.

5.3.3 Development of the Environmental Sustainability and Circularity Assessment Indicator (ESCi)

Finally, having quantified the environmental impacts of the cradle-to-gate life cycle stage of the examined products, i.e. the asphalt mixtures with RA, and their Material Circularity Index, the final step is the definition of the indicator able to assess their combined circularity and environmental sustainability, under a closed-loop product system perspective. This was deemed essential since the framework of LCA is not taking under consideration the circularity of the end-product, and the framework of the MCI_{MRA} quantification is not considering the environmental impacts of the corresponding production process. Thus, it appears imperative, for a decision-making friendly indicator that can rank different alternatives in terms of their intertwined environmental sustainability and circularity, to be developed. As mentioned before, attempts to improve the circularity of asphalt mixtures, might end up exhibiting adverse effects for the environment; and oppositely, attempts to reduce the environmental impacts of the production of asphalt mixtures could potentially lead to decreased circularity [63], [177]. For this very reason, the indicator developed has as its base value; the aggregated, normalized and weighted LCA results (LCA_T) to the power of the value (1-MCI_{MRA}). It thus, proposes the weighting of the aggregated environmental impacts of an asphalt mixture's production, by its circularity level. The formula describing the indicator can be seen below:

$$ESC_i = \frac{1}{LCA_T^{(1-MCI_{MRA})}} * 100 \qquad \textit{Equation 6}$$

In order to calculate the Environmental Sustainability and Circularity Indicator, as described in the previous chapters, the environmental impacts of the examined product and its' Material Circularity Index must be quantified. In order to do so, the environmental impacts quantified via the conduction of an LCA exercise, must be converted to a single unitless number through a reductive process. The suggested process is constituted by two sub-processes; the utilization of normalization and weighting; two optional elements of the Life Cycle Impact Assessment phase of an LCA, as described in the International Standard ISO 14044 [178]. Normalization is the calculation of the magnitude of the category indicators results relative to reference information. Thus, it is able to assist with the communication of the information on the relative significance of the indicator results [33], [178]. Weighting is the process of converting the impact category indicators' results by utilizing numerical factors and it allows for further aggregation of the converted indicators [33], [178]. Consequently, the combined normalization and weighting can ultimately provide a single unitless number (LCA_T) that describes the magnitude of the environmental impacts of a product and enables the comparison between different alternatives. In other words, this methodology can be used as a tool to rank different alternatives of asphalt mixtures with RA, in terms of their environmental sustainability and circularity. The higher the value of the indicator for an alternative, the preferable it is compared to the lower-ranked ones. An essential aspect of this methodology is that both types of assessment, environmental sustainability and circularity, are following identical system boundaries. Thus, the product system under study for the quantification of the environmental impacts of the asphalt mixtures is identical with the corresponding product system used to quantify the Material Circularity Index. This is an important consideration, that enables the incorporation of both assessments' outcomes into one single indicator.

5.4 Case study and Results

5.4.1 Definition of the Case Study

In order to demonstrate the usefulness and functionality of the developed indicator and provide an insight into how it ought to be utilized in a comparative approach, a case study has been defined and undertaken. Four different asphalt mixtures for surface courses are analyzed in terms of their environmental impacts (LCA_T), Material Circularity Index (MCI_{MRA}) and ultimately environmental sustainability and circularity indicator (ESC_i). As the baseline, a conventional asphalt concrete mixture with nominal grain size of 12.5mm with 0%RA (AC12.5) was selected and the rest of the alternatives were defined as three asphalt concrete mixtures with 12.5mm nominal grain size, containing 30%, 60% and 90% RA, respectively [180]–[185]. The asphalt mixtures were designed according to the ANAS (Italian National Road Authority) specification, which is followed for the asphalt mix designs in Italy [169] and were produced in Catania, Italy. The description of the asphalt mixtures under study can be seen in **Table 5.1**.

Table 5.1. Specifications and recipes of the investigated asphalt mixtures

Mixture	0% RA	30% RA	60% RA	90% RA
Definition	Asphalt mixture for surface courses, following the ANAS specifications			
Coarse aggregates [Kg]	505.5	399.69	238.4	88.5
Fine aggregates [Kg]	368.1	223.4	95.8	-
Filler [Kg]	65.4	36.4	38.5	-
Virgin Bitumen [Kg]	61	40.51	27.3	11.5
RA [Kg]	0	300	600	900

**The values refer to a total of 1tonne of asphalt mixture produced.*

Moreover, the transport distances of the raw materials from the quarry to asphalt mixing plant were 23Km for the coarse and fine aggregates, and the filler; 35Km for the bitumen, while for the RA, the transport distance has been considered 0Km. This assumption encompasses two considerations. Firstly, the transport distance and the impacts of the transportation itself, between the site where the asphalt layer was milled and the asphalt mixing plant, was already considered at the end of life stage of the previous life cycle of the asphalt pavements. Secondly, the RA after being produced through milling was transported and stored inside the very same mixing plant, where the production of the asphalt mixtures took place, setting thus the transport distance to 0Km. Finally, in **Table 5.2**, the energy and fuel requirements to produce 1tonne of each mixture can be seen. Finally, considering the utilization of RA, according to the EAPA's guidance document for preparing PCR and EPD for asphalt mixtures [158], the energy requirements for the screening and processing of 1tonne of RA was assumed as 47MJ/t.

Table 5.2. Energy and fuel requirements for the production of the asphalt mixtures [186]–[189]

Mixture	0% RA	30% RA	60% RA	90% RA
Electricity [MJ/t]	23	17.02	11.3	8.9
Diesel [Kg/t]	7.8	7.1	6.6	6.2
Heating Oil [Kg/t]	7.3	5.4	4.38	3.86
Natural Gas [Kg/t]	0.95	0.81	0.67	0.54

5.4.2 Quantifying the environmental impacts of the asphalt mixtures through Life Cycle Assessment

5.4.2.1 Goal and Scope

After the definition of the asphalt mixtures used in the case study, the LCA exercise was undertaken. As aforementioned, the LCA was conducted following the ISO 14040 and 14044. The software and databases utilized were Gabi ts, by Thinkstep -a Sphera company-, and Gabi Professional and Ecoinvent 3, respectively. The data for the completion of the LCA was secondary data, acquired by EPDs, PCRs and reputable literature sources [186]–[189]**.** The goal is to quantify the environmental impacts of the predefined asphalt mixtures following a cradle-to-gate approach, to normalize and weight them, for use in the quantification of the ESC_i. The impact assessment methodology utilized was the ReCiPe 2008 (H), along with its EndPoint Normalization [Europe, including biogenic carbon (person equivalents)], and EndPoint Weighting [(H/H) including biogenic carbon (person equivalents)] methodologies [190].

5.4.2.2 System Boundaries and Declared Unit

The system boundaries of the product systems under study were defined as the production of the asphalt mixtures, namely Product Stage A1-A3. This stage includes the extraction of raw materials, their transport to the asphalt mixing plant and the production of the final asphalt mixtures. The system boundaries' definition was conducted according to the EAPA and NAPA guidelines, and the EN 15804 specifications [158], [174], [191]. A more detailed representation of the system boundaries can be seen in **Figure 5.4**.

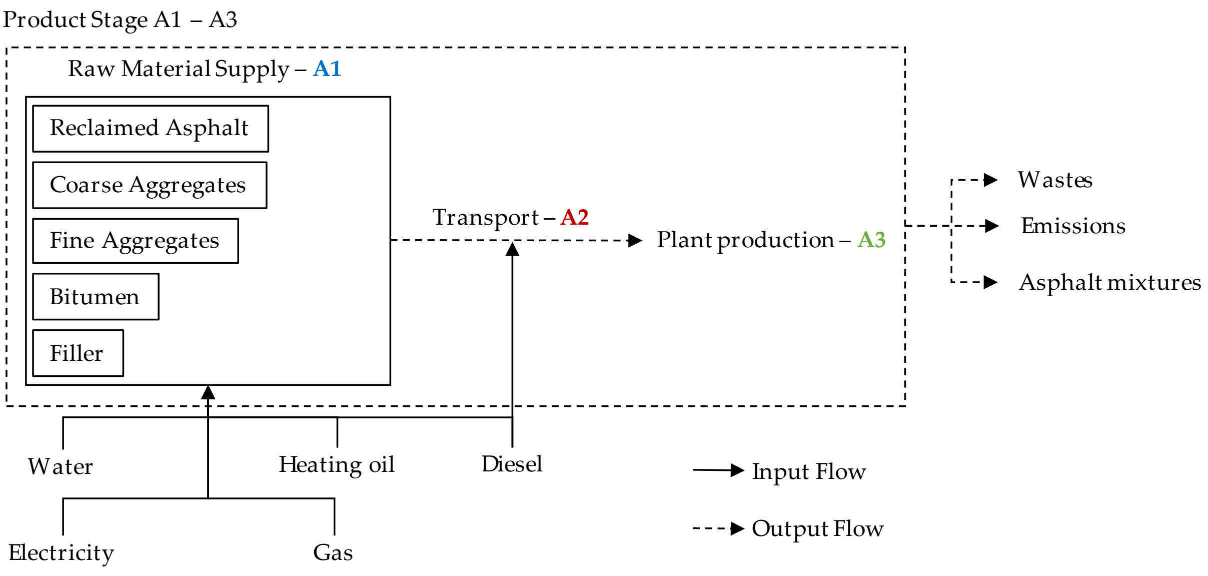

Figure 5.4 *System boundaries of the investigated product systems*

Finally, since the adopted approach is cradle-to-gate, the declared unit defined for the LCA exercise, according to EAPA and NAPA guidelines and the EN 15804 specifications [158], [174], [191], is 1tonne of produced asphalt mixture.

5.4.2.3 Normalized and Weighted Results of the LCA

Having defined the case study and acquired all the required data, the LCA exercise was conducted, along with the normalization and weighting of the final outcomes of the impact category indicators. The results are summarized in **Table 5.3** As mentioned before, the methodologies utilized for the normalization and weighting were:

- ReCiPe2008 (H): EndPoint Normalization [Europe, including biogenic carbon (person equivalents)],
- ReCiPe2008 (H): EndPoint Weighting [(H/H) including biogenic carbon (person equivalents)]

Table 5.3. *Normalized and weighted results of the LCA exercise*

Mixture	**LCA_T**
0% RA	18.10
30% RA	12.90
60% RA	9.32
90% RA	5.71

It is worth mentioning, for transparency reasons, that the normalization and weighting factors can be found in the official document describing the ReCiPe 2008 life cycle impact assessment methodology [190].

5.4.3 Quantifying the Product level Material Circularity Index of the asphalt mixtures

Moving on to quantify the product level Material Circularity Index of the predefined asphalt mixtures with RA, the methodology proposed by Mantalovas and Di Mino was utilized [37]. It is a methodology based on the EMF, with the exception that it also incorporates within the Utility factor [X] of the end-products, the asphalt mixtures in this case, their fatigue and permanent deformation resistances. In other words, the utility factor, is now calculated through a two-step process. Firstly, the performance of the asphalt mixtures in terms of fatigue and permanent deformation is defined and secondly, the utility factor is calculated. At this point it is worth mentioning that for higher utility of the asphalt mixtures, it is preferable that for the same value of microstrain, a higher amount of loading cycles is achieved regarding the fatigue resistance of the mixtures, while for the permanent deformation resistance, lower rutting depth is preferred for the same amount of loading cycles. The formulae, that are used for the calculation of the utility factors' performances parameters can be found below:

$$P_F = \frac{F}{F_{av}}$$ *Equation 7*

$$P_{PD} = \frac{1}{\frac{PD}{PD_{av}}}$$ *Equation 8*

Where F, is the average number of loading cycles before fatigue failure, and F_{av} is the actual average lifetime of an industry average asphalt mixture; namely, the asphalt concrete mixture with 0%RA in this case. Accordingly, PD is the average rutting depth value obtained after a specific number of loading cycles and PD_{av} is the equivalent rutting depth value for the same loading cycles of an industry-average asphalt mixture. The utility factor in this way can be calculated as the productor of all the quantified performances; In this work, the fatigue and permanent deformation performances were utilized, as they are two independent characteristics of the end-products that correspond to different mechanical stresses. The formula quantifying the utility factor can be seen below:

$$X = \prod_{i=1}^{n}[P_i] \qquad \textit{Equation 9}$$

It, hence, becomes apparent that for the evaluation of the final Material Circularity Index of the investigated asphalt mixtures, data about their fatigue and permanent deformation resistance is necessary.

5.4.3.1 *Results obtained by the laboratory testing and calculation of the Utility Factors*

In order to proceed, two experimental campaigns were utilized. The first one included the implementation of a permanent deformation resistance test by utilizing a wheel tracking machine (WTM) [192], while the second one was the identification of the fatigue resistance of the asphalt mixtures by means of Four-point bending tests on prismatic asphalt specimens [193]. **Table 5.4** presents the results obtained by the completion of the aforementioned tests in terms of the number of loading cycles when 0.5με of deformation was reached for fatigue, and depth of rutting (mm) after 20.000 loading cycles for permanent deformation. Moreover, the final values of the utility factors [X] can be seen in **Table 5.4**, as well. It is worth mentioning that the laboratory testing took place during and within the AllBack2Pave project funded by the CEDR (Conference of European Directors of Roads) and the results can be found at the official website of the project: **http://allback2pave.fehrl.org/**. Moreover, the result values obtained under this laboratory investigation reflect the characteristics of the mixtures under study, implementing the aforementioned testing procedures and specifications and conditions. Thus, are not necessarily generalizable.

Table 5.4. *Results obtained for the fatigue and permanent deformation resistance for the asphalt mixtures under study*

Mixture	0% RA	30% RA	60% RA	90% RA
Number of loading cycles at 0.5με [N_f]	4461	3641	5527	1198
Rutting depth at 20.000 loading cycles [mm]	5.2	6.7	3.1	2.7
Utility Factor [X]	1	0.63	2.08	0.52

5.4.3.2 *Final calculation of the Material Circularity Index of the asphalt mixtures (MCI_{MRA})*

Having obtained the corresponding utility factors for every asphalt mixture, the next step is to calculate the Material Circularity Indices of the asphalt mixtures. To do so, the described methodology has been utilized. The required data for the quantification has been acquired and summarized in **Table 5.5**, where the inputs and outputs of the final Material Circularity Index can be found.

Table 5.5. *Inputs and outputs of the Material Circularity Index quantification*

MCI_{MRA} of the investigated asphalt mixtures with RA		0%RA	30%RA	60%RA	90%RA
DEFINITION	*SYMBOL*	*VALUE*			
Mass of Virgin Feedstock used	V (Kg)	1000.00	700.00	400.00	100.00
Fraction of feedstock derived from recycled sources	P_{RA}	0.00	0.30	0.60	0.90
Mass of the finished product	G_{MRA} (Kg)	1000.00	1000.00	1000.00	1000.00
Fraction of the mass of the product collected for recycling at the End-of-Life	$F_{RA} = \Delta U$	0.00			
Amount of waste going to landfill or energy recovery	W_{EoL} (Kg)	1000.00	700.00	400.00	100.00
Quantity of waste generated in the recycling process	W_T (Kg)	0.00	0.00	0.00	0.00
Quantity of waste generated to produce any recycled content used as feedstock	W_P (Kg)	0.00	6.12	12.24	18.37
Efficiency of recycling process as treatment	E_T	98%			
Efficiency of the recycling process as production	E_P	100%			
Overall amount of unrecoverable waste	W (Kg)	1000.00	703.06	406.12	109.18
Linear flow index (LFI)	LFI	1.00	0.70	0.40	0.10
Utility factor	X	1.00	0.63	2.08	0.52
Utility factor built as a function of the utility factor X of the asphalt mixtures	F[X]	0.90	1.43	0.43	1.73
Product Level Material Circularity Index	MCI_{MRA}	***0.1***	***0.1***	***0.83***	***0.82***

5.4.4 Assessing the Environmental Sustainability and Circularity Indicator (ESCi)

The final step of the methodology is the quantification of the Environmental Sustainability and Circularity Indicator. As described in **Chapter 5.3**, the required inputs for this quantification are the normalized and weighted results of the LCA exercise (LCA_T) per mixture, and the MCI_{MRA} with the integrated fatigue and permanent deformation performances, also per mixture. The latter has been calculated and presented in **Chapter 5.4.2.3** and the former in **Chapter 5.4.3.2.** The calculation has been performed according to Equation 6, defined in **Chapter 5.3.3.** The final values of the ESC_i can be seen in **Table 5.6** below

***Table 5.6**. Results of the ESCi quantification*

Mixture	**ESC_i**
0% RA	7.38
30% RA	10.01
60% RA	68.42
90% RA	73.08

It can be clearly seen that the higher the percentage of reclaimed asphalt into the asphalt mixtures, the higher the value of the ESC_i. However, a higher rate of increase in the value of the described indicator can be observed between the alternatives with 30%RA and 60%RA than between the cases of 0%RA and 30%RA and 60%RA and 90%RA, respectively. This is something strongly corelated with the fatigue and permanent deformation performances of the asphalt mixtures, and with the increasing reclaimed asphalt percentages utilized in the mixtures. The higher the RA% incorporated into an asphalt mixture, the higher the energy demands for its screening and processing since an increased amount of RA is now in need to undergo these processes.

5.5 Discussion

In addition, **Figure 5.5** depicts the summarized results for the LCA_T, MCI_{MRA}, and ESC_i, versus the RA% incorporated into the asphalt mixtures. For the specific case study, the higher the percentage of the incorporated RA in the asphalt mixtures, the higher their combined environmental sustainability and circularity, as end-products. This is something to be expected.

Significantly fewer virgin materials are introduced into the product system, less energy is required for the heating and mixing of the aggregates and the bitumen for the production of the asphalt mixtures, and fewer materials have to be transported to the asphalt mixing plant from a distant location. All these parameters assist in reducing the damage to humans, ecosystems and resource availability. Moreover, decreasing the utilization of virgin raw materials seems to have direct effects on the environmental performance of the asphalt mixtures. In other words, increasing the RA% within the asphalt mixtures, their aggregated environmental impacts to human health, ecosystems and resource availability are consistently decreasing. It is also noteworthy that the developed indicator can emphasize the most environmentally friendly alternative since it can provide an enhanced discriminating criterion. This criterion is the ratio between the maximum and minimum values per alternative and indicator quantified. In other words, for the LCA_T, the aforementioned ratio accounts for 18.10/5.71=3.17, for the MCI_{MRA} is 0.83/0.1=8.3, and finally, for the ESC_i the value is 73.08/7.38=9.9, indicating an even more rigorous discriminative aspect between the most environmentally-friendly and circular alternative, than only considering the environmental impacts and the Material Circularity Index of the asphalt mixtures separately.

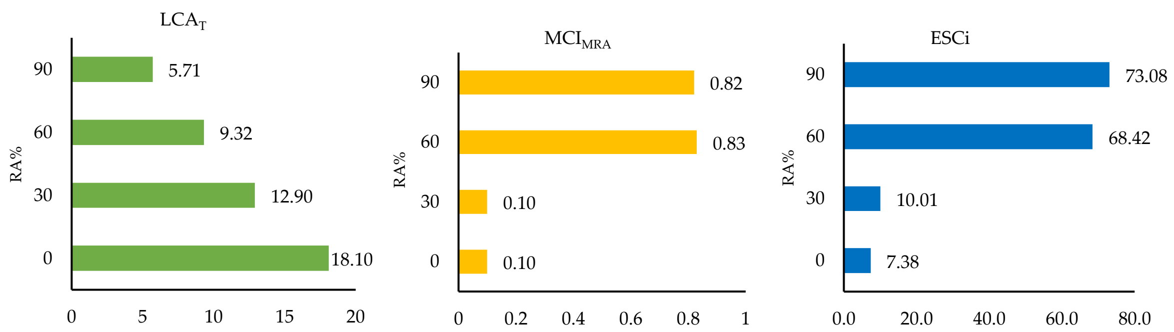

Figure 5.5. *Summarized results for the LCAT, MCI_{MRA}, and ESCi values per mixture (0%, 30%, 60%, and 90%)*

However, the same trend is not exhibited for the MCI_{MRA} of the asphalt mixtures, if investigated individually. From **Figure 5.5**, it can be seen that the MCI_{MRA} of the mixture with 0%RA is the same with the MCI_{MRA} of the 30%RA mixture. In addition, it is noteworthy that the Material Circularity Index of the 60%RA mixture is higher than the corresponding MCI_{MRA} of the asphalt mixture with 90%RA. A key parameter that led to these results is the technical performance of the mixtures. The environmental benefits acquired by the inclusion of RA within the 30%RA and

90%RA mixtures, are partially jeopardized by their poorer performance in terms of fatigue and permanent deformation. For the same achieved deformation (0.5με), the mixture with 60%RA had to undergo 5527 loading cycles, while for the mixture with 90%RA, 1198 loading cycles were required, indicating the superiority in terms of fatigue resistance of the former. This also indicates the key role that the technical performance of an asphalt mixture plays for its circularity. Regarding the investigated RA values, the percentage of 30% is considered, in current technical practices, as a threshold not to be exceeded, especially if the final bituminous mixture is designed for the surface course of an asphalt pavement. However, several studies confirm the adequacy of the mechanical performance of mixtures with higher percentages RA [146], [161], [164], [181], [194]. It is therefore essential, for the RA content threshold, to be revised and updated upwards, so that the impacts of the asphalt mixture production on ecosystems, humans and resources, can actually be reduced. Hence, although the actual recycling practice of re-incorporating RA into asphalt mixtures is environmentally sustainable, it cannot be characterized circular in every case and under any circumstances. This proves that, as aforementioned, it is important that the sustainability implications of a CE-related action must be thoroughly investigated case by case.

5.6 Summary and Conclusions

Paving the path towards more sustainable and circular operational patterns within the road engineering industry and its satellite clusters, frameworks such as Life Cycle Sustainability Assessment, Life Cycle Assessment, Life Cycle Cost Analysis, and Multi-Criteria Decision Analysis, seem to be gaining strength and establishing their influence on decision-making processes in a steadily increasing rate. However, so far, during the implementation of these frameworks, individually or in parallel, a significant element for these assessments seems to be missing; the Circularity Assessment [195]–[197]. This work, thus, attempts to provide a steppingstone towards the merging of two assessments; Sustainability and Circularity. To do so, a composite indicator expressed as a relationship between the aggregated, by means of normalization and weighting, environmental impacts of the cradle-to-gate life cycle stage of asphalt mixtures and their product level Material Circularity Index, was developed. It can be characterized as a weighting method, capable of weighting the aggregated environmental impacts of an asphalt mixture with RA, using as a weighting factor its own circularity. In this way, when different alternatives are considered, the utilization of the indicator, can provide national road authorities and involved stakeholders a ranking of their alternatives in terms of combined environmental sustainability and circularity. In this way, the road engineering industry can progress towards more accurate environmental assessment of their circular practices and their operational patterns in general.

A case study has been defined and undertaken for the functionality and usefulness of the indicator to be presented. Four asphalt mixtures with 0%, 30%, 60%, and 90% Reclaimed Asphalt, respectively, have been assessed in terms of their Environmental Sustainability and Circularity Indicator. It became apparent that the mixture with 90%RA exhibits the highest ESC_i, along with the lower environmental impacts and the second highest Material Circularity Index. While the RA% that is incorporated into the asphalt mixtures is increasing, the values of the ESC_i indicator are increasing as well, proving that the most circular and environmentally sustainable alternative, for the context of this work is the one with 90%RA. Having developed the ESC_i indicator and utilized it into the described, pragmatic case study the following conclusions can be drown from it:

- For the specific case study, the asphalt mixture with 90%RA presents the highest value of ESC_i and thus, represents the most environmentally sustainable and circular alternative among all the investigated ones.
- Higher RA% in some cases can alter the mechanical performances of the asphalt mixtures but they tend to reduce the cradle-to-gate environmental impacts of the asphalt mixtures.
- The circularity of the asphalt mixtures with RA is highly dependent upon the fatigue and permanent deformation resistances of the asphalt mixtures and thus, directly related to the RA% incorporated in them.
- The utilization of the ESC_i indicator can weigh the cradle-to-gate environmental impacts of an asphalt mixture through its circularity and thus, provide a more appropriate ranking factor than considering the mixture's environmental impacts or level of circularity individually.

Road authorities, public or private, along with the involved stakeholders and actors could utilize the developed indicator in the stages of design, construction and maintenance to better discriminate and promote asphalt mixture alternatives that can be environmentally beneficial while exhibiting high levels of circularity and adequate mechanical performance [146], [161], [164], [181], [194]. The results that can be obtained through its utilization can help them identify the most environmentally sustainable option that simultaneously exhibits the most desirable levels of circularity. A more sustainable and circular decision-making approach, which is also data and evidence-based can be adopted in this way; and the riddance of the currently dominating linear operating patterns can be achieved in a controlled way, promoting the desirable preservation or even enhancement of ecosystems, societies and human health. Responsible governmental bodies along with their corresponding national road authorities and pavement engineers should move towards the implementation of sustainability and circularity assessment methodologies and support the update of technical standards and specification, in order to promote the utilization of increased percentages of recycled and innovative materials that are affiliated with lower environmental impacts, higher circularity indices and equivalently accepted mechanical performances.

This process, which is aligned with the global attempts of safeguarding natural resources, the environment and human health, seems to be strictly dependent upon the will of national road authorities to implement policies aimed at revising and updating technical standards and specifications. This could be achieved through the inclusion of innovative and/or circular materials, after having evaluated both the technical and economic compliance, as well as the environmental profitability of their production and utilization processes, which is something that the developed indicator is taking under consideration and can ultimately project. In this direction, the research revolving around innovative tools, methodologies and decision-making support criteria, such as the ESC_i, is set with the aim to establish the choices made by the national road authorities and the relevant actors as scientifically valid and publicly transparent. This can support a controlled and transparent transition from the currently linear approaches, to scientifically-sound, circular and environmentally sustainable ones.

The extensive application of the decision-making tool to other products and materials belonging to the civil construction market, or in any case to other product markets, appears absolutely adequate when the type of circular approach is of a closed loop type; namely, when the original product, materials or components are integrated back into the manufacturing process or processes in which they were generated, and manufactured into new, similar, or equal value and performance products. However, for circular processes of products that go through different sectors and/or markets, the developed decision-making tool can still be utilized via sensitivity analyses of the ESC_i indicator, since the LCA_T and MCI_{MRA} parameters vary respectively, by giving prominence to the one considered strategically most relevant in a case-by-case perspective.

6 **Chapter VI:** Conclusions and Future Perspectives

At this stage it is essential to reiterate the objectives that represent the research questions revolving around this thesis. As seen in **Chapter 1.8**, the main objectives driving the development of the current thesis are:

- The development of a background knowledge on the topics of sustainability and circular economy, especially in the context of asphalt pavements.
- The identification of sustainable and circular practices within the transportation engineering sector, through the review of published CE road maps, from regional and/or national authorities; along with the recommendation of targeted knowledge development areas that could assist to the transition to CE.
- The identification of sustainable and circular practices in the pavement engineering sector. Namely the assimilation of the ways the NRAs communicate and implement principles of the CE in the pavement engineering sector, through questionnaires sent and thus, the development of suggestions and recommendations for strategies towards the implementation of CE.
- The development of a framework and methodology able to quantify the Material Circularity Index of asphalt mixtures with reclaimed asphalt as end products in a closed loop product system.
- The development of a methodology and a framework accompanied by an indicator able to integrate the circularity within the sustainability assessment of asphalt mixtures with reclaimed asphalt as end products in a closed loop product system.

Firstly, as also concluded in **Chapter 1**, the concept of CE is not something entirely new. It has been shaped through time under the influence of various schools of thought and it has lately been strongly interconnected with the concept of sustainability. Thus, if CE and sustainable development co-existed; the outcomes of their combined implementation would only be beneficial in an economic, social, and environmental level. The same principle would apply also for the pavement and road engineering sector. However, the lack of guidelines for the circular and sustainable development of the pavement engineering sector emphasizes the gaps of knowledge that exist in the managerial aspect of the sector. In other words, national and regional authorities and private stakeholders in some cases should expand their knowledge in CE and sustainability topics, in order for a holistic transition towards CE to be achieved successfully. Apart from working towards the implementation of CE and the sustainability of asphalt pavements it is important for the various NRAs to also find more attractive and innovative ways of communicating their status in terms of circularity, since appropriate communication of an organization's business patterns can play an essential role towards the implementation and dissemination of CE practices. Moreover, moving to the lack of knowledge that was identified within the NRAs, and assuming that most NRAs represent the area of a "Cluster", it can be said that even if by themselves develop the knowledge in the suggested areas, for a holistic life cycle approach, various other stakeholders will have to be a committed part of the equation -as well- in order to collectively progress towards a systemic -at least- regional circular economy. Therefore, it is worth reiterating that communication, transparent supply chains and stakeholders' engagement are key components towards a CE.

Only a few NRAs have taken under consideration the potential benefits of implementing circular operational patterns. Thus, in general, NRAs so far have not adequately invested into producing roadmaps towards the implementation of CE. This is happening due to lack of budget, lack of experts in CE within the national road authorities and due to the uncertainty of the successful implementation of CE, which also incorporates the lack of well-structured and comprehensive circular business models and incentives for the stakeholders associated with the market of asphalt pavements. This could lead to the conclusion that more people with specialization in CE should be operating within the NRAs providing higher accuracy, more insights and knowledge in terms of CE implementation. Finally, more and more NRAs should allocate percentages of their budgets towards the development of circularity metrics and roadmaps/strategies towards the implementation of CE and the assessment of the levels of this implementation. This could help to monitor and evaluate the progress that is being made and finally develop a feasible and spherical framework of how they should actually be implementing CE in asphalt pavements in the best way possible. The only NRA that has published an "Approach and Route Map" towards circular economy is the Highways England, in which future visions and plans that are aligned with the implementation of CE are described. It can be seen however, that the majority of the investigated NRAs is publishing sustainability reports and communicating their plans in terms of sustainability, but CE is still not a matter that seems to be under their attention. They should develop a larger spectrum of knowledge about the benefits of

CE implementation and ultimately implement and properly communicate their plans. In this way they will be able not only to act environmentally responsibly but also to increase the firm value and reputation. For this very reason, circular recommendations can enable NRAs to detect those internal opportunities that could be exploited towards the transition to a more circular way of operating. Implementing the recommendations can immediately increase their circularity and thus, reduce their environmental impact. Some of the most immediately applicable recommendations that can be given to NRAs towards the implementation of CE are:

- Establish compulsory and regulated end of life strategies.
- Adapt pavement designs that allow the utilisation of lower amounts of materials.
- Optimise preventive maintenance strategies by implementing a holistic sustainable pavement management system.
- Use material flows and material passports to track the life cycles of materials.
- Maximise the use of Reclaimed asphalt and increase the reuse of secondary materials.
- Use of lower percentages of virgin materials should be established as the norm.
- Target setting towards the exploitation of all the available Reclaimed Asphalt.
- Use of renewable energy sources.
- Change utilisation patters (sharing models, product as service).
- Minimise the construction of new road networks by optimising the layouts of existing ones.

However, it is highly recommended that NRAs implement the circular recommendations in conjunction with the implementation of the ESC_i indicator or at least simply coupled with an LCA study, in order to validate the environmental benefits of their circular choices, since as mentioned earlier, the sustainability of circular practices can be context-sensitive.

From the development and validation of the Material Circularity Index framework for asphalt mixtures with RA; and while pursuing effective policies aimed at implementing the principles of sustainability and CE, it can be concluded that a strong cooperation between stakeholders should be considered, focused on optimizing:

- **ΔU**, by encouraging waste recycling techniques, while at the same time discouraging landfilling through incentives, bonuses and penalties.
- **P_{RA}**, by increasing the allowed limits of RA incorporation in the asphalt mixtures, following the current direction of scientific research.
- **X**, by increasing the utility factor through an appropriate and specifically tailored mix design addressed to RA/
- **F[X]**, by further analysing and fully defining the parameter of utility function according to "ad hoc" structure for the end-product.
- **Capability and Efficiency**, by accordingly adapting and strengthening the asphalt production chain, with reference to the structure and equipment of the treatment and mixing plants.

Moreover, on the other hand, the development and implementation of the environmental sustainability and circularity assessment indicator has proven that not necessarily all the practices that are considered highly circular are also highly sustainable. It emphasizes the need for sustainability assessment to be integrated with circularity assessment and thoroughly implemented case by case, if the desired choice is one that is both sustainable and circular. The results that can be obtained through its utilization can help the identification of the most environmentally sustainable options that simultaneously exhibits the most desirable levels of circularity. A more sustainable and circular decision-making approach, which is also data and evidence-based can be adopted in this way; and the riddance of the currently dominating linear operating patterns can be achieved in a controlled way, promoting the desirable preservation or even enhancement of ecosystems, societies and human health. This process, which is aligned with the global attempts of safeguarding natural resources, the environment and human health, seems to be strictly dependent upon the will of national road authorities to implement policies aimed at revising and updating technical standards and specifications.

It can hence, finally, be concluded that a more strategic effort must be made not only by local and regional authorities and governmental bodies, but also from National Road Authorities and private stakeholders towards the realization of a more circular and sustainable pavement engineering sector. These players and decision-makers should invest more in gaining knowledge about CE and sustainability in order to be able to implement them all across the supply chain and during the construction and management of their assets. They can now monitor their progress in terms of circularity and environmental sustainability via the utilisation of the proposed frameworks and indicator.

Summing up the research undertaken for the development of this thesis, it can be concluded that governmental bodies, NRAs, and private stakeholders involved in the pavement engineering sector, have not adequately invested and progressed in the development of tools and guidelines that will enable the pavement engineering industry to shift towards an holistic implementation of sustainability and circularity principles. Through this research a first step has been made towards this direction. A novel indicator (ESC_i) has been developed and it can integrate the environmental sustainability assessment with the circularity assessment of the most fundamental component of an asphalt pavement; an asphalt mixture. Hence, as a first step, the integration of circularity within one of the pillars of sustainability has been achieved. Further research should be conducted towards the direction of the full integration of circularity assessment into the sustainability assessment of asphalt mixtures. In other words, the interaction between the social and economic aspects with the circularity of asphalt mixtures should be furtherly researched and defined, so ultimately the circularity assessment should be fully integrated with all the pillars that the term sustainability entails. In this way circular practices able to increase the implementation of CE principles in pavement engineer, will automatically provide increased levels of sustainability.

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Appendix A

Questionnaire about Circular Economy

1. Are you familiar with the concept of Circular Economy and its principles?

Yes	No

If yes, which principles of Circular Economy are you familiar with? (tick as many as needed)

- Design out/minimise waste
- Use waste as resource (recycle, reuse)
- Prioritize regenerative resources
- Preserve and extend what is already made
- Other, please specify:

2. Which of those principles have already been introduced within established pavement life cycle management practices?
   - Design out/minimise waste
   - Use waste as resource (recycle, reuse)
   - Prioritize regenerative resources
   - Preserve and extend what is already made
   - Other, please specify:
3. Which practices are you using to implement those principles for Circular Economy?

4. If these principles are currently not implemented into practices, which reasons/challenges are impeding it? Is there a future strategy to implement them?

5. Are there any current metrics/indicators to assess the level of circularity of these practices and/or the pavement management process?

Yes	No

6. If yes, which are these metrics/indicators?

- Product Material Circularity Index (MCIP) [Ellen MacArthur foundation (EMF)]
- Company Material Circularity Index (MCIC) [Ellen MacArthur foundation (EMF)]
- End of Life recycling input rate [Available in the EU's Raw Material Scoreboard and in EC Monitoring framework for the CE (under development)]
- Resource Efficiency [EU Resource Efficiency scoreboard (EURES)]
- Other, please specify:

7. If no, which reasons/challenges are impeding their development? Is there a future strategy to define them?

8. Has a "Roadmap" towards Circular Economy been produced/published, to achieve more sustainable and circular management of asphalt pavements?

Yes	No

9. If yes, could you please provide us with a copy or link to find it:

10. If not, which are the current challenges, posing as obstacles towards the production of such a roadmap? Is there a future strategy to produce one?