Performance Measures of Road Infrastructure

A Life Cycle Thinking Approach

BABAK EBRAHIMI

Department of Architecture and Civil Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT

Roads have been an important asset of human society and the approach we adopt towards planning, designing, constructing, operating, and maintaining of the road infrastructure has significant consequences in the long-term for not only the humans, but all species on planet Earth. Hence, the lifecycle performance of the road infrastructure that sustain our socioeconomic development with a low environmental impact, while fulfilling their technical and functional requirements is of critical importance and needs to be improved. This thesis aims to understand the nature of the information that helps improve the performance of road infrastructure over their lifecycle and propose solutions that close the existing research gaps.

This thesis is essentially divided into two parts. In the first part, it focuses on the current lifecycle thinking towards the public physical infrastructure. It carries out a survey of the literature to gain a holistic understanding of the current challenges that infrastructure faces, namely population growth, anthropogenic greenhouse gas emissions, land use and coverage change, and abiotic depletion. It then recommends potential approaches to close the identified gaps. The investigation reveals that considering the entire lifecycle of the infrastructure helps avoid partial thinking, which affects the mankind and the ecosystem adversely and results in problem shifting. It shows how the lifecycle-based methods that incorporate uncertainties help enhance the depth of understanding and decisions regarding the lifecycle performance of infrastructure. In addition, it advocates that the collaboration between and within different fields of science and practice needs to be increased to better capture the consequences of various risks and avoid adverse effects.

In the second part, a systematic desk (or secondary) research and regular interactions with the Norwegian Public Road Administration (NPRA) were carried out which revealed the following research gaps to improve the environmental and economic performance of the Norwegian road networks: (1) measure environmental performance of the construction machinery over their entire lifecycle based on regionalized data, which helps increase both the resolution and exclusiveness of the results; (2) estimate lifetimes of pavements based on their technical performance, which helps in improving the validity of the results when benchmarking different pavements with respect to different criteria, e.g., environment, economy, and society, and supports the decision-making at different phases of road infrastructure projects; and (3) capture material flows and stocks of road infrastructure, which helps get an overview of the availability in terms of quantities and time of the secondary materials to theoretically substitute the virgin/primary materials. Hence, potential approaches were used by means of different methods and models, namely geographical information systems (GIS), life cycle assessment (LCA), survival analysis, decision tree

model, and material flow accounting (MFA), for the three focus areas to bridge the identified gaps. Also, the Norwegian input data were applied to show the proposed approaches quantitatively. Findings from the research carried out in the second part of the thesis show that:

- Although the operation phase of the construction machinery has been studied solely in most of the prior research, the investigation in this research showed that the inclusion of the other phases is equally important. This means that the production, delivery, maintenance, dismantling, waste processing, and circulation of energetic and non-energetic materials at different phases of a machine's lifespan contribute to the overall environmental impacts.
- The proposed approach to measure the durability of the pavements showed discrepancies between the maintenance records and the technical requirements and explained how different factors increased or decreased the lifetimes of pavements in different traffic classes. In addition, the results from the statistical tables (showing relative values) were transformed to absolute values to ease the readability and comparability of lifetimes between different pavements.
- The amount of stock in the Norwegian road network has continuously increased and in 2017 there were about 420 Mt of road materials in-service. The growth was owing to the continuous expansion of the road networks. However, the growth in the amount of road stock was predicted to increase by 9 % – 10 % between 2018 and 2050 as well, though it was assumed that the network would not expand after 2017.

Keywords: Road infrastructure, Lifetime Estimation, Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Geographic Information System (GIS), Life Cycle Thinking (LCT).

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Göteborg, August 2019

Babak Ebrahimi

LIST OF PUBLICATIONS

The doctoral thesis is supported by the following publications, which are appended at the end of the thesis.

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Journal paper

i. Vignisdottir, H. R., Bohne, R. A., Booto, G. K., Brattebø, H., Ebrahimi, B., Wallbaum, H., Born R. O. (2018). *A review of environmental impacts of winter road maintenance operations*. Journal of Cold Regions Science and Technology. DOI: 10.1016/j.coldregions.2018.10.013

ii. Vignisdottir, H. R., Verones, F., Booto, G. K., Ebrahimi, B., Brattebø, H., Bohne R. A., *Considering the environmental effects of road de-icer in life cycle assessment: A theoretical approach*. Journal of Transportation Research Part D: Transport and Environment

iii. Gontia, P., Thuvander, L., Ebrahimi, B., Vinas, V., Rosado, L., Wallbaum, H. (2019). *Spatial analysis of urban material stock with clustering algorithms: A Northern European case study*. Journal of Industrial Ecology. DOI: 10.1111/jiec.12939

iv. Vignisdottir, H. R., Ebrahimi, B., Booto, G. K., Born, R., Brattebø, H., Wallbaum, H., Bohne, R. A. *Life cycle assessment of winter road maintenance*. Status: Submitted

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ii. Adl-Zarrabi, B., Ebrahimi, B., Hoseini, M., Johnsson, J., Mirzanamadi, R., Taljegård, M. (2016). *Safe and Sustainable Coastal Highway Route E39*. Transportation Research Procedia, 14, 3350-3359. DOI: 10.1016/j.trpro.2016.05.286

iii. Ebrahimi, B., Wallbaum, H., Bohne, R. A., Brattebø, H., Vignisdottir, H. R., Booto, G. K. (2016). *Environmental Life Cycle Assessment (LCA) of Road Pavements: Comparing the Quality and Point of Application of Existing Software Tools on the basis of a Norwegian Case Study*. Conference proceeding paper: CIB World Building Congress, Tampere, Finland., pp. 749-760.

iv. Vignisdottir, H. R., Booto, G. K., Bohne, R. A., Ebrahimi, B., Brattebø, H. & Wallbaum, H. (2016). *Life Cycle assessment of Anti- and De-icing Operations in Norway*. Conference proceeding paper: CIB World Building Congress, Tampere, Finland., pp. 441-454.

v. Booto, G. K., Bohne, R. A., Vignisdottir, H., Pitera, K., Marinelli, G., Brattebø, H., Wallbaum, H., Ebrahimi, B. (2016). *The effect of highway geometry on fuel consumption of heavy-duty vehicles operating in eco-driving mode*. Conference proceeding paper: Tenth International Conference on the Bearing Capacity of Roads, Railways and Airfields. DOI: 10.1201/9781315100333-308

vi. Born, R. O., Booto G. K., Ebrahimi, B., Vignisdottir, H. R., Wallbaum, H., Bohne R. A. (2018). *Sustainability review of Norwegian road construction and infrastructure*. Proceedings of the 1st International Conference on Sustainable Mega Infrastructures - SMI 2018

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Report

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DEFINITION OF TERMS

Annual average daily traffic (AADT): Road traffic has an important role in road planning as it determines the traffic volume for which a road needs to be designed, and how funding, as well as timing for road maintenance, needs to be assessed. Traffic volume is most often expressed by the annual average daily traffic (AADT) which equals the number of vehicles passing in a 24-hour period. This is obtained by dividing the number of vehicles passing over a year by 365.

Building information modelling (BIM): It is a field that involves digitally creating, changing, and managing infrastructure projects in the domains of architecture, engineering, designing, and construction. It uses modeling software to integrate the semantic data, such as elements and components from different sources to create a digital representation of a project (Issitt, 2018).

Circular economy (CE): It is the notion of transforming the linear approach towards the utilization of natural resources (i.e., take, make, use, and dispose) into a circular approach that minimizes the material use and waste generation by maximizing the recycling and reusing of materials at the end of their lifespan (Lowe, 2005).

Effective hour: It is a time that a machine operates efficiently, accounting for both direct and indirect productive time necessary to perform the required operations (Aune, Bruland and Johannessen, 1992).

Environmental product declaration: It is a voluntary declaration to communicate the environmental impacts associated with a product in a systematic and transparent way with business and consumers in a document verified by an independent institute (EPD International AB, 2019b).

Engine load factor: The rate of power utilized by an engine during the work (Klanfar, Korman and Kujundzic, 2016).

Fourth power law: It is a simple way to measure the rate of damage caused by a particular load, as it measures the load equivalency factor by a power of four.

Functional Unit: Environmental life cycle assessment is a relative approach based on a functional unit as all the inputs, outputs, and consequently, their environmental impact are proportioned to the functional unit. The functional unit quantifies the performance of a product system for use as a reference unit (ISO, 2006).

Independent variable: Also known as an explanatory variable, it is a variable that affects the value of a dependent variable in a statistical model (Clapham and Nicholson, 2014).

Life cycle assessment (LCA): It is a quantitative method to analyze the potential environmental impact associated with a product system, activity, or service throughout its lifecycle (ISO, 2006).

LC-based assessment: It is a process of measuring the impact from a life cycle perspective.

Life cycle inventory (LCI): It is the inventory for a product system in its life cycle assessment by investigation, compilation, and quantification of information (ISO, 2006; Islam and Kumar, 2019).

Life cycle management (LCM): It is a concept that brings the life cycle thinking into action by enhancing the sustainability performance of a product value chain within a business or an organization. LCM works as a bridge connecting various tools and concepts (United Nations Environment, 2019a).

Life cycle thinking (LCT): It is the philosophy of broadening the range of view with a holistic approach to capture the entire system rather than focus on select parts of the system (United Nations Environment, 2019b).

Public physical infrastructure: A collection of structures (buildings, roads, and other amenities) that are designed to facilitate the operation or functioning of a society.

Regionalized LCA: It refers to an LCA, which is based on a geographically specified life cycle inventory data.

Structural number: It is an abstract number to indicate the structural strength and is calculated by means of the material coefficients (e.g., load distribution coefficients).

Sustainability: In the context of this thesis sustainability is the adoption of several interconnected pillars in response to the existing multi-dimensional challenges to ensure that the opportunities for the future generations will not be lost. For example, the pillars of sustainability for infrastructure are environment, economy, society, technicality, and functionality (Kono, 2018; Salzer, 2018).

Sustainable development: Here, the definition of sustainable development is derived from Brundtland's report, "Our Common Future" (1987) which defines it as the development that meets the needs of the present without compromising the ability of the future generations to meet their own needs.

Transverse unevenness (i.e., rutting): It is a longitudinal surface depression on the road wheel path that weakens the pavement's bearing capacity. Rutting also has a substantial role in traffic safety due to its impact on traffic overtaking, track aquaplaning, and winter operations. Premature rutting is an epidemic issue in Scandinavia. This is due to the

abrasion on the wearing course of the pavement as a result of the use of studded tires during the winter season. However, there are other causes that may result in rutting, such as consolidation of pavement layers (owing to the compaction deficiency, excessive air voids, binder, and filler), and abrasion due to raveling on the wheel path.

LIST OF ACRONYMS AND ABBREVIATIONS

AADT	Annual Average Daily Traffic
AD	non-fossil-fuel-based abiotic depletion potential
ADP_F	fossil-fuel-based abiotic depletion potential
AP	acidification potential
BIM	Building information modelling
CDW	Construction and demolition waste
CEN	European Committee and Standardization
EP	eutrophication potential
EEA	European Environmental Agency
EH	Effective Hour
EMEP	European Monitoring and Evaluation Programme
EPD	Environmental Product Declaration
EU	European Union
FE	fresh water aquatic eco-toxicity
GHG	greenhouse gases
GWP	global warming potential
HT	human toxicity
LC	Lifecycle
LCA	Life Cycle Assessment
LCE	Life Cycle Engineering
LCT	Life Cycle Thinking
LCM	Life Cycle Management
ME	marine aquatic eco-toxicity

MEF	Maskin-entreprenörenes Forbund (in English: Norwegian Association of Heavy Equipment Contractors)
NPRA	Norwegian Public Road Administration
ODP	ozone layer depletion potential
OECD	Organization for Economic Co-operation and Development
PH	proportional hazard
PM	particulate matter
PO	photochemical oxidation
RQ	Research question
SDGs	Sustinable Development Goals
TE	terrestrial eco-toxicity
UN	United Nation
VOC	volatile organic carbon

INTRODUCTION

This chapter explains briefly, the current situation and challenges facing the road infrastructure. Next, the aim of this thesis and some research questions are formulated, followed by the scope and structure of the thesis.

Constant connectivity and accessibility have become our definition of robust and reliable mobility. Whether it is related to the movement of the people, goods, or immaterial things, we are constantly in need of infrastructure, which are always available and provide services with no interruption (Fabbro, 2015). In modern societies, transport infrastructure should successfully support mobility, while ensuring socioeconomic development. Furthermore, the transport infrastructure need to consider sustainability in their long-term performance to minimize their negative impact.

1.1 Background

Over the last two decades, more than two trillion euros have been invested in the inland transportation infrastructure by the European member countries in the Organization for Economic Co-operation and Development (OECD). The investments, used for the expansion, rebuilding, and upgrading of the transport networks, have increased over the years and the total growth rate of investments has been about 54 % since the mid-90s (OECD, 2019). Such a considerable growth in the investments, to some degree, has been linked to the growth of population, urbanization, and globalization, which subsequently has put more pressure on the transport infrastructure to provide more connectivity in the networks.

Between the two main inland transport infrastructure, namely the roads and the railways, the amount of investment on the road transport infrastructure has been approx. 1.7 times higher than that on the railway infrastructure in the past two decades. In total, about 1.42 trillion euros have been spent on the road infrastructure since 1995 (OECD, 2019). This large share of investment can be attributed to the strategic role of the road infrastructure. Roads have always been a major player in bringing various transport modes together to ensure that the domestic and the international travels are conveniently connected. In addition, a large share of the motorized vehicles uses road infrastructure throughout the year. It is estimated that about 90% of the passenger transport and about 75% of the freight transport happen on the road infrastructure only (Eurostat, 2019b, 2019a).

Along with the continuous increase in the investment in the road infrastructure, the usage of the road transport has also continued to grow in the EU. The annual passenger kilometers and ton kilometers on the roads have increased continuously since 2000, on an average, at 1.1 % and 3.3 %, respectively (OECD, 2019). This continuous growth is owing to the supporting role that the road infrastructure plays in enhancing the socio-economic activities and the gross domestic product (Elena Garbarino *et al.*, 2014). In addition, the road transport has been a source of income for about 5 million people in Europe, engaged in carrying passengers and freight (European Commission, 2017).

1.2 Motivation

Following the Paris agreement of 2015 reinforced by the United Nations Sustainable Development Goals (UNSDG), which sets up targeted goals to address global challenges, different strategies have been mandated in various sectors to mitigate the negative effects of development (European Commission, 2019a). Some strategic goals have been formulated in the transport sector as well to ensure that we improve our current practices and reduce our negative impact while securing the socioeconomic practices and the community welfare. In other words, it is the intension to maximize the social welfare and the economic growth while minimizing the demands on the natural and financial resources by means of sustainable solutions.

The contemporary elucidation of sustainability is the product of intellectual development over the years. It started its journey from being a marginal idea and has now become the focus of attention in international events and agreements (Caradonna, 2014). The adoption of several interconnected pillars has been advocated by various scholars in the Anthropocene to respond to the multi-dimensional challenges that violate the natural equilibria and affect the mankind. Hence, providing a balance between these different pillars is essential, as it ensures that opportunities for the future generation will not be lost (Kono, 2018; Salzer, 2018).

The assessment approach provided by the European Committee for Standardization (2010) appropriately illustrates sustainability for the civil works. Based on this standard, the incorporation of the intrinsically related pillars is essential to assess sustainability. Along with the most frequently used pillars over the last couple of decades, which reflect on the environmental, economic, and social dimensions, the standard emphasizes on the importance of accounting for the technical characteristics and the functionality of the system to capture a comprehensive picture. Hence, sustainability is the incorporation of the environmental, economic, and social aspects while fulfilling the technical and functional requirements.

1.2.1 Sustainability: some of road infrastructure challenges

For most countries, the immediate answer to the pressing issue associated with the road transport systems lies in the reduction of greenhouse gas (GHG) emissions exhausted directly by the traffic. The motorized vehicles contribute a higher share of the GHG emissions (about 85% – 90%) compared to the construction and maintenance of the road infrastructure (Miliutenko, 2016; European Commission, 2019b). Hence, many nations have set their targeted goals and pathways to achieve the reductions in GHG emissions by phasing out motorized vehicles using fossil-based fuels. More precisely, they collectively defined that the mitigation needs to be achieved by decarbonization of the transport and replacing the fossil fuels by biofuels.

However, the sustainability of the road transport should not be limited to the vehicle side of the system. By merely reducing the non-biogenic GHG emissions from the operation of the vehicles, the environmental impact associated with the road infrastructure would not cease to be insignificant. The relative environmental impact associated with the road infrastructure will increase as vehicles become more efficient and have less harmful ecological impacts (Miliutenko, 2016). Hence, while we work on the sustainability of motorized vehicles, road infrastructure should also be planned and maintained sustainably to minimize its negative impact. In view of their long service lives, due importance should be given to the performance of the roads in assuring security, safety, and efficiency of service to their users.

Roads are designed adaptively to cope with the difficulties of terrain with a view to creating a safe environment for the road users. The expansion rate of the road infrastructure in the European networks has continuously been above 20 % since the early 90s. By now, about 5.5 million km of road networks exist in Europe (European Commission, 2016; Eurostat, 2017). Although such an expansion over the past three decades has resulted in changes in connectivity, mobility patterns, and settlements, which have made various socio-economic activities possible (Guessous *et al.*, 2014; Ji *et al.*, 2015; Iacono and Levinson, 2016), it has negatively affected the environment, as well as the natural and financial resources.

Conversion of natural land into impervious surfaces for transportation has steadily increased in Europe (European Commission, 2012, 2013). By cutting through the natural habitat and fragmenting the land, the road infrastructure has caused irreversible damages. Depending on the sensitivity of the area, they have resulted in disturbances and interruption in the migration of wildlife. The natural balance of the areas adjacent to roads has been damaged or disturbed either due to the chemical pollution from the road traffic or the road surface itself (IENE, 2003).

Vast amounts of construction materials have been consumed in the road infrastructure over the decades owing to the construction of new roads and the ageing of in-service ones which require maintenance interventions. Utilization of virgin materials in high proportions during such activities is resulting in mining and extraction of raw materials instead of recycling the used materials. Hence, a proper response to this burden on the finite resources is needed, as the 'business-as-usual' approach will jeopardize our future.

In addition, a large amount of energy is consumed and pollutants are emitted by construction equipment during the lifecycle of the road infrastructure. Based on some extrapolated data, construction equipment is responsible for about 335 kton of CO_2 emissions annually in Norway (MEF, 2016; Statistics Norway, 2017a, 2017b). The consumption and emission by construction equipment may happen directly in situ, like in earthworks, or indirectly upstream, like in mining activities. Over the last years, there have been technological improvements which increased the fuel efficiency and reduced the tailpipe emissions. However, the market for the construction machinery is expected to continue its upward trend in the coming years, which may increase the demand for more energy and natural resources (CECE, 2019).

Continuous growth of traffic volumes has resulted in an increase in the cyclic loading, which in combination with other external factors has resulted in the accelerated deterioration and increased maintenance of the roads. Even with the growth of yearly investment on the maintenance budget, not enough has been allocated to keep the in-service roads at a level that matches the growing traffic (ERF, 2013; European Commission, 2016; Eurostat, 2017). Such insufficient financing has led to a gradual reduction in the level of service provided by these roads, which often results in overdue maintenance works and puts the in-service roads in a poor condition.

Prolonged delays in maintenance result in an exponential increase in the costs for both the agencies and the users. If they are not addressed by proper maintenance planning, we may end up with either partial or total loss of the road infrastructure, which puts a stress on the upcoming reinvestments. The loss of road infrastructure would also translate to an interruption in the transport flows and traffic diversions. The diversions would increase the

cyclic loading of the hitherto un-damaged roads and accelerate their deterioration. Therefore, more roads eventually end up on the accumulated list of roads waiting for maintenance and reinvestment works.

1.3 Introduction to Norwegian case

The Norwegian government has aimed to spend a thousand billion Norwegian Kroner over 12 years to modernize the transport infrastructure to enhance its safety, efficiency, and effectivity. At the same time, the government also enforced different climate policies to help the nation reach its reduction goals for the GHG emissions. The green movement has been motivated by a high share of emissions from the transport sector, which is about one-third of the total GHG emissions in Norway (Ministry of The Environment, 2012).

In the domain of road infrastructure, the government has given the Norwegian Public Road Administration (NPRA) the responsibility to find reduction pathways in the GHG emissions. For achieving its goal, the NPRA needs to find 40 % and 50 % reductions in the construction and maintenance activities of the road infrastructure, respectively, by the year 2030 (Avinor *et al.*, 2016; Ministry of Transport and Communications, 2017). This drastic reduction in the road infrastructure investment is linked, to some degree, to the public procurement done by the NPRA and the introduction of green initiatives in its procurement practices to safeguard the Norwegian climate policy.

About 35% of the public roads in Norway are in poor condition owing to the overdue maintenance works (Rådgivende Ingeniørers Forening, 2010; Sund, 2014). The accumulated maintenance backlogs are due to (i) the budget constraints, (ii) the continuous ageing of the road networks, (iii) the constant growth of the road traffic, and (iv) the stricter technical requirements of the road infrastructure. These factors have made it very challenging for the NPRA to meet its objectives. Although the NPRA has tried to improve the condition of the roads, the speed of intervention has not been able to cope with the growing number of roads in the poor-condition list.

1.4 Aim and research questions

Different answers can be identified in the published studies aimed at the reduction of the negative impacts in terms of the environment and the economy associated with road infrastructure. These include incorporation of the GIS assessment, use of multi-objective programs, use of less energy intensive materials, and increased use of reclaimed materials (Muga *et al.*, 2009; Lee *et al.*, 2010; Mandapaka *et al.*, 2012; Pissarra Cavaleiro, Batista dos Santos and de Picado Santos, 2014; Wang and Chong, 2014; Karlsson *et al.*, 2017; Pantini, Borghi and Rigamonti, 2018; Santos *et al.*, 2018). In addition to the above, various tools have been developed that help quantify the impacts associated with the road infrastructure (Zukowska *et al.*, 2014). However, some of these prior environmental studies and tools were

developed for different purposes and system boundaries, thus making their answers uncomparable. While some used generic data to answer regional problems without considering the uncertainties of their findings, the others focused on certain indicators and/or phases of the road infrastructure that were critical only for their studied systems without taking into account the full life cycle approach.

The use of absolute average lifetimes for materials in some of the environmental and economic research studies have become the pathway to assess the performance of the road infrastructure (Chan, Keoleian and Gabler, 2008; Giustozzi, Crispino and Flintsch, 2012; Santos, Ferreira and Flintsch, 2014; Giani *et al.*, 2015). Although the application of the absolute values (while comparing different construction and maintenance strategies) provided a streamlined overview of the performance, these values were incapable of considering the variability of the lifetimes with respect to factors, such as climatic conditions, traffic volume, and speed limits. Thus, they failed to reduce the biases in their investigations by not applying lifetimes quantified by different independent variables.

Besides, some of the environmental and economic researchers conducted their assessment at a project level or for a small network without demonstrating the significance of their findings at the national level (Fernández-Sánchez *et al.*, 2015; Trunzo, Moretti and D'Andrea, 2019). In other words, they did not consider how much cost and/or environmental impact could have been reduced for the nation-wide road networks. The lack of attention to the nation-wide results was owing to the inadequate physical accounting that could show the changes in the stock/material levels related to the road infrastructure over time at the national level. Since massive quantities of materials are moved every year to build and manage the road infrastructure (Koll-Schretzenmayr, Keiner and Nussbaumer, 2004), a deeper knowledge with respect to the material consumption and disposal over a long time, aids in understanding the future needs and availability of the road materials at the national level. Furthermore, the obtained results help in understanding the burden that building and managing the road infrastructure would put on the environment and the economy, and provide a platform to investigate on new pathways to reduce this burden.

The aim of this work is to *explore and gain a deeper understanding of the lifecycle of the road infrastructure by applying a systematic approach and propose solutions that close the research gaps.*

Four research questions (RQs) were formulated to achieve the research goals of the study, namely exploring potential approaches to bridge the current gaps in the lifecycle of the road infrastructure. However, prior to asking these RQs, it is necessary to gain a holistic understanding of the current lifecycle thinking and practice in the area of infrastructure. RQ 1 was thus formulated for this purpose.

RQ 1. *What is life cycle thinking for public-owned physical infrastructure and how should they be managed?*

The first question was used to understand how the life cycle thinking (LCT) is viewed in the literature for the public-owned physical infrastructure. It is intended to identify the challenges and opportunities and propose recommendations to enhance the lifecycle performance of the studied infrastructure.

RQ 2. *How can a regionalized cradle-to-grave life cycle assessment (LCA) be conducted by means of a generic life cycle inventory (LCI) database? And for what product system does this investigation need be conducted?*

The second question was meant to carry out a regionalized LCA, showcasing it on a product system that requires further attention within the domain of road infrastructure.

RQ 3. *How can a multivariate estimation of lifetimes be conducted?*

The third research question was derived to introduce an approach to estimate lifetimes by means of different independent variables.

RQ 4. *How can the long-term material flow and stock within the road networks at the administrative level be modeled?*

The fourth question was aimed at proposing an approach to measure the past, present, and future of the road infrastructure at the network level to show the amount of stocks and flows over time.

1.5 Scope of research

Based on the European standard 15978 (CEN/TC 350, 2011), the system boundary focuses on the following LC stages: product stage, construction process stage, use stage (only the maintenance work), and end-of-life stage. A wide area of focus is considered in the thesis to identify important elements and ensure that the thesis provides a comprehensive coverage of the above mentioned RQs. In addition, the research uses Norwegian cases to realize the work and provide quantitative values.

1.6 Thesis structure

This thesis is structured around seven chapters reflecting on the appended book chapter and three articles (papers I – III). The summary of each of the chapters is as follows:

Chapter 1 provides a brief introduction into the topic of road infrastructure and highlights their significance, and elucidates the role of this thesis in the context of the road infrastructure. It also explains the direction that Norway aims to take in respect of its road infrastructure. **Chapter 2** formulates the research based on the identified gaps in the research

scope that need to be investigated. In addition, it talks about the case study used for the investigations, and gives a brief introduction to Norway, its road networks and visions. **Chapter 3** explains the research approach taken, based on the identified gaps, and explains the implemented methods in the appended papers. **Chapter 4** summarizes the findings from the appended book chapter and articles. **Chapter 5** discusses the obtained findings in relation to the research questions. **Chapter 6** concludes the thesis and presents the highlights of this work, and **Chapter 7** suggests some direction that a future research may need to consider.

THEORY

This chapter provides an evaluation based on the previously conducted studies to identify the gaps in the research and carve out a niche for bridging them. In addition, it provides a brief introduction to the case study in this thesis.

2.1 The life cycle of infrastructure

Very often, a huge amount of work and effort are dedicated to building new infrastructure. This requires positive involvement and contributions by different actors at various stages of the infrastructure project to ensure that it is *successful*. In the current context, a successful project provides safety, welfare, mobility, and accessibility to its users, while at the same time, reduces the overall negative impact during its lifetime (Jonsson and Johansson, 2006). Thus, in view of their long service lifetime, the infrastructure projects require to be carefully planned, designed, constructed, and maintained to mitigate their adverse effect on the society and the environment (ERTRAC, 2009, 2010; European Commission, 2011a; Steger and Bleischwitz, 2011).

Sustainability of infrastructure has become an important consideration for the decision makers. Various scientific articles suggest ways of measuring the sustainability of infrastructure projects considering various direct and indirect impacts that they can cause during their lifetime (Sahely, Kennedy and Adams, no date; Johnson *et al.*, 2004; Ugwu and Haupt, 2007; Bocchini *et al.*, 2014; Perz, 2014). These sustainability measures are often coupled with the LCT principle to capture the sustainability performance of a system (Hallstedt, Thompson and Lindahl, 2013). The LCT has been proven to be a promising

approach to support the decision-making process by not only examining the potential and the limitations of the system under investigation, but also prescribing the response measures to address them (Mont and Bleischwitz, 2007).

Despite the incorporation of the LCT-based approaches in the sustainability measures of the infrastructure, it often lacks the capability to fully incorporate state-of-the-art science into its practices. This could be because of various reasons, for example, the lack of funding initiatives, data, tools, and harmonized guidelines. This consequently limits a wider range of application of the LCT (UNEP, 2005; Glass *et al.*, 2013; Klöpffer, 2014). At the same time, not all lifecycle stages may be covered in the assessment. This could be because of the complexity and uncertainties of the work, as well as the lack of having adequate resources that are beyond the control of the decision-makers, architects, and builders. These inconsistences result in unrealistic findings, which in return, put the decisions in a disadvantageous position and stop us from achieving comprehensive solutions.

This thesis investigates into the LCT approach in public-owned physical infrastructure to gain an understanding of the challenges and the opportunities, and how they need to be managed to enhance the sustainability performance of such infrastructure.

2.2 LCA of road infrastructure

LCA is a well-established methodology that helps measure the sustainability performance of a system from an environmental perspective. Although the use and application of life cycle costing (LCC) goes way beyond the origin of LCA (Grant, 1930), the growing trend in the development and use of LCA is significant (Hauschild, Rosenbaum and Olsen, 2018). In addition, LCA is a standardized methodology (ISO, 2006) that follows the LCT principle. Standardization of LCA was very important as it structured the work by defining steps and criteria to enhance the transparency and communication of the results (ISO, 1997, 2006). In addition to the latest version of the LCA standard in 2006, complimentary guidelines have been also introduced by various actors to further improve the clarity of the LCA process. Some of these include EN 15978:2011 (CEN/TC 350, 2011), EN 15804:2012 (CEN, 2013), UN CPC 53211 (The International EPD® System, 2013), and indicators for the sustainability assessment of roads (CEN/TC, 2016).

LCA of road infrastructure is not new and has been investigated by prior researchers. In some studies, LCA was used as a stand-alone method. However, in some other cases, it was paired with other lifecycle-based methods, like the LCC and the social life cycle assessment (SLCA) to have a more comprehensive coverage. By only focusing on the LCA part of the prior research, it could be seen that there was no consistency in the boundary of the system. Based on the evaluation, attentions were paid to some specific stages of the road infrastructure, like construction, operation, and transportation. Furthermore, it is noticeable

that not often did the studies focus on the entire lifecycle of a road, see for instance (Mroueh, Eskola and Laine-Ylijoki, 2001; Park *et al.*, 2003; Stripple and Erlandsson, 2004; Treloar, Love and Crawford, 2004; Birgisdóttir *et al.*, 2006; Huang, Bird and Heidrich, 2009; Muench, 2010; Stripple, 2011; Cass and Mukherjee, 2011; Yu and Lu, 2012; Gschösser, Wallbaum and Boesch, 2012; Barandica *et al.*, 2013; Gschösser and Wallbaum, 2013; Santos, Ferreira and Flintsch, 2014; Adibi *et al.*, 2015; Wang *et al.*, 2015; Hammervold, 2015; Miliutenko, 2016; Krantz, 2017). A review of the above suggests that depending on the goal of the research, the area of the investigation may vary. In addition, because of the differences in the applied functional units, geographical locations, databases, impact assessment methods, and analysis periods, benchmarking of their results with the same system boundary becomes very difficult.

In view of the variations in the prior studies, it becomes very essential to identify and investigate the key elements that need further improvement. A clear majority of the reviewed LCA studies solidly emphasized that the construction phase of the road infrastructure (excluding tunnels and bridges) had a considerable share of the environmental impact over the lifetime of a road. This was corroborated from the studies related to the impact and the energy associated with the road materials, and the use of construction machinery (Karlsson, Rönnqvist and Bergström, 2004; Muench, 2010; Cass and Mukherjee, 2011; Barandica *et al.*, 2013; E. Garbarino *et al.*, 2014; Wang *et al.*, 2015; Barati and Shen, 2016). As a result, the material choice and the difficulty of terrain have a considerable effect on the results.

With the increasing availability of data and higher resolution LCA databases (Steubing *et al.*, 2016; Wernet *et al.*, 2016), more in-depth knowledge about the performance of the studied system has been made possible. However, very little has been done to include the full life cycle of the construction equipment in the LCA databases and the environmental product declaration (EPD) reports (Lee *et al.*, 2000; Athanassiadis, Lidestav and Nordfjell, 2002; H. Kim *et al.*, 2012; H. M. Kim *et al.*, 2012). This is not only important for the earthworks and maintenance activities of the road infrastructure but it also brings in a higher resolution for the LCI of quarried materials. Various types of construction equipment are used in various capacities to carry out work in mining activities, like excavating, loading, and hauling. However, these types of activities are fully ignored in the generic LCA database, and instead they are simply treated as energy consumption activities or in some instances as exhaust gas emitting activities.

2.3 Service life of road materials

Owing to the insufficient attention paid over the years to the maintenance of damaged road infrastructure, a huge backlog has been created in the system that causes various economic harms. While clearing such delayed maintenance works is unavoidable, it also puts pressure on the economy, environment, and the society (Garemo, Hjerpe and Halleman, 2018).

Maintenance of road infrastructure at acceptable levels is an important task for road authorities and governments because of its effects on the businesses and the society. This task requires a good understanding of the road conditions, as well as perfect timing, to avoid issues such as budget shortages and traffic congestion. Reliability of the pavement maintenance planning depends highly on the predicted pavement performance (Yang, 2007). Furthermore, the accuracy of the prediction not only affects the selection of the maintenance options, but also helps the pavement mangers take conscious and informed decisions.

In addition, a deeper understanding of material performance helps in superior planning to attain long-lasting road infrastructure that fulfil the technical requirements. This is very important, as nearly all infrastructure require maintenance works at some point in their lifetime. However, the frequency of the maintenance works is proportionately higher for road infrastructure compared to other infrastructure in our built environment (Kapur *et al.*, 2008; Wiedenhofer *et al.*, 2015). Any LC-related infrastructure studies having reliable information about the performance of the materials vindicate this assessment. Such information comes very handy when benchmarking different materials with respect to different criteria, like environment, economy, and society etc.

In several LCA studies, the construction phase was shown to have a dominant share of the impact compared to other phases (O'Born *et al.*, 2014; Hammervold, 2015; Miliutenko, 2016). Although the relative impact of a maintenance work is quite low compared to that of a construction work, a study by Gschösser and Wallbaum (2013) showed the total impact from the maintenance works would not be insignificant when the analysis period was extended. This is especially true of high frequency maintenance activities for road infrastructure projects that would last for many decades.

Predicting the performance of the pavements and measuring their remaining lifetimes has been a hot topic in pavement engineering research. It captures the degradation characteristics of the pavements and provides deterioration models to guarantee that the agency's maintenance budgets are used optimally. Among various approaches, utilization of historical records and coupling them with statistical models has been proven to be a feasible way to gain reliable understanding. Published studies in this area revealed the potential of the statistical modeling to capture the performance of the pavement materials (Prozzl and Madanat, 2003; Wang, Mahboub and Hancher, 2005; Ker, Lee and Wu, 2008; Do, 2011; Gao, Aguiar-Moya and Zhang, 2012; Han, Kaito and Kobayashi, 2014; Karlaftis and Badr, 2015; Dong, Dong and Huang, 2016). Although the wealth of available data is very crucial in gaining a deeper understanding of the longevity of the pavements, the right selection of methods and models helps overcome some challenges. This thesis investigated into this matter to provide a new approach to use the existing data in the Norwegian system for explaining the longevity of the pavement materials.

2.4 Material stocks and flows accounting

Growing awareness of the limitation of our natural system vis-à-vis our unlimited demand has brought us to a point where we need to think in a circular fashion. This is especially true in the present times as we have been extracting the natural resources at an alarming rate. At the beginning of 2000, we extracted some of the natural resources almost eight times greater than what we did in 1900s (OECD, 2015). It is expected that if the current consumption is not addressed properly, the rate by 2050 will be three times the current consumption rate (UN, 2011). Safe operational space for humanity heavily depends on the path that we choose and how successfully we can change the current behaviors. Circular Economy (CE) has proven itself to be a practical way to reduce the waste generation and the demand for virgin resources by bringing the LCT principle into practice to increase the resource efficiency (Haas *et al.*, 2015; Kalmykova and Rosado, 2015).

Various initiatives have been taken up over the last two years in Europe emphasizing on the importance of better management of abiotic resources. Waste Framework Directory (WFD 2008/98/EC) highlighted the importance of responsibility towards the use of natural resources and increasing the recycling of materials (European Commission, 2008b). Roadmap to a "Resource Efficient Europe" (COM(2011) 571) emphasized on the reduction of the use of natural resources and generation of waste while mitigating the 'no net land take' target by 2050 (European Commission, 2011c). Sustainable use of natural resources as one of the seven basic requirements stated by the "European Construction Products Regulation" (CPR 305/2011/EU), highlights the optimal and efficient use of natural resources in such a way as to ensure different regulative requirements (European Commission, 2011b). In addition, the "European Raw Materials Initiative" was established as an integrated strategy to tackle issues related to raw materials used by the European industries (European Commission, 2008a).

Addressing the current movements in Europe and providing a systematic approach based on the CE principle requires an adequate understanding of the in-service materials. Since the end of the 90s, the use of material flow accounting (MFA) method has been gaining attention and proving to be a potential way to study CE. MFA represents a system by providing its metabolic behavior at different times to show the flow rates, hot spots, and potential recycling within the system (Anthonissen *et al.*, 2015; European Commission, 2018)

Vast amounts of natural resources have been deposited over the years in the road infrastructure. This accumulated deposition of road materials has caused road infrastructure to become man-made quarries of construction materials. Utilization of MFA in accounting the stock and flow of construction materials is a potential way to depict the status of the road infrastructure. Except for a few studies (Hashimoto, Tanikawa and Moriguchi, 2009; Kapur *et al.*, 2009; Tanikawa *et al.*, 2010; Miatto *et al.*, 2016; Han *et al.*, 2018; Huang *et al.*, 2018),

very little has been done to project the amount of road materials in the past, present, and future. This is often because of a lack of adequate and reliable primary information from the historical records. In addition, there is only a limited insight into the longevity of the materials, as a result of which, it becomes challenging to predict the future metabolic behavior of the system.

Implementation of the state-of-the-art scientific practices in the MFA studies is a solution for the current challenges. Hence, different methods and models have been showcased in this thesis to suggest ways to overcome the current limitations and create a comprehensive work. This also helps enhance the depth of knowledge and quality of work when considering the design of CE for road infrastructure.

2.5 OVERVIEW OF NORWEGIAN ROAD INFRASTRUCTURE

Norway is a land with an eye-catching nature and an extreme topology (see Fig. 1). In addition, owing to the long distribution of its land from the south to the north and a long coast Norway can boast of diverse climatic conditions across the nation.

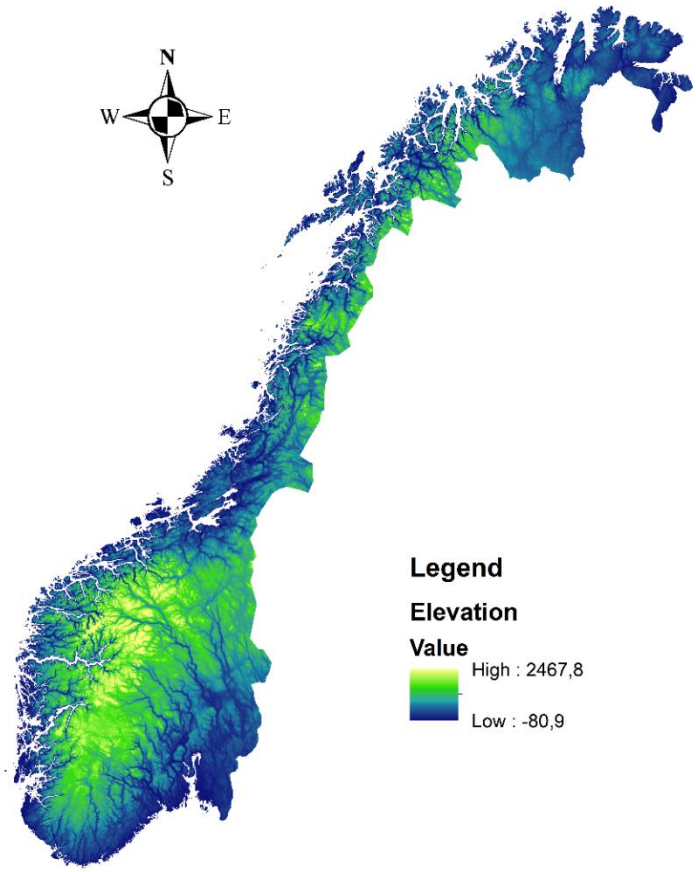

Fig. 1: Topology of land in Norway; data source from GeoNorge *(2019)*

Norway is listed among the countries with the lowest population density in Europe, with about 13.7 inhabitants per sq.km (see Fig. 2). Despite its low population density, it is

expected that the population in Norway will grow in coming years. Currently, Norway has a population of about 5.3 million which is expected to grow at an annual growth rate of approximately 1 %. It is expected that Norway will eventually be home to 6.3 million by 2040 (Statistics Norway, 2019b).

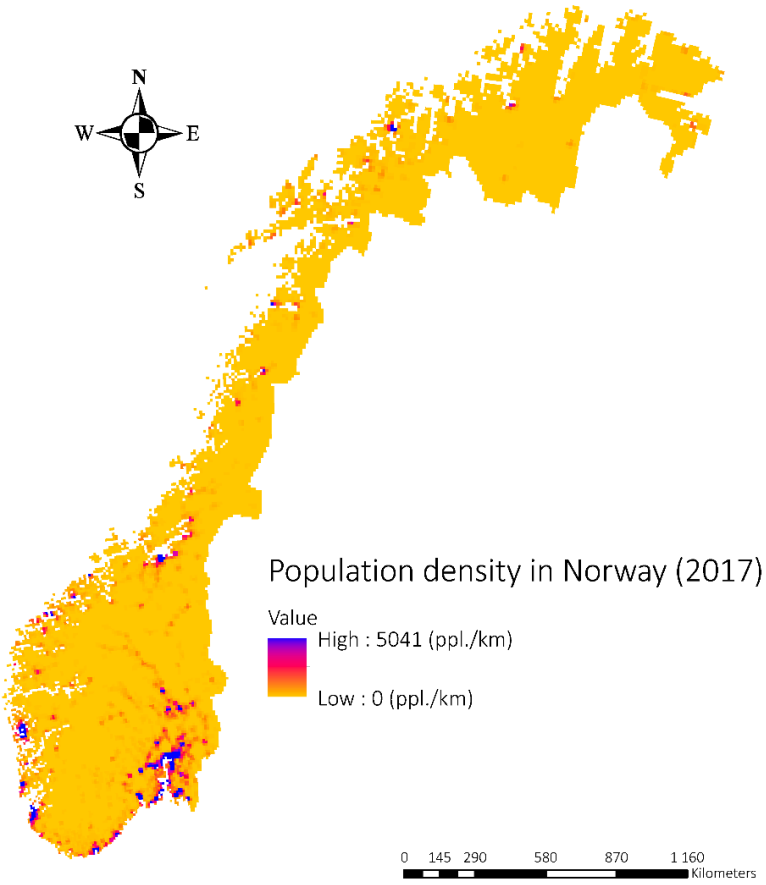

Fig. 2: Population density in 2017

Major cities in Norway are located along the coastline and the road infrastructure is often a key element in supporting the mobility and the socio-economy activities across Norway. Owing to the importance of the road infrastructure, the Norwegian government plans to invest more on the Norwegian transport system to increase the connectivity and help the nation come closer together. Hence, various road projects have been financed in Norway to improve the quality of service provided for the users. A recent example is the Coastal Highway Route E39 that strives to enhance the connectivity and assist in the socio-economic prosperity of the regions along the route E39 (Dunham, 2016).

The importance of the road infrastructure has also been reconfirmed by the statistical data available (Statistisk sentralbyrå, 2017). Around 88 % of all the motorized transport in Norway happens on the roads, while above 90 % of the goods are transported over short distances on the roads (Ministry of Transport and Communications, 2015; TØI, 2015). The total vehicle millage in Norway has continued to grow since 1930 by a factor of ten. Such a

10-fold growth can be explained by the increase in the total length of the public roads during the same timeframe.

Over time, the total length of the public roads has kept growing annually by about 1 %, on an average, since 1990 and it is expected that an average of about 250 km of new roads are built every year in Norway (Granden, Johansen and Bakløkk, 2017). Today, the total length of the public road infrastructure in Norway is about 93000 km. About 11 % of the road infrastructure is accounted for by the national and EU roads, about 47% by county roads, and 42% by municipal roads (The Norwegian Ministry of Foreign Affairs, 2015).

Since the beginning of this millennium, the rate of growth in the traffic volume, measured by the Annual Average Daily Traffic (AADT), has not slowed down. Although the growth rates may vary across the nation, the overall growth has been positive (see Fig. 3). Furthermore, the growth rate is more pronounced for the heavy-duty vehicles, i.e., vehicles with a gross weight of 3.5 tons or more. Since the early 2000, the rate of growth has doubled for the heavy vehicle traffic, which is significantly higher than that of the light vehicle traffic; see Fig. 4. This is an alarming situation for the Norwegian road infrastructure, especially when considering the damage caused by the traffic with respect to the fourth power law.

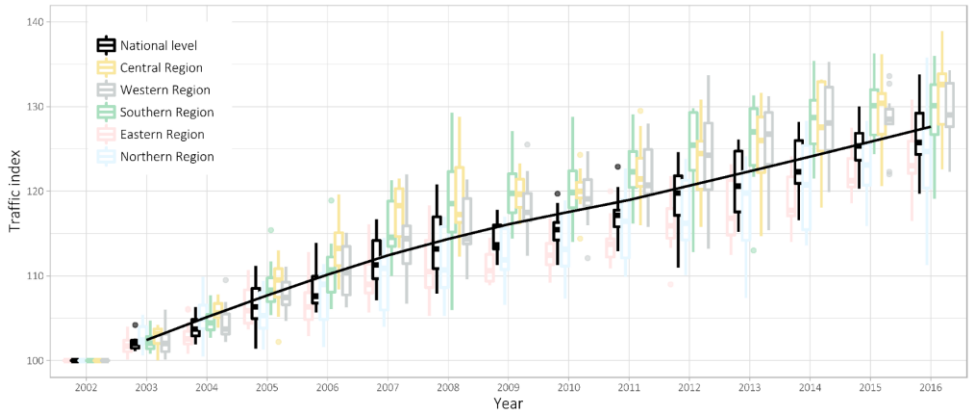

Fig. 3: Changes in the total traffic volumes in five administrative regions of Norway since 2002 (the national level information is calculated based on the changes in the five regions)

Despite the continuing growth in the traffic volume, a clear majority of public roads in Norway have low traffic volumes. About 75 % of the public roads in Norway km-wise, have an AADT below 1500 vehicles (based on the data in 2017). Ordinary two-lane roads account for most of the public roads in Norway and open-road infrastructure accounts for over 95 % of public roads in Norway.

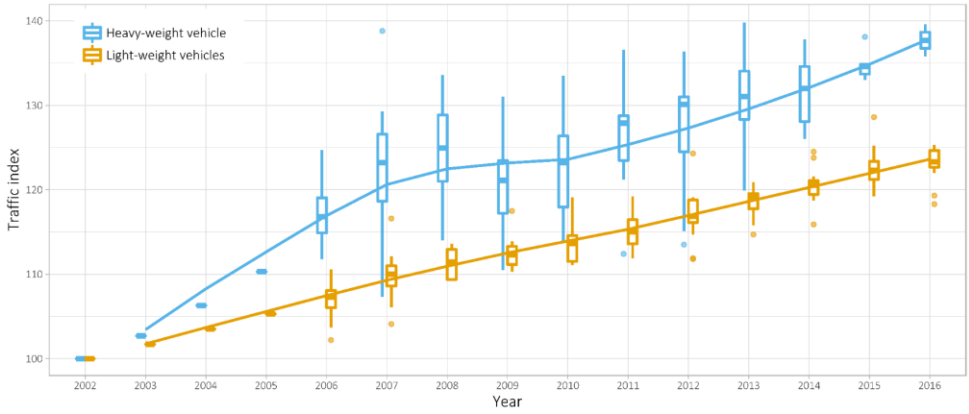

Fig. 4: Comparison of changes in the rate of heavy- and light-weight vehicles

2.5.1 National Transport Plan

To ensure safe, efficient, and effect transportation that nourishes socio-economic development with reduced climate impact, a White Paper is submitted every four years to the Norwegian parliament recommending goals and strategies for the Norwegian transport for a long-term planning period (recently the period was extended from ten to twelve years) (regjeringen, 2017). The White Paper, which is called National Transport Plan (NTP), is prepared in a joint document by the governmental transport agencies (air, sea, road, and railway as the main contributors) based on the guidelines provided by the Ministry of Transport and Communications. However, the NTP preparation is supported by the involvement of other crucial actors, like municipality, business, and industry.

The last planning document (NTP 2018–2029) has recommended important strategic plans in connection with the road transport infrastructure. These recommendations aimed at enhancing the transportation policy in Norway tackling essential areas that require responsive actions (Ministry of Transport and Communications, 2017). Among different areas of interest stated in the document, this thesis focuses on the two existing challenges in the domain of road infrastructure and the outcome of this research inquiry may offer pathways for the decision-makers to reach their objectives.

- Reduction of the emissions from the road construction and maintenance by 40% and 50% by 2030, respectively, and
- Reduction of the delayed maintenance works from the in-service road infrastructure.

METHOD

This chapter explains the approach adopted, as well as the method, model, and software used in the appended papers.

A combination of methods and models was applied to reach the aim of the study. The selections were made based on the findings from the review of prior scientific literature and their relevance to the RQs. Furthermore, different data and software tools were considered for the analysis. The clear majority of data were sourced from Norway to examining the developed methodologies and showcase the findings. Table 1 presents the overview of the taken approaches used in the appended papers.

Table 1: Snapshot of the scope of the four appended papers

Article	Topic	Approach
Book chapter	Life cycle thinking	Scientific literature study
Paper I	LCA of construction machinery	LCA, Monte Carlo simulation
Paper II	Estimation of pavements lifetimes	GIS, survival analysis
Paper III	Dynamic stock and flow modelling	GIS, MFA, survival analysis, decision tree model

3.1 Life cycle assessment

Life cycle assessment (LCA) is a method that analyses and evaluates the environmental impact associated with a product system or an activity in a systematic way throughout a

defined lifecycle (Christiansen *et al.*, 1995; Baumann and Tillman, 2004; ISO, 2006). In principle, the recommended lifecycle is 'from cradle to grave', as it covers the entire lifecycle of a product (i.e., the whole value-chain), consisting of extraction, manufacturing, transportation, use, and disposal activities. The LCA is often performed to compare different product systems within the same functional unit, find critical stages and processes, identify the sensitivity of the system to changes, and document their environmental impact (Robèrt *et al.*, 2002; Baumann and Tillman, 2004).

To carry out any standardized LCA study, it is essential to follow the guidance provided by the ISO standard 14040:2006 (ISO, 2006). Based on this standard, an LCA study needs to cover four critical phases: goal and scope, inventory analysis, life cycle impact assessment, and interpretation, see Fig. 5. This is necessary, as the information accumulates from one phase to the next. However, in actual practice, an LCA does not follow a linear procedure (starting a new phase with the assumption that the current phase does not need any further adjustment or improvement). In fact, the LCA goes through iterations by adjusting or modifying the goal and scope, as well as the inventory analysis.

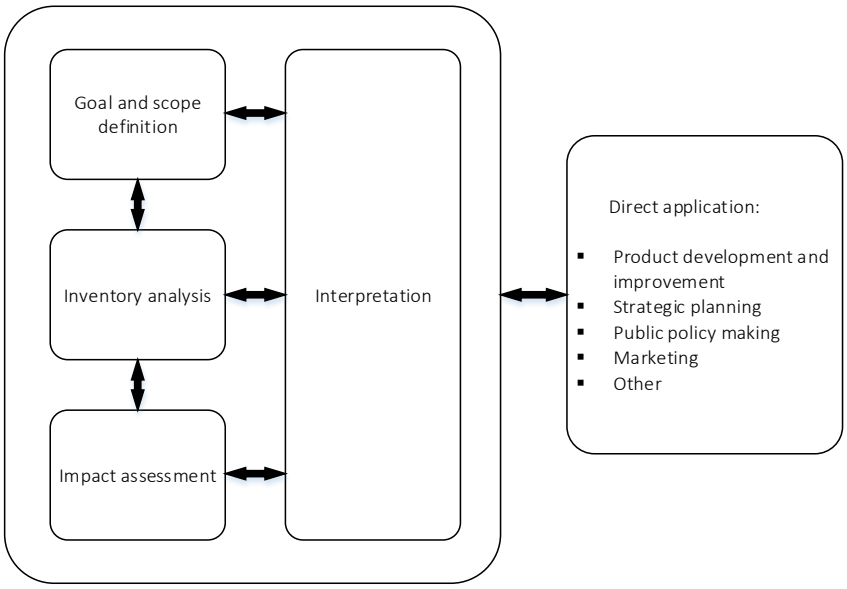

Fig. 5: Four stages of an LCA (ISO, 2006)

- Goal and scope describe the objective, purpose, and relevant choices.
- Inventory analysis identifies the input material, energy, and corresponding emissions.
- Life cycle impact assessment measures the potential impact of the developed inventory in a qualitative way.
- Interpretation explains the results in each stage to increase the transparency and helps make informed decisions.

3.2 Material flow accounting

Material flow accounting (MFA) is an stablished methodology that is based on the law of conservation of mass and aims to quantify the amount of material stock and flow in an abstract system (Kaufman, 2012; Augiseau and Barles, 2017). It studies the balance of flows into and out of a system, defined in space and time, to capture the metabolism of the system. MFA investigations help understand a system and provide valuable inputs to make informed decisions to improve the system, based on set priorities, such as environmental protection and waste management.

MFA is a flexible method and it can be conducted in different ways to answer the RQs. Depending on the resolution of the input data, it can become a bottom-up or top-down approach. It can be static (focusing on a particular time), or dynamic (measuring the change over a time period). It can be retrospective (backward looking) and/or prospective (forward looking). It can also be applied at different levels of spatial resolutions, namely local, regional, national, and global.

3.3 Modelling

3.3.1 Spatial and temporal modelling

The global recognition of Geographic Information Systems (GIS) has grown at a staggering pace, and currently many studies integrate GIS to carry out various investigations, followed by evaluations. This recognition has been accorded owing to GIS's capability to provide decision support in various fields, such as aviation, ecology, economy, and weather applications.

GIS is designed to manage, store, analyze, and visually present the geographical information. GIS allows us to overlay, interpolate semantic layers of geographic data, and carry out complex spatio-temporal analyses through various tools. The obtained results from the GIS analysis are often visualized in maps to graphically illustrate and communicate patterns and trends.

The GIS modeling was applied in two appended papers (i.e., papers II and III) of this work. The application of GIS was not limited to data mining and analyses in the papers. Instead, it was also used to change the architecture of the data, join various types of data, and visualize the obtained results in maps. This approach was necessary as there were many limitations in the data source that needed to be handled to reach the intended outcome. In the GIS analyses primary, vector data was used. However, raster and non-geographic data were also used in some instances to bridge the gaps.

3.3.2 Survival analysis

Survival analysis (also known as time-to-event analysis) is an analytical method in statistics that examines the duration of time until the occurrence of an event. This statistical method

was primarily developed in the medical and biological sciences, and represents the events of interest as 'failures' (e.g. death, relapse, disease, or recovery) and the waiting time as 'survival time' (Kleinbaum and Klein, 2012). However, this method also finds applications in other disciplines, such as engineering, social and economic sciences under different names.

A major advantage of survival analysis as compared to linear regression is its capability to handle censored data. Such cases can occur when there is a lack of information about the survival time of certain observations over the study period. Data can be right censored, left censored, or interval censored. Right censored data occur naturally when the survival time is longer than the observation period, i.e., the true lifetime of a certain observation extends even after the termination of the study. In contrast, left censored data occur when an observation has failed during the study period, but the time origin of the event is unknown, which means that the true survival time is less than or equal to the observed survival time. Interval censoring is a special case, as it incorporates characteristics of the two previous censoring types. It occurs when observation fails within a known interval, but the true survival time is unknown.

Among different types of survival models (i.e., parametric, semiparametric, and non-parametric), this research study used a semiparametric model to capture the longevity of the pavements. Stratified Cox Proportional hazard (PH) model was used for this purpose to measure the effect of different explanatory variables in the estimation (Cox, 1972). Equation 1 shows the risk of failure (hazard) for the Cox PH model at time t for stratum s.

$$h_i(t|Z) = h_{0i}(t)e^{(Z\beta)}, i = \{1,2,\dots,s\} \qquad \text{eq. 1}$$

where h_i is the hazard rate, Z denotes a vector of covariates, h_{0i} denotes baseline hazard stratified over i^{th} stratum, and β denotes vector of coefficient measuring the impacts of covariates.

The PH model was implemented in both papers II and III to measure the longevity of pavements. In paper II, the model was used to estimate the lifetimes and explain the results with respect to certain covariates. In paper III, Weibull distribution was fitted to the results from the Cox PH model to estimate the distributional lifetimes of the pavements.

The density function of a two-parameter Weibull distribution at time t can be written as

$$f(t|a,b) = \frac{a}{b}\left(\frac{t}{a}\right)^{b-1} e^{-(t/a)^b} \qquad \text{eq. 2}$$

where a denotes the scale parameter and b denotes the shape parameter. Both a and b only accept positive values.

3.3.3 Decision tree model

The decision tree can be applied for both classification and regression problems to predict a dependent variable. Decision is made on the hierarchical data by the model to provide a set of decision rules and capture the decision knowledge from the supplied data (De Ville, Neville and Institute, 2013; Barros, Carvalho and Freitas, 2015). This is done by arranging sets from the root node to the leaf nodes (local regions), which results in the creation of a tree structure. Depending on the complexity, there can be a need for different decision nodes in between the root node and the leaf nodes to perform logical judgments by splitting them into attributes with the highest information gain (Shucai, 2012; S.L., D.B. and S., 2014). This results in partitioning a set of features to reduce impurity.

Both classification and regression trees were used in paper III to predict the layered structures for the road foundation. This was done by training and testing the historical data and using the Gini index to measure the purity of partition in a set of features. Equation 3 expresses how the Gini index measures the impurity of a partitioning feature.

$$Gini(D) = 1 - \sum_{i=1}^{m} P_i^2 \qquad \text{eq. 3}$$

where P_i is the probability of partitioning feature D belonging to a class set (from $i = 1, \dots, m$) and the summation is computed over m classes.

3.3.4 Monte Carlo simulation

It is a typical technique used to capture the uncertainty of the results obtained within a physical or mathematical system (Najarian, 2018). The technique consists of variables and probability functions, which select random samples over a certain number of iterations to quantify the numerical uncertainty (Thomopoulos, 2013). The outcome from a Monte Carlo simulation is a random distribution showing the stochastic nature of the problem.

Monte Carlo simulation was used in papers I and III. In paper I, it was used to show the uncertainty of the impact assessment for the entire lifecycle of construction machinery. In paper III, it was used to show the uncertainty of accounted mass in stocks and flows over the studied period.

3.3.5 EEA/EMEP emission model

It is a guidebook developed jointly by the European Environmental Agency (EEA) and the European Monitoring and Evaluation Program (EMEP) (Winther *et al.*, 2017). It contains procedures and information that allow a user to compile emission inventories at various levels of sophistication (European Environment Agency, 2016). Tier 3 emission model, as

developed in the EMEP/EEA guidebook was used in paper I to measure the emissions associated with the machinery.

3.4 Software

3.4.1 GIS software

Both ArcGIS Pro and FME Workbench were used to transform, convert, validate, integrate, manage, and visualize spatio-temporal data (ESRI, 2017; Safe Software, 2017). Both these software have been used at different capacities and for various purposes. Here, FME Workbench was used as the main GIS software in papers II and III to prepare the primary data for post-processing. However, in a few instances, ArcGIS Pro was coupled with the FME Workbench to complement the assessment.

3.4.2 R

R is an open-source programming language and environment and can be deployed on a wide range of operating systems. It is often used to perform statistical computations and create graphical output. The program is equipped with a variety of statistical models and graphical techniques and can carry out data management also to some degree (R Core Team, 2016). This thesis used R version 3.3.2 primarily for statistical purposes. The statistical results presented in papers II and III were calculated by this software. In addition, the graphs presented in papers I and II were created in this environment.

3.4.3 Matlab

It is a commercial software requiring licensed that provides numerous libraries and packages to analyze data, develop algorithms, and create models (MathWork, 2019). In this study Matlab version, R2017b was used partially in paper I and extensively in paper III. Paper I used Matlab language to estimate the effect of the engine deterioration on the emission levels. Whereas, paper III used the language to program stock and flow of road material data processed by means of the GIS software.

3.4.4 Python

Like R, Python is an open-source software used for a different purpose, e.g., software development and research (Python Software Foundation, 2019). It has gained its popularity over the last years due to its fast learning curve, supportive community (eager in troubleshooting), and extensive standard library. This software was used in a small part in paper II for data engineering purpose.

3.4.5 SimaPro

SimaPro is an LCA tool that provides modeling and data management capabilities to assess the environmental impact associated with a system or product over a certain period. It supports various life cycle databases and impact assessment methods to calculate the impacts. It assists in carrying out hotspots and comparative analyses to map important phases

or processes within a system and shows differences among the products or systems to support the decision-making. It is also capable of conducting sensitivity and uncertainty analyses to measure the robustness of the impact assessment results. The LCA results presented in paper I were structured in SimaPro environment version 8.4 (SimaPro, 2017).

3.5 Data source

3.5.1 Ecoinvent database

It is one of the existing LCA databases which has been developed in the last decades. The database covers over 10,000 processes, and is well-established in the LCA-based research (Ecoinvent, 2018). Here, the database was used in paper I as the generic source of the LCA data. It was also used as a template to create inventory processes for the construction machinery.

3.5.2 MEF data

Data from the Norwegian Association of Heavy Equipment Contractors (MEF) database was used in paper I. The database covers a range of historical data for various construction projects since the 1970s and shows the performance of construction machinery operated under the Norwegian conditions (i.e., climate, requirements, and operation conditions).

3.5.3 Machinery specification

Published report and documents were used in paper I to create LCI processes with higher resolution. Volvo Construction Equipment reports (Volvoce, 2018), tire production (Krömer et al., 1999; UNEP, 2011), and service manual (Caterpillar, 2010, 2011, 2012; Johan Deere, 2012) were among the selected information.

3.5.4 NVDB database

Majority of the road-related data in this research were sourced from the NPRA depository. This database covers more than 400 road objects in the Norwegian road network, and is designed for use by both public and private actors. The database is kept updated and it has a fundamental role in supporting the decision-making process in various ways. Here, this database was used for papers II and III.

3.5.5 EPD reports

An EPD is an environmental report audited by a certified environmental party to show the environmental performance of a product system in a transparent and comparable way. This study used the existing EPD reports to fill up the gaps in paper I.

3.6 Flowchart

This subchapter outlines the linkages between the conducted research papers and the applied models, data, and executing software. Here, the illustrated flowcharts are in connection with

the quantitative papers (papers I, II, and III) and show the general steps taken to reach the research goals.

3.6.1 Paper I

The research method followed the ISO 14040 guideline (ISO, 2006) to assess the environmental impacts over the machinery lifetimes, i.e., cradle-to-grave. It used the SimaPro software and the CML impact assessment method for the impact assessment, and it used the software to conduct additional analyses, like path analysis and Monte Carlo simulation, see Fig. 6. In doing so, two channels of inputs were considered for modeling in the software. For the operation phase of the machinery, the MEF data were coupled with the EMEP/EEA emission model and modeled in MATLAB. However, for the remaining phases, the Ecoinvent database (Allocation at the point of Substitution) was used as the foundation for the LCI processes and the supplementary data were added to enhance the representativeness of the processes. Besides, the study went through a series of iterations to improve the quality of the conducted research.

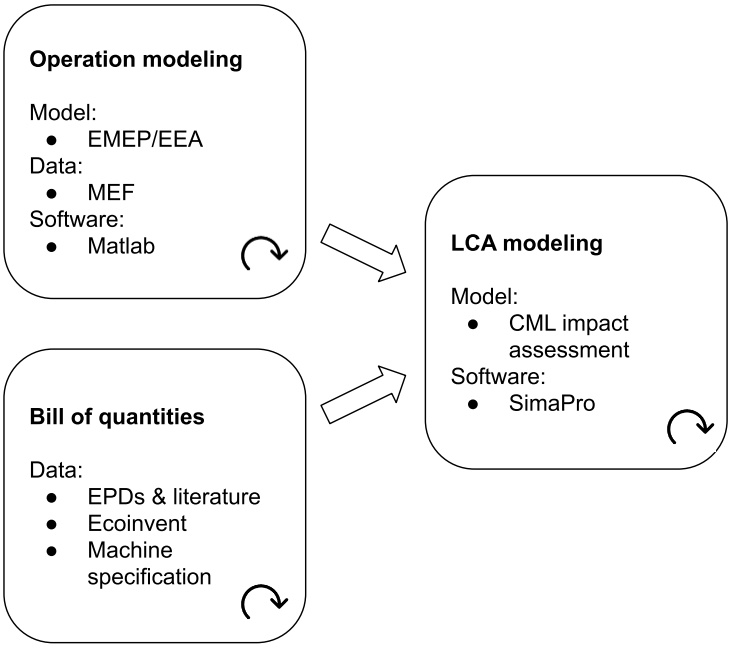

Fig. 6: Generic workflow in Paper I

3.6.2 Paper II

To reach the intended research goal, the study used primary datasets from the NVDB database and performed a series of data engineering in two commercial GIS software (FME and ArcGIS) and Python, see Fig. 7. After preparing the data, happened after rounds of corrections, the secondary data were used for statistical analysis. Cox PH model was used as the chosen statistical model to assess the longevity of pavements, and R was the supporting software for the modeling and plotting purpose.

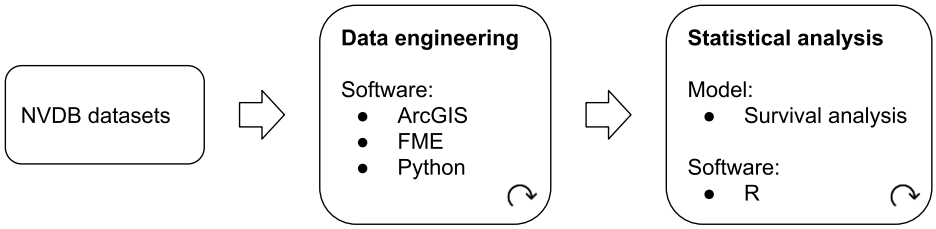

Fig. 7: Generic workflow in Paper II

3.6.3 Paper III

Paper III followed the MFA methodology to assess the past, present, and future of road material stocks and flows. Based on the experience gained from the engineering of the data in Paper II, this paper performed data engineering in a larger scale focusing on the entire road networks, see Fig. 8. The outcomes from the data engineering (developed in FME) were used for the modeling. Three main models and a scenario were used in the post-processing stage, and R and Matlab were software for the modelling. Later, the outcomes from the modeling were used to estimate and predict the material stocks and flows.

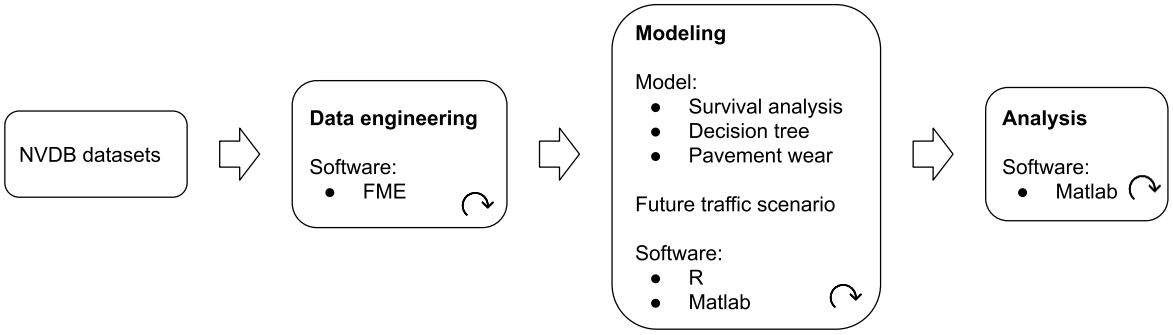

Fig. 8: Generic workflow in Paper III

Similar to the two successor papers, this study also went trough a round of iteration to enhance the quality of the work and remove bugs from the written computer codes.

RESULTS

This section explains the summary of findings in the appended papers and follows the same order as the appended papers.

4.1 Life cycle thinking

A holistic understanding of a system assists in better planning and evaluation. Paper I delivered an overarching explanation for the concept of life cycle thinking (LCT) from a managerial viewpoint. The paper took a holistic approach and tried to be as generic as possible regarding the subject matter. In other words, the work carried out in paper I strove to not limit itself to the road infrastructure only, but instead provide a general explanation based on the findings.

The work touched upon general challenges and opportunities alongside the global and local infrastructure. It explained that although these challenges have been around for generations, our effort in addressing them has been insignificant compared to the rise of difficulties. Anthropogenic greenhouse gas emissions, land use and coverage change, abiotic depletion, and constant waste generation were used as some of the examples of such multi-dimensional challenges that have been handled improperly over time.

Nevertheless, it considered that answering these pressing challenges would present us opportunities to strengthen our development; however, this would be possible only if a systematic approach were taken, which is essential to ensure that our answers to these challenges encompass all the aspects of sustainability. This is because answering one challenge is not attainable without understanding the others. In addition, the boundary of the

system should not be narrowly defined, as it may prevent us from capturing the whole picture and result in problem shifting.

The LCT approach that considers the entire life cycle of a system and covers all the connected processes and flows, helps us gain a deeper knowledge of the system. It also helps us identify the weaknesses of the system by picking out the bottlenecks and the hotspots. In addition, it shows the resilience and sensitivity of the system to changes over the entire lifecycle of the system. Thus, it helps the decision-makers take informed decisions.

In addition to the above, some of the current challenges occurring in different phases of the infrastructure were explained. These challenges include (1) gaps between the actors during the infrastructure projects (from the initiation phase till the operation and maintenance phase), (2) improperly defined periods of assessment during the evaluation of the infrastructure projects in the early-planning phase, (3) paying inadequate attention to the maintenance planning of the in-service infrastructure that results in a massive backlogs and budget shortages, and finally, (4) not addressing the end-of-life phase of the infrastructure. This study recommended initiatives that assist in improving the identified challenges, such as (1) inclusion of public and private expertise from the beginning of the infrastructure projects, (2) increasing the inclusiveness of the contract to make contractors accountable beyond the design and construction of infrastructure, (3) feedback looping the lessons learned from the infrastructure projects, (4) increasing the natural resource efficiency by reusing and recycling the materials at the end of their cycles, (5) using interdisciplinary and transdisciplinary approaches in an open-dialogue setting to answer multi-dimensional challenges without causing rebound effects, and (6) transferring validated scientific approaches to practice to enhance the sustainability performance of infrastructure projects.

4.2 LCA of construction machinery

The aim of this study (paper I) was to introduce a new approach to carry out a regionalized LCA to estimate the potential impacts associated with the construction machinery. This was done with the help of generic data and statistical figures to estimate the impact from ‘cradle-to-grave’ of the machinery. A small group of construction machinery was considered which were operated under the Norwegian conditions, see Table 2. In this investigation, it was considered that the functional unit was one construction machine operated over its entire lifetime, i.e., from ‘cradle to grave’, see Fig. 9. However, the lifetime was measured by the number of effective hours to harmonize variability of carried out tasks by different machines. In addition, the studied machinery was equipped with diesel-powered engines, certified by the European emission standard Stage V, and they had power output ranging between 75-560 kW.

Table 2: Summary of studied construction machinery

Machine type	Engine net power (kW)	Operating weight (ton)	Economic lifetime (EH)	No. of tires	Lifetime of tire	Fuel efficiency (l/EH)	Abbreviation of machine
Articulated hauler	220	20	9000	6	1700	30	AH20
	330	30	11000	6	1900	42	AH30
Crawler excavator	75	16	10000	-	-	16	CE16
	120	22	10500	-	-	22	CE22
	120	23	10600	-	-	24	CE23
	150	31	11600	-	-	31	CE31
	260	48	12000	-	-	51	CE48
Grade	160	20	9300	6	780	25	G20
Wheel excavator	87	14	9500	8	1300[a]	15	WE14
	110	20	10000	8	1500[a]	20	WE20
Wheel loader	140	16	8300	4	1650	23	WL16
	180	21	8400	4	1700	30	WL21
	200	23	9200	4	1800	36	WL23
	260	30	9800	4	2075	46	WL30

[a] Assumptions

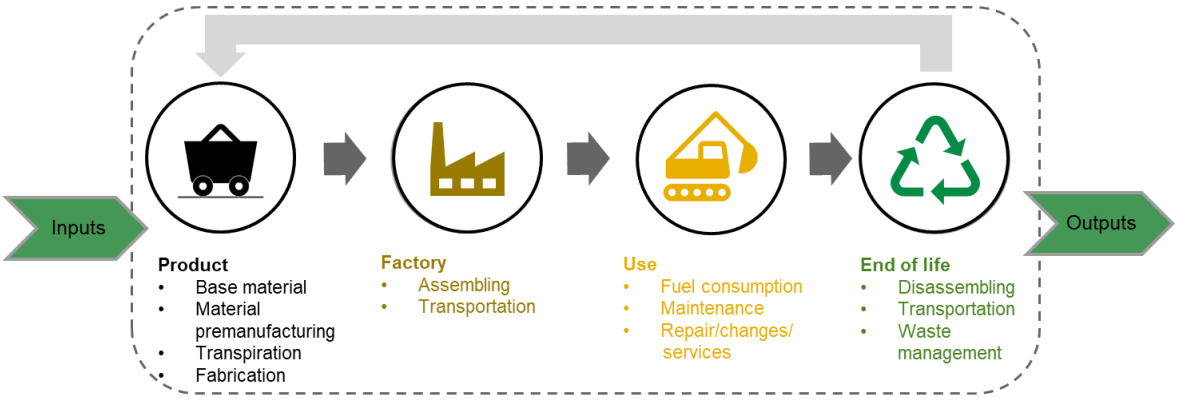

Fig. 9: Life cycle of construction machinery in a schematic form

SimaPro environment (version 8.4) was used for the LCA modeling, and Ecoinvent database (version 3.3) was used as the source for the generic LCI data. In addition, some of the processes in Ecoinvent were used as templates to create regionalized processes representing the studied construction machinery. The selected processes for this purpose were related to manufacturing, maintenance, and end-of-life of lorries. However, supplementary information and processes were used and created to modify the selected processes, and make them representative, respectively.

In addition, tailpipe emissions from the operation of the machinery were estimated. In doing so, the Tier 3 model introduced by the European Monitoring and Evaluation Program (EMEP) and the European Environmental Agency (EEA) was employed. In this model, the following emissions were accounted for: black carbon, methane, carbon monoxide, ammonia, dinitrogen oxide, nitrogen oxides, particulate matter, and volatile organic compounds. However, the emission of carbon dioxide and sulfur dioxide was calculated based on the CO_2 intensity and the sulfur content of the fuel.

To create a more realistic picture of the tailpipe emissions over the economic lifetime of the machinery, a simplified approach was used to estimate the effect of the engine deterioration. This was done to show the effect of the ageing of the vehicles on the intensity of the tailpipe emissions. Here, it was assumed that the engine deterioration followed the logistic distribution model and it caused an increase in the fuel consumption and emission of some pollutants, namely methane, carbon monoxide, carbon dioxide, nitrogen oxides, particulate matter (PM), volatile organic compounds (VOC), and sulfur dioxide.

Based on the assumed model, three deterioration scenarios were considered to assess the increase in the tailpipe emissions over the economic lifetimes of the machinery. Fig. 10 depicts how the rate of deterioration would be at a certain point in time. Here, we used 'retardation' to show the time that the rate changed and the term retardation depicts the midpoint in the sigmoid function. For the baseline scenario, we considered a 50 % retardation happening exactly in the mid-economic lifetime of a machine. However, 30 % and 70 % retardations were used for the sensitivity part of the assessment.

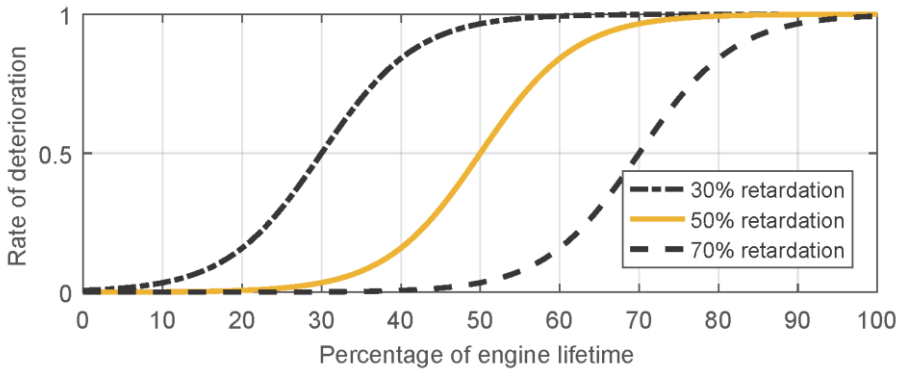

Fig. 10: Assumed engine deterioration model for the construction machinery

The life cycle impact assessment in this study was based on the CML method v4.2 (Pre' 2018) and the following impact categories were assessed: abiotic depletion (AD, kg Sb eq.), fossil-fuel-based abiotic depletion (ADP, MJ), acidification (AP, kg SO_2 eq.), eutrophication (EP, kg PO_4^{-3} eq.), fresh water aquatic eco-toxicity (FE, kg 1.4-DB eq.), global warming (GWP, kg CO_2 eq.), human toxicity (HT, kg 1.4-DB eq.), marine aquatic eco-toxicity (ME,

kg 1.4-DB eq.), ozone layer depletion (ODP, kg CFC-11 eq.), photochemical oxidation (PO, kg C_2H_4 eq.), and terrestrial eco-toxicity (TE, kg 1.4-DB eq.).

From the results obtained by applying the described approach (see Fig. 11), it was observed that the machines, which were equipped with a higher-powered engine and had a heavier operational weight, had relatively higher potential environmental impact. The higher relative emissions for heavier machinery could be explained by their longer lifetime and higher fuel consumption rate. Furthermore, the operational phase of the construction machinery once again proved to be the phase with the dominant contributions in nearly all the impact categories. Although the tailpipe emission gases from the consumption of the diesel fuel showed to be more relevant in the categories of global warming potential and photochemical oxidation, the production and delivery of the diesel fuel also appeared to be significant in nearly all the impact categories. The impact from the production and delivery of the base materials, used in the manufacturing and maintenance of the machinery, appeared to be the second most important contributor after the operational phase.

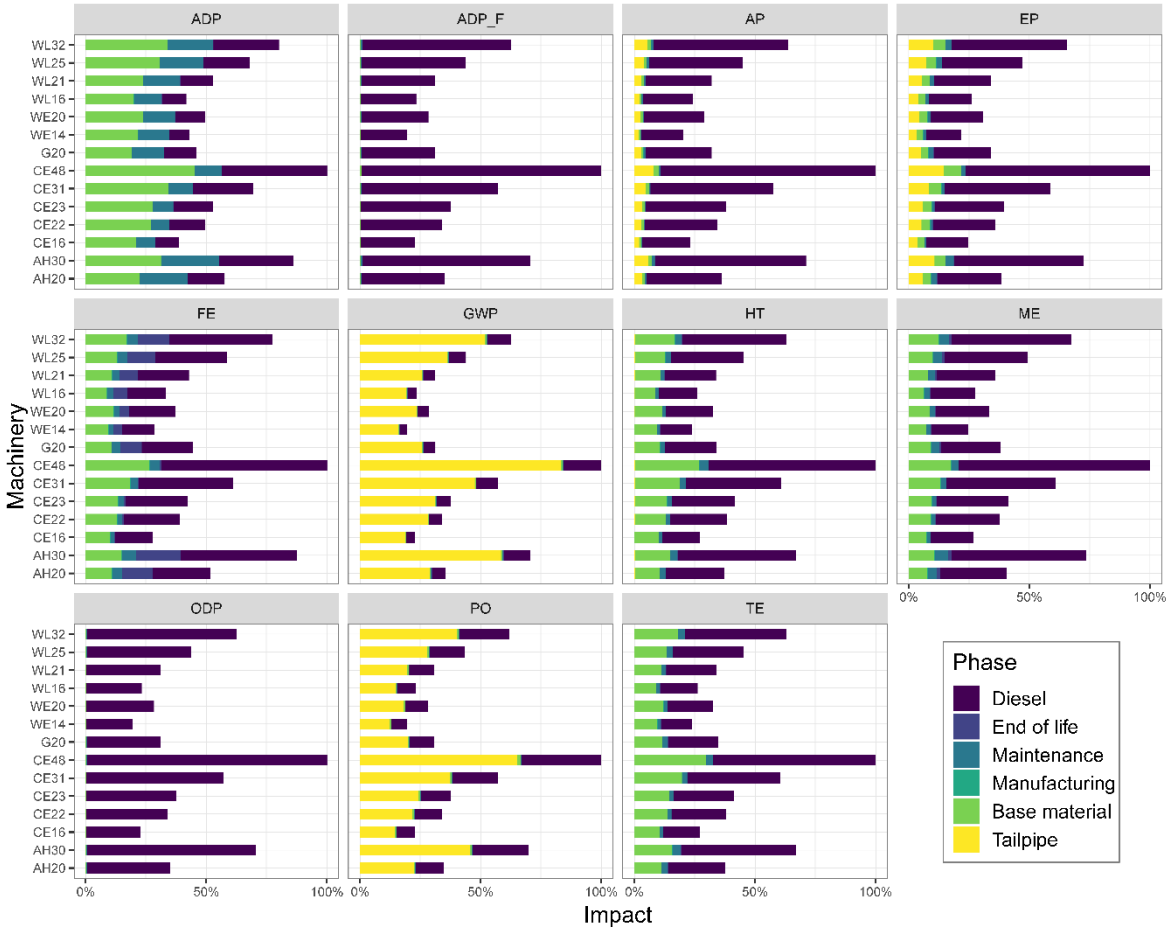

Fig. 11: Normalized impact assessment of results

The end-of-life phase covered the dismantling and the waste processing of the machinery parts generated during the maintenance and the end-of-life of machinery. Up-cycling was

considered for certain products after the dismantling, whereas waste tires were down-cycled. This was done by assuming that all tires were incinerated as a fuel source to produce cement. Because of this assumption, the end-of-life phase appeared to contribute considerably to the fresh water aquatic eco-toxicity impact category. Furthermore, a sensitivity analysis of the studied system showed that the response rate was significant for the diesel consumption. This means that by 1 unit increase in the diesel consumption the total impact increased by an equal amount for certain impact categories. However, the system was resilient to changes in the other inputs.

4.3 Estimation of pavements lifetimes

To ensure that the results of any life cycle studies are not compromised with wrong inputs, it is essential to have unbiased and reliable information. Paper II introduced a potential approach to estimate the longevity of different asphalt pavements. The work incorporated the spatio-temporal analyses for Norway to transform the data and make it amenable for the survival analysis. Later, the Cox Proportional Hazard (PH) model was applied to assess the longevity of the homogeneous road segments, with rutting as the response variable.

To resolve the issue arising out of the linear prediction model, this study carried out a series of actions to estimate the lifetimes of asphalt surfacing in Norway. While doing so, the study obtained historical road data from various platforms and coupled them with a GIS to ease the process of transformation of data. The transformation was done to manage the data by restructuring, merging, analyzing, and visualizing. For this purpose, two GIS platforms were used in tandem to create the methods for the transformation, namely ArcGIS and FME Workbench (ESRI, 2017; Safe Software, 2017).

The study limited its boundary of investigation to three areas in Norway that had significantly different outdoor climates. Vest-Agder from the south, Sør-Trøndelag from the middle, and Troms from the North of Norway were chosen (see Fig. 12). In addition, only the data related to the registered asphalt surfacing, location of the bridges and tunnels, road referencing, signed speed limit, bearing-capacity class, AADT, road width, and rut measurement were fetched from the databases that had registration records between the years 2000 (2000.01.01) and 2017 (2016.12.31). Furthermore, this study only focused on roads that had registered annual average daily traffic between 1500 and 20000 vehicles.

The outputs from the GIS analyses represented homogeneous segments that had consistent characteristics with respect to the surfacing mixture type, surfacing record, traffic volume (both total and heavy traffic volume), speed limit, bearing-capacity class, aggregate nominal maximum size, climate zone, asphalt content usage, and traveled-way width. In addition, the length of each homogenous segment was chosen to be equal to or greater than 50 meters, and the difference between the median and the maximum value in each homogenous segment

needed to be less than or equal to 20 %. Fig. 12 illustrates the length of the paved roads that were considered for the statistical assessments.

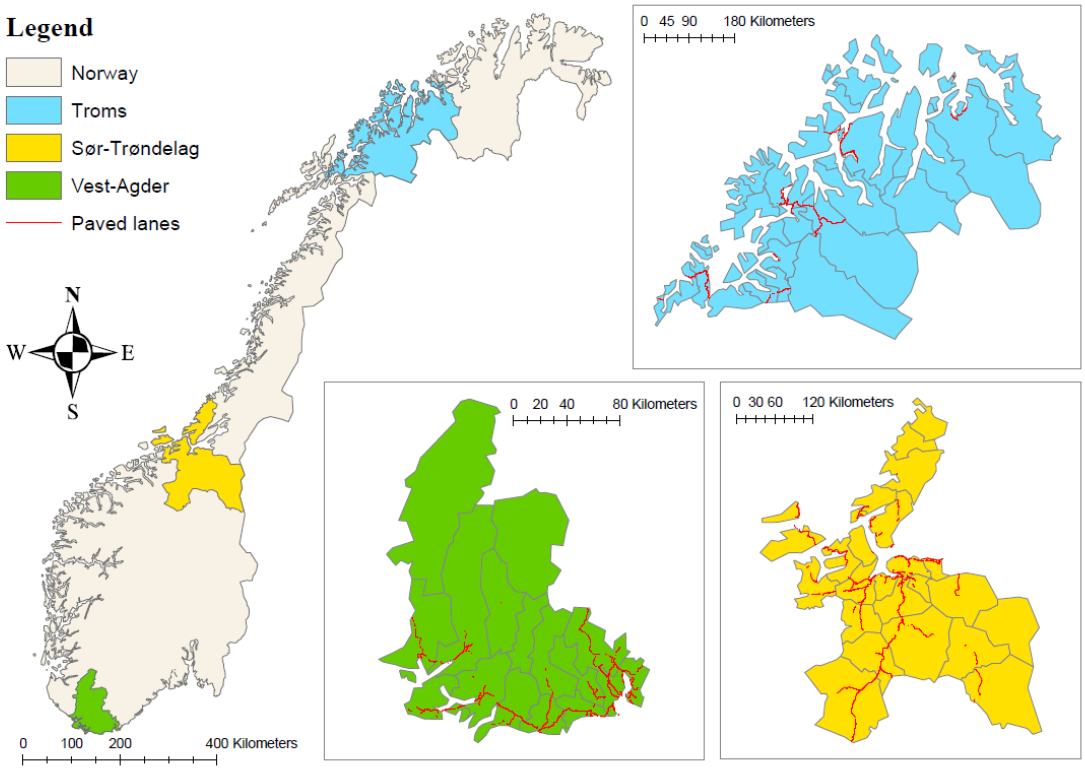

Fig. 12: Roads and areas of coverage

Transverse unevenness, i.e., rutting, was added to the assessment as a response variable to monitor the condition of surface for each segment. It is possible that sometimes the maintenance activities were forgotten to be registered or were registered but no maintenance activity was conducted. Hence, a nested *if*–clause was implemented to consider whether a homogenous segment was paved or a segment passed the maximum allowed threshold required by the state. Inclusion of rutting also helped to overcome the limitations in the Cox PH models in handling the left- and interval-censored data. Besides, this response variable measured the technical lifetimes of the pavements and compared them with the maintenance records.

The results from the Cox PH model discussed the findings for each explanatory variable based on the results in the survival tables. However, among the six explanatory variables, aggregate nominal maximum size and heavy traffic-loading had significant hazard ratios in all the traffic classes. This means that an increase in the aggregate nominal maximum size extended the lifetimes while an increase in the heavy traffic-loading shortened the lifetimes. The study used traveled-road width to explain some of the behaviors in the results of the signed speed limit and the climate zone, and it showed how the width of the road influenced

the longevity of the surfacing. In addition, this paper showed to what extent the actual lifetimes of asphalt surfacing differed from the nominal lifetimes in the Norwegian context. This was done to show a practical way to interpret the relative values from the survival table. In doing so, the reference categories were fitted to the survival curves in each traffic class to find the absolute lifetimes of the asphalt surfacing.

4.4 Material stocks and flows modelling

The issues of availability and optimal use of natural resources have always been challenges, which require systematic thinking and approach to comprehend and respond in a sustainable manner. Paper III aimed at performing dynamic modeling to understand the scale and composition for the past, present, and future stock and flow of road materials. The method used for this research was based on the bottom-up principle by compiling the annual sink and flow of road materials from different road sections in the networks to calculate the accumulation and streams. The conceptual framework of this research is illustrated in Fig. 13.

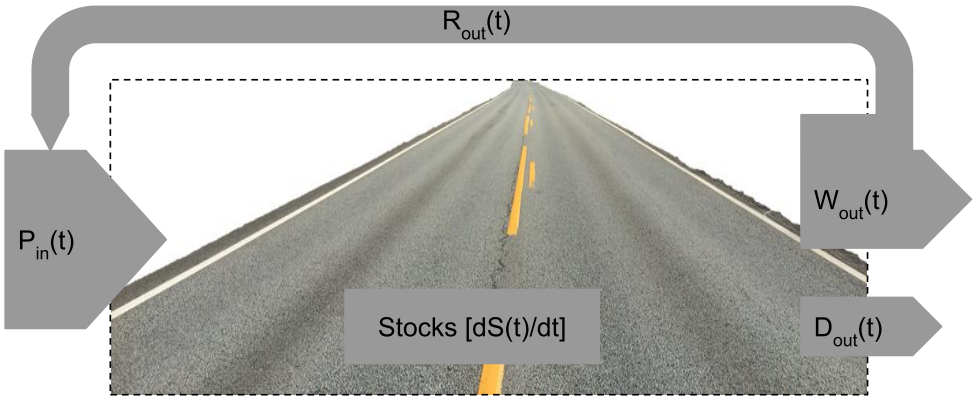

Fig. 13: Conceptual view of the MFA of road infrastructure

$P_{in}(t)$ is the input road materials like aggregates and bitumen.
$W_{out}(t)$ is the road waste materials during the maintenance and rehabilitation activities, or decommissioning.
$D_{out}(t)$ is the dissipative road materials (due to abrasion, aging, and loading).
$R_{out}(t)$ is the recycled or reused road materials.

This study was a GIS-based MFA analysis. It used data from the Norwegian public road infrastructure to model the number of stocks and flows during the time between 1980 and 2050. Among different categories of roads, only European-, national-, and county-level roads were considered. These three categories covered about 55% of the entire public road networks and accounted for about 6% of the total built-up area in the whole of Norway (Statistics Norway, 2019c). Fig. 14 illustrates the share of the network with respect to seven traffic classes in Norway.

The core of the dynamic model used in this research was divided into two parts. In the first part of the accounting, the study carried out the input-driven MFA to calculate the number

of stocks. This was done by means of historical records (i.e., paving history and pavement structure) to capture the metabolism of materials over the analysis period from 1980 to 2017. In the second part, however, the study became stock-driven MFA. In the stock driven accounting, it was assumed that the total amount of stock would stay constant after the year 2017, but the system would be maintained as is.

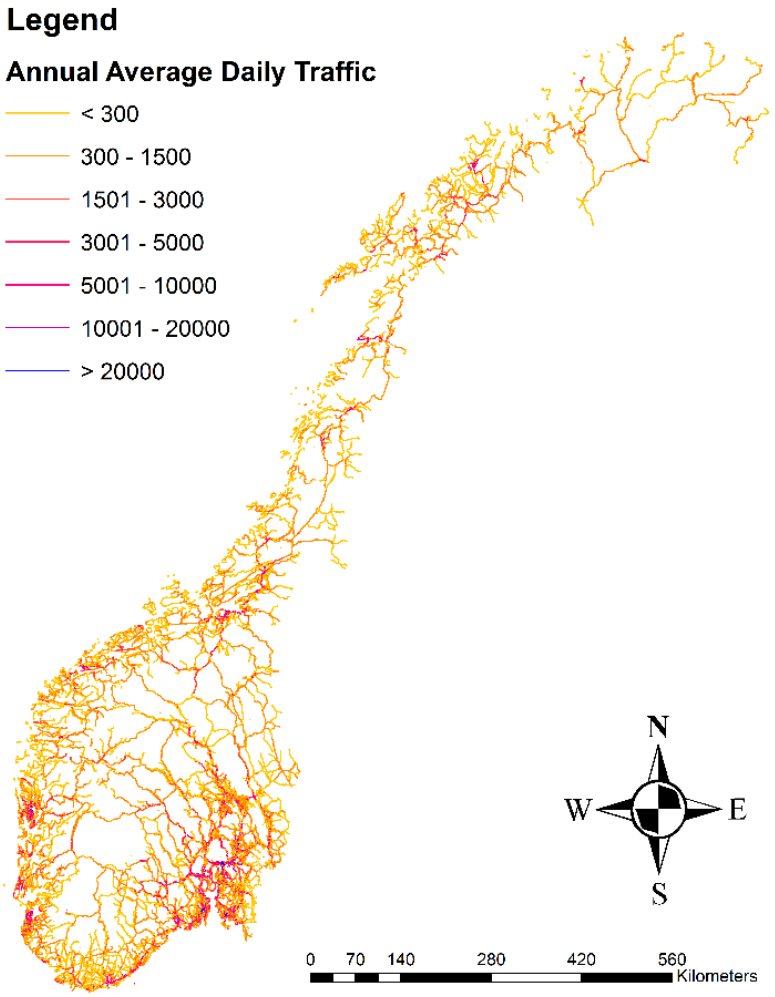

Fig. 14: Distribution of the road traffic in Norway, based on records in 2017

Even though the used data in the first part of the model had a very good coverage, there was still one chunk of data missing that needed to be covered in some way. The missing part was found in the inexistence of the foundation information for more than 70% of the roads. To overcome this challenge, like in paper II, GIS-based statistics was used to manage the missing data for post-processing. Here, GIS was used to attribute the characteristics of roads for sections with and without information about the road foundations, see Fig. 15. The attributed information to the road section was based on independent variables, like registered speed limit, traffic volume class, subgrade type, and road category type, to explain the

characteristics of each road foundation. After creating the attribute tables in the GIS environment, the post-processing work was conducted to estimate the missing information about the layer structure of road sections. Classified and regression decision-tree were used to train, validate, and estimate for the first four layers from the subgrade.

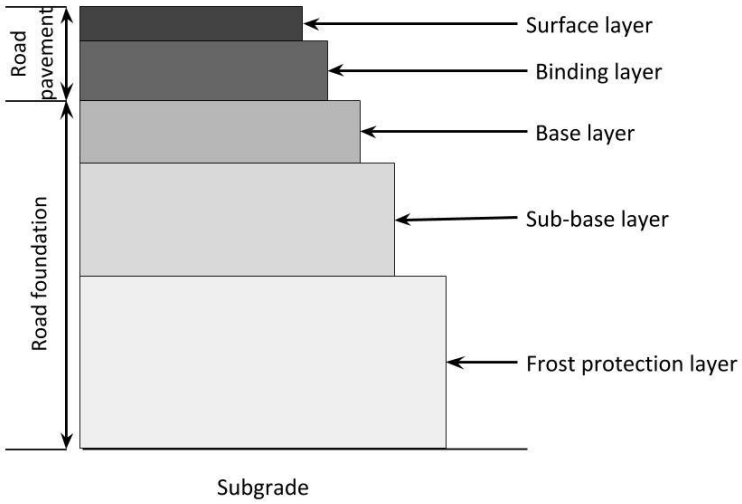

Fig. 15: Common layered structure for a road infrastructure, adapted from a published report (NPRA, 2014)

In the stock-driven part of this research, it was assumed that the road networks would not expand or shrink after 2017. Instead, the network would be kept maintained at a certain rate and interval. The approach introduced in paper II was used in this regard to understand the maintenance practice for different roads in Norway and show the distributional lifetimes. Despite considering the effect of different explanatory variables, the data were stratified by their traffic classes and then fitted to two-parametric Weibull distributions. Later, the identified distributional lifetimes for the seven traffic classes were applied to the roads that had been in service from the year 1980.

Although the identified distributional lifetimes were applied to the in-service roads to predict the intensity of the upcoming interventions, it was only able to cover the initial interventions. However, after the initial intervention follow-up interventions need to be applied to keep the roads in service. Hence, follow-up interventions, namely secondary, tertiary, quaternary, etc. were applied for this purpose.

The prediction of maintenance activities was continued until 2050. However, three scenarios were considered to reach the coming mid-century in 2050. In the considered scenarios, it was assumed that the changes in the traffic volume would result in changes in the share of roads staying in their traffic class since they were paved. In doing so, each paved section was followed, with respect to its traffic class, until the year that the area underneath the probability density function became greater than 99%, see Fig. 17.

- Scenario 1: Traffic will stay constant after 2017
- Scenario 2: Traffic will grow after 2017 by 1%
- Scenario 3: Traffic will grow by 2% after 2017

In addition, in the stock-driven assessment, the dissipation of road materials from the infrastructure was considered. The dissipative flows from the system were related to the pavement wear due to the tire-pavement interaction. Here, a simple model was implemented to explain the rate of outflows with respect to the changes in the share of tire types in different seasons and years. Since 1970, regulatory setups tightened the period of studded tire usage during the winter season which resulted in a shift in the market for the non-studded tires (Snilsberg, 2008). To capture how the shift in the share of the two tire types during the winter season might appear, an extrapolation was done based on a few observations in Norway. Fig. 16 is based on the extrapolation of observations between 2001 and 2018 showing the shifts of studded and non-studded tires during the winter seasons over time, and it was assumed that all winter tires used before 1950 were studded tires.

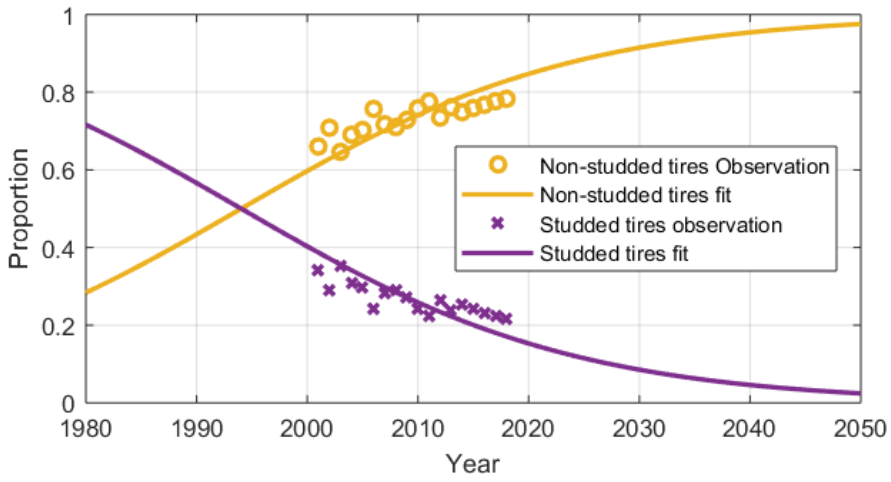

Fig. 16: Share of vehicles with respect to their tire types during the winter season

In addition to the changes in the regulations to limit the period of usage for studded tire, the pavement technology has also improved, and the roads has become more resistant to wear caused by the studded tires. Table 3 is a generic table that shows the improvement in the resistance to wear in different cohorts, see Fig. 18–21.

Table 3: Wear amount of surface caused by passenger vehicles equipped with studded tires

Period	Wear (g/km)
1980 – 1989	15 – 20
1990 – 1999	10 – 15
2000 – 2050	5 – 10

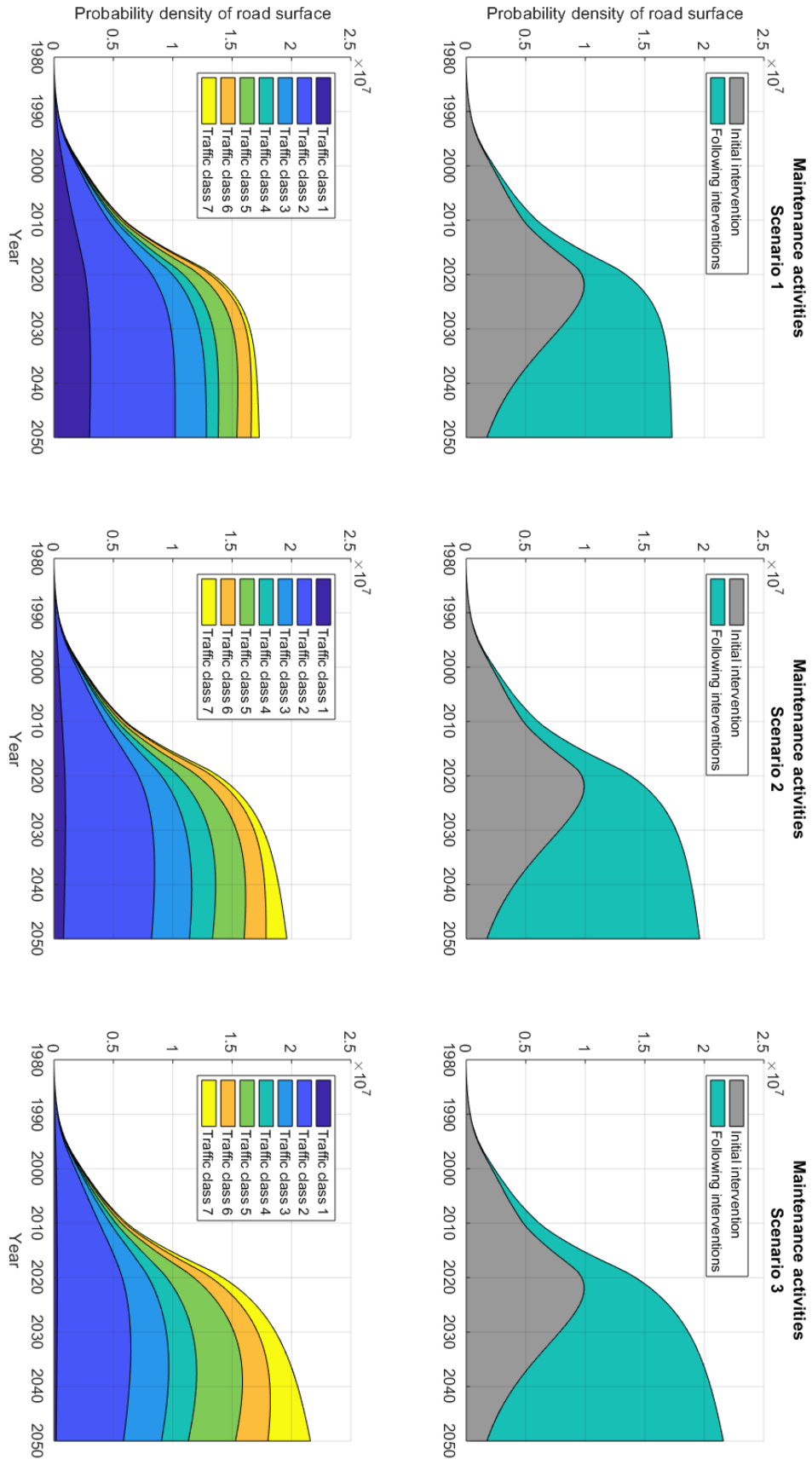

Fig. 17: Stacked probability density function estimating the intensity of maintenance works

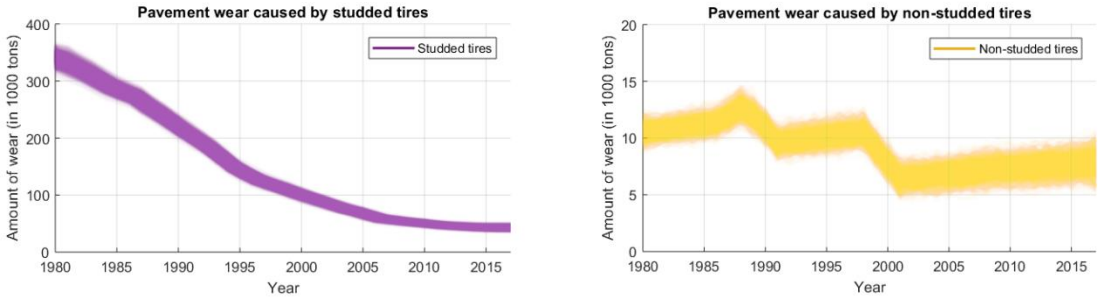

Fig. 18: Amount of pavement wear between 1980 and 2017

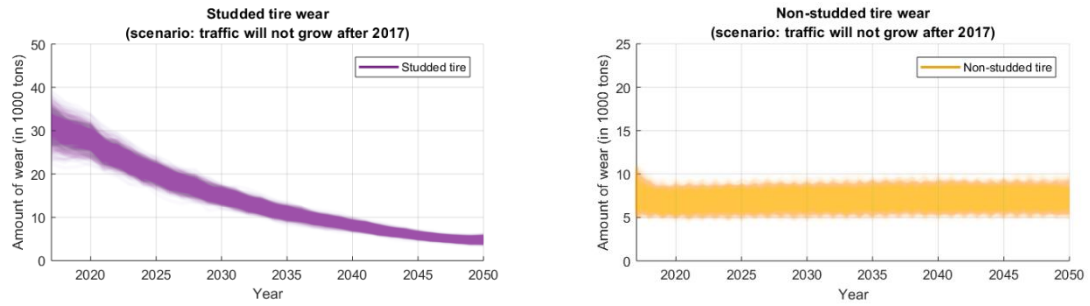

Fig. 19: Amount of pavement wear between 2018 and 2050 based on Scenario 1

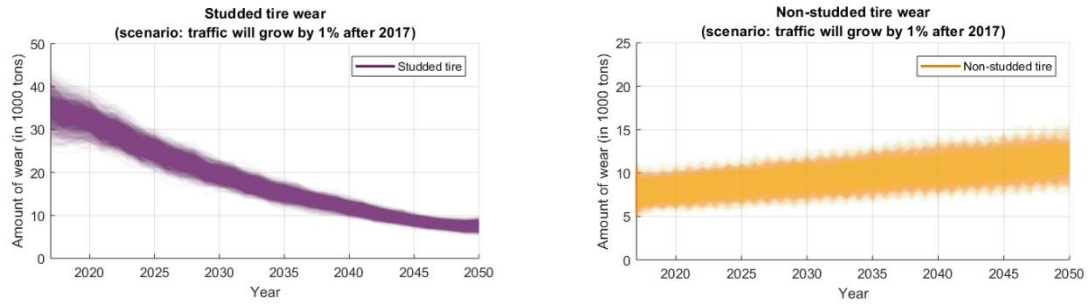

Fig. 20: Amount of pavement wear between 2018 and 2050 based on Scenario 2

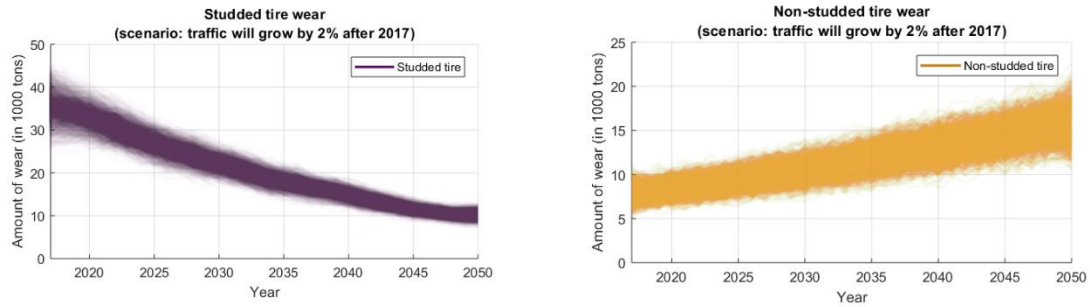

Fig. 21: Amount of pavement wear between 2018 and 2050 based on Scenario 3

The findings from the described approach in this paper were divided into two segments: retrospective and prospective results. The retrospective results, shown in Fig. 22, covered the studied system from 1980 till 2017 and were based on three scenarios. Furthermore, the presented results were formed on the following variables: (1) the road structure, (2) historical maintenance activities, (3) predictive maintenance activities, and (4) dissipative flow. The figure also shows the uncertainties of the results for each year by means of vertical error bars incorporating 10 and 90 percentiles of the random calculation.

The prospective results, on the other hand, covered the assessment from 2018 till 2050. Since the coverage of the registered historical data was limited to 2017, the obtained results from the prospective assessment were purely based on predictions. Here, the results from the assessment based on the three scenarios are presented in Fig. 23. The selected variables to carry out the prediction were: (1) predictive maintenance activities, and (2) dissipative flow. Like the retrospective analysis, the vertical error bars were used to show the uncertainties based on the random variations.

4.5 Uncertainty of findings

Uncertainty assessment of the appended papers needed to be investigated to assess the accuracy of the results. The book chapter which was a qualitative research based on the literature findings was not assessed. However, the assessment was done on the quantitative papers I, II, and III to show the reliability of the findings.

The pedigree approach was used in paper I to measure the uncertainty of the input values in each created LCI process. This was done by assigning uncertainties of input and output flows within the studied system, based on a calculation made by the pedigree matrix to quantify the quality of information. By identifying the uncertainties for each flow, the study carried out a Monte Carlo simulation to capture the variability of LCI results.

Different approaches were taken to capture the uncertainties in paper II. In the initial part of the work, the measured rut depth in each segment of the road was used to check the validity of the recorded maintenance activities. This was done by comparing the pattern or rut with the registered date of maintenance activities and reassigning new dates for segments that were wrongly registered or forgotten to be reported for maintenance works.

In the statistical modeling part of paper II, significant testing was done on the obtained results to show the likelihood of the estimate to reject the null hypothesis. Insignificant covariates and categories should have been removed from the tables to get only the significant results from the model. However, it was the intention of the paper to consider the same structure and assessment scheme in all the AADT classes. Even though some of the p- values were above 5% and were unable to reject the null hypotheses, the shown hazard ratios in the tables

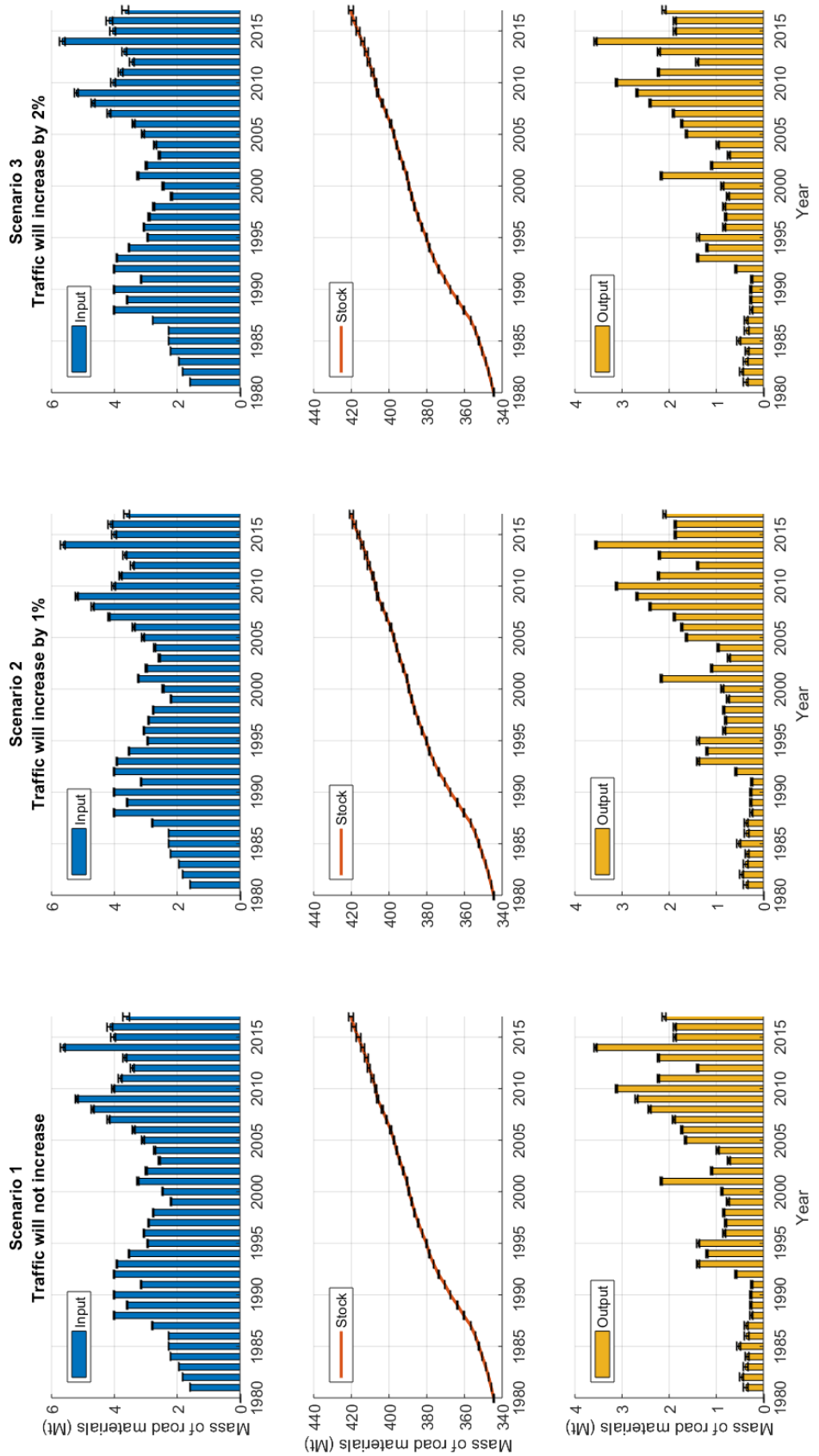

Fig. 22: Retrospective analysis to project the evolution of material flows and stocks between 1980 and 2017

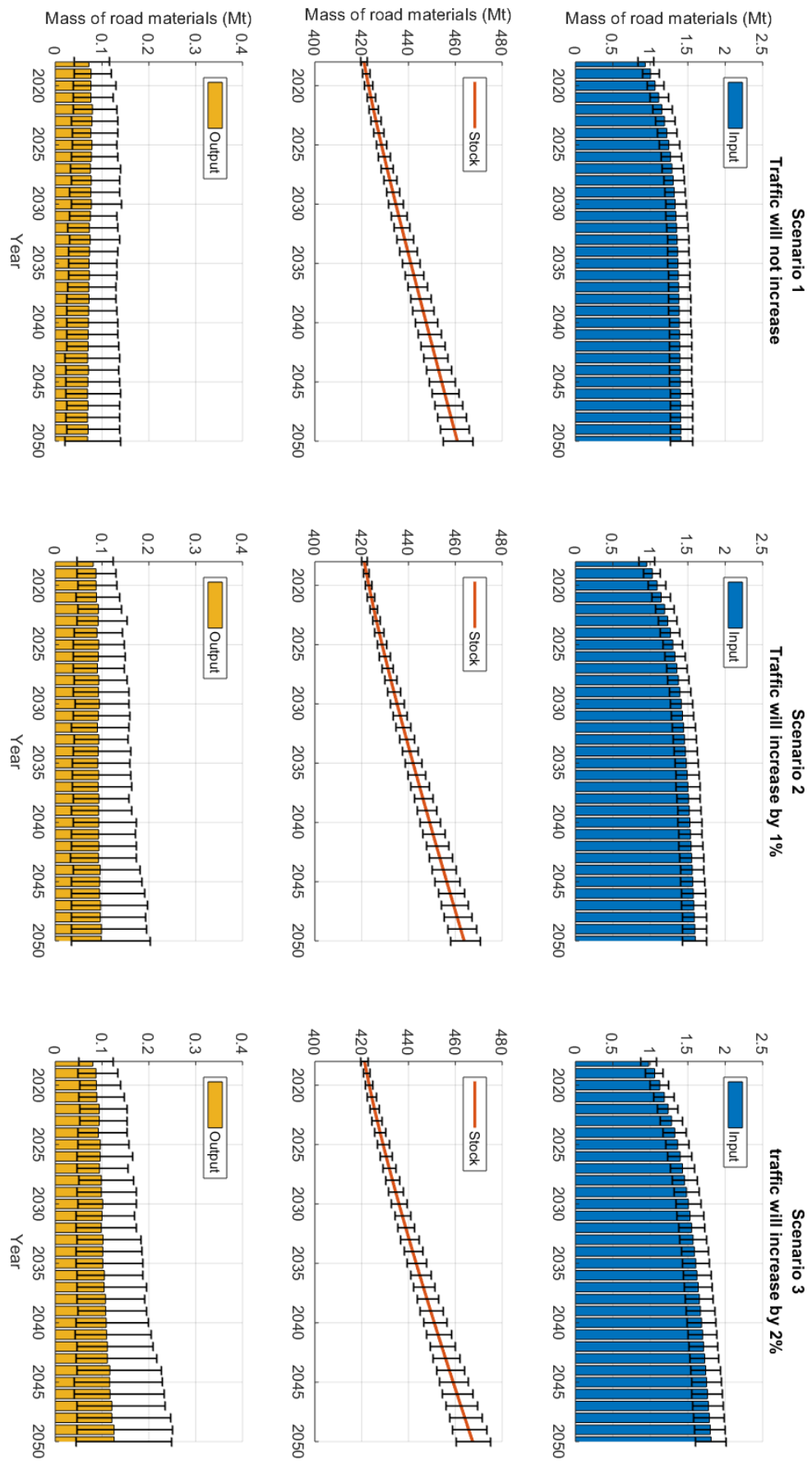

Fig. 23: Prospective analysis to project the evolution of stocks and flows between 2018 and 2050

were aligned with the findings from the prior studies. In addition to significant testing, the standard error was also used to show the precision of the observation mean from the population mean and it was used to drive the confidence interval. In addition, the validity of the results from the fitted results was compared with the Norwegian data to show the accuracy of estimation.

Uncertainty assessment was done on both parts of paper III. In the input-driven part, the assessment was conducted for the decision tree learner. To predict the thickness of each layer, the training and testing were iterated for 100 rounds, and in each round of training only 50% of data were used. In the stock-driven part, the distributional lifetimes were used to predict the longevity of roads in different classes. The identified distributions were later used to quantify the square km of the road surface in each traffic class that would require to be in maintenance for different years. Furthermore, a logistic distribution was used to extrapolate the pattern of a shift in the use of winter tires in Norway between 1980 and 2050. Besides, uniform distribution and lognormal distribution was used to take random values for different variables. The uniform distribution was used to take the random values showing the intensity of pavement wear due to winter tires in different cohorts, and the density of road materials was used in the roads. On the other hand, a lognormal distribution was used to take the random values for the thickness and portion of the road surface required to be milled and paved.

DISCUSSION

The aim of this research study was to study the lifecycle of road infrastructure in Norway. In addition, it investigated into areas with high significance that may help Norwegians gain a deeper understanding about their road infrastructure and strengthen its sustainability. This section elaborates on the relation of the research approach to the RQs and explains the findings.

5.1 Research question 1

What is the life cycle thinking for public-owned physical infrastructure and how they should be managed?

The purpose of RQ 1 was to understand the state-of-the-art life cycle thinking and management for certain types of infrastructure within the research community and show how science can contribute to practical management of the infrastructure. In doing so, the book chapter was used to answer the research question, and it hence took a generic approach to avoid narrowly defined answers. In this subsection, the findings from the paper are, however, adapted to road infrastructure to keep the discussion connected with the overall theme of the thesis.

The conservative business practice between the partners in some projects has created an isolated environment that often stops them from having a fruitful collaboration. Even though creating the pooled experience where partners collaborate and share their risks and

uncertainties shown to be an effective way of collaboration, project-based collaborations in the construction sector have shown to be sometimes weak in exchanging knowledge and experiences (Lingegård and Lindahl, 2015). There have been a number of examples in the research highlighting the issues between the partners that disturbed the collaboration (e.g., competitive business relationship between the project partners, conflictual events (tension) that distance partners, and the lack of interpersonal trust), and might eventually stop the project from reaching its goal (Paul and McDaniel, 2004; Vaaland, 2004; San Martín-Rodríguez *et al.*, 2005; Dietrich *et al.*, 2010). Creating a successful collaboration between the involving actors can improve the success of an infrastructure project and provide benefits in the overall lifecycle performance of infrastructure (Lenferink, Tillema and Arts, 2013; Lousberg and Noorderhaven, 2014). Early involvement of industrial partners, who share common goals with the infrastructure owners, in the decision-making process facilitates exchange of knowledge and information at reduced risks, and helps the decision-makers take informed decisions by looking at the environmental, economic, and social impacts, while fulfilling the technical and functional requirements. At the same time, the information exchange from the learning outcomes of different projects helps in improving infrastructure designs and the benefits of innovative solutions.

The use of generic LCI databases containing the industry average values for different products are often beneficial in the early-planning phase of infrastructure projects. The information in the early-planning phase is often basic and roughly described. As the result, generic databases can help in gaining insight into the overall environmental performance (O'Born *et al.*, 2014; Hammervold, 2015; Miliutenko, 2016). However, when it comes to the detailed-designing phase, the generic databases do often lack the specificity that the design phase requires (Shadram, 2018). The limitation in the generic databases is because of not having the values for specific products provided by specific suppliers. This is important since there are differences in the functionality of products and services, the embodied impacts associated with the procured inputs, the manufacturing line-up, the logistics for the delivery of the manufactured products etc. To overcome the limitations, the use of EPDs that declare product-specific environmental impacts were found to be advantageous in the detailed-design phase (Shadram, 2018). In addition, EPDs help the public procurement by assuring that environmentally friendly products and services are constructed by contractors (EPD International AB, 2019a).

Whether it is about the early-design phase or the maintenance phase of road infrastructure, it is essential to measure the long-term impact of the decisions. Even though the importance of LC-based assessment in different phases of the road infrastructure projects has been highlighted by research, the end-of-life phase of the infrastructure is not adequately covered. The insufficient coverage is often due to the uncertainties about the fate of the in-service materials at the end of their service lives. However, it is of importance to improve the

assessment for the construction materials at the end of their service lives and ensure that the materials flow in a closed loop. The improvement is necessary as the increase in the recycling of the construction materials help in increasing the natural resource efficiency, which enables the substitution of primary materials. Hence, it is essential that new incentives are encouraged by public procurers to assure the provision of reused and recycled materials in civil projects (Deloitte SA, 2016). Incentives that encourage the actors, for example, the contractors to take active roles in reusing and recycling of materials. In addition, the traditional practice that has been product-driven design needs to be reformulated to waste-driven design to enhance natural resource efficiency and minimize waste generation and the subsequent demand for landfills. Utilization of building information modelling (BIM) more actively in the road infrastructure projects provides a safe platform to evaluate the consequence of decisions from the early stage of a project to enhance the robustness of decisions from the sustainability perspective (Akinade *et al.*, 2018; Giorgi, Lavagna and Campioli, 2018). However, alongside the work to enhance the recycling, it is essential to standardize the utilization of recycled materials for various purposes (Deloitte SA, 2016). The standardization guaranties that the recycled materials comply with norms and quality requirement and put them in an advantageous position compared to primary raw materials.

Road infrastructure owners should create interactive platforms to stimulate interdisciplinary and transdisciplinary collaborations to address the sustainability of their complex system (McMichael, Butler and Folke, 2003). The shared platforms coordinated by scientific and technical committees provide a creative environment to produce new decentralized and specialized knowledge that handles high level of complexity by providing systematic solutions (Jahn, Bergmann and Keil, 2012; Schaltegger, Beckmann and Hansen, 2013). For instance, one of these shared platforms needs to be allocated to the resilience of the road infrastructure to climate changes to ensure that the infrastructure can withstand the extreme weather events of the future, like changes in the pattern and frequency of rainfall affecting the occurrence of stormwater runoff and landslide, increase in the water table and sea level weakening the structural strength, and increase in the temperature damaging the seasonal ground frost. Such a platform helps understand the vulnerability of in-service road infrastructure to climate change (causing service disruption) and proposes measures to strengthen climate resilience infrastructure, like: planning, designing, building, and operating new road infrastructure that takes into account the effect of climate change while they are sustainably sound; enhancing adaptive management of the existing road infrastructure that increase asset life by advance monitoring and planned intervention activities; and amending and extending standards for products and civil engineering works to address climate risks (OECD, 2018).

5.1.1 Limitations

Even though the book chapter was purely based on a literature study, owing to the complexity and broadness of the topics, the authors might have missed to reflect on some points. Hence, it is recommended to consider the appended book chapter and the reflected discussion as potential solutions towards answering RQ 1.

5.2 Research question 2

How can a regionalized 'cradle-to-grave' LCA analysis be conducted by means of a generic LCI database? In which product system should this investigation be conducted?

The purpose of this RQ was to show how the pre-build inventories can be used to perform a full-LCA assessment. Based on the identified niche, explained in the first two chapters, for the development of this work, we introduced a new approach to assess the regionalized environmental impact associated with the construction machinery over its lifetime. The method introduced by paper I closed some of the existing gaps in the LCA that were identified to be only slightly covered by prior research (in other words, the previous research did not provide a full LCA picture of the construction machinery throughout their lifespans). In addition, the outcomes from the investigation could help enhance the resolution of the LCA database during the production of raw materials in quarries.

Besides, the obtained findings may be of interest for the Norwegian government (the NTP emission goals), as they aim to reduce by half the emissions from the construction and maintenance of road infrastructure (Avinor *et al.*, 2016; Ministry of Transport and Communications, 2017). This is important because the reduction in the direct emissions from the construction machinery can contribute considerably to the Norwegian NTP.

- Since 2005, a yearly average of ca. 155 million liters of diesel has been sold to the Norwegian construction industry (Statistics Norway, 2017b). The construction machinery has been responsible for the consumption of 80% of the sold fuel, i.e., about 124 million liters per year (MEF, 2016). The consumed diesel by the Norwegian construction machinery was estimated to be equivalent to about 335 kilo tons of emitted CO2, i.e., 2.7 kg of CO_2 per liter of diesel. This figure corresponded to about 4% of the total CO_2 emissions from the road traffic in the Norwegian territory, based on the figures for the year 2018 (Statistics Norway, 2019a).

This study came to the same conclusion as the prior studies (for instance: Lewis et al. (2009; 2012), Fu et al. (2012), Lijewski et al. (2013), Sennoune et al. (2014), Barati and Shen (2016) and Cao et al. (2016)), that the operation phase, especially considering the fuel consumption, has a relatively dominant contribution. Even though the operation phase of a machine was shown in paper I to be the dominant phase affecting the majority of the indicators (especially, ADP_F, GWP, ODP, and PO with almost 100 % contribution), covering the full life cycle showed that it is not the only phase that needs to be considered. In addition to the operation

phase, (1) accumulation of materials for manufacturing and maintenance of the machinery, and (2) the treatment of the materials at the end of their lifetimes, have also made considerable contributions.

The presented results in this study used the latest version of the CML impact assessment method —version 2.4 (Pre', 2018). Although the impact assessment method was suggested by the European standard 15978:2011 (2011), it was not capable of capturing the impacts associated with the PM and VOC. Construction machinery equipped with diesel engines emit a considerable amount of PM and VOC over their lifespan. As a result they impact human health, acidity of water, nutrition balance of the soil, and formation of ground level ozone and smog (Lee *et al.*, 2002; Grantz, Garner and Johnson, 2003; Koppmann, 2007; Kampa and Castanas, 2008; Zhou *et al.*, 2011; Zhao *et al.*, 2013; Costagliola, Murena and Prati, 2014; Gronlund *et al.*, 2015; Kim, Kabir and Kabir, 2015).

The logistic model used to explain the engine deterioration behavior showed how the emission rates would change over the lifespan of each machine. This was done to establish that the effect of the engine deterioration on the increase of emissions would not be linear (Chen and Borken-Kleefeld, 2014; Pang, Fuentes and Rieger, 2014; Ercan *et al.*, 2015; Zhang *et al.*, 2017). However, there was no recommendation in the literature showing how the profile of the growth in the emission factors for different tailpipe emissions would appear.

The emissions over the operation phase of each machine, as calculated in this paper, when compared with other studies (Lewis, Leming and Rasdorf, 2012; Sennoune *et al.*, 2014) showed a considerable difference. The difference was owing to three factors. Firstly, this study used a 100% load factor (the rate of the engine power used during the operation) for each effective hour of operation, which drastically affected the results by producing higher emissions. Secondly, the lack of continuous measurements in the prior studies that missed capturing the effects of 'wear and tear' during the accumulated engine hours. Thirdly, the assumed energy intensity and emission factors, coupled with the assumed engine deterioration model, might have resulted in higher calculated values for the operation phase.

There is an ongoing discussion by various actors to reduce or diminish the GHG emissions associated with the construction machinery by using fossil free fuels or electric alternatives. However, it is of interest to know to what extend the alternative construction machinery (powered by renewable fuels or electricity) outperform the conventional machinery from the environmental perspective. The pros and cons of the new construction machinery are often better understood if they are compared with the existing ones. The findings and recommended approach from paper I could be of use to benchmark the environmental

performance of different construction machinery to understand the benefits and drawbacks of different technologies.

5.2.1 Limitations

The regionalized LCI processes were created based on the Ecoinvent database version 3.3 (allocation at the point of substitution). Due to the lack of available LCI processes, EPDs, and literature, this study was unable to include some machine parts in the developed LCI processes to increase the resolution, like catalytic convertors, braking systems, and filters, etc.

Based on the findings from paper I, the applied CML impact assessment method was found to be unable to capture the impacts from the PM and the VOC. Further development of the impact assessment methods is necessary to bridge the current limitations in the applied methodology. However, ReCiPe 2016 impact assessment method version 1.1 is already capable of addressing the impacts associated with these two tailpipe emissions through photochemical oxidation formation and particulate matter formation indicators (Pre', 2018). Hence, we recommend that we should consider the impact assessment methods that are capable of capturing the impacts associated with all the substances and not miss out any.

Various studies have proved that the exhaust emissions increase with hours of engine use (Chen and Borken-Kleefeld, 2014; Pang, Fuentes and Rieger, 2014; Ercan *et al.*, 2015; Zhang *et al.*, 2017). However, no deterioration profile was recommended to capture the increase in the rate of emissions. Despite considering the effect of the engine deterioration in paper I and using three retardation scenarios to capture the uncertainties, the study yielded limited knowledge on implementing any representative models to show accurate deterioration distributions for different emitted gases over the lifetime of the machinery. A deeper understanding of how the chemical reactions in engines would change over time and result in changes in the intensity of emissions is needed for the same.

The emission factors used in paper I were based on the published reports by EMEP and EEA. They were based on the laboratory testing and not from the real-world measurements, and hence, cannot fully capture the potential emission rates from the real-world operations. Thus, it would be necessary to use *in situ* measurements from the machinery and create representative emission factors to get a more realistic picture of the operational emissions. Furthermore, this study assumed a 100 % load factor for each effective hour. This assumption might lead to over-predictions and needs to be adjusted by appropriate load factor.

5.3 Research question 3

How can the lifetime of road materials be quantified?

Paper II introduced a new approach to estimate the longevity of asphalt pavements based on different independent variables to enhance the long-term maintenance planning. This was done by stratifying certain asphalt types in a traffic class to calculate the risks of failure for different covariates within a small-time interval.

The benefit of this approach was its capability to provide immediate information for experts dealing with the LC-based analyses, such as, life cycle assessment, life cycle costing, and social life cycle assessment, to increase the accuracy of their work. In addition, the obtained results from this approach had the potential to support pavement managers to gain a deeper knowledge about the performance of the road materials and apply that knowledge during the planning of intervention works to enhance the efficiency in the use of resources, both economic and natural resources.

Incorporation of rut data as a response variable offered the opportunity to evaluate the historical maintenance efforts with respect to the Norwegian technical requirements for the quality of the maintained roads. Taking this approach helped in understanding how long the maintenance work was delayed with respect to the determining factors. Based on the findings, it was revealed that the maintenance activities, with respect to the median survival time, were backlogged for about two years in each traffic class.

Correction of such maintenance backlogs has been pointed out in the NTP 2018 – 2029 as one of the paramount priorities for the NPRA (Ministry of Transport and Communications, 2017). This, in fact, is a result of the continuous increase in the traffic volume (Statistisk sentralbyrå, 2017) and yearly expansion of the road networks in Norway by 250 km (Granden, Johansen and Bakløkk, 2017), which put pressure on the maintenance budget. Inadequate response to the backlog means that more roads will be added to the list of roads needing maintenance, which in turn, means more costs for the agency and the users.

Furthermore, the findings reconfirmed that the traveled-road width had a direct effect on the profile of rut propagation which dictated how fast a pavement would fail. Although the traveled-road width was not considered as a continuous covariate in the model, it was used to explain certain pavement behaviors. By looking at the layout of the roads in the colder climate regions of Norway, i.e., Troms, it became obvious that the relatively shorter lifetimes of the roads was partially linked to their narrower width (the word ‘partially’ is used here because no information regarding the structural number, modulus of resilience, and weight and dimensions of the heavy vehicles was available). Thus, the width of the roads played a significant role in lowering the risks of pavement failures.

Fitting the obtained results from the Cox PH model to the examined reference categories, helped in presenting the absolute lifetimes for different stratified pavements. This approach was followed to create results from the statistical tables with the aim of supporting scientific

findings in practical applications. Fitting also allowed us to compare the median lifetimes of different asphalt surfacing materials with the nominal lifetimes projected by the NPRA, and evaluate which materials under-performed or over-performed.

5.3.1 Limitations

In paper II, due to the lack of information, the effect of the quality of the maintenance activities on the longevity of the pavement materials was not considered. Instead, it was assumed that the intervention quality was satisfying the NPRA requirements. However, it was shown in a published report by the NPRA that low quality of the finished work often resulted in early failure of the Norwegian roads (Telle, 2015). In future research, it would be useful to consider the quality of the finished work (for instance, with respect to the application of a tack coat, homogeneity of the paved mixtures, unevenness, and sealing joints) after the intervention to increase the validity of the obtained results not only for the applied model (stratified Cox PH model), but also for other statistical assessments.

The AADT classification in paper II was based on a number of passages for the entire cross section of a paved road and not per lane. Because of this, it was difficult to appropriately interpret the effect of the traffic loading per road lane, especially when using the heavy traffic volume as a continuous variable. Thus, the lack of certainty about the AADT per lane had increased the risk of uncertainty in the obtained results from the model. However, it would be beneficial to expand the investigation to explore the effect of the traffic loading per lane on the pavements' lifetimes. In addition, the lack of resolution in clustering heavy traffic vehicles into different groups made it impossible to know what the explanatory variable "AADT of heavy vehicles" meant. This, in fact, was because of a wide range of variations in the axle and tire configurations for heavy vehicles that affect the speed of rut formation (NVF, 2008). It would be of help to carry out a parallel investigation to enhance both the clustering of the heavy traffic vehicles and the share of passages per lane for different roads (ordinary 2-lane roads, 2+1 roads, 4-lane roads, etc.) based on different variables.

5.4 Research question 4

How can the long-term material flow and stock within the road networks at the administrative level be modeled?

Paper III aimed to capture the past and present of the road infrastructure by looking at certain categories of roads and showed how the studied system would change in the future. It also strove to expand the research in the MFA community dealing with the road infrastructure. The presented findings showed the metabolism of the road materials within the investigated system that could be valuable for the NPRA in gaining insights into the availability and flow of the road materials at different times. These insights could be of use for the future allocation of economic and natural resources, and for reducing the potential environmental

impacts. The knowledge from this investigation can also be used to identify practices that enhance responsible material consumption and reduce pressing demands on virgin materials while increasing the upcycling of the used materials. In addition, this paper became a practical example showing how the research results from paper II can be applied to explain the behavior of pavement materials.

This study used historical records to monitor certain categories of roads in Norway from 1980 to 2017 to explain when roads have been built and have left the system. Roads that left the system were often replaced by higher capacity roads; however, there were instances that the terminated roads were not replaced. By looking at the historical changes in the amount of road stock, it showed that more roads were built than terminated. The infrastructure development showed that in total about 45 Mt road materials were added to the system owing to the investment on the new road infrastructure.

The retrospective analysis showed that there were insignificant differences between the three scenarios; see Fig. 22. This was because of using the estimated milling and paving works as the only two variables that differed in the time-series results between 1980 and 2017 in the three scenarios. The time-series results for the other variables (recorded road pavement, recorded and predicted road structure, estimated pavement wear, and recorded surface milling) were identical in the three scenarios.

The variations in the results for the estimated milling and paving works were owing to the differences in the profile of the maintenance works. The estimation for paving and milling was quantified by the probability density functions (PDFs) that incorporated both the initial and the following interventions, see Fig. 17. However, the three PDF profiles showed that the area underneath the three scenarios were nearly identical up until the year 2010, and slightly changed till 2017. This similarity was because of fewer roads requiring to be maintained at the beginning of the analysis and having most of these roads in lower traffic classes (mainly in traffic class 1 and 2). The lower traffic classes appeared to have longer distributional lifetimes compared to the higher traffic classes, and as a result, fewer roads required following interventions.

Even though the prospective analysis considered the maintenance of the in-service road infrastructure, i.e., resurfacing and milling, and pavement wear, it showed that the amount of stock would continue to grow, even if the traffic volume would not grow after 2017 (which is an unlikely assumption). The identified growth in the amount of stock, regardless of the scenarios, was linked to the ongoing needs for keeping the infrastructure maintained and placing more layers on the existing pavements rather than removing them by milling activities. Furthermore, it was assumed that the system would be maintained indefinitely (i.e., after the primary intervention come the secondary, tertiary, and so on) and no road

infrastructure in the networks would leave the system (due to the termination of their service). The continuous maintenance works accounted for 352 sq.km of in-service road infrastructure. The unlimited maintenance of the road showed that it resulted in a growth in the accumulation of the road system related material stock.

Since the presumed model considered the usage of winter tires, it showed a shift in the share of studded to non-studded tires; a massive reduction in the amount of pavement wear was seen. The reduction in wear caused by studded tires appeared to be about 300 kilotons in the period 1980–2017; however, the reduction of pavement wear caused by the non-studded tires was not as significant as that by the studded tires.

The reason for the overall reductions in pavement wear caused by the both tire types was owing to (1) the introduction of pavements with higher resistance to wear and (2) regulations that limited the duration and the type of studded tire usage (Snilsberg, 2008). In addition, the study showed that the pavement wear was strongly responsive to the amount of traffic volume (the more traffic on the roads, the higher the pavement wear). However, due to a combination of factors (the presumed model showing the proportion of winter and summer tires, as well as the intensity and uncertainty of wear during different cohorts), the total pavement wear continued to decrease even though the traffic volume was assumed to increase after 2017 in Scenarios 2 and 3.

5.4.1 Limitations

Although the proposed approach in paper III showed how we could measure the availability of the road materials over time, it only considered the roads in three categories (EU, national, and county roads), which in total, covered about 55% of the public roads. Furthermore, it excluded road tunnels and bridges from the domain of research. Hence, the showcased findings in the Norwegian context were not presenting the full picture.

In addition, the classification and the regression tree did not differentiate between the old and the new road infrastructure design. This was due to the lack of information showing the design of roads in different projects. However, it is necessary to bridge this limitation by comparing the structural numbers of the predicted pavement structure with those in the design sketch of the theoretical pavement structure, as the control measure to understand whether the predicted pavement structures were over- or under-designed.

Paper III showed a single estimated lifetime for pavements in different traffic classes and did not consider the results from the upper- and lower-level confidence intervals. This was owing to the insignificant variations when comparing the upper- and lower-level confidence intervals with the single estimate results. However, it is recommended that the future research apply upper- and lower-level confidence intervals in the assessment to comprehend the uncertainties of the estimated lifetimes.

Even though we expect to see a growth in the expansion of road networks, paper III did not consider that the networks would expand or shrink after 2017. Instead, it was assumed that the networks would only be maintained. In future research, it would be valuable to expand this work and consider scenarios (reinforced by uncertainty analysis) involving the combination of network expansion and maintenance activities.

Even though this study showed the effect of the traffic volume change in each road section on the pavement wear, it did not provide a high-resolution picture. The assumed method for measuring the dissipative flows was generic and aggregated, and hence, did not show the effect of the pavement wear with respect to surfacing types, aggregate nominal maximum size, speed limits, and climatic condition.

Uncertainties exist with respect to the comprehensiveness of the used data, as reported by earlier studies that used the Norwegian data. Not all data were uploaded to the database in a prompt manner. There were instances of data pertaining to some counties being uploaded with a delay of a few years, and some other times of data not being uploaded at all.

CONCLUSION

This chapter draws a conclusion on the contributions made by this research study based on the formulated RQs.

Awareness about the sustainability of the road transport system has become increasingly important and has resulted in a series of mandates by the governments to address the existing challenges. Even though a gradual momentum has emerged in the research field aiming at showing comprehensive solutions concerning different dimensions of sustainability; still rooms for improvement has left to be field to ensure the thoroughness in the sustainability performance of the road infrastructure. The contribution of this research study was that it identified the LCT challenges in the physical infrastructure and proposed recommendations that enhance the planning and evaluation. In addition, it recommended research methods that have potential to improve the LC-based assessment of the road infrastructure, and this was accomplished by taking a systematic approach to propose solutions to close the identified gaps in the previous research studies. Besides, the provided research methods not only contribute to scientific research but also support practitioners involved in the road infrastructure projects to apply the developed methods to existing cases to enhance their LC-based assessment. The developed research methods were also tested on Norwegian cases; however, this research does not limit the relevance of its application. In fact, the developed research methods can be adapted to other geographical areas to attain localized outcomes.

Ensuring a prosperous future for our society is a challenge that requires a holistic perspective and comprehensive solutions. The implementation of the LCT has proved to be a potential approach for road infrastructure projects, as it creates opportunities to measure various

dimensions of sustainability and assists in taking more informed decisions. However, there is no single approach that can be used for road infrastructure to improve their lifecycle performance. Instead, a combination of approaches (recommended by prior research) needs to be implemented to safeguard the direction of pace towards the sustainability of the road infrastructure. Some of these approaches include early involvement of private sector in complex and uncertain projects, creating high-performing collaborations between the parties to reduce risks and uncertainties, using product-specific LCI data (e.g., EPDs) during the detailed-design phase, inclusion of the end-of-life phase to enhance the comprehensiveness of decision making, waste-driven designs to maximize the reusability and recyclability of natural resources, increase in the interdisciplinary and transdisciplinary collaborations, and climate-resilient infrastructure that incorporates adaptive management to reduce risks.

By charting out a full-LCA that is based on a regionalized LCI data, it was found that increasing both the resolution and the exclusiveness of the LCA in the road infrastructure projects was a potential gap that needed to be bridged. To close this identified gap, an investigation was conducted on the construction machinery, as it was considered to have a considerable environmental impact during the construction phase (earthworks activities) and the mineral production phase (mining activities). In doing so, the investigation took a 'cradle-to-grave' approach and applied relevant data, information, methods, and models. Conducting the full-LCA study showed that even though the operational phase of the construction machinery equipped with diesel engines (using fossil-based diesel fuel) was considered as the main contributor in various environmental indicators (ADP_F, GWP, ODP, and PO), inclusion of other phases was equally important. This means that the production, delivery, maintenance, dismantling, waste processing, and circulation of non-energetic materials at different phases of a machine contributed to the overall impacts (with the highest contribution in ADP of up to 60%, and the lowest contribution in GWP, of below 1%).

To support the decision-makers for the intervention planning and the LC-based assessments of road infrastructure, it was found necessary to develop knowledge regarding the lifetimes of road materials. The approach introduced in paper II showed a potential way to estimate the lifetimes of asphalt surfacing materials by means of GIS-based survival modeling in the Norwegian context. It showed the difference between the maintenance records and the technical requirements and discussed how long the maintenance activities were backlogged in each traffic class. Stratification of the model by surfacing types made it possible to reconfirm some prior findings, such as the effect of aggregate nominal maximum size, and heavy traffic volume on the longevity of the asphalt surfacing materials. It also explained how the behavior of some explanatory variables was affected by the variations in the traveled-road width and the range of AADTs. Moreover, the research showed how

transforming the relative values from the survival tables into absolute lifetimes (based on certain explanatory variables), enhances the practicality of the interpretation of the results.

Continuous demand on abiotic resources in road infrastructure requires designing and implementing more circular thinking to increase the efficiency of the natural resources, and replacing the need for the primary materials. Over time, massive amounts of natural resources have been stocked in the road infrastructure networks that make them valuable for use as secondary source of materials at the end of their lifetimes. However, the information as to how much materials have been stocked and how much would be input and output in the future is very limited. This is because of lack of adequate amount of data and insufficient knowledge about the lifetimes of the materials. Paper III proposed a promising approach to quantify the material flow and stock over a long analysis period (i.e., 1980 – 2050) and used the Norwegian road networks as the case study. The expansion of the road networks appeared to be a significant factor in the increase of the material flow by 80 Mt (from 345 Mt to 420 Mt), between 1980 and 2017. However, the maintenance of the road networks showed that the stock would grow by 9 % – 10 % between 2018 and 2050 (even though it was assumed that the network would not expand after 2017). The reason for the growth in the period of 2018-2050 is because of continuous maintenance requirement and laying more layers on the existing pavements rather than removing them.

FUTURE RESEARCH DEVELOPMENT

Even though the carried-out research work was directed toward the road infrastructure in this thesis, the findings and developed research methods have the potential to be transferred to the other domains in the research or practice. This is, in fact, because of the similarity of the challenges that physical infrastructure has in common, which brings the opportunity to transfer the learning outcomes. Besides, further exploration and development of the areas covered in this thesis is needed to increase the precision and accuracy in the conducted studies. In addition to the limitations mentioned in this research, which could be considered as opportunities for future improvements, some more areas that need further attention are briefly discussed below:

Incorporation of risk assessment in the LCA studies has proven to be an appropriate approach to complement the results of the environmental impact assessment. This was shown to be linked to the existing challenges in the traditional LCA analysis, namely the inability to capture the availability of the abiotic resources from the site of production. The existing model in the LCA currently measures the environmental impact based on the consumed mass and energy of the abiotic resources and their geological depletion, without considering the supply-side risks (Schneider *et al.*, 2014). In this direction, the use of

different complementary methods, for example, the economic scarcity potential and the geographic supply risk are suggested to fill the current voids and assist the LCA to take into account the resource security (Kobayashi, Peters and Khan, 2015; Mancini, Benini and Sala, 2018; Cimprich *et al.*, 2019).

The growing need for a comprehensive approach to solve multi-dimensional challenges has accelerated the utilization of mathematical optimization to solve problems and identify (global) optimum solutions from a set of available solutions. A combination of the proposed approaches in this thesis can be integrated with mathematical optimization tools to answer various questions related to sustainability.

Based on the defined research questions, this thesis touched upon certain areas in the domain of road infrastructure. However, this PhD study, by itself, is not enough to deliver answers to all the questions related to the sustainability of road infrastructure. Hence, it is essential to couple the findings from this study with other research topics, such as winter road maintenance, road alignment design, and utilization of local materials for road construction, and include non-engineering fields, such as stakeholder engagement and public procurement to gain a deeper understanding of the system. This, in a sense, helps the decision-makers avoid taking narrowly defined solutions and shows them prominent pathways to reach the overall sustainability of the road transport system.

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