Development of a CO_2e quantification method and of solutions for reducing the greenhouse gas emissions of construction machines

For the academic degree of

DOCTOR OF ENGINEERING (Dr.-Ing.)

by the KIT-Mechanical Engineering Faculty
of the Karlsruhe Institute of Technology (KIT)

accepted

DISSERTATION

by

Dipl.-Ing. Isabelle Charlotte Ays

Date of the oral examination : 22.11.2019
First expert examiner: Prof. Dr.-Ing. Marcus Geimer
Second expert examiner: Prof. Dr. Ludger Frerichs

Entwicklung einer CO_2e Quantifizierungsmethode und von Lösungen zur Reduzierung von Treibhausgasemissionen in Baumaschinen

Zur Erlangung des akademischen Grades einer

DOKTORIN DER INGENIEURWISSENSCHAFTEN (Dr.-Ing.)

von der KIT-Fakultät für Maschinenbau des
Karlsruher Instituts für Technologie (KIT)
angenommene

DISSERTATION

von

Dipl.-Ing. Isabelle Charlotte Ays

Tag der mündlichen Prüfung: 22.11.2019
Hauptreferent: Prof. Dr.-Ing. Marcus Geimer
Korreferent: Prof. Dr. Ludger Frerichs

Abstract

Motivated by global warming, this thesis focuses on the development of a quantification method for greenhouse gas (CO_2e) emissions from construction equipment. This thesis presents a method that closes identified research gaps derived from the analysis of measures from different industries and from existing CO_2 quantification methods. The method considers CO_2e reduction potentials through influencing factors from six pillars: Machine efficiency, process efficiency, energy source, operating efficiency, material efficiency and CO_2e capture and storage. Applying the method to representative construction applications for Europe in the timeline past - present - future, demonstrate that the method can be applied to any construction application and to any timeline. By comparing the results from two timelines, it is possible to quantify the reduction or increase of greenhouse gas emissions. On the example of selected construction machineries, it is shown that the method is valid and thus allows for making statements about certain CO_2e reduction measures. Finally, transformation solutions are proposed to reduce greenhouse gas emissions from construction machinery. Liquid methane is proposed as an alternative energy source, which is able to reduce CO_2e emissions by up to 84 %. Its combination with a fuel cell drive can reduce CO_2e emissions by up to 89 %. As a third solution, the use of a CO_2 capture and storage system is proposed, which reduces CO_2e emissions from fossil diesel up to 82 %. The combination of the three proposed solutions transforms mobile machines into machines that cleanse the atmosphere of greenhouse gases, as negative CO_2e emissions are generated.

Kurzfassung

Motiviert durch die globale Erwärmung konzentriert sich diese Arbeit auf die Entwicklung einer Quantifizierungsmethode für Treibhausgas (CO_2e) Emissionen von Baumaschinen. Im Rahmen dieser Arbeit wird eine Methode vorgestellt, welche identifizierte Forschungslücken schließt, die durch die Analyse von Maßnahmen aus unterschiedlichen Industrien und von existierenden CO_2 Quantifizierungsmethoden abgeleitet worden sind. Dabei berücksichtigt die Methode mit Hilfe von Einflussfaktoren aus sechs Säulen CO_2e Reduktionspotentiale, welche lauten: Maschineneffizienz, Prozesseffizienz, Energieträger, Betriebseffizienz, Materialeffizienz und CO_2e Abscheidung und Lagerung. Durch den Einsatz der Methode auf repräsentative Bauanwendungen für Europa für drei Zeitschienen Vergangenheit-Gegenwart-Zukunft wird gezeigt, dass diese für beliebige Bauanwendungen und Zeitschienen anwendbar ist. Beim Vergleichen der Ergebnisse aus zwei Zeitschienen ist es möglich die Reduktion oder Steigerung an Treibhausgasemissionen zu erfassen. Am Beispiel von ausgewählten Baumaschinen wird gezeigt, dass die Methode gültig ist und damit Aussagen über bestimmten CO_2e Reduktionsmaßnahmen ermöglicht werden. Zum Schluss werden Transformationslösungen vorgeschlagen, um die Treibhausgasemissionen von Baumaschinen zu reduzieren. Dabei wird flüssiges Methan als alternativer Energieträger vorgeschlagen, der die CO_2e Emissionen bis zu 84 % reduzieren kann. Die zusätzliche Kombination mit einem Brennstoffzellenantrieb können die CO_2e Emission bis zu 89 % reduzieren. Als dritte Lösung wird der Einsatz eines CO_2 Abscheide- und Speichersystems vorgeschlagen, welches die CO_2e Emissionen von fossilen Diesel bis zu 82 % reduziert. Durch Kombination der drei vorgeschlagenen Lösungen wird aus der mobilen Arbeitsmaschine eine Maschine, welche die Atmosphäre von Treibhausgas reinigt, da negative CO_2e Emissionen damit entstehen.

Table of content

List of figures

List of tables

List of abbreviations

α	Elementary process
A_{con}	Area affected by the construction
A_i	Estimated fuel use rate for mode i
A_k	Amount of material k
Al^{3+}	Aluminium cations
A_{res}	Restoration area with vegetation
A_{ser}	Area occupied by the built product
$a_{w(8)z}$	Frequency-weighted acceleration in z direction for a working shift of 8h
b'	Working width
BAFU	Federal office for the environment
$b_{Bö}$	Embankment width
BDI	Confederation of German industry
b_{eff}	Effective working width
Bft	Beaufort scale for measuring wind speed
$BGF_{average}$	Average gross external area
$B_{idle,\alpha,r}$	Sum of fuel consumption at idle for elementary process α for machine type r
BK10	Road belonging to road class 10
BK3,2	Road belonging to road class 3.2
BK32	Road belonging to road class 32
b_l	Fuel consumption of truck of type l
b_m	Average fuel consumption of the considered machine type
BSFC	Brake-specific fuel consumption
$B_{work,\alpha,r}$	Sum of fuel consumption at work for elementary process α for machine type r
C_2F_6	Hexafluoroethane
CANBUS	Controller Area Network
CaO	Calcium oxide

CARB	California air resource board
$C_{CO_2e,T}$	Amount of CO_2e emitted expressed as currency
CCS	Carbon capture and storage
CECE	Committee for European construction equipment
CEMA	Committee for European agricultural machinery
CF_1	Correction factor 1
CF_3	Correction factor 3
CF_4	Tetrafluoromethane
CH_4	Methane
CHrs	Total of accumulated operation hours of the machine
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent (greenhouse gas)
$c_{p\ x,y}$	Specific heat capacity of gas x and temperature y
$\Delta_{c,s}$	Annual CO_2 sequestration from the topsoil
$\Delta_{c,v}$	Annual CO_2 sequestration of the dominated vegetation
$\Delta_{c,v1}$	Annual CO_2 sequestration of the newly planted dominant vegetation
$\Delta_{c,v2}$	CO_2 sequestration during the fast growth phase
$DF(X)_{i,j,k}$	Deterioration factor machine type i, engine size j and engine age k
DFA	Deterioration factor adjustment
$DF_{y,z}$	Deterioration factor for engine size class y and emission level z
DME	Dimethyl ether
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
dr	Deterioration factor
η_x	Efficiency of x

E	Energy output
$E(X)_{i,j,k}$	Amount of carbon dioxide emission with machine type i, engine size j and engine age k
$E_{Basis}(X)_{i,j,k}$	Amount of carbon dioxide emission during basis situation with machine type i, engine size j and engine age k
E_{CH_4}	Annual emitting fluxes of CH_4
E_{CO_2}	Carbon dioxide emission or Annual emitting fluxes of CO_2
ECO-mode	Economy driving mode on a machine
$E_{compressor}$	Energy demand of the compressor
EEA	European environment agency
$EF_{adj(CO_2)}$	Adjusted carbon dioxide emission factor for transient operations
EF_{Base}	Base emission factor
EF_{CO_2}	Emission factor for carbon dioxide
$EF_{CO_2\ for\ fuel\ type}$	Carbon dioxide emission factor for the fuel type considered
$EF_{SS(CO_2)}$	Carbon dioxide emission factor for steady-state test measurements of engines
$EF_{y,z}$	Emission factor for engine size class y and emission level z
EMEP	Long-range transboundary air pollution
E_{N_2O}	Annual emitting fluxes of N_2O
EPA	United States Environmental Protection Agency
EU	European Union
ε_{FC}	Constant fuel consumption factor
f_1	Pivoting angle
f_2	Digging depth
f_3	Kind of bucket emptying for an excavator
f_4	The influence of the type of environment on work performance
f_{age}	Factor describing efficiency decrease through

	machine aging
$f_{air/diesel}$	Converting factor of how much air is needed to burn diesel in an ICE engine
f_{CCS}	Factor representing the percentage amount of greenhouse gas emissions captured and stored
$FC_{for\ fuel\ type}$	Fuel consumption for a fuel type
f_{CH_4}	GWP value for CH_4
f_{CO_2}	GWP value for CO_2
$f_{CO_2e/energy\ carrier}$	Conversion factor from energy carrier into amount of CO_2e emissions
$f_{CO_{2,TTW}}$	Converting factor of diesel into CO_2 during combustion (tank-to-wheel)
$f_{constr.\ complexity}$	Factor describing efficiency variation through construction complexity
$f_{construction\ time}$	Factor describing efficiency through limited construction time
f_{driver}	Factor describing efficiency through the driver
f_E	Utilisation factor
f_{eco}	Factor describing efficiency through the ECO-mode
F_{eff}	Efficiency factor typical for office building
f_{engine}	Factor describing efficiency through the engine
FeO	Ferrous oxide
f_F	Filling factor
$f_{idle\ unavoidable}$	Factor describing amount of idle time unavoidable for the process
$f_{knowledge\&skills}$	Factor describing efficiency through the driver's knowledge and skills
f_L	Load factor
F_{liquid}	Amount of energy of liquid fuel used in manufac-turing and construction equipment
$f_{machine\ condition}$	Factor describing efficiency decrease through machine condition

$f_{machine\ technology}$	Factor describing efficiency through machine technology
f_{N_2O}	GWP value for N_2O
$f_{physical\&mental\ state}$	Factor describing efficiency through physiological and psychological state of the driver
f_{price/CO_2e}	Factor representing the price for an amount of CO_2e emissions
$f_{process\ assistant}$	Factor describing efficiency through process assistant in the machine
f_S	Decompaction factor of the soil
$f_{service\ regularity}$	Factor describing efficiency decrease through lack of service
$f_{significant\ improvement}$	Factor describing efficiency through machine technology which are not through the engine and ECO-mode
$f_{site\ freedom}$	Factor describing efficiency decrease through limited construction site freedom
$f_{site\ orga}$	Factor describing efficiency decrease through construction site organisation
$f_{stop\&go}$	Factor describing the amount of standstill time
f_T	Transport service factor
$Fuel_{wt.avg}$	Weighted-average fuel use rate
f_{ui}	Factor describing unpredictable influence leading to an increase in CO_2e emissions
$f_{weather}$	Factor describing efficiency decrease through weather
$f_{workplace\&working\ environment}$	Factor describing efficiency through the work-place and working environment
f_x	Specific compaction work
G1	Research gap 1
G2	Research gap 2
G3	Research gap 3
G4	Research gap 4

G5	Research gap 5
G6	Research gap 6
G7	Research gap 7
G_{after}	The resulting gains from replanting and CO_2e sinks restoration after construction work
GF_{floor}	Gross floor area
GHG	Greenhouse gas
$G_{potential}$	Gain over the lifetime of the built product, resulting from new CO_2e sinks formation
G_{rapid}	Effect of fast growing plants during the first 20 years which leads during this period to a higher amount of CO_2 removal from the atmosphere
GVA	Gross value added for manufacturing and construction
GWP	Global warming potential
GWP_k	Conversion factor expressing the relative contribution to the greenhouse effect by producing material *k* per amount of material *k*
H	Enthalpy or operation hours
h	Thickness of the layer
H_2	Dihydrogen
H_2O	Water
$h_{average}$	Average storey height
HC	Mass of hydrocarbon emissions
HFCs	Hydrofluorocarbons
HP	averaged rated horsepower
HPDI	High-pressure direct injection
HRS	annual hours of use of the emitting source
$HRS_{i,j,k}$	Annual working hours with machine type i, engine size j and engine age k
$H_{u,x}$	Lower heating value of fuel x
ICCT	International council on clean transportation

ICE	Internal combustion engine
ifo	Institute for economic research
ifeu	Institute for energy and environmental research
IPCC	Intergovernmental Panel on Climate Change
$K_{i,j,k}$	Engine age with machinery type i, engine size j and engine age k
KIT	Karlsruhe Institute of Technology
KL	Concentration performance
λ	Air-fuel ratio for combustion
$L_{aeq,T}$	Continuous sound level of a noise source
L_{before}	Loss of CO_2e sinks due to deforestation, removal of vegetation or topsoil
LBG	Liquefied biogas (liquefied methane from bio-mass)
LCA	Life-cycle assessment approach
L_{con}	Loss of CO_2e sinks during the construction period
$L_{EX,8h}$	Daily noise exposure level (8h shift)
LF	Load factor
LFA	Transient load adjustment factor
LF_i	Load factor for engine size i
L_{flux}	Additional soil emissions, resulting in the first two to three years due to vegetation removal
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
L_{ser}	Loss of CO_2e sinks during the service life of the built product
LT_i	Lifetime of machinery type i
MAF	Mass air flow sensor
MAP	Manifold absolute pressure
M_{CO_2}	Mass of emitted carbon dioxide
M_x	Molar mass of x

$m_{CO_2,absorbed\ air}$	Mass of CO_2 in the air absorbed to cool the exhaust gas
m_{CO_2e}	Mass of CO_2e emitted
$m_{CO_2e,\alpha,r}^{NRMM}$	Total of greenhouse gases emitted during construction processes from construction equipment
$m_{CO_2e,i}$	The mass of CO_2e emitted for sub process *i*
$m_{CO_2e,T}$	Total mass of CO_2e emitted for the construction process
$m_{CO_2,fuel}$	Mass of CO_2 produced by combusting fuel
$m_{CO_2/tank}$	CO_2 mass per tank
m_{fuel}	Fuel mass
MgO	Magnesium Oxide
M_i	Mass of emitted pollutant i in an area
MOF	Metal-organic Framework
$m_{tank,x}$	Mass of the tank of fuel x
m_x	Mass of fuel x
N	Number of engines or units emitting the pollutant
n	Trippage rate for a truck or cycle criterion for an excavator
N_k	Number of units of material *k*
N1	Need 1
N_2	Dinitrogen
N2	Need 2
N_2O	Nitrous oxide
N3	Need 3
N4	Need 4
$N_{building}$	Quantity of office building
NEDC	New European Driving Cycle
NF_{total}	Total useable area
$N_{i,j,k}$	Number of engines with machine type i, engine size j and engine age k

NOx	Nitrogen oxides
NRMM	Non road mobile machinery
O_2	Oxygen
O^{2-}	Oxygen anions
OECD	Organisation for economic cooperation and development
OME	oxymethylene ether
P	Average rated engine size or engine power
$P_{eff.max,l}$	Effective engine performance of truck of type l
PSA	Pressure-swing-adsorption
PTSA	Pressure-temperature-swing-adsorption
$Q_{A-truck,l}$	Effective performance of a truck of type l
$Q_{B,r}$	Basic work performance of machine r
$Q_{E,r}$	Effective work performance of machine r
Q_x	Heat of x
ρ_{fuel}	Fuel density
$\rho_{tank,x}$	Tank density of fuel x
ρ_x	Density of x
r	Machine of type r
RDE	Real driving emission
s	Index s for topsoil removal
SCR	Selective catalytic reduction
SF_6	Sulfur hexafluoride
Si^{4+}	Silicon cations
T	Time of exposure
t	Total period of circulation
TAF	Transient adjustment factor
t_B	Loading time
t_{con}	Construction time
$TF(X)_{i,j,k}$	Transient factor for machinery type i, engine size j and engine age k

TF_z	Transient factor for emission level z
t_i	Time spend in engine mode i
$t_{idle,\alpha,r}$	Total idle time of machine r during elementary process α
T_r	Reference assessment time
t_{rapid}	Time of the fast growth phase
TREMOD	Transport emission model
TREMOD-MM	Transport emission model for mobile machines
TSA	Temperature-swing-adsorption
t_{ser}	Lifetime of the built product
$t_{standstill,\alpha,r}$	Total standstill time of machine r during elementary process α
$t_{total,\alpha,r}$	Total time of machine r during elementary process α
TTW	Tank-to-wheel
TWC	Three-way- catalyst
$t_{work,\alpha,r}$	Total working time of machine r during elementary process α
U.S.	United states
UBA	German Federal Environmental Agency
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
v	Velocity
v	Index for vegetation removal
V_{diesel}	Volume of the diesel fuel tank
VECTO	Vehicle energy consumption calculation tool
V_{fuel}	Fuel volume
$V_{fuel,x}$	Volume of fuel x
$V_{Material,l}$	Material amount to transport with truck of type l
VPSA	Vacuum-pressure-swing-adsorption
V_R	Nominal capacity of the truck or of the excavator bucket

VSA	Vacuum-swing-adsorption
V_{total}	Gross volume
VTSA	Vacuum-temperature-swing-adsorption
WC	Water closet
WLTP	Worldwide harmonized light vehicle test procedures
WTT	Well-to-tank
WTW	Well-to-wheel
z	Number of trucks or number of passages of a roller on a layer
ZH_{CO_2}	Carbon dioxide emission rate when the equipment is new
$ZnCl_2$	Zinc chloride

Preface

My journey to obtain the degree "doctor of engineering" started on May 2014. This long and stony trail can be compared to the ascent of the Machu Pichu Mountain. I was equipped with a light rucksack full of enthusiasm and energy. On my way to the summit I met people climbing with different baggage. With some I spent only brief moments, with others I walked parts of the path together. I was repeatedly confronted with various challenges. These allowed me to fill my rucksack with more experiences and more knowledge each time. Along the way to the top my rucksack became heavier and the air thinner. Luckily the decreasing provisions of enthusiasm and energy were regularly being refilled by my life partner.

In order to keep the pace, especially when you approach the peak, it is necessary to take little breaks in order to reassemble. The break times were strictly coordinated by my baby daughter. She forced me to take breaks and to enjoy all of them. Unfortunately, even with breaks, when you approach the top, the dizziness due to the lack of oxygen as well as the fog makes it really difficult to see straight. Thankfully my daughter had the solution for that and showed me how to see the world in a different way. A way where I was able to see through the fog to the peak of the mountain.

Finally, I reached the summit of Machu Pichu Mountain on July 2019.

This has been a big adventure, I was able to see and experience so much. Today my rucksack is full of experiences, knowledge, enthusiasm and energy. So I know with certainty that this ascent was only the warm-up exercise to get in shape for other more adventurous trails.

At this point I would like to thank my family who helped me to pack my rucksack and to choose the right equipment for the trip. Further, I would like to thanks my baby daughter and my life partner for having played key roles during the ascent.

A special thanks goes to my KIT colleagues and project partners, who accompanied me at some parts of the trail and stood by my side, even when it was raining or thundering.

A deep gratitude goes to my examiners who not only accompanied me from the beginning until the end, but also gave me the opportunity to start this journey.

Karlsruhe, July 2019
Isabelle Ays

« L’empire du climat est le premier de tous les empires »

Montesquieu, *De l’esprit des Lois*, 1748

1 Introduction

The scientific world has since the second half of the 19th century discussed the extent of the consequences of manmade (anthropogenic) emissions on the global warming (Randalls 2010). There is general agreement, that it is unknown what too much of anthropogenic greenhouse gases can cause. This is the reason why it is important to monitor the drivers, the impact and the adaptation of emitted greenhouse gases (CO_2e).

In this chapter, first international as well as European climate change initiatives will be reported. Then statistics will be reported regarding shares of greenhouse gas emissions in the construction sector. Finally, research objectives as well as the thesis outline of this work will be presented.

1.1 International climate change initiatives

The first international environmental treaty about greenhouse gas emissions was the “United Nations Framework Convention on Climate Change (UNFCCC)” which was adopted in 1992 and entered into force in 1994 with 166 parties[1] (UNFCCC 2019) participating. This convention has the aim to stabilize greenhouse gas concentrations in order to prevent “dangerous interference with the climate system” (UNFCCC 1992).

The objective of this treaty was implemented later in 1997 through emission targets in the Kyoto Protocol. This Protocol was ratified in 2005 by 37 industrialised countries and the European Community (EU-15), which committed to reduce greenhouse gas emissions to an average of 5 % below the level of 1990. The first commitment period of the treaty from 2008 to 2012 achieved its aim. As soon as 144 parties have deposited their instruments of ratification with the United Nation, a second commitment period from 2013 to 2020 will follow. (UNFCCC 2014; European Commission 2013)

[1] Parties are called countries that have ratified the convention. Today 197 countries have ratified the Convention.

The latest global effort to combat climate change is the Paris Agreement adopted in 2015 and ratified in 2016. It seeks to strengthen undertaken efforts and adaptation to climate change effects as well as to support developing countries to do so. The overall goal to limit the global average temperature by more than 2 °C above the 1990 level was further reinforced by limiting it to 1.5 °C. (UNFCCC 2017; Eurostat 2017b)

1.2 European motivation

There have been many debates and much criticism about how to reach a consensus on what actions needed to be taken to reduce greenhouse gas emissions. Uncertainties[2] about climate change itself, the costs of reducing greenhouse gas emission and effects of defining targets were addressed. In 1996 and again in 2005, the European Union was the first to formulate the goal of not raising the global average temperature by more than 2 °C compared to 1990 (Randalls 2010).

This goal is still facing a dual challenge. On one hand, the European Union wants to stimulate economic growth and on the other hand, it wants to reduce greenhouse gas emissions.

Based on this goal, derived targets to reduce greenhouse gas emissions are being pursued by the European Union. One action is the 2020 climate and energy package where the EU and its Member States reduce their greenhouse gas emissions by 20 % by 2020 (European Commission 2013, 2017a). Another action is the 2030 climate and energy framework where the EU commits to a reduction of at least 40 % with the aim to reach a low-carbon economy by 2050, equivalent to a cut of 80 % of the greenhouse gas emissions below 1990 levels (European Commission 2013, 2017a).

Through European regulation, the European Commission addresses the causes and consequences of climate change and at the same time turns these regulations into opportunities for our economy.

Latest projections confirmed that the goal for 2020 is well on track. In 2015, for example, the European Union had reached an emission reduction of 22 %

[2] Climate change uncertainties arises from three primary sources: natural climate variability, future emissions of greenhouse gases and modelling uncertainty

compared to 1990 and so surpassed its target for 2020. However, these same projections predict that the goals for 2030 or 2050 will not be reached with existing or additional known measures. (EEA 2016)

The urgency of the current situation in not reaching the goals is repeatedly being reported and encouraging actions by different parties (Stocker 9/19/2018; Macron 2017; Golombek and Klovert 2019).Therefore, in order to reach the different targets to reduce greenhouse gas emissions, every industry has to contribute its share.

1.3 Greenhouse gases in the construction equipment industry

Among the greenhouse gases (CO_2e) emitted in the construction equipment industry is the carbon dioxide gas (CO_2).

In 2016, 8.5 % of all carbon dioxide emitted in EU-28 came from “construction and construction work”. This correspond to 310 million tonnes out of 3,636 million tonnes of carbon dioxide. It’s the second biggest industry sector share after “electricity, gas, steam and air conditioning”. (Eurostat 2017a, p. 26)

The intensity of carbon dioxide (g CO_2/€) describes the amount of CO_2 “produced per unit of output or value added of the economic activity“ (ibid., p. 24). Comparing statistics from 2016 vis a vis 2008, for two economic activities, the intensity of carbon dioxide (g CO_2/€) has increased (ibid.). These two sectors are “construction” with an increase of 9.5 % and “mining and quarrying” with an increase of 3.4 % (ibid.). An explanation could be the economic recession, especially present in the construction industry since 2008. In 2016 the production volume in construction was reduced by 20% compared to 2008 (ibid., p.10).

In the present day, construction machines in Europe are mainly powered by engines that burn diesel fuel. Greenhouse gas emissions from such equipment arise indirectly through the production of fuel in plants and directly through the combustion process of diesel. The CO_2 amount as well as the greenhouse gas amount (CO_2e) emitted by construction machines can thus be derived from their diesel consumption[3]. According to the Arcadis study from 2010, for the European Commission, 13 % (43 million tons out of 343 million tons diesel) of the European diesel consumption of vehicles was combusted by non-road mobile machinery. The remaining 87 % are allocated to road traffic. From these 13 %, 43 % are allotted to construction machines. This correspond to 5 % of the total European diesel consumption (18.6 million tons of a total of 343 million tons of diesel) or 58.8 million tons of CO_2 emissions or 59.1 million tons of CO_2e emissions. (Vandenbroucke et al. 2010, pp. 19–36)

1.4 Research objectives

The aim of this thesis is to develop a scientifically robust quantification method of greenhouse gas reductions in construction applications from the construction equipment industry. Based on this method, the evolution of greenhouse gas amount along a specific timeline will be able to be reported.

In this thesis, data from the past, the present and the future will be analysed. This will enable to compare and to make conclusions about application optimisation.

This method will be valid for construction applications in quarry, earthmoving, road construction and building construction applications. The entire active chain will be considered from the extraction to the provision of materials or energy carriers as well as their transformation into products or movement energy. Contrary to a life cycle analysis, the method will not take into account the emissions produced during construction machines manufacturing or during the lifetime of the construction product.

In the course of the active chain, various factors influence the total greenhouse gas emissions. Even if a change in these factors has no or little effect on the order fulfilment of the construction project, they can have a strong impact on the greenhouse gas balance.

Within the scope of this thesis, the influences of machine efficiency, process efficiency, energy sources, operation efficiency, material efficiency and CO_2e

[3] The diesel amount is multiplied by 3.16 kg CO_2/l diesel or by 3.18 kg CO_2e/l diesel. The value of 0.832 kg/l is used for the diesel density.

capture and storage will be considered. By varying these influences, it will be possible to find a greenhouse gas optimised application.
The quantified amount of emissions in construction applications does not necessarily reflect the absolute value of greenhouse gases emitted. Rather, it provides credible quantitative estimates of greenhouse emissions, particularly on larger scales, so that statements about which measures and about how much influence they have on the final emission balance can be made.
A side-effect of reducing greenhouse gases is increasing efficiency during the construction application, which results in a reduction of the fuel consumption and so protects the environment and saves money.
The most important benefit resulting from the method is the possibility to understand and verify the attained greenhouse gas reductions from the machine equipment industry and thus contribute to improving the air quality, good living conditions for our and next generations. Finally, this thesis will be a contribution to the realisation of the European Union goals as well as for the global effort to keep the Earth mean temperature below 1.5 °C above preindustrial levels.

1.5 Thesis outline

Chapter 1 of the thesis provided the background and so the motivation for the thesis. A short overview about the thesis objectives was presented as well.
Chapter 2 will explain greenhouse gas emissions in general and the interpretation from the political scene together with scientific findings. Afterwards, the description of example concepts from different industries on how greenhouse gases emissions can be limited follows. The chapter ends with a summary of needs for an effective method in the construction equipment industry.
Chapter 3 will consist of analysing weaknesses and strengths of different existing methods, assessment tools and databases quantifying greenhouse gas emissions. Based on the analysis results, research gaps will be derived.
Chapter 4 will present the CO_2e quantification method for construction equipment. First, a general approach will be described and then the investigation scope will be defined. Afterwards the description of the main CO_2e

influences will follow. The chapter will end with the quantification procedure by considering all influences described earlier.
Chapter 5 will define nine representative European construction applications from four construction sectors based on statistical analyses.
In chapter 6, first through expert survey according to the Delphi method and a literature review, all influences will be verified and their influence range will be determined. Values for each CO_2e influencing factor in the times past, present and near future will be defined in order to carry out the developed CO_2e quantification method along with a factor influence analysis of an excavator. Additionally, the CO_2e amount emitted during the representative construction applications as well as the reached and expected CO_2e reduction for this timescale will be quantified. The chapter will end with showing the influence of CO_2e sinks destruction and formation based on a road construction example.
In chapter 7, the developed CO_2e quantification method will be validated based on an excavator, rollers and pavers.
In chapter 8, three possible measures enabling the reduction of CO_2e emissions from nonroad mobile machinery will be presented. The first will consist of using an alternative energy carrier, the second in an alternative drive and the third in the implementation of a CO_2 capture and storage system.
Lastly, chapter 9 will conclude the thesis with a summary and an outlook.

2 Anthropogenic greenhouse gas emissions

This chapter will summarise the state of the art about greenhouse gas emission reductions. First, the greenhouse effect and greenhouse gas emissions will be explained briefly. Then, the chapter will analyse emission reduction actions in different industries. The results analysis will lead to the identification of needs.

2.1 Greenhouse effect

The radiation equilibrium of the Earth is called the natural greenhouse effect. The sun's rays are partially absorbed by the atmosphere and the Earth's surface. Like every physical body, when the temperature increases, the earth's surface emits more heat (emissions of long-wave radiation). Some of the atmospheric trace gases, also called greenhouse gases, absorb more long-wave radiation then solar radiation. Consequently, the heat is not radiated directly into space but is absorbed by the greenhouse gas in the lower atmosphere and partly reflected back to the earth's surface. Therefore, not only solar radiation but also long-wave radiation reaches the earth's surface. Consequently, the earth radiates accordingly more heat, which means the temperature rises. Without this process or rather if greenhouse gases did not absorb long-wave radiation, the average temperature on Earth would be -18 °C instead of the necessary temperature for life to exist of +15 °C. The manmade greenhouse effect results from human activities increasing the concentration of existing trace gases and so increases the temperature of the Earth surface. (Rahmstorf and Schellnhuber 2007)

2.2 Greenhouse gas emissions CO_2e

All parties of the UNFCCC, including the European Union define under the term greenhouse gases (GHG), gases which contribute to the greenhouse effect. Monitored greenhouse gases are listed in Table 2-1. In order to compare these gases to each other and so assess their effects on the radiation equilibrium of the Earth; each gas is converted to an equivalent effect on carbon dioxide (GWP value). The abbreviation is called "CO_2-equivalent" (CO_2e). The average heating effect of each gas is taken into account over a period of 100 years. The Intergovernmental Panel on Climate Change (IPCC) have together with scientists and politicians determined the GWP value for each greenhouse gas. The GWP-value for each gas is delineated in Table 2-1.(Greenhouse Gas Protocol 2016)

The GWP values of the second assessment report (SAR) were used for the duration of the first commitment period of the Kyoto Protocol (2008-2012). For the second commitment period (2013-2020), the GWP values of the fourth assessment (AR4) report are valid. The IPCC recommends using the latest values of the 5. assessment report (AR5). (EEA 2016; Greenhouse Gas Protocol 2016)

Table 2-1: GWP values of most common greenhouse gases (based on Greenhouse Gas Protocol 2016)

Name	Chemical formula	GWP-values for 100 year time horizon		
		2. Assessment-Repot (SAR)	4. Assessment-Report (AR4)	5. Assessment Report (AR5)
Carbon dioxide	CO_2	1	1	1
Methane	CH_4	21	25	28
Nitrous oxide	N_2O	310	298	265
Sulfur hexafluoride	SF_6	23,900	22,800	23,500
Hydrofluorocarbons	HFCs	140 – 11,700	124 – 14,800	4 – 12,400
Tetrafluoromethane	CF_4	6,500	7,390	6,630
Hexafluoroethane	C_2F_6	9,200	12,200	11,100

The Table 2-1 shows that the emissions, referenced on a timescale of 100 years, of e.g. 1 kg of methane (CH_4) corresponds to a greenhouse effect 21 times[4] larger than the effect of 1 kg of carbon dioxide (CO_2) emissions.

Further, two types of emissions are differentiated: direct and indirect GHG emissions. Direct GHG emissions are emitted on site through energy consumption, in particular through fuel consumption. Otherwise, indirect GHG emissions come to pass from sources owned or controlled by another entity

[4] The effect is 21 times larger if the values are taken from AR2. It would be 25 times larger if the values are taken from AR4 or 28 times according to AR5.

like emissions from extraction and transportation of material, of fuel or electricity. (Greenhouse Gas Protocol 2016)

2.3 Emission reduction actions in different industries

Current circumstances show that if there is no careful holistic reflection beforehand, positive intentions can lead to negative side effects. In the following text, some examples from different industries will be described.
The first example is from the automotive industry. It will be followed by an example from the heavy-duty vehicle industry. Then, the effects of the German Biofuel Quota Act will be described briefly. Finally, this subchapter will end with an example of self-commitment from the Confederation of German Industry.

2.3.1 Automotive industry

The automotive industry uses driving cycle in order to verify emission limit values. The regulation EG-No. 443/2009 indicates that until 2015, new passenger car fleets will not exceed emissions of 130 g CO_2/km. The NEDC European driving cycle is used to carry out emission measurements for type approvals in the EU. (Ernst 2014)
The NEDC driving cycle has long been heavily criticised since it is not able to give information about an average travelled distance. Consequently it raised the question for the automotive industry whether the CO_2 emissions during the driving cycle or during real customer drives should be reduced.
A new cycle called "Worldwide Harmonized Light Vehicle Test Procedures (WLTP)" which is closer to reality, has been gradually introduced since September 2017 (ACEA 2019). This cycle has been complemented with a real driving emission (RDE) test valid for new car types since September 2017 (AECC 2019).
At the moment, the WLTP seems to be the solution, so that the automotive effort contributes to the global effort of reducing greenhouse gas emissions.

2.3.2 Heavy-duty vehicle industry

The international council on clean transportation (ICCT) published a study in which it is shown that over the last 13 years the fuel consumption over 100 km for heavy-duty vehicle tractor trailers have not significantly changed (Rachel Muncrief and Ben Sharpe 2015). Between 1990 and 2007, road freight traffic increased by 19 % which is the main cause for the 30 % rise of CO_2 emissions compared to 1990 (European Commission 2017b).
This has triggered discussions about introducing emission limit values for this industry sector (CEMA and CECE 2011; European Commission 2017b).
The dialogue with the European Union and the heavy-duty vehicle industry led to the agreement that CO_2 emissions from heavy-duty vehicles will be quantified with a simulation program. The program “Vehicle Energy Consumption Calculation Tool (VECTO)” has been mandatory for new trucks since January 2019 and CO_2 reduction targets have been formulated for 2025 and 2030 (European Commission 2019; CECE 2016).

2.3.3 Fuel industry

In 2007, the Biofuel Quota Act was introduced in Germany and led to an unexpected effect. It forced the fuel industry to add a minimum quota of biofuel to regular diesel fuel in order to reduce greenhouse gas emissions. For economic reasons, fuel producers started to add imported biofuel from e.g. Argentina or Indonesia. The imported biofuel had long transport routes and was so not reducing greenhouse gas emissions. In 2009, the Biofuel Quota Act was revised and complemented with a climate protection quota. (Kirchner 2013; Europäische Parlament und Rat der Europäischen Union 2003, 2009)

2.3.4 Confederation of German Industry (BDI)

In 1995 an agreement was reached between the Confederation of German Industry (BDI) and the German Federal Government to reduce CO_2 emissions and the energy consumption of the German economy by 20 % compared to the level of 1987 by 2005. First monitoring reports from the RWI Leibniz Institute for Economic Research describe in the first two years undesirable side effects like a reduction of CO_2 emissions coupled with an increase of greenhouse gases (CO_2e). In March 1996, the self-commitment was reformulated and expanded so that by the year 2005 the CO_2 emissions would drop by 28 % and by 2012, the other Kyoto-gases would drop by 35 % compared to the level of 1990. In addition to the BDI, this “Expanded Agreement on Climate Protection” was also accepted by 17 other associations (and later from 2001 until 2002 by three more associations). The expanded agreement consisted of 19 individual commitments. Some of these individual commitments had to be fulfilled by 2005, but the target year for the whole self-commitment was 2012. In return for the expanded self-commitment, the federal government ensured they would refrain from an energy audit and acknowledged the efforts of the industry through a surplus settlement when it instituted the ecological tax reform. In 2012, the total achieved greenhouse gas reduction was 117 % of the original target. This means, that the strived target was exceeded. (von Schlippenbach 2001; Rheinisch-Westfällisches Institut für Wirtschaftsforschung 2008, 2013)

2.4 Summary of needs (Nx)

In this chapter, the natural and anthropogenic greenhouse gas effect has been explained. Afterwards, the main greenhouse gases contributing to the greenhouse effect were listed and their effect numbered (GWP value). The last subchapter reported on action examples from different industries with the objective of reducing greenhouse gases.

These action examples have shown that an environmental improvement method which is not well thought out, not reliable and yet upon which regulations are based can lead to a contrary effect of the original objective.

In summary, the environmental improvement method has to consider all greenhouse gases listed in the IPCC fourth assessment report and not only carbon dioxide like in the first BDI self-commitment. (N1)

Moreover, for the method, a holistic approach is needed where the entire process is being considered. The fuel industry showed that if not the whole process like transport routes of fuel are taken into account, a false statement can happen. (N2)

Some successful reach targets are based on self-commitments from industry and from legislation (BDI 2004). In Germany, a large number of successful agreements concerning e.g. the use of certain substances such as asbestos, CFCs, etc. were concluded (von Schlippenbach 2001). The BDI and the truck industry have shown that cooperation and discussions between industries and legislation are essentials in order to reach common climate goals (N3).

The weather prediction model, the climate prediction model or the NEDC driving cycle in the car industry can be demonstrated to be right or wrong. In fact a model is based on accepted physical principles and verified with accumulated statistics. Even if a model like a climate model shows "quantitative estimates of future climate change, particularly at larger scale" (Solomon et al. 2007), it still has potential significant errors. The main source of such errors is that small-scale processes can't be exactly represented in models (Solomon et al. 2007). Nevertheless, models have proven to be a valuable tool to understand and simulate aspects of a system even when not all processes can explicitly be modelled (ibid.). The developed method should enable simulation of CO_2e reduction measures in order to make a statement about their impact (N4).

3 State of research

Different scientific entities have developed methods, assessment tools and databases to quantify greenhouse gas emissions of construction equipment. In this chapter, first, the analysis framework will be explained. Afterwards the current state of research will be reviewed and strengths and weaknesses will be worked out. Initial searches took place in June 2014 and were reviewed in July 2018. In total, 80 different matches were investigated which were developed by governmental, non-governmental organisations and academic researchers. The review of the investigated matches will lead to the identification of the research gaps.

3.1 Analysis framework

In order to analyse the state of research, CO_2 and CO_2e quantification methods for construction equipment were reviewed and analysed. In the reviewing process, the main focus lies in identifying the quantification method, its system boundary and the parameters influencing the result of the applied method. Thus, the method has to be transparent on these three aspects and has to consider the overall impact on the environment of efficiency improvements.

In addition, the validity of the reviewed method was investigated for the application areas as well as the transferability of the method to other types of construction equipment as referred to in the publications. This means, the method has to be valid for different construction applications and for different construction machines.

Further, in order to quantify the evolution of CO_2 and CO_2e emissions over time, the method needs to be applicable on different time lines.

The methods were classified according to three categories: core models, which are explained in detail, studies and tools, comprised of assessment tools and databases. The category "core models" summarise all particular procedures for quantifying CO_2 or CO_2e gases from machines during construction processes. The methods are described through a mathematical

equation. In “studies” further methods are described in summary form. In the category “tools”, the method is within a software tool and not always transparent and neutral. In order to work, those software tools have to be comprised of a method and a database. When the quantification procedure is not identifiable, via the input area of the tool, it is possible to determine the influencing factors. Likewise, data collections about emissions of construction equipment are reviewed. In case of non-transparency of the database, information is sought from publications reviewing the tool.
During the analysis of the selected contributions, descriptions of existing relations will be questioned and their strengths and weaknesses will be worked out. The result of the analysis will enable identification of research gaps.

3.2 GHG & CO_2 quantification methods for construction equipment

In this part, seven “core models” will be described, followed by a short analysis of other models and an analysis of existing “tools” which can be time based, fuel based or of database nature.

3.2.1 NONROAD–Model

The method of the United States Environmental Protection Agency (EPA) is being used as a basis in different studies (Arocho et al. 2016; Zhang 2015; Shao 2016; Li and Lei 2010; Egbu et al. 2009; Sandanayake et al. 2016; Millstein and Harley 2009) or as the basis of CO_2 quantification methods (Ahn et al. 2010; Ahn et al. 2009; Hajji and Lewis 2013a; Trani et al. 2016; Ahn and Lee 2013). Initially, this pollutant quantification method was developed to calculate the emissions of nonroad diesel machinery during the inventory period in an area (M_i), like per state. The equation *(3-1)* is being used for this purpose. It consists of multiplying the number of units emitting the pollutant (N) with the source’s annual hours of use (HRS), averaged rated horsepower (HP), typical load factor (LF) and its average mass of emitted pollutant i per unit of use(EF_i). (EPA 1991, 2010a)

$$M_i = N \times HRS \times HP \times LF \times EF_i \qquad (3\text{-}1)$$

When considering the pollutant CO_2, the EPA calculates M_{CO_2} with an adjusted emission factor for transient operations $\mathrm{EF}_{adj\,(\mathrm{CO_2})}$ in g/(hp × hr). The original CO_2 emission factor $\mathrm{EF}_{SS\,(\mathrm{CO_2})}$ was determined during steady-state test measurements of engines, and therefore is multiplied with a transient adjustment factor (TAF) which can take following values: 1.00, 1.18 (average low load factor) and 1.01 (average high load factor). The calculation formula corresponds to following equation (3-2). (EPA 2002)

$$\mathrm{EF}_{adj\,(\mathrm{CO_2})} = EF_{SS(CO_2)} \times TAF \qquad (3\text{-}2)$$

The emission factor $\mathrm{EF}_{\mathrm{SS(CO_2)}}$ is calculated based on the steady state fuel combustion of the engine according to equation (3-3). For this equation, all the carbons of the fuel burnt are assumed to be converted into CO_2. The fuel burnt is the subtraction of the total available fuel with the unburned fuel. The amount of fuel consumed is being indicated with the brake-specific fuel consumption (*BSFC*). The unburned fuel is assumed to be indicated by the power specific mass of the hydrocarbon emissions (*HC*). Further the EPA estimates that 87 % is the carbon mass fraction of diesel. 44/12 represents the ratio of CO_2 molar mass to C molar mass. (EPA 2010a)

$$\mathrm{EF}_{\mathrm{SS(CO_2)}} = (BSFC - HC) \times 0.87 \times (44/12) \qquad (3\text{-}3)$$

The brake-specific fuel consumption can take two average values depending on the power level of the engine. The values were calculated based on measurements of five different engines with a power level of 37 to 75 kW and thirteen different engines with a power level over 75 kW. These two values are considered constant over the years and over exhaust gas Tier generations. (EPA 2002).

Using a constant fuel consumption is incorrect because it varies depending on the activity of the equipment, its machine efficiency which can be classified according to the Tier generations, its process efficiency, its operation efficiency and the fuel type used during operation. Consequently using an emission factor based on time and horsepower is inaccurate and a transient adjustment factor (*TAF*) is not enough. The amount of CO_2 emission is in relation to the amount of carbon atoms in the fuel (Edwards et al. 2014a). It will therefore vary relative to fuel consumption, consequently a fuel based CO_2 emission factor is advocated.

Another weakness in this method is the load factor (*LF*). It is true that "engines typically operate at a variety of speeds and loads" (EPA 2010b) and that they seldom reach the maximum power described in the machine data sheet. Nonetheless taking into account the idle state distorts the results concerning the load factor. During idle state of the machine, the engine is running at low power and so reduces the actual load factor. This load factor is not representative for the machine at work. Idle time of a machine varies not only depending on the assignment but also depending on the construction site organisation, the amount of unavoidable idle time due to the process and the machine driver's behaviour e.g. switching off the engine when the machine is not needed.

Further this method does not make any difference if the machine is being rented or is privately owned. Rental machines have greater annual utilisation, higher average horsepower rating and so a shorter lifetime. Heidari and Marr compared the CO_2 emission rates of this method with real data from earthmoving machines in the US and found out a difference of 60-90 % (Heidari and Marr 2015). This study proves that consideration of further factors are necessary in the Nonroad model.

3.2.2 OFFROAD-Model

The OFFROAD model was developed by the California Air resource Board (CARB) for estimating emissions from nonroad machinery for the state of California. The methodology is very similar to the Nonroad model. The emission inventory formula is like equation *(3-1)*. The emission factor for CO_2 is expressed in grams per brake horsepower hour and is calculated using equation (3-4). (CARB 2006)

$$\mathrm{EF}_{\mathrm{CO_2}} = dr \times CHrs + ZH_{CO_2} \qquad (3\text{-}4)$$

During the useful life of a machine, engine parts wear out and an increase in emissions occurs. This effect is taken into account with the deterioration factor *dr* in grams per brake horsepower hour squared, multiplied by the total accumulated operation hours of the machine (*CHrs*). The Offroad model assumes that a diesel engine is rebuilt after 12,000 hours. As a result the deterioration factor is constant when the engine's cumulative hours are equal or bigger than 12,000 hours. In this case *CHrs* takes the value of 12,000

hours. ZH_{CO_2} represents the CO_2 emission rate when the equipment is new, in grams per brake horsepower hour. Data from the EPA is used for the determination of ZH_{CO_2} and the brake specific fuel consumption. (CARB 2009)
Interesting in this method is the consideration of the increase of emissions according to the useful life of the machine. However, the focus lies only on the engine, which doesn't correspond to reality. Not only the engine wears out but also hydraulics, gears, tyres, etc. All this can significantly increase fuel consumption and hence the CO_2 emission quantity. The deterioration rate is based on data from on-road motor vehicles (CARB 2006), which is not representative. Nonroad vehicles have the task of performing work processes as well as driving (Geimer 2014). Therefore, they have different functions and are under different stresses than on-road vehicles. Further, the same weaknesses are identified as in the Nonroad model concerning the emission factor, the load factor and the influence considerations.

3.2.3 Lewis Method

Lewis defines that the weighted-average fuel use rate ($\text{Fuel}_{\text{wt.avg.}}$) for a duty cycle equals the sum of fuel spent during each engine mode like in equation *(3-5)*. Engine mode 1 corresponds to the engine at idle. Engine modes 2 to 10 represent the machine at work where 10 describes the highest possible engine load. t_i and A_i correspond to the time spent in engine mode *i* and to the estimated fuel use rate for mode *i*, respectively. (Lewis 2009)

$$\text{Fuel}_{\text{wt.avg.}} = \sum_{i=1}^{n} t_i \times A_i \qquad (3\text{-}5)$$

In Lewis et al. fuel consumption as well as CO_2 emission rate are identified to have a linear relationship with the manifold absolute pressure (MAP), the engine speed and the intake air temperature (Lewis et al. 2015). In Hajji and Lewis equation *(3-6)* is used to calculate the CO_2 emissions for earthwork construction activities (Hajji and Lewis 2013b). The activity construction duration is described with the quantity of soil moved over the productivity rate. Where the productivity rate is calculated according to a linear relationship of factors depending on the earthmoving machine. For a bulldozer, the productivity rate will be dependent on the engine horsepower, the distance and the soil type; for the excavator it will be dependent on the soil factor, the scraper type, the trench depth and the bucket capacity (Hajji 2015, p. 117).

$$\mathrm{E}_{CO_2} = \frac{\text{soil quantity}}{\text{productivity rate}} \times HP \times \left[(BSFC - HC) \times 0.87 \times \frac{44}{12} \right] \qquad (3\text{-}6)$$

Lewis discovered that fuel consumption varies between engine at idle and at work. In order to fulfil an activity, different engine modes from 2 to 10 are combined together. This results in small variations in average fuel consumption per activity. (Lewis 2009, pp. 74–125)

Therefore, the "most significant change in emission rates for construction equipment occurs between idle and non idle activities" (Lewis et al. 2012a, p. 69). This means that "the total emission of a particular pollutant can be calculated as the sum of the average emissions quantity during non idle time plus the average emissions quantity during idle time" (Lewis et al. 2012a, p. 69).

This statement and consideration of idle time is not being used by Lewis in his following work, e.g. in equation *(3-6)*. Another weakness in equation *(3-6)* is the lack of consideration that construction machines do not work at maximum engine load. The average engine load varies depending on the machine type and its application. Equation *(3-6)* contains equation *(3-3)* and so the same remarks about the Nonroad model are valid. Further the method do not take into account enough representative influences on emissions of construction equipment like the driver, the weather or machine deterioration over time.

Weaknesses and the lack of further factor considerations in the Lewis method are approved in the study of Heidari and Marr, where real CO_2 emission rates from eighteen earthmoving machines are compared with calculation results from the Lewis method. A difference to the real data is calculated to be ± 70 %. Only four of the eighteen machines had a difference below 10 %. (Heidari and Marr 2015)

3.2.4 EMEP/EEA Air pollutant Emission Inventory Guidebook

The Long-range Transboundary Air Pollution (EMEP) together with the European Environment Agency (EEA) provide in form of a guidebook

emissions quantification methods (Dore et al. 2016, p. 12). For nonroad mobile sources and machinery, three methodological levels are proposed and are named Tier 1, Tier 2 and Tier 3 (ibid., p. 15). Tier 1, equation *(3-7)* is recommended when very little information is available, Tier 2 when information about engine stages are attainable and Tier 3, equation *(3-9)* when all data at equipment level are present. For the pollutant CO_2 the equation Tier 2 equals the equation of Tier 1 and will therefore not be discussed further. Tier 3 is the recommended method. (Winther et al. 2017, pp. 20–22)
The Tier 1 equation according to the EEA method is as follows (Winther et al. 2017):

$$\mathrm{E}_{\mathrm{CO}_2} = \sum_{fuel\ type} FC_{for\ fuel\ type} \times EF_{CO_2 for\ fuel\ type} \tag{3-7}$$

The CO_2 emissions in kg ($\mathrm{E}_{\mathrm{CO}_2}$) are calculated when adding up all CO_2 emissions for each fuel. The CO_2 emissions for each fuel are determined by multiplying fuel consumption ($FC_{for\ fuel\ type}$) in tons with the CO_2 emissions factor for the fuel type considered ($EF_{CO_2\ for\ fuel\ type}$). For diesel, $EF_{CO_2\ diesel}$ equals 3,160 kg/t diesel. If the amount of fuel consumption is unknown the following relationship *(3-8)* has to be used. (Winther et al. 2017, pp. 20–22)

$$\frac{F_{liquid}}{TJ} = 0.49 \times \frac{GVA}{10^6\ €} \tag{3-8}$$

Where F_{liquid} in TJ is the amount of energy of liquid fuel used in manufacturing and construction equipment and *GVA* corresponds to the gross value added for manufacturing and construction in millions of Euro (Winther et al. 2017, pp. 27–28).
The following equation *(3-9)* represents level Tier 3 (Winther et al. 2017, p. 35)

$$E_{CO_2} = N \times HRS \times P \times (1 + DFA) \times LFA \times EF_{Base} \tag{3-9}$$

The mass of emissions of CO_2 during the inventory period (E_{CO_2}) is calculated through multiplication of the number of engines (*N*) by the annual hours of use (*HRS*), by the engine power (*P*), by the transient load adjustment factor (*LFA*), by (*1+DFA*) which represents the deterioration factor adjustment (*DFA*) and by the base emission factor (EF_{Base}) in g/kWh. (Winther et al. 2017, 35-ff)

This calculation method is used in Sweden as well as in the tool CO_2NSTRUCT (Lindgren 2007; Barandica et al. 2013).
Only CO_2 emissions from the past can be determined using the Tier 1 algorithm. It does not permit prediction of CO_2 emissions. If the amount of fuel consumption is unknown, the equation *(3-8)* is recommended. This equation cannot be assumed to be correct because many uncertainties are not taken into account. The sector of application (construction or manufacturing), types of activities and types of machineries (stationary or mobile) are not distinguished. Further the average fuel consumption for each machine type has changed during each machine generation. This change is also not taken into account in equation *(3-8)*. In Winther et al., the data used to develop equation *(3-8)* can be seen (Winther et al. 2017, p. 78). It shows that equation *(3-8)* is only valid for Denmark, Finland, Hungary, Norway and UK for projects with a GVA below 50,000 million Euros. The equation is also not valid for Belgium, Italy or France and data from east European countries were not considered.
A factor to reduce the maximum engine power is missing in equation *(3-9)* since construction machines rarely work at full engine power. Data to determine the LFA factor from stationary to transient engine use are based on data from the United States Environmental Protection Agency complemented with data from the Graz University of Technology. US engines and European engines are not the same because of the different emission limits classes ("Stages" in Europe and "Tier" in the US) (Ehrhard and Widmann 2017). Therefore, engine data from US are not necessarily valid for European engines. Equation *(3-9)* uses a base emission factor in g/kWh like the Nonroad model. The emitted CO_2 amount depends on the amount of carbon atoms in the fuel and the base emission factor should therefore be in g CO_2/g fuel (Edwards et al. 2014a). Further, to focus only on the wear on the engine is not enough. Wear on other parts of the machine also has consequences on the fuel consumption and on CO_2 emissions (CAT 1999). Winther et al. identify that mobile construction machines owned by a rental company are used for more hours in a year which means that its usable lifetime is reduced, and needs to be replaced more frequently than a privately owned machine (Winther et al. 2017, p. 7). This statement is not taken into account in any Tier-methodology.

3.2.5 Denmark Model

Winther and Nielsen quantify the fuel consumption and the emissions for nonroad machinery in Denmark from 1985-2004 and for 2005-2030. For this purpose, equation *(3-10)* is used to calculate the amount of CO_2 emissions. (Winther and Nielsen 2006)

$$E(X)_{i,j,k} = E_{Basis}(X)_{i,j,k} \times TF(X)_{i,j,k} \times (1 + DF(X)_{i,j,k}) \qquad (3\text{-}10)$$

Where *i* stands for the machinery type, *j* for the engine size and *k* for the engine age. $TF(X)_{i,j,k}$ describes a factor adjusting stationary cycles to transient cycles. $DF(X)_{i,j,k}$ is the deterioration factor and takes into account the effects of engine wear. $E_{Basis}(X)_{i,j,k}$ represents the amount of CO_2 emissions during ideal situation and is calculated with algorithm *(3-11)*. (Winther and Nielsen 2006, pp. 46–47)

$$E_{Basis}(X)_{i,j,k} = N_{i,j,k} \times HRS_{i,j,k} \times P \times LF_i \times EF_{y,z} \qquad (3\text{-}11)$$

N describes the number of engines, *HRS* the annual working hours, *P* the average rated engine size, *i* the machine type, *j* the engine size, *k* the engine age, *LF* the load factor and *EF* the emission factor in g/kWh. (Winther and Nielsen 2006, pp. 46–47)

The deterioration factor considers wear on the engine and is calculated for diesel or gasoline 2-stroke engines with equation *(3-12)* and for 4-stroke engines with *(3-13)*. *K* represents the engine age, *LT* the lifetime and $DF_{y,z}$ the deterioration factor for engine size class *y* and emissions level *z*. *i* stands for the machinery type, *j* for the engine size and *k* the for engine age. (Winther and Nielsen 2006, pp. 46–47)

$$DF(X)_{i,j,k} = \frac{K_{i,j,k}}{LT_i} \times DF_{y,z} \qquad (3\text{-}12)$$

$$DF(X)_{i,j,k} = \sqrt{\frac{K_{i,j,k}}{LT_i}} \times DF_{y,z} \qquad (3\text{-}13)$$

The transient factor $TF(X)_{i,j,k}$ is calculated with equation *(3-14)* where *z* stands for the emissions level (Winther and Nielsen 2006, pp. 46–47).

$$TF(X)_{i,j,k} = TF_z \qquad (3\text{-}14)$$

Two main weaknesses are identified in the Denmark Model: the focus only on the engine instead of the whole machine and on the CO_2 emissions factor related to kWh instead of the amount of fuel.

3.2.6 TREMOD- Mobile Machinery model (TREMOD-MM)

The ifeu institute for energy and environmental research developed the Transport Emission Model (TREMOD) for the German Federal Environmental Agency (UBA) to determine and process information from the German transportation sector and from mobile machinery. The model comprises driving and traffic performance, load factors, specific energy consumption and emissions factors from 1960 to 2030. (Umweltbundesamt 2018; Knörr et al. 2016)
The TREMOD-MM model uses the same equation *(3-1)* as the EPA model to calculate pollutant emissions (Helms and Heidt 2014). For the calculation of the amount of CO_2 emitted, a CO_2 emissions factor is needed. This is calculated based on fuel consumption data (not CO_2 measurements) from engines on the test bench. Therefore, a transient adjustment factor (*TAF*) based on data from U.S. EPA surveys and from the Graz University of Technology is used like in equation *(3-2)*. The steady CO_2 emissions factor is derived from data on the fuel quality and the carbon content. (Helms and Heidt 2014; Knörr et al. 2010)
This model is similar to the EPA model and thus has the same weaknesses.

3.2.7 Swiss non-road Database

The Swiss non-road database is an online database accessible on the website of the federal office for the environment (BAFU) (Swiss Federal Office for the Environment 2016). It calculates the direct pollutant emission amount for mobile nonroad machinery and has been created for the annual climate gas inventory and as the basis for planning measures to prevent air pollution (Notter and Schmied 2015). Electrical machines have no direct emissions and so no CO_2 emissions are reported for these machines (ibid., p.11). The direct CO_2 emissions from mobile machines are calculated by multiplying the fuel consumption by the emissions factor from Table 3-1 (ibid., p.22).

Table 3-1: Conversion factor from fuel to CO_2 emissions (Notter and Schmied 2015)

Fuel	Conversion factor
Diesel	3.150 g CO_2/g fuel
Petrol	3.141 g CO_2/g fuel
Fuel oil	3.140 g CO_2/g fuel
Liquefied petroleum gas	2.558 g CO_2/g fuel

The fuel consumption (FC) is calculated with the following equation *(3-15)*.

$$FC = N \times H \times P \times \lambda \times \varepsilon_{FC} \times CF_1 \times CF_3 \qquad (3\text{-}15)$$

Where N stands for the number of machines, H for the operation hours, P for the average rated power and λ for the load factor. ε_{FC} represents a constant fuel consumption factor which is taken from the Nonroad model. For diesel machines with a rated power below 75 kW the fuel consumption equals 248 g diesel/kWh and for bigger than 75 kW, it equals to 223 g diesel/kWh. The fuel consumption factor is given for a stationary engine at 48 % of its full load. The specific fuel consumption is conditional on the load point, therefore for diesel machines, a correction factor CF_1 is introduced to rectify ε_{FC}. CF_1 is calculated according to the ratio of the effective load to the standard load according to ISO-Cycle 8178 C1. CF_3 is a correction factor which takes into account the fuel consumption variation during the ageing process of the machine. This correction factor is only applicable for engines with emissions regulation limits older than Stage EU-IIIa. For diesel engines, the correction factor CF_3 equals 1.0. EU-IIIa engines or newer engines are considered to have no deterioration over time. (Notter and Schmied 2015)

The amount of CO_2 emissions is derived from the fuel consumption using a conversion factor into g CO_2/g fuel which is rated as positive. The fuel consumption calculation only focuses on the engine behaviour and not on the entire machine. Fuel consumption and so CO_2 emissions are dependent on the machine technology, on the machine deterioration, on the machine process application, and on its operator. Further, the fuel consumption data used in the calculation is data from US engines from 2002 or older. This CO_2 calculation method takes no efficiency improvement of either the engine or the machine technology into account.

3.2.8 Other studies on construction equipment

Several other studies have attempted to quantify the CO_2 emissions emitted from construction equipment during its application. Kim et al. compared three methods for this purpose. The first method is recommended by the IPCC, where CO_2 emissions are calculated by multiplying the fuel consumption by the carbon emission factor, with the oxidation rate and with the conversion factor. The second method is based on the chemical reaction formula of diesel oil. The third method consists of using flow velocity measurement, where the vehicle exhaust gas is collected and stabilised before measuring the CO_2 concentration. By comparing these three methods, Kim et al. found that direct measurements of CO_2 were between 7.5-61.5 % lower than the other two theoretical methods. This result is foreseeable when no consideration of idle state is made in the theoretical calculation methods even though it is recognised during measurement. Kim et al. also found during direct measurement that climate temperature and engine speed have strong correlation only during idle state which indicates that during working state other factors have an impact and should be identified and considered as well. (Kim et al. 2015)

Jassim et al. proposed two models for calculating the energy use and the CO_2 emissions of an excavator in advance. The first is based on artificial neural networks and the second on a multivariate linear regression analysis. Both methods have been developed by including the parameters of excavation depth, density of material, bucket payload, cycle time and horsepower. The missing differentiation between idle and working time limits both models. This means that effects from idling, variation of engine generation, working in ECO-mode, machine state, process conditions, operator capacity and use of alternative fuels instead of diesel are not considered. (Jassim et al. 2016)

Barati and Shen developed a CO_2 quantification method based on the engine load of on-road construction machines (Barati and Shen 2016). Also in this method the focus lies on the engine and road conditions. Machine condition, operator, process efficiencies are not taken into account.

Krantz et al. calculate CO_2 emissions by multiplying the conversion factor diesel into CO_2 by the total fuel consumption of all mobile machines used in the construction project. The fuel consumption of one machine is defined by multiplying the activity time by the rated power, the average load factor and the brake specific fuel consumption. (Krantz et al. 2017)

Similar to Krantz et al., Ji et al., Yan et al. as well as Feng and Zhong, calculate the CO_2 emissions by multiplying the diesel-CO_2 conversion factor by the total fuel consumption of a machine. Interesting in the study of Ji et al. is how the effects of recycling material are being considered. It is assumed that a percentage of the construction material will be recycled at the end of the construction life. This percentage is taken into account during quantification of carbon emissions of construction material. (Ji et al. 2015; Yan et al. 2010; Feng and Zhong 2015)

These calculation methods from Krantz et al., Ji et al., Yan et al. and Feng and Zhong do not take into account individual efficiencies from machine, process and operation.

Fan identifies that the proper equipment and equipment size for the jobsite, the equipment generation, its age, its maintenance quality, the fuel type used, the altitude of the construction site, the soil type, the weather, the working and idle time and the operator skills based on education, experience and salary pay level affect construction equipment emissions (Fan 2017). For sustainable construction Sing et al. recommend considering site specific impacts, impacts of different materials and products used, the construction process, uncertainties as well as indoor and outdoor construction quality (Singh et al. 2011). Li and al. quantify the environmental impact of construction processes on human health, resource depletion and ecosystem damage in US dollars (Li et al. 2010). The study shows that ecosystem damages due to construction is important and should not be neglected (ibid.).

Studies on construction productivity identified production influencing factors to be as follows: basic performance of a machine due to jobsite location, service and maintenance conditions of the machine, operator skills, motivation and condition during construction, overtime working hours, overcrowding site organisation, change of process orders, material management, weather, idling and working time as well as unforeseeable events like errors in prefabricated materials, drawing errors, absenteeism, material delivery delays etc. (Rashidi et al. 2014; Park 2006; Naoum 2016; Dai et al. 2009).

3.2.9 Other tools for construction equipment

A variety of tools exist on the market for the purpose of quantifying CO_2 or CO_2e emissions during construction stages. Twenty two tools for road construction, eleven tools for building construction, two for earthmoving work, two for waste recycling and twenty databases were analysed within the scope of this work. In Table 3-2 a selection of analysed tools best suited for CO_2 or CO_2e quantification of construction equipment in their applications are shown.

The tool asPECT focuses mainly on the production of asphalt types. By selecting the content and composition of an asphalt as well as the energy use to produce and transport it, CO_2 emissions are calculated. The paving process in this tool is assessed in a general way by multiplying the amount of material by a factor of 4.7 kg CO_2e/t. Therefore, no variation for the paving process is possible like numbers or type of construction machines. The quantification method is fuel based which means that the total amount of fuel or energy is multiplied by the corresponding CO_2e factor. (asPECT 2014)

Other tools for quantifying the CO_2e emissions of materials production are databases like Ecoinvent, Gemis, ProBas or Ökobaudat. With the exception of Ökobaudat these databases have information and a CO_2e conversion factor for different fuel types. Ökobaudat contains data about all materials, material transport and some construction processes necessary for building construction. (Ecoinvent 2007; Gemis 1989; ProBas 2015; Ökobaudat 2013)

CO_2nstruct, CEREAL and PaLATE are tools developed for road construction. CO_2nstruct works with a life-cycle assessment approach (LCA) by considering total energy consumption, material, waste, transport and elimination as well as restoration of environmental systems. The EEA method is used as CO_2e quantification method for construction machinery. (Fernández-Sánchez et al. 2015)

CEREAL and PaLATE are tools using a time based approach. This means that first the time needed for each machine to do their tasks is calculated. Then this calculated time is multiplied by the fuel consumption and after that by the CO_2e conversion factor. Through this approach, the machine fleet working on the construction site is considered in the CO_2e quantification. (van Gurp and Larsen 2014; PaLATE 2003)

The GreenDOT tool gives the user three options for calculating the CO_2 emissions of construction equipment: the total amount of fuel consumption multiplied by the CO_2 conversion factor in kg CO_2/gal, by a maintenance factor and by an anti-idle factor; the sum of the product of fuel consumption for each machine with a machine individual CO_2 emissions factor in kg CO_2/gal; or according to the EPA- Method (Nonroad-Model). (GreenDOT 2010)
The PCC-tool shows CO_2 emissions resulting from two scenarios: the conventional construction scenario and the scenario with reduction measures. The CO_2 emissions of construction equipment is calculated by multiplying the engine power by the working time and by the emissions factor 0.267 kg CO_2/(kW×h). The total CO_2 emissions from the construction site is the sum of CO_2 emissions emitted for the material production, equipment, waste disposal, energy consumed and labour. Labour represents the CO_2 emissions produced by employees driving from their homes to the construction site and back. (PCC 2009)
All tools analysed do not consider the influence of the operator. Frank et al. have shown that the same work done under same conditions, the fuel consumption of expert operators can vary up to 43 % (Frank et al. 2012a; Stec 9/7/2016). Therefore, the operator's influence should be considered in CO_2e quantification tools.

Table 3-2: Selection of fitted tools for CO_2 or CO_2e quantification of construction equipment

Name	Method	Type of application	Transparency on						Source
			Machine	Process	Operation	Material	Fuel	Other	
asPECT	Fuel based	Road construction: Asphalt & transport	-	-	-	X	-	Truck type for transportation	(asPECT 2014)
CO2NSTRUCT	EEA	LCA-approach for road construction	X	X	-	X	X	Waste, transport, reforestation, resoil	(Fernández-Sánchez et al. 2015)
CEREAL	Time based	Road construction LCA	X	X	-	X	X	Maintenance work	(CEREAL 2014)
Ecoinvent	Database	Material & fuel production	-	X	-	X	X	CO_2e, CO_2 and other pollutants	(Ecoinvent 2007)
GEMIS	Database	Material & fuel production	-	-	-	X	X	CO_2 and other pollutants	(Gemis 1989)
GreenDOT	Fuel / EPA based	Construction & maintenance	X	-	-	X	X	Transportation, electricity consumption	(GreenDOT 2010)
Ökobaudat	Database	Building construction	X	X	-	X	X	Material transport	(Ökobaudat 2013)
PaLATE	Time based	Road construction	X	X	-	X	X	Costs calculation, maintenance	(PaLATE 2003)
PCC	Time based	Construction applications	X	-	-	X	-	Reduction measures, CO_2 from labour & site hut & waste	(PCC 2009)
ProBas	Database	Material & fuel production & transport	-	-	-	X	X	Textile, leather, waste	(ProBas 2015)

3.3 Summary of research gaps

According to the literature review above, seven major research gaps in existing CO_2 or CO_2e quantification methods for construction equipment have been identified and are summarised as follows.

G1: Machine focus

Most methods focus only on the engine, which consumes fuel and thus emits CO_2 emissions. The U.S. and the EU have different engine emissions legislation (VDMA 2017) and therefore U.S. engines are not necessarily identical to EU engines. Reference engine data for the EU method cannot be based on U.S. engine tests, which is the case for many methods described previously. Further, on-road behaviours of engines or of machines can not be assumed to be identical to nonroad behaviours. Nonroad environments (road surface, construction dust, etc.) stress engines and machines differently than on-road environments. Further, mobile nonroad machines not only have a driving but also a working function (Geimer 2014). Another matter to point out is the assumption of constant fuel consumption for engines or machines from Stage I or Tier 1 to Stage V or Tier 4. Over the years significant technological improvements have taken place in the engine as well as in the machine from competition between manufacturers (CEMA and CECE 2011). Some methods take into account deterioration aspects of only the engine. In doing so, wear on other parts of the machine like hydraulics, bucket teeth, etc. are neglected which can have a major influence on the fuel consumption (Caterpillar-Video). All methods lack differentiation between privately owned and rental machines. Rental machines have reduced lifetimes (Winther et al. 2017, p. 7) and will so wear out faster.

To solve all these issues, instead of placing the focus on the engine, the focus needs to be on the machine and its environment as well as operating processes.

G2: Time specification

The CO_2e quantification method should be applicable in the past, present and future and show differences over the years due to machine, process, and material development. In no method of the literature review, is it possible to differentiate time and its corresponding improvements.

G3: Construction materials and construction processes

Not all methods reviewed consider construction materials. A construction machine is constantly in contact with construction material during work. For some cases machine efficiencies can only be identified if the material is being considered. This is the case for e.g. for the cold recycler. A modern cold recycler typically used in road renewals, mills, recycles the milled asphalt and then paves the recycled asphalt. Such a machine emits more CO_2e emissions than a paver or a milling machine (machine perspective). Nevertheless, if the whole conventional process including material production is compared with the road renewal on-site process with the cold recycler, it becomes clear that in total the work with the cold recycler emits less CO_2e emissions (process perspective). Depending on the requirements of the construction, a road renewal with a cold recycler is not always the right construction method to choose.

G4: Construction operation

All reviewed methods do not consider the operator. Frank et al. have shown that the operator can have a significant impact on the total fuel consumption and so the CO_2 emissions (Frank et al. 2012a; Stec 9/7/2016).

The load factor of mobile machines in the literature is the result of the average of idle and working time. However, idle time varies strongly depending on the operator's driving behaviour, construction site conditions and the machine type. Further Cao et al. showed in their study that two machines can have the same average load factor over 7 hours but completely different duty cycles (Cao et al. 2016) and so different fuel consumptions. By taking into account the idle time in the load factor calculation, the load factor value cannot be representative for the machine.

On these grounds, it is necessary to calculate emissions separately at idle and at work as well as to consider machine operator influences.

G5: Same method for different construction applications

Individual machine types are used in different construction applications e.g. a wheel loader. A wheel loader works in quarries, mines, road construction, building construction, material production sites, etc. A CO_2e quantification method for construction machines is only representative if it is applicable in all different construction activities for different machine types, which is not the case for all reviewed methods.

G6: Energy carrier

The amount of CO_2e emissions is in relation to the amount of carbon atoms in the fuel used (Edwards et al. 2014a). By changing the fuel or using sustainable fuels, the CO_2e impact can vary. Therefore, a reliable CO_2e quantification method needs to consider the energy carrier used.

G7: Greenhouse gas and CO_2 emissions

In order to correctly evaluate possible efficiency improvements, the overall impact of greenhouse gases (CO_2e) instead of only CO_2 needs to be taken into account.

This aspect is especially true for materials production, which emits more greenhouse gases than only CO_2 or for alternative energy carriers (e.g. liquefied methane).

In summary, no method was found to consider all seven aspects in their quantification method. Even though these aspects were discussed in different studies. Increased efficiencies need to be taken into account in order to quantify the achieved and future attainable greenhouse gas reductions. These identified research gaps lead to the next stage of research on investigating solutions to fill them.

4 Scientific contribution

The objective in this chapter is to tackle the needs identified in chapter 2 and the research gaps identified in chapter 3 by developing a scientific method in order to quantify achieved and expected CO_2e reduction of typical mobile machines for construction applications. First, the description of the general approach for mobile machines will be presented. Then comes the definition of the chosen system boundaries. Afterwards the different CO_2e influence factors will be worked out. Lastly, the detailed calculation procedure for mobile construction machines will be described.

4.1 CO_2e reduction quantification method of typical mobile machines

The developed method to quantify the achieved and the expected CO_2e reduction of typical mobile machines for construction applications is not based on reference cycles, but rather on a holistic approach where the construction process is considered. In lieu of examining the individual machine in isolation, machines are investigated based on their applications, taking into account the various influences. The resulting quantified CO_2e emissions will therefore vary, if efficiency enhancement measures are taking place.

The influences or efficiencies can be allotted to six pillars as shown in Figure 4.1: machine efficiency, process efficiency, energy source, operation efficiency, material efficiency and CO_2e capture systems[5]. Through these pillars, the large field of possibilities for CO_2e emissions reduction for mobile machines from the agricultural as well as from the construction sector will be shown. As a matter of fact, some mobile machines find application in the agriculture as well as the construction sector e.g. tractor or wheel loader.

Additionally, the method will be applicable for construction processes from the past, present, near future and distant future, which makes it particularly

[5] The six pillars are explained in chapter 4.3 and are inspired by the four pillars of the CECE and CEMA (CEMA and CECE 2011).

suitable for making comparisons of conventional and modified construction applications.
The first procedure step is to collect or define data from the mobile machine in its application in accordance with the six pillars. Then, the developed method is applied, resulting in the quantification of its total CO_2e emissions.

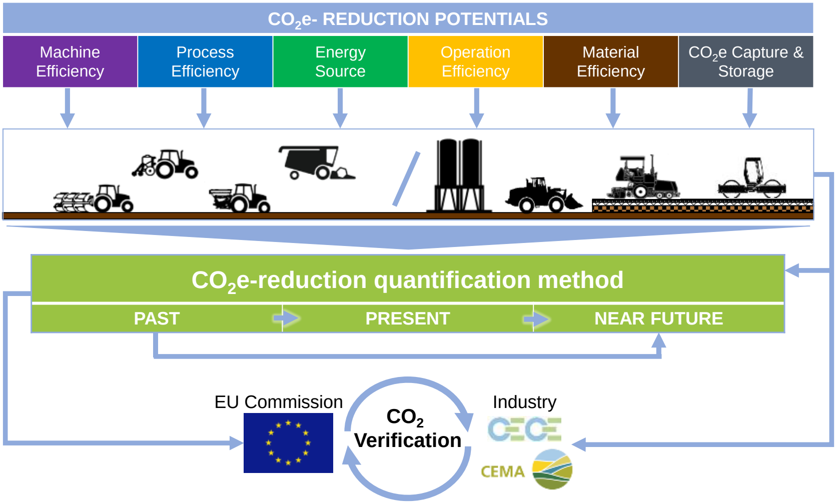


Figure 4.1: General CO_2e reduction quantification method of typical mobile machines

By comparing this result with scenarios of different times (past, present, near future) or with scenarios with differentiated data, the CO_2e emissions variations being a reduction or augmentation can be assessed. CO_2e intensive construction steps and main influencing factors for the analysed scenario having the greatest impact on CO_2e emissions can be identified. This permits deriving key measures that need to be taken and research trends aiming to reduce greenhouse gases.

Scenarios corresponding to the past have process steps matching construction procedures of the past and uses machine data from former recordings. E.g. the requirements for a BK10 road were different in 1990 and 2016. By varying the materials and machines used, it will be possible to demonstrate a reduction in CO_2e emissions through these measures.

Just like measures from the past, new construction methods and new technologies implemented in the newest machine sold on the market can be examined. Construction machines are exchanged by rental companies with new ones every 3.5 to 5 years (Zou 2018). It can be assumed that today new machines sold in Europe will represent the state of the art on construction sites for the next five years. In this way a fairly certain near future scenarios can be assessed. For further future scenarios representing the next ten years, individual technologies already implemented in mobile machine research prototypes can serve as reference and be examined for their effectiveness in terms of CO_2e reduction potential. This is due to the development time of a new construction machine, which takes in average five years from concept to realisation[6] and then five years to become state of the art on European construction sites. On this basis a reliable forecast can be made for future scenarios.

The lower part of Figure 4.1 represent the case where there is a demand from the state or the European Union commission on industry to prove the effectiveness of its implemented efficiency enhancement measures. The method can be applied for this purpose. The results can then be verified together by the European Union commission and by the industry. The industry is represented by the committee for European construction equipment (CECE) and the committee for European agricultural machinery (CEMA). Finally, the results form the basis for a discussion between industry and policy makers.[7]

4.2 Determination of the investigation scope

The quantification of a CO_2e emission reduction on construction sites can only take place, if the amount of CO_2e emissions is given for at least two scenarios. This means that the CO_2e emissions of each scenario need to be quantified within the same system boundaries. The system boundaries describe how to separate the planned system from its environment and from

[6] Assumption based on the author‘s experience.
[7] Similar approach to the Ekotech project (PTBLE 2016).

other product systems. It is then possible to define what processes the developed method will include and exclude.
According to the Pareto principle, the method will quantify 80 % of the CO_2e emissions related to construction equipment. An analysis of mobile machines with regard to CO_2e emissions was undertaken at the Technical University of Brunswick. It was found that over 80 % of all CO_2e emissions from mobile machines are released during their use and 10 % to 14 % CO_2e are emitted during the manufacture of the machines (Hanke 2014). The CO_2e quantification method will therefore not consider the emissions emitted during production or recycle of mobile machines and will focus on machine emissions emitted during construction processes. The CO_2e emissions resulting from the transport of mobile machinery to and from the construction site are not taken into account. Such transports are considered as one-time and therefore the greenhouse gas emissions are negligible compared to the total emitted at the construction site.
The CO_2e emissions emitted from a mobile machine during construction processes are in direct relation with the type and amount of fuel consumed (Edwards et al. 2014a). In order to determine the impact of each type of fuel, the entire effect chain (well-to-wheel) from the extraction and production (well-to-tank) to the consumption (tank-to-wheel) needs to be considered. The amount of fuel is related to the work performed, which is influenced by the machine characteristics, the process and the operator.
In general, construction requires material or its disposal. The construction machine is in direct contact with the material and depending of it, the right machine for the process can be chosen. In some cases machines can turn out to be efficient if the process and material are considered e.g. for the cold recycler. Most of the time, material is produced somewhere else than on the construction site and then transported there. If the material used is recycled material instead of conventionally produced material, the balancing of CO_2e for the investigated scenario should vary. The transport is performed by rail, water or road. Therefore, the material will be considered from resource extraction to the factory gate (cradle-to-gate) as well as its transport process-

es[8]. The use phase of the material in the construction product and then the demolition phase of the product, which means to dispose of the material, are omitted in this method.
CO_2e emissions for energy carriers and construction materials will be quantified with data from scientifically reliable databases.
During construction operation, construction personnel commute to the site or headquarters to work in site trailers or in offices. The consumed fuel for commuting, the electricity used for lights, computers, etc. and gas used for heating systems are not taken into account in the CO_2e quantification method. Processes also excluded from the method are the CO_2e emissions released after the construction of the product. This means that the CO_2e emissions that are released during use of the product are not included in the CO_2e quantification method, e.g. traffic emissions from vehicles using a paved road.

4.3 CO_2e influences in construction applications

Figure 4.1 shows the influences on the amount of CO_2e emitted by mobile machines from the construction and agriculture sector. In this subchapter the focus will be to work out these influences for the construction sector, which will then be used in the CO_2e quantification method, see 4.4. First, the influence of the legislator and the contracting authority will be described, then will follow the description of CO_2e reduction potentials according to the six pillars from Figure 4.1. In the process, representative factors for each pillar will be formulated. The subchapter will lastly end with influence factor considered but not part of the six pillar approach.

4.3.1 Legislator & contracting authority

A construction application is influenced by the legislator and the contracting authority. “Legislator” describes all land development regulations valid nationwide, state-wide and local wide as well as private, public and criminal

[8] The GWP value of a material can be reduced by using recycling material during production. Recycling material, which is reusing waste, has in this thesis the GWP value of zero.

laws (Menzel et al. 2015; Goris and Schneider 2010). Only if laws and regulations are respected, can a construction process take place. Consequently, the "legislator" influences decisions and behaviours of each party involved in a construction process as illustrated in Figure 4.2.
The contracting authority or builder-owner carries out a construction project on his own responsibility and thus exerts a determining influence on each stage of its implementation. The contracting authority can have support from consultants in fulfilling his functions like project controlling, facility management during construction, forming interior lighting concept, office organisation, leasing organisation, etc. The contracting authority contracts an architect or civil engineer who does the planning, the construction design, the construction site preparation and management. He or the contracting authority can, if they don't have sufficient speciality knowledge for the task, contract a specialist planner. Finally, the construction is carried out by the general contractor who can, if necessary, contract subcontractors for the realisation of some construction tasks. Alternatively, the contracting authority can assign the task to several subcontractors. (Gralla 2011)
Consequently, the way construction processes on construction sites takes place depends on all parties involved (see Figure 4.2) where legislator and contracting authority define the boundary conditions and thus have a major influence on the amount of CO_2e emissions emitted.

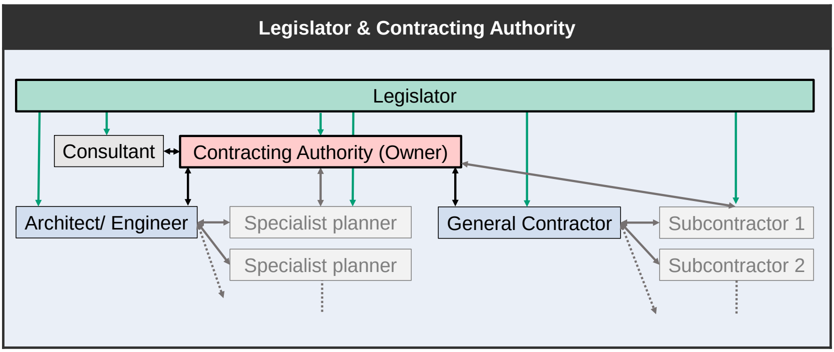


Figure 4.2: Relations between parties involved in a construction process

4.3.2 Machine efficiency

One of the pillars holding the potential of reducing CO_2e emissions from mobile machines is machine efficiency. Machine efficiency pertains to all technologies on the machine required to perform the work task. The more efficient these technologies are, the less fuel the machine will consume and the lower the amount of CO_2e emitted directly by the machine will be. The efficiency of these technologies depend on its type and functions as well as on its state during the work task. The machine technology efficiency describes the efficiency in the engine, transmission, hydraulics, electrics and exhaust after-treatment system. It is assessed through the basic work performance[9] (Q_B) of the machine in tons or m³ per hour and the fuel consumption in litres per hour. The efficiency of the fuel consumption will be described with $f_{machine\ technology}$ which represents the difference of the average fuel consumption of the considered machine type (b_m). In order to determine $f_{machine\ technology}$, information will be combined together like in *(4-1)*. This is information about the engine stage (f_{engine}) which will be used to determine the basic built-in technology of the machine, the information about whether the machine worked in ECO-mode[10] or not (f_{eco}) and the information about other significant technological improvements implemented in the machine ($f_{significant\ improvement}$)[11].

$$f_{machine\ technology} = f_{engine} \times f_{eco} \times f_{significant\ improvement} \qquad (4\text{-}1)$$

The state of these technologies is influenced by the age of the machine (f_{age}), the machine owner and the regularity of maintenance work on the machine ($f_{service\ regularity}$). The influence of the age varies depending on whether the machine is privately owned or from a rental company. This distinction needs to be made because rental machines have greater annual use, higher average horsepower ratings and so shorter lifetimes than privately owned machines. Further, new machines are typically operated at a higher number of hours per

---

9 The basic work performance is calculated differently for each type of machine, see 4.4.

10 ECO-mode stands for an economical modus where the engine speed is reduced to a fix value.

11 $f_{significant\ improvement}$ takes into account other significant technology improvements (single technologies or combination of technologies) having an influence on the fuel consumption (see A.1 pp.199-201).

year compared to older machines (EPA 1997, p. 17). The machine technology condition will be described by the factor $f_{machine\ condition}$ representing the average fuel consumption differences of the considered machine type (b_m). It will be calculated as follows:

$$f_{machine\ condition} = f_{age} \times f_{service\ regularity} \qquad (4\text{-}2)$$

4.3.3 Process efficiency

Another pillar holding the potential of reducing CO_2e emissions from mobile machines is process efficiency. This pillar represents the setup effectiveness of the construction application fulfilled at the jobsite. It is influenced by the interaction and the appropriate combination of the quality of the construction site organisation, the construction complexity degree, the use of technologies aiming to support process efficiency and the process-related idle time. Depending on these, the amount of sub processes necessary to complete the construction work can be reduced or increased. Additionally, these single parameters have an impact on the effective performance of the machine and the amount of time at idle.

A high quality of construction organisation is reached when good planning of the construction has taken place and the right types and sizes of construction machines are available for the construction process. As a result, waiting times caused by poor coordination of the machine outputs or capacities involved can be avoided. The impact of the construction site organisation on the idle time will be represented with the factor $f_{site\ orga.}$.

The idle time of a machine depends also on the process-related idling denoted with $f_{idle\ unavoidable}$.Unavoidable idle times are times that are planned and necessary for the process flow. An example can be observed during road maintenance. After the paver has laid the binder course, manual work is necessary to bridge the gap between old and new course. During this time, the paver is at idle and is not allowed to be switched off, in order to maintain the temperature of the screed for the subsequent sub process, consisting of laying the driving course. This idle time is being defined as unavoidable process-related idling.

Technologies supporting process efficiencies are called process assistant systems. Depending on the driver's experience, the support of the technology on the process is different. The support for an expert driver will be less than for a medium experienced driver or for a beginner. This support has a direct impact on the machine performance and will be denoted with $f_{process\ assistant}$. Each construction site is different and so the work is done each time under other conditions. Conditions like bad weather ($f_{weather}$), limited construction time ($f_{construction\ time}$) or limited construction site freedom ($f_{site\ freedom}$) can make the construction complex. The construction complexity degree is expressed with $f_{constr.\ complexity}$ like in *(4-3)* and has an impact on the machine performance. When the degree of site complexity is high, an efficient driver and use of process assistant systems have minor influences on process efficiency.

$$f_{constr.\ complexity} = f_{weather} \times f_{construction\ time} \times f_{site\ freedom} \qquad (4\text{-}3)$$

4.3.4 Energy source

The pillar "Energy source" describes the influence on the CO_2e impact of a mobile machine by using alternative energy carriers from other sources than conventional diesel. In this pillar, the entire process chain from the energy source to the energy carrier to the usable energy in the machine has to be considered in order to determine the CO_2e impact. In the CO_2e quantification formula, the energy carrier will be considered with the factor $f_{CO_2e/energy\ carrier}$.

The relation between energy source, energy carrier and usable energy is illustrated in Figure 4.3. Resources that are extracted are called primary energy sources (Jäger and Stieglitz 2017/2018). They can be from non-renewable nature like fossils (e.g. coal, natural gas, petroleum) and nuclear (e.g. uranium, deuterium) or from renewable nature like solar (e.g. wind, waves, biomass, radiation) or others (e.g. geothermal) (ibid.). Then the conversion from primary energy sources into secondary energy sources takes place into combustible sources, electricity or heat (ibid.). Combustibles can be in solid form e.g. wood, coal, biomass, or in liquid form e.g. fuel, or in gas form like biogas, LPG, hydrogen, etc. (ibid.). Secondary energy sources are then processed into energy carriers which are ready for operation. The next conversion phase takes place in the mobile machine itself where the energy carrier is converted into heat, light or power.

The analysis of the entire process chain is called well-to-wheel (WTW) analysis. The well-to-wheel analysis is a methodology to quantify the amount of CO_2e emissions during production (well-to-tank) and combustion of the energy carrier (tank-to-wheel) (European Commission 2016).

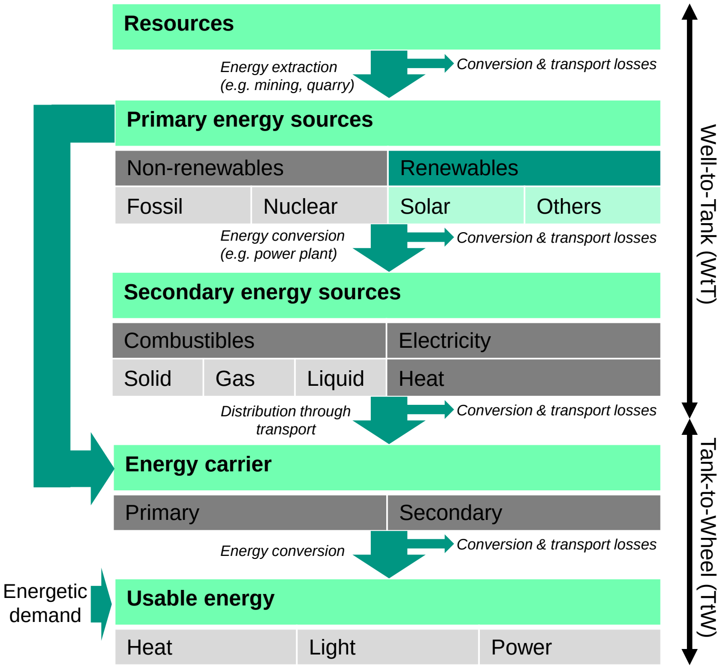


Figure 4.3: Energy source and energy carrier (Jäger and Stieglitz 2017/2018)

When the energy carrier is from a renewable source, it is considered to be in a closed CO_2 cycle and so no CO_2 emissions are balanced within the conversion process into mechanical energy (e.g. combustion). The release of CO_2 emissions during this conversion process correspond to the CO_2 emissions absorbed during the production process (e.g. growing process of a plant if the energy carrier is from biomass sources). In contrast, the temporal eco-balance does not add up for energy carriers from non–renewable primary energy sources because they take a long time to replenish e.g. petroleum with 100 million of years (Tissot and Welte 2013, p. 227).

The CO_2e emission amount released from an energy carrier is equivalent to the amount of C-atoms in its composition (Edwards et al. 2014a).
On the one hand, the machine requires enough energy to fulfil the task without having to interrupt for energy supply, on the other hand unrestricted movement of the machine must be possible. That's the reason why three other aspects have to be considered when looking for an alternative energy carrier for mobile machines. These are the calorific value, the gravimetric and the volumetric energy densities. Some examples of alternative energy carriers including their energy sources can be seen in chapter 8.

4.3.5 Operation efficiency

Decisive on the operation efficiency are the speed and the cycle time of a machine which are the result of the machine operator ability to adapt to new working environments and changing workplaces. The reason is that there are no identical construction sites and working conditions can suddenly change during the construction process (e.g. due the weather). In order to increase operation efficiency, it is essential to understand the interaction between human and machine forming a control loop like in Figure 4.4.

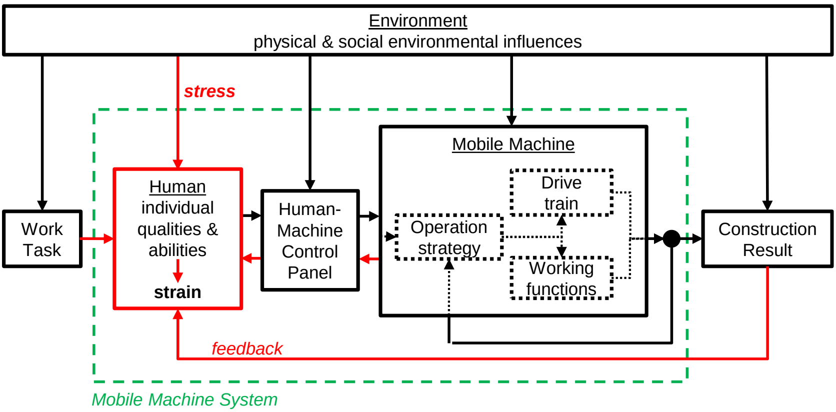


Figure 4.4: Human – machine control loop system

The work task adapted to the environmental conditions is handed over to the machine operator. The machine operator receives information through his senses from the human-machine control panel and from the construction result. This human controller compares the work task with the current state of the machine and the working process. Based on all this information and his experience he evaluates the situation in his brain, enabling him to take decisions. Then he transfers his decisions with movement commands via his limbs on the panel to the machine. The machine then does the work according to its operation strategy ensuing into the “construction result”. The environment exerts influence on each step of the human–machine control loop system. Two types of environment influences are distinguished: the physical environmental influences such as noise, weather, dust, etc. and the social environment influences such as e.g. human relations. The environmental stress, the working task and all feedbacks result on an individual human reaction called “strain”.

The pillar “operation efficiency” describes the potential for improvements during the machine operation and so the potential of reducing CO_2e emissions. In that sense it is the effectiveness of the mutual influence of human and machine during the operating time of the machine. Consequently two groups can be differentiated which is the machine operator and the avoidable idle time as shown in Figure 4.5.

The group "machine operator" expressed with f_{driver} contains all factors and their interaction on the operator and so influence indirectly the CO_2e emission amount. These factors are the operator’s physical and mental state, his level of experience, the ergonomic of his workplace as well as the view and the temperature in the cabin.

The first factor $f_{physical\&mental\ state}$ expresses the physiological and psychological state of the driver. A person's performance is influenced by his physiological willingness to perform also called disposition, i.e. daily rhythm, physical condition, fatigue, etc. and his psychological willingness to perform also called motivation, i.e. mood, attitude to work, social environment (Zülch 2012). The person’s performance is co-defined with its characteristics and basic abilities, such as constitution, gender, age, etc. (ibid.).

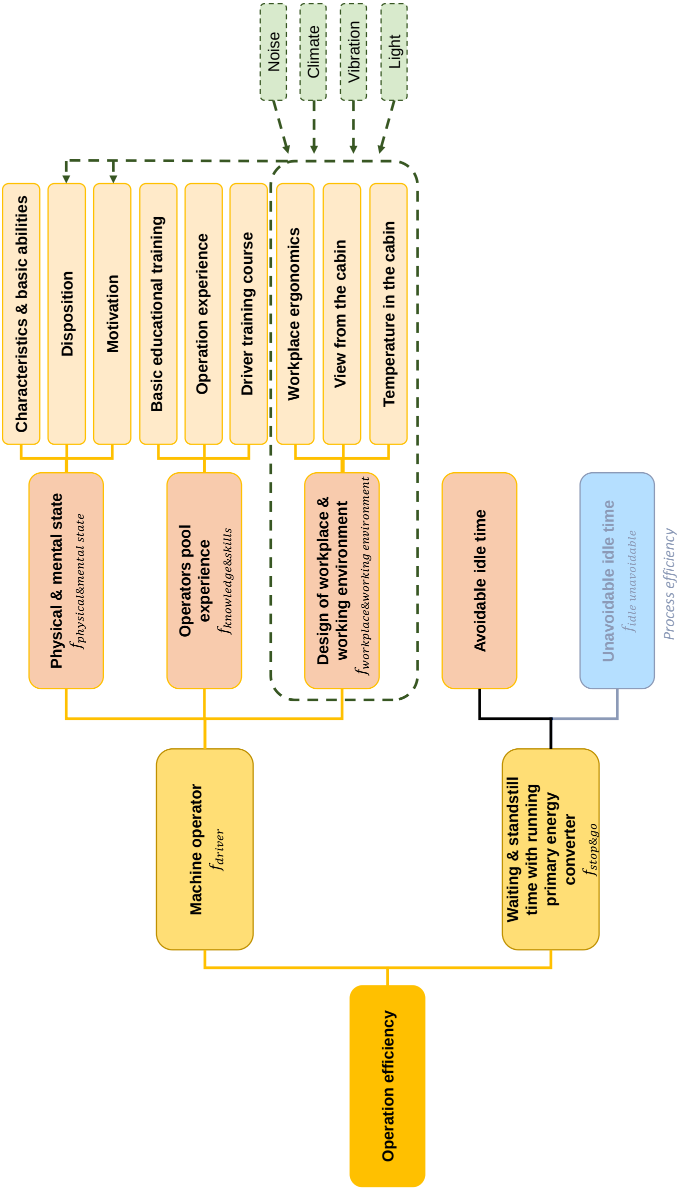


Figure 4.5: Definition of operation efficiency

The second factor is the pool experience of the machine operator $f_{knowledge\&skills}$, including the basic educational training, operation experience and regularity of participation in driver training courses. Little influence can be exerted on the level of basic educational training and the operation experience of the driver. On the other hand, regular driver training courses can help to maintain and improve the driver's knowledge and skills. The third factor is $f_{workplace\&working\ environment}$ representing the design of the workplace and working environment. The design of the workplace comprises in creating and arranging things so that the people using these things, interact most efficiently and safely with them. The design of the working environment consist to protect the operators from negative environment influences such as climate, noise, vibration and bad light or the social environment, such as the working time regime. In other words the workplace ergonomics, the view from the cabin due to the weather and the climate in the cabin have major influences on the driver and so on the released CO_2e emissions. The effect of the workplace and working environment varies depending on whether it is determined scientifically, individually or by cultural studies. (Zülch 2012)

Finally f_{driver} can be calculated as follow:

$$f_{driver} = f_{physical\&mentalstate} \times f_{knowledge\&skills} \times f_{workplace\&workingenvironment} \quad (4\text{-}4)$$

Waiting or standstill periods are times at which a machine stops performing an activity. These work interruptions can be differentiated in avoidable and unavoidable. Unavoidable waiting or downtimes causing CO_2e emissions are considered in the pillar process efficiency with $f_{idle\ unavoidable}$. Avoidable waiting times or downtimes are times that could have been prevented by taking precautions such as better planning and coordination of construction site processes.

If during these waiting times or downtimes the primary energy converter like e.g. the engine is switch on which corresponds to the idle state, then CO_2e emissions will be emitted and they need to be considered in the method. This means that the idle state of a machine is when no active work is carry out and therefore its primary energy converter runs at low speed. In the construction sector it is today not uncommon for mobile machines to be in idle for a long time like e.g. 30 % to 50 % of the operating time (Ays et al. 2018b; Ahn and Lee 2013).

Table 4-1: States possibilities of an equipment during the operating period

Equipment operating period					
Working time		Waiting time or standstill time			
necessary	avoidable	unavoidable		avoidable	
Primary energy converter *running*	Primary energy converter *running*	Primary energy converter *running*	Primary energy converter *switch off*	Primary energy converter *running*	Primary energy converter *switch off*

The idle time can be reduced with the factor for standstill time ($f_{stop\&go}$). Idle time is reducible through switching off the machine, either by the driver or automatically (start-stop systems). If the idle time decreases, the fuel consumption and so the CO_2e emissions will be reduced.
In conclusion, for each application, it must be examined whether idle times are unavoidable or avoidable, since certain processes do not permit the switching off of machines. Table 4-1 shows the relation between the different terms described above.

4.3.6 Material efficiency

Another pillar having the potential to reduce CO_2e emissions from mobile machines is material efficiency.

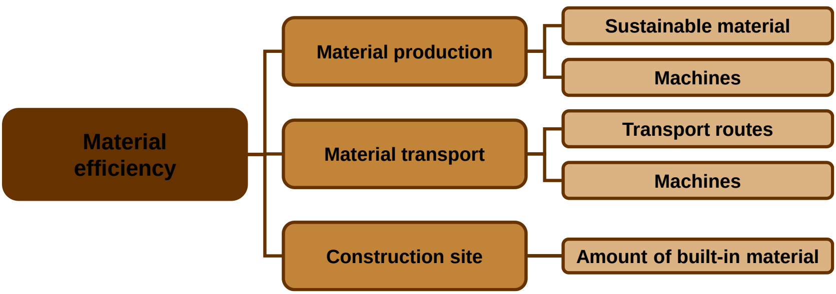


Figure 4.6: Definition of material efficiency

In the previous part of this work, it has been explained that mobile machines are constantly in contact with construction material and without its consideration some machine efficiencies may not be identified.

Material efficiencies are possible on three levels: during material production, during its transport or during the construction process. During material production, material efficiency consist in producing sustainable material. Sustainable material is defined as having a positive effect on the environment which means not only reducing emissions but also sequestrating carbon, i.e. increasing the binding of carbon in the material. Therefore materials should be favoured that come from renewable sources and that can be recycled in order to be reused. The aspect of quality must be included, because high quality means a high life time which consequently means less waste. For the production of material machines including mixing plants and mobile machines are necessary. The production process of the material is sustainable if also the machines used are sustainable[12].

Another material efficiency level is material transport. The fuel industry has shown that neglecting the transport routes can lead to a false efficiency statement (see 2.3.3). Material for the construction sector comes from different parts of the world and are chosen according to economical and quality aspects. Consequently material efficiency increases when transport routes are shortened. Material transport is carried out with machines i.e. trucks, ships, trains, airplanes or mobile machines[13]. Transport routes are efficient if they are short and transported with efficient machines.

The third material efficiency level is on the construction site. It aims to use as few material amount and types as possible. The effect is maximize if it is in accordance with the other six pillars: mobile machine efficiency, process efficiency, energy source, operation efficiency and CO_2e capture and storage.

4.3.7 CO_2e capture and storage

The sixth pillar from Figure 4.1 is called CO_2e capture and storage. This pillar describes technologies for mobile machines not yet existing today, capable of capturing CO_2e emissions and storing them until the possibility is

[12] Sustainability is defined as the way in which the needs of present generations are met without depriving future generations of their livelihoods. It aims on positive impacts on the environment and society by reducing emissions and sequestrating carbon.

[13] A mobile machine is defined as a machine having a drive train and working functions (Geimer 2014.

given to pass them on to other systems. Overall aim of these technologies is to prevent greenhouse gas emissions from being released into the atmosphere. A function analysis diagram for such technologies for mobile machines are described in Figure 4.7.

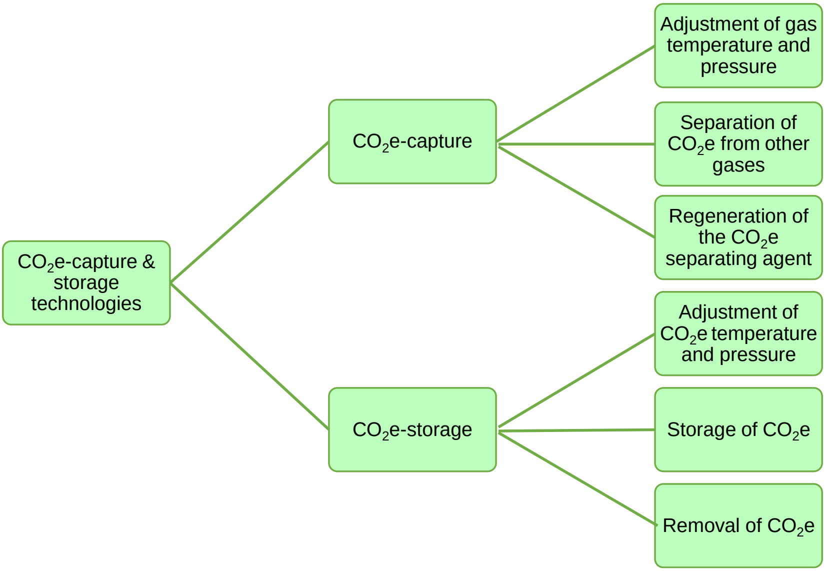


Figure 4.7: Function analysis diagram of the CO_2ecapture and storage system for mobile machines

Technologies capturing carbon dioxide emissions exists already for stationary plants such as e.g. power plants. These technologies are called CCS technologies and are considered by Pfluger et al. to be the solution to reduce CO_2 emissions from the energy sector. (Pfluger et al. 2017)

Jonker describes three CO_2 capture and storage technology types called *pre-combustion*, *oxy-combustion* and *post-combustion technologies*. In pre-combustion technologies, the CO_2 is captured before power is generated with the energy carrier. In the oxy-combustion technologies, the power generation with the primary energy converter takes place with oxygen (O_2) instead of air (mixture of gases like N_2, O_2, CO_2, etc.). Post-combustion technologies describe the separation and storage of CO_2 from the exhaust gas, after power generation took place with the primary energy converter. (Jonker 2017, p. 3)

A concept development method for CO_2 capture and storage systems in mobile machines were developed and is described in 8.3. The factor f_{CCS} will represent the percentage amount of greenhouse gas emissions captured and stored in the CO_2e quantification method for mobile machines in construction applications.

4.3.8 Other influence factors

Besides the influencing factors corresponding to the six pillars, three additional influences could be identified: unpredictable influences on construction site, CO_2 cost factor and effects of CO_2e sink destruction and new formation.

4.3.8.1 Unpredictable influence

Many factors influence a construction project. Some factors are predictable and can therefore be managed and controlled but others are unpredictable. Unpredictable influence cannot be foreseen and are therefore difficult to avoid. (Dai et al. 2009)
In the CO_2e quantification method only unpredictable influence leading to an increase of CO_2e emission are considered with f_{ui}. Events that lead to unpredictable influences can be e.g. material transport difficulties due to traffic jams, errors in prefabricated material, drawing errors, absenteeism of construction workers.

4.3.8.2 CO_2e cost factor

By allocating a price to the amount of CO_2e emitted, the significance of the urgency in transforming to a carbon neutral economy becomes evident. The effect on the planet of a certain amount of CO_2e varies depending on the total CO_2e amount in the atmosphere. Today's worldwide total CO_2e amount tend to increase year per year (Stocker 9/19/2018). Consequently the global warming is felt more intensively and its direct damages and indirect consequences such as adaptation measures increases (OECD 2018).
The organisation for Economic Cooperation and Development (OECD) estimates today a low-end value for climate costs f_{price/CO_2e} to correspond to 30 € per ton CO_2e emitted. In 2020, it is estimated to reach a value of 60 € per ton CO_2e emitted. (OECD 2018)

The factor f_{price/CO_2e} will represent the cost of direct damages and indirect consequences in the CO_2e quantification method for mobile machines in construction applications.

4.3.8.3 CO_2e sink destruction and restoration

Before a construction starts, preparation work takes place where the vegetation and topsoil is removed from the construction area. During the growth process of vegetation CO_2 is absorbed, therefore by removing and so destroying these CO_2e sinks more CO_2e is left present in the atmosphere. New CO_2e sinks can be created through reforestation or replanting after the construction work. These effects of CO_2e sink destruction and vegetation restoration have to be considered in the CO_2 quantification method in order to minimise the negative consequences of a construction process. Therefore the original ecosystem is chosen as reference which would still exist if it were not removed due to construction work.

All influences on CO_2e emissions from mobile machines were described in this subchapter 4.3. They show that the CO_2e reduction from construction mobile machines is only possible if the interaction of all partners involved in the process is considered. These form the basis for the development of the CO_2e quantification method.

4.4 CO_2e quantification method for mobile machines during construction applications

In this subchapter, the developed method to quantify CO_2e emissions from mobile machines for construction applications will be described. This method is generally valid for all construction applications and mobile machines. In this work, the method is investigated on representative mobile machines i.e. excavators, pavers and rollers as well as on representative construction applications i.e. building construction, earthworks, road construction and quarrying.

The method is illustrated in Figure 4.8. The legislator and contracting authority lay basic framework conditions for construction processes and the final construction result. Depending on the definition of the framework, reduction potentials can vary more or less and thus differ from one construction site to another. Reduction potentials can be classified into six CO_2e reduction pillars, which are: machine efficiency, process efficiency, energy source, operation efficiency, material efficiency and CO_2e capture and storage. These pillars enable the examination of CO_2e emissions from mobile machines in their applications. The construction of a final product is carried out via a large number of different construction processes. Each construction process has different characteristics and conditions. The entire construction procedure is divided into sub processes, then the CO_2e emissions for machines or materials used in each sub process can be assessed. By dividing the sub process into further sub-sub processes, the method gives the possibility to quantify CO_2e emissions in a more detailed approach. The detail degree can thus vary in dependence on the amount of division levels of the processes. This enables adapting the quantification model and consequently the result accordingly to the necessary quantification level.

Finally, all quantified CO_2e emissions for each (sub-) sub process are added together and result in the total amount of CO_2e emitted during the analysed construction applications.

The quantification formula for one level of division can be formulated as follows:

$$m_{CO_2e,T} = \sum_{i=1}^{n} m_{CO_2e,i} \qquad (4\text{-}5)$$

Where $m_{CO_2e,T}$ represents the total mass of CO_2e emitted for the construction process, *n* the number of sub processes and $m_{CO_2e,i}$ the mass of CO_2e emitted for sub process *i*.

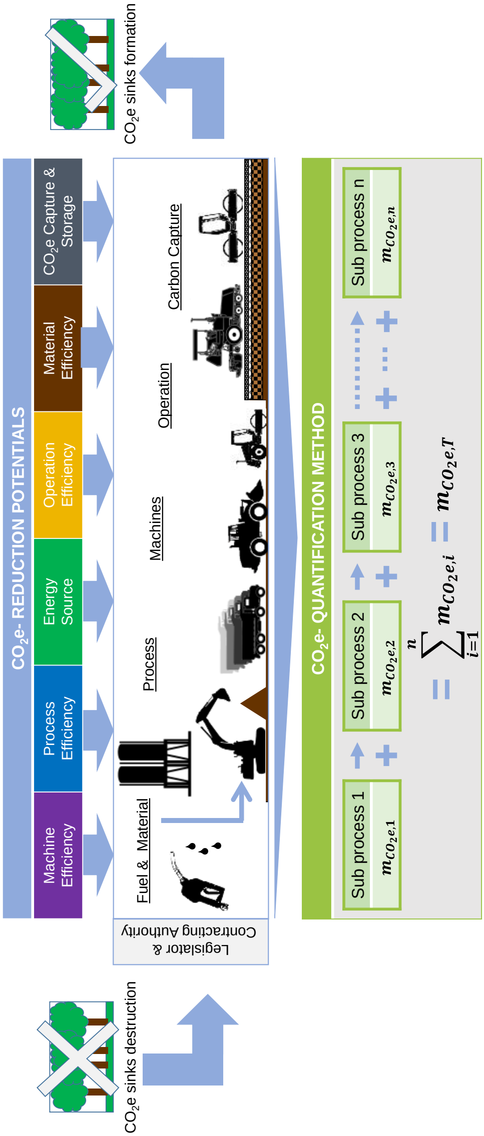


Figure 4.8: CO_2e quantification method for mobile machines during construction applications

If each construction sub process can further be divided into different sub processes, then a multi indexes α is introduced. α enables to index the sub processes, such that the full construction application and its decomposition into sub processes can be represented by a indexed tree D. Figure 4.9 is an example of indexed tree.

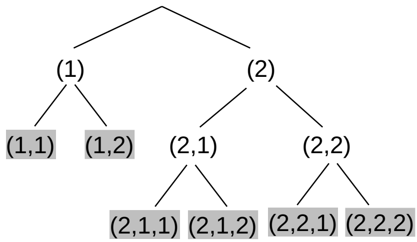


Figure 4.9: Exemplary sub process tree

If a n-tuplet index α represents a sub process, the indexes of sub processes composing it, will be (n+1)-tuplets where the first n indexes are identical to the indexes of α. The indexed tree is given by the set of the multi-indexes α denoted i_x, corresponding to a sub process, see (4-6).

$$D = \{\alpha = (i_1, i_2, \dots)\backslash \alpha \ represents\ a\ sub\ process\} \qquad (4\text{-}6)$$

If a sub process can not be further devided into different sub processes, it is then called “elementary process”. The set of the indexes of all elementary processes is denoted I_e as follow:

$$I_e = \{\alpha = (i_1, i_2, \dots)\backslash \alpha \ represents\ an\ elementary\ process\} \qquad (4\text{-}7)$$

Where I_e also corresponds to the set of bottom leafs of the tree D (in grey in Figure 4.9). The total mass of CO_2e emitted for the construction application will then be given by equation (4-8).

$$m_{CO_2e,T} = \sum_{\alpha \in I_e} m_{CO_2e,\alpha} \qquad (4\text{-}8)$$

Depending on the type of elementary process, $m_{CO_2e,\alpha}$ is calculated differently. Four different types of elementary processes are differentiated: material production, transport to and from the site, construction equipment as well as CO_2e sinks destruction and formation.

In order to convert the amount of CO_2e emitted into a currency value $C_{CO_2e,T}$, the total mass of CO_2e emitted for the construction process is multiplied by the factor f_{price/CO_2e}, representing the cost of direct damages and indirect consequences per mass of emitted CO_2e, like in equation *(4-9)*.

$$C_{CO_2e,T} = f_{price/CO_2e} \times m_{CO_2e,T} \quad (4\text{-}9)$$

If the elementary process is the amount of CO_2e emitted during material production then equation *(4-10)* is valid.

$$m_{CO_2e,\alpha} = \sum_{k=1}^{m_\alpha} N_k \times A_k \times GWP_k \quad (4\text{-}10)$$

Where m_α stands for the total number of different types of construction material, k for the type of construction material considered, N_k for the number of units of material k, A_k for the amount of material k and GWP_k for the global warming potential factor for material k. GWP_k is a conversion factor expressing the relative contribution to the greenhouse effect by producing material k per amount of material k. For GWP_k, data from material databases like ecoinvent or Ökobaudat are used (Ecoinvent 2007; Ökobaudat 2013).

If the elementary process is the amount of CO_2e emissions released during transport of material to and from the site, then equation *(4-11)* is valid.

$$m_{CO_2e,\alpha} = f_{CO_2e/energy\ carrier} \times \frac{V_{Material,\alpha}}{Q_{A-truck,\alpha}} \times b_\alpha \times P_{eff.max,\alpha} \times z_\alpha \quad (4\text{-}11)$$

α stands for the investigated transporting vehicle. For each material transported, the number of trucks (z) is multiplied by the fuel consumption of each truck and the fuel conversion factor into CO_2e emissions $f_{CO_2e/energy\ carrier}$. The working time of one truck is calculated by dividing the material amount to transport $V_{Material}$ by the effective performance of the transport operation, calculated according to Hoffmann et al. (Hoffmann et al. 2011). The fuel consumption of one truck is calculated by multiplying the working time by the specific fuel consumption b and by the maximum effective engine performance $P_{eff.max,\alpha}$. In this work, $P_{eff.max,\alpha}$ is assumed to be equal to 0.7 of P_{max} specified in the data sheets of the trucks.

The effective performance of the transport operation ($Q_{A-truck}$) is calculated according to Hoffmann et al. according to equation *(4-12)* (Hoffmann et al. 2011).

$$Q_{A-truck} = V_R \times f_L \times n \times \frac{t}{t_B} \times f_T \times f_E \tag{4-12}$$

Where V_R stands for the nominal capacity of the truck, f_L for the load factor calculated using (4-30), n for the trippage rate[14], t for the total period of circulation, t_B for the loading time, f_T for the transport service factor taking into account the interaction of several transport vehicles with a charger and f_E for the utilisation factor. The utilisation factor is determined using equation (4-24).

The total of greenhouse gases emitted during construction processes from construction equipment $m_{CO_2e,\alpha}$ is the sum of all CO_2e emitted from nonroad mobile machinery (NRMM) during the elementary construction processes α as in equation *(4-13)*.

$$m_{CO_2e,\alpha} = \sum_{r=1}^{s} m_{CO_2e,\alpha,r}^{NRMM} \tag{4-13}$$

Where r stands for the investigated machine and s for the number of construction machines used in the analysed construction application.

The formula for $m_{CO_2e,\alpha,r}^{NRMM}$ is calculated using equation *(4-14)*. During construction applications, nonroad mobile machinery is at work or at idle. Therefore, the total fuel consumption of the machine from the elementary process α is the sum of fuel consumption at idle ($B_{idle,\alpha,r}$) and at work ($B_{work,\alpha,r}$). It is then multiplied by the conversion factor ($f_{CO_2e/energy\ carrier,\alpha,r}$). In case the mobile machine has a built-in carbon capture and storage system, the real CO_2e emissions are reduced by the factor $f_{CCS,\alpha,r}$.

$$m_{CO_2e,\alpha,r}^{NRMM} = (1 - f_{ccs,\alpha,r}) \times f_{CO_2e/energy\ carrier,\alpha,r} \times (B_{work,\alpha,r} + B_{idle,\alpha,r}) \tag{4-14}$$

[14] The trippage rate correspond to 1 divided by the period of circulation of the truck.

The total fuel consumption at idle of machine r from the elementary process α corresponds to the product of the time at idle ($t_{idle,\alpha,\mathrm{r}}$) and the fuel consumption during idle ($b_{idle,r}$), see equation *(4-15)*. The time at idle of machine r can be expressed as a percentage ($f_{idle,\alpha,r}$) of total operation time ($t_{total,\alpha,r}$), like in equation *(4-16)*.
Where $f_{idle,r}$ is influenced by the construction site organisation ($f_{site\ orga.,\alpha,\mathrm{r}}$), the amount of unavoidable idle time ($f_{idle\ unavoidable,\alpha,r}$) and the standstill time factor resulting from actively switching-off and switching-on the engine ($f_{stop\&go,\alpha,r}$). This relation is described in equation *(4-17)*.

$$B_{idle,\alpha,r} = b_{idle,r} \times t_{idle,\alpha,r} \tag{4-15}$$

$$t_{idle,\alpha,r} = f_{idle,\alpha,r} \times t_{total,\alpha,r} \tag{4-16}$$

$$f_{idle,\alpha,r} = f_{stop\&go,\alpha,r} \times (f_{site\ orga.,\alpha,\mathrm{r}} + f_{idle\ unavoidable,\alpha,r}) \tag{4-17}$$

The time at idle during elementary process α and machine r can also be expressed as the subtraction from the total operation time of the working time ($t_{work,\alpha,r}$) and standstill time ($t_{standstill,\alpha,r}$) of machine r in elementary process α, like in equation *(4-18)*.

$$t_{idle,\alpha,r} = t_{total,\alpha,r} - t_{work,\alpha,r} - t_{standstill,\alpha,r} \tag{4-18}$$

Further, the standstill time can also be described by multiplying the factor resulting from actively switching-off and switching-on the engine ($1 - f_{stop\&go,\alpha,r}$) by the non working time ($t_{total,\alpha,r} - t_{work,\alpha,r}$), see equation *(4-19)*.

$$t_{standstill,\alpha,r} = (t_{total,\alpha,r} - t_{work,\alpha,r}) \times (1 - f_{stop\&go,\alpha,r}) \tag{4-19}$$

The non working time can also be expressed by the factors describing the non working time due to site organisation ($f_{site\ orga.,\alpha,\mathrm{r}}$) and due to unavoidable idle ($f_{idle\ unavoidable,\alpha,r}$) as the following equation.

$$(t_{total,\alpha,r} - t_{work,\alpha,r}) = (f_{site\ orga.,\alpha,\mathrm{r}} + f_{idle\ unavoidable,\alpha,r}) \times t_{total,\alpha,r} \tag{4-20}$$

When inserting equation *(4-16)*, *(4-17)*, *(4-18)*, *(4-19)* and *(4-20)* in *(4-15)*, equation *(4-21)* is obtained for the total fuel consumption at idle.

$$B_{idle,\alpha,r} = b_{idle,r} \times t_{work,\alpha,r} \times \frac{f_{stop\&go,\alpha,r} \times (f_{site\ orga.,\alpha,r} + f_{idle\ unavoidable,\alpha,r})}{1 - (f_{site\ orga.,\alpha,r} + f_{idle\ unavoidable,\alpha,r})} \quad (4\text{-}21)$$

The total fuel consumption during work of machine r ($B_{work,\alpha,r}$) is calculated with equation (4-22) by multiplying the working time of elementary process α of machine r with its fuel consumption. The fuel consumption of machine r is defined through multiplication of the average fuel consumption at work for a machine of type r ($b_{m,r}$) with the correcting factors, taking into account the machine condition ($f_{machine\ condition,\alpha,r}$) and the built-in technology of the machine ($f_{machine\ technology,\alpha,r}$). r stands for the machine type and α for the elementary process considered.

$$B_{work,\alpha,r} = t_{work,\alpha,r} \times b_{m,r} \times f_{machine\ condition,\alpha,r} \times f_{machine\ technology,\alpha,r} \quad (4\text{-}22)$$

The working time of machine r ($t_{work,\alpha,r}$) is calculated in equation (4-23) by dividing the quantity of material processed with machine r ($V_{material,\alpha,r}$) by the effective work performance of machine *r* ($Q_{E,\alpha,r}$,). Where α stands for the elementary process.

$$t_{work,\alpha,r} = \frac{V_{material,\alpha,r}}{Q_{E,\alpha,r}} \quad (4\text{-}23)$$

Construction is rarely performed under ideal conditions, therefore the effective work performance for machine *r* ($Q_{E,\alpha,r}$,), corresponds to the basic performance $Q_{B,r}$ reduced by a utilisation factor $f_{E,r}$ like in equation (4-24).

$$Q_{E,r} = Q_{B,\alpha,r} \times f_{E,\alpha,r} = Q_{B,\alpha,r} \times f_{driver,\alpha,r} \times f_{process\ assistant,\alpha,r} \times f_{constr.complexity,\alpha,r} \times f_{ui,\alpha,r} \quad (4\text{-}24)$$

Where $f_{E,\alpha,r}$ results from $f_{driver,\alpha,r}$, $f_{process\ assistant,\alpha,r}$, $f_{constr.\ complexity,\alpha,r}$, $f_{ui,\alpha,r}$, which are the factors describing the influence on the CO_2e emissions released by the elementary process α and machine r of the machine driver, of the process assistant systems integrated in the machine *r*, of the construction complexity degree and of unpredictable influence factors, respectively.

Finally, by replacing the terms of equation *(4-14)* with their relations described in *(4-21)*, *(4-22)*, *(4-23)* and (4-24), the following two cases can be distinguished.

Case 1 describes the usual situation where the machine has some working time. Therefore, the following equation is valid.

$t_{work,r} \neq 0$;

$$m^{NRMM}_{CO_2e,\alpha} = (1 - f_{ccs,\alpha,r}) \times f_{CO_2e/\text{energy carrier},\alpha,r} \times \frac{V_{material,\alpha,r}}{Q_{B,\alpha,r} \times f_{driver,\alpha,r} \times f_{\text{process assistant},\alpha,r} \times f_{\text{construction complexity},\alpha,r} \times f_{ui,\alpha,r}} \times (b_{m,r} \times f_{\text{machine condition},\alpha,r} \times f_{\text{machine technology},\alpha,r} + b_{idle,r} \times \frac{f_{stop\&go,\alpha,r} \times (f_{\text{site orga.},\alpha,r} + f_{\text{idle unavoidable},\alpha,r})}{1 - (f_{\text{site orga.},\alpha,r} + f_{\text{idle unavoidable},\alpha,r})} \qquad (4\text{-}25)$$

In case 2, there is no working time and consequently the only amount of CO_2e emitted is during idle time. Therefore, the following equation is to be used.

$t_{work,r} = 0$

$$m^{NRMM}_{CO_2e,\alpha} = (1 - f_{ccs,\alpha,r}) \times f_{CO_2e/\text{energy carrier},\alpha,r} \times b_{idle,r} \times t_{total,\alpha,r} \times f_{stop\&go,\alpha,r} \times (f_{\text{site orga.},\alpha,r} + f_{\text{idle unavoidable},\alpha,r}) \qquad (4\text{-}26)$$

$Q_{B,\alpha,r}$ is the basic work performance of nonroad mobile machinery during elementary process α. This performance represents the machine performance for the type of application under ideal conditions.

The basic work performance is calculated differently for each type of machinery. For this thesis, three representative mobile machines are chosen as references: excavators, pavers and rollers. They are calculated according to Hoffmann et al. as shown in (4-27) to (4-29). (Hoffmann et al. 2011)

Excavator:

$$Q_{B,excavator} = V_R \times f_L \times n \times f_1 \times f_2 \times f_3 \times f_4 \qquad (4\text{-}27)$$

Paver:

$$Q_{B,paver} = b' \times v \times h \qquad (4\text{-}28)$$

Roller:

$$Q_{B,roller} = b' \times v \times h \times \frac{1}{z} \tag{4-29}$$

Where V_R corresponds to the bucket capacity, n the cycle criterion for an excavator, f_1 the pivoting angle of the excavator body, f_2 the digging depth of the excavator. f_3 describes the kind of bucket emptying. It can be emptied non-targeted like on a dump or targeted e.g. on a truck. Factor f_4 describes the influence of the type of environment on work performance. The ideal situation for an excavator would be working without hindrance. The second best situation would be for the excavator to be used for trench excavation without shoring equipment. Alternatively, it would be that frequent repositioning of the machine is necessary or the excavated trench comprises trench shoring equipment to prevent cave-ins. f_L represents the load factor and is calculated by dividing the filling factor f_F by the decompaction factor of the soil f_S like in equation (4-30) from Hoffmann et al.. (Hoffmann et al. 2011)

$$f_L = \frac{f_F}{f_S} \tag{4-30}$$

b' represents the working width of a paver or a roller (ibid.). The working width of a roller is calculated with the following equation, where b_{eff} corresponds to the effective working width multiplied by a reduction factor of 0.75 (Bomag GmbH 2009).

$$b' = b_{eff} \times 0.75 \tag{4-31}$$

In equation *(4-28*) and *(4-29*), *v* and *h* stands for the velocity of the machine and the thickness of the layer worked on, respectively. *z* represents the number of passages of a roller on a layer until it has reached the required compaction level. (Hoffmann et al. 2011)

The quantification of the total additional CO_2e emitted into the atmosphere $m_{CO_2e,\alpha}$ due to the destruction and new formation of CO_2e sinks is calculated using the equation developed by Chen as follows (Chen 2019b):

$$m_{CO_2e,\alpha} = L_{before} - G_{after} = L_{con,v} + L_{con,s} + L_{ser,v} + L_{ser,s} + L_{flux} - G_{potential} - G_{rapid} \tag{4-32}$$

Where L_{before} describes the loss of CO_2e sinks due to deforestation, removal of vegetation or topsoil during the construction period (L_{con}) and during the maintenance or service life of the built product e.g. a road (L_{ser}).

Table 4-2: Annual CO_2 sequestration values for different vegetation categories (Chen 2019b; Barandica et al. 2014)

Vegetation categories	Annual sequestration $\Delta_{c,v}$ or $\Delta_{c,v1}$ [kg CO_2.m^{-2}.$year^{-1}$]
Cantabrian and mountain fir, eucalyptus and pine forests	1.25
Mediterranean eucalyptus forest	0.45
Chestnut forest	1.03
Poplar forest	1.34
Beech forest	0.70
Riparian forest	0.08
Myrica faya forest with heath	2.07
Eurosiberian oak forest	0.64
Evergreen Quercus	0.03
Mediterranean oak and gall-oak forests	0.18
Olive trees	0.03
Fruit trees	0.03
Other broad-leaved forests	0.47
Conifers and broad-leaved trees	0.36
Spanish juniper with or without Holm oak	0.05
Pine forests dominated by P. halepensis or P. pinea	0.24
Canarian pine	0.44
Other pine forests	0.53
Other conifers	1.17
Sparse and incipient forests	0.04
Grassland	0.20
Cropland	0.79
High-development shrubland	0.60
Low-development shrubland	0.30

During these two time periods, following losses can be differentiated (Chen 2019b):

- Losses through vegetation removal ($L_{con,v}$) and ($L_{ser,v}$)
- Additional soil emissions (L_{flux}), resulting in the first two to three years due to vegetation removal
- Losses due to topsoil removal ($L_{con,s}$) and ($L_{serv,s}$)

The resulting gains from replanting and CO_2e sinks restoration after construction work is taken into account with G_{after}, which can be differentiated into G_{rapid} and $G_{potential}$. G_{rapid} describes the effect of fast growing plants during the first 20 years which leads during this period to a higher amount of CO_2 removal from the atmosphere. $G_{potential}$ describes the gain over the lifetime of the built product, resulting from new CO_2e sinks formation. (Chen 2019b)

Table 4-3: Annual CO_2 sequestration values for different soil categories (Grüneberg et al. 2014; Chen 2019b)

Soil classification	Soil characteristics	Soil types	Annual CO_2 sequestration of the soil $\Delta_{c,s}$ [kg CO_2.m^{-2}.year^{-1}]
1	Dystrophic sand deposits	Regosols, Arenosols, Podzols	0.348
2	Sandy to loamy deposits	Fluvisols, Gleysols, Podzols	0.007
3	Loamy to clayey partly calcareous deposits	Fluvisols, Gleysols, Luvisols	0.070
4	Boulder clay and till	Cambisols, Luvisols, Regosols, Podzoluvisols	0.051
5	Sandy deposits overlaying boulder clay	Gleysols, Arenosols, Regosols, Cambisols	0.070
6	Eutrophic sand deposits	Cambisols, Arenosols	0.495
7	Sandy loess to loessic loam partly overlying various rocks	Luvisols, Podzoluvisols, Cambisols	0.172
8	Slope deposits over limestone, marlstone and dolomite	Cambisols, Leptosols	0.070
9	Redeposited material derived from limestone, marlstone, and dolomite	Cambisols, Luvisols	0.139
10	Marlstone and claystone or calcareous gravels	Cambisols, Gleysols	0.161
11	Basic and intermediate igneous rocks	Cambisols	0.128
12	Igneous and metamorphic rocks	Cambisols, Gleysols	0.147

$L_{con,v}$, $L_{con,s}$, $L_{ser,v}$ and $L_{ser,s}$ are calculated with the equations (4-33), (4-34), (4-35) and (4-36), respectively (Chen 2019b).

$$L_{con,v} = \Delta_{c,v} \times A_{con} \times t_{con} \quad (4\text{-}33)$$

$$L_{con,s} = \Delta_{c,s} \times A_{con} \times t_{con} \quad (4\text{-}34)$$

$$L_{ser,v} = \Delta_{c,v} \times A_{ser} \times t_{ser} \quad (4\text{-}35)$$

$$L_{ser,s} = \Delta_{c,s} \times A_{ser} \times t_{ser} \quad (4\text{-}36)$$

Where $\Delta_{c,v}$ (kg.m^{-2}.yr^{-1}) represents the annual CO_2 sequestration of the dominated vegetation; $\Delta_{c,s}$ (kg.m^{-2}.yr^{-1}) represents the annual CO_2 sequestration from the topsoil; A_{con} (m^2) is the entire area affected by the construction; A_{ser} (m^2) is the area occupied by the built product over its lifetime; t_{con}

(year) stands for the construction time; t_{ser} (year) stands for the lifetime of the built product. (Chen 2019b)

The annual CO_2 sequestration values for vegetation are taken from Table 4-2 and for soil are taken from Table 4-3.

The individual emissions are formed as follows (ibid.):

- CO_2 fluxes are caused by the fast decomposing crop residues that lie on the ground and the missing CO_2 photosynthesis of the flora.
- CH_4 fluxes are produced by the anaerobic degradation of organic substances by methanogenic bacteria. These bacteria thrive especially in the absence of oxygen. Therefore, an enhanced anaerobic environment leads to a larger amount of CH_4 fluxes.
- N_2O fluxes are influenced by changes in nitrification and denitrification rates. Denitrification is a microbial assisted process in which nitrate (NO_3^-) is reduced through decomposition of organic substances and finally molecular nitrogen (N_2) is produced by a series of gaseous intermediates. Denitrification depends mainly on the presence of sufficient organic matter. Vegetation clearing results in an excess of decomposed organic substances, which leads to high proportions of nitrogen mineralisation and nitrification, at the same time there is a lack of plants which leads to a denitrification problem. Thus, N_2O fluxes are formed.

CO_2, CH_4 and N_2O fluxes belong to the greenhouse gases and therefore have a GWP value of 1, 28 and 265 respectively for f_{CO_2}, f_{CH_4}, f_{N_2O}. The annual fluxes after the removal of vegetation of CO_2, CH_4 and N_2O are measured with 1.8, 0.8 and 0.2 $kg.m^{-2}.year^{-1}$, respectively. Thus the greenhouse gas effect of these fluxes can be calculated with the following equation. (Chen 2019b; Greenhouse Gas Protocol 2016)

$$L_{flux} = \left(f_{CO_2} \times E_{CO_2} + f_{CH_4} \times E_{CH_4} + f_{N_2O} \times E_{N_2O}\right) \times A_{con} \times t_{con} \quad (4\text{-}37)$$

Where E_{CO_2}, E_{CH_4} and E_{N_2O} describe the amount of annual emitting fluxes of CO_2, CH_4 and N_2O. Also here, A_{con} stands for the total area affected by the construction and t_{con} for the construction period.

Table 4-4: CO_2 sequestration during the fast growth phase of different plantation categories (Chen 2019b; Barandica et al. 2014)

Plantation categories	CO_2 sequestration in high planting density $\Delta_{c,v2}$ [kg CO_2.m^{-2}.year^{-1}]	CO_2 sequestration in low planting density $\Delta_{c,v2}$ [kg CO_2.m^{-2}.year^{-1}]
Cantabrian and mountain fir, eucalyptus and pine forests	2.49	1.61
Mediterranean eucalyptus forest	1.24	0.73
Chestnut forest	3.86	2.58
Poplar forest	2.23	1.43
Beech forest	4.38	2.94
Riparian forest	1.52	0.93
Myrica faya forest with heath	6.31	4.31
Eurosiberian oak forest	3.02	1.98
Evergreen Quercus	0.93	0.58
Mediterranean oak and gall-oak forests	1.95	1.23
Olive trees	0.27	0.09
Fruit trees	0.15	-
Other broad-leaved forests	2.14	1.37
Conifers and broad-leaved trees	2.26	1.45
Spanish juniper with or without Holm oak	0.89	0.55
Pine forests dominated by P. halepensis or P. pinea	2.26	1.45
Canarian pine	3.70	2.47
Other pine forests	2.46	1.59
Other conifers	2.53	1.64
Scattered trees	0.93	-
Low shrubland	0.58	0.30
High-development resprouting shrubland	3.91	2.80
Medium development resprouting shrubland	2.43	1.66
Residential garden	0.4	0.4
Grassland	0.36	0.36

Young plants are replanted after construction work. These plants grow faster in the first 20 years of their lifetime and therefore absorb more CO_2 during this time. In replanting, different decisions about plantation spectra and environmental variables can significantly affect long-term carbon sequestration. This effect is taken into account with G_{rapid} and equation (4-38). (Chen 2019b)

$$G_{rapid} = (\Delta_{c,v2} - \Delta_{c,v1}) \times A_{res} \times t_{rapid} \quad (4\text{-}38)$$

$\Delta_{c,v2}$ stands for the CO_2 sequestration during the fast growth phase (see Table 4-4), $\Delta_{c,v1}$ for the annual CO_2 sequestration of the newly planted dominant vegetation in the long run (see Table 4-2), A_{res} for the vegetation restoration

area and t_{rapid} for the time of the fast growth phase of the newly planted vegetation.
The gains over the lifetime of the built product $G_{potential}$, resulting from new CO_2e sinks formation is calculated using equation (4-39) (Chen 2019b).

$$G_{potential} = (\Delta_{c,v1} - \Delta_{c,v}) \times A_{res} \times t_{ser} \quad (4\text{-}39)$$

Where $\Delta_{c,v1}$ describes the annual CO_2 sequestration of the newly planted dominant vegetation, $\Delta_{c,v}$ the reference vegetation or ecosystem, A_{res} the restoration area with vegetation and t_{ser} the lifetime of the built product.

Finally, by replacing the terms of equation (4-32) with their relations described in (4-33), (4-34), (4-35), (4-36), (4-37), (4-38) and (4-39) the following equation (4-40) is obtained for the elementary process considering CO_2e sinks destruction and formation.

$$\begin{aligned} m_{CO_2e,\alpha} = {} & \Delta_{c,v} \times A_{con} \times t_{con} + \Delta_{c,s} \times A_{con} \times t_{con} + \Delta_{c,v} \times A_{ser} \\ & \times t_{ser} + \Delta_{c,s} \times A_{ser} \times t_{ser} \\ & + \left(f_{CO_2} \times E_{CO_2} + f_{CH_4} \times E_{CH_4} + f_{N_2O} \times E_{N_2O}\right) \\ & \times A_{con} \times t_{con} - (\Delta_{c,v1} - \Delta_{c,v}) \times A_{res} \times t_{ser} \\ & - (\Delta_{c,v2} - \Delta_{c,v1}) \times A_{res} \times t_{rapid} \end{aligned} \quad (4\text{-}40)$$

In summary, the developed method quantifies not only CO_2 emissions but all greenhouse gas emissions produced during a construction process. The method thus fulfils need N1, defined in 2.4. In addition, the method is based on a holistic approach by considering CO_2e sink destruction and vegetation restoration, material transportation, material production and construction processes. Additionally, not only direct emissions at the construction site are considered but also indirect emissions. This holistic approach fulfils the need N2 and enables an overview of all emitters and influencers of CO_2e emissions for construction applications, which in turn permits taking the right measures to minimise the negative consequences of a construction process on the climate.

5 Determination of representative construction applications

In order to verify the developed method, construction applications representative for Europe have to be defined. These applications are determined through the analysis of statistics. In a first step, application sectors will be determined which will permit the second step to determine application processes.

5.1 Selection of application sectors

The ifo institute publishes statistics about the construction volume in Euros in Europe by countries and by segments on a regular basis. In 2012, 28 % of construction volume was invested for residential renovation; 22 % for civil engineering, 17 % for new housing, 17 % for new non-residential buildings and 15 % for non-residential renovation. (ifo 2012, p. 118)

“Renovation” describes work where only limited use is made of mobile machines like in restoration, modernisation, extension construction, conversions or maintenance work. Therefore, representative application processes for mobile construction machines will be from the three constructions segments: new housing, new non-residential buildings and civil engineering.

Germany (21 %), France (16 %), Italy (13 %) and the UK (12 %) combined have a construction volume of 62 % [15] and consume 63 % of domestic cement[16] in Europe (ifo 2012, p. 119). Consequently, these four countries will be used as a reference in order to determine the construction processes for the three construction segments.

Further, a report about the land area used in different sectors for EU-15 countries was analysed. In the sectors where mobile construction machines

[15] The construction volume has been determined with construction prices (ifo 2012).

[16] The domestic cement consumption has been determined in million tons cement (ifo 2012).

are used, “mining and quarrying” have the biggest share (0.2 %) followed by the construction sector (0.1 %) [17]. (Eurostat 2003, p. 12)
Therefore, also the segment mining and quarry will be considered for the determination of representative applications of mobile construction machines.

5.2 Determination of construction applications for mobile construction machines

This subchapter focuses on explaining how representative construction applications are chosen. First, an application from a new housing type will be determined. It will be followed by an application from the non-residential building sector, the road construction sector, the earthmoving sector and the quarry sector.

5.2.1 New Housing

In order to define the nature of new housing, statistics about issued dwelling permits were consulted. In 2017, 51.3 % of the permits issued in the European Union were for flats and 48.7 % for single family homes. This same trend to issue more permits for dwellings in flats than in single family homes is valid for the years 2000 to 2017. (Eurostat 2018)
Germany is used as reference for the determination of reference construction processes for new housing because on the one hand data from other European countries since 1991 (past) is lacking and on the other hand because Germany has the biggest construction volume (21 %) (ifo 2012, p. 119). German national statistical data also shows that in 1991 more permits for dwellings in flats than in single family homes were issued (Destatis 2018a, p. 4). Additionally, statistics show that the majority of flats since 1993 are built as non-prefabricated construction (Destatis 2018b, pp. 3–9). This same statistics shows that in 1993 (corresponding to the “past” scenario), it was popular to

[17] Agriculture has the biggest share (41.5 %) followed by forestry with 30 %. Mobile agriculture machines and mobile forestry machines are used in the agriculture and forestry sector, respectively.

build flats with bricks, in 2010 with reinforced concrete and in 2017 with sand-lime brick (ibid.). Based on the main construction material, the construction method can be determined. In summary, a representative construction for the European Union in the segment new housing is a multi-storey dwelling in a non-prefabricated solid construction. The past scenario will use bricks as the main material for a masonry design. For the present scenario reinforced concrete as the main material for a reinforced concrete design is chosen. In the future scenario of a multi storey dwelling construction sand-lime brick as the main material for a masonry design will be used. Table 5-1 summarises the chosen data for the different scenarios.

Table 5-1: Key data summary of the new housing

Construction segment	New Housing: flat (multi storey dwelling)		
Times	Past	Present	Future
Construction type	Non-prefabricated construction		
Construction method	Solid construction in masonry design	Solid construction in reinforced concrete design	Solid construction in masonry design
Material	Bricks	Reinforced concrete	Sand-lime brick
Dimensions (L x W x H)	17.5 m x 12.5 m x 17.5 m		
Number of dwelling	10		
Number of floors	5 floors + 1 basement		
Living space	82 m²		
Storey height	2.8 m		
Headroom	~2.45		

The ifo institute has calculated the average household sizes for 19 European countries, corresponding to 2.35 persons per household in 2012 (ifo 2012, p. 58). This household size corresponds to the size in France (2.29) (ibid). Therefore, the number of rooms per dwellings are defined according to national statistics from France. According to Demaison, the average number of rooms per dwelling in flats correspond to 2.9 in France (Demaison et al. 2017, p. 142). In accordance with national German statistics, a flat in 2014 had an average number of dwellings of 7.6-11.5 (Destatis 2018b). For a realistic representation, a flat with 10 dwellings of each 82 m², three rooms, a kitchen and a bathroom is chosen, like in Figure 5.1 and Figure 5.2.

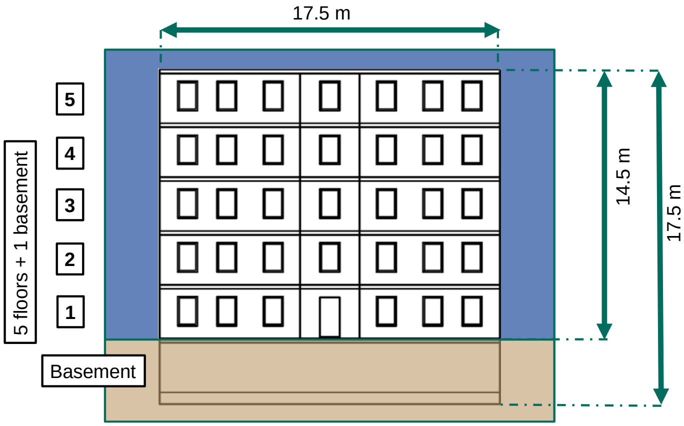


Figure 5.1: New Housing-flat with five floors and one basement

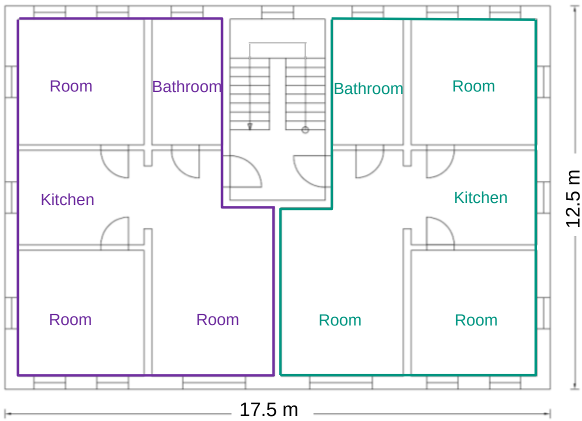


Figure 5.2: Floor plan of the flat

5.2.2 Non-residential building

In order to define the nature of non-residential buildings, statistics for Europe were consulted. Non-residential building are described as buildings with very mixed type of structures, e.g. the warehouse varying from the office building. Ifo statistics describes that in 2011, the biggest share of non-residential buildings was commercial buildings with 18.2 %, followed by industrial buildings with 16.4 %, then office buildings with 16.3 %, buildings for education with 12.2 %, buildings for health 8.3 %, agricultural buildings with 7.4 %, storage buildings with 6.7 % and the rest is categorised as miscellaneous non-residential buildings. (ifo 2012, p. 73)

The three biggest shares and therefore generating the most activities are commercial, industrial and office buildings. Industrial building structures differ from one industry to another. It can have a simple structure similar to a warehouse or a more complex one similar to an office building. Further, these buildings are modifiable so that production can be adapted to demand, which makes them a special construction adapted to the type of industry and product. It is similar for commercial buildings, depending on the commerce it can either be built with a simple structure or a more complex one like an office building. Therefore, an office building combined with a commercial area is chosen as a representative non-residential building. Its structure will be based on typical construction structures for office buildings. For the dimensioning of the office building, information and values from German statistics are used because Germany has the biggest construction volume in Europe (see 5.2.1) and is so representative for Europe. Additionally, only German statistics gives information about which construction trend was and is popular for non-residential buildings in the different times of past, present and future. In the past (1993) the main material for commercial, industrial or office building was steel (Destatis 2018b). Therefore a steel composite construction is chosen for the past scenario. The main material used in 2010 or 2014 is reinforced concrete (Destatis 2018b). Therefore, a reinforced concrete skeleton construction is chosen for the present and future scenario. Another statistic from Destatis stipulates that non-residential building are built as non-prefabricated construction (Destatis 2015).

Based on data from Destatis and from Liebchen et. al. it is possible to calculate the average gross external area ($BGF_{average}$) of an office building as well as its average storey height ($h_{average}$), see equation*(5-1)* and *(5-2)* (Destatis 2015; Liebchen et al. 2007).

$$BGF_{average} = \frac{NF_{total} \times F_{eff}}{N_{building}} = \frac{2{,}576{,}000 \times 151\%}{1{,}817} = 2{,}141\ m^2 \qquad (5\text{-}1)$$

$$h_{average} = \frac{V_{total}}{N_{building} \times BGF_{average}} = \frac{14{,}285{,}000}{1{,}817 \times 2{,}141} = 3.7\ m \qquad (5\text{-}2)$$

Where NF_{total} is the total useable area, $N_{building}$ the quantity of office buildings, F_{eff} the efficency factor typical for office buildings and V_{total} the gross volume.

Concerning the internal design of an average office building, no data was found in any statistics. For this reason, a different approach was chosen based on fire protection regulations. According to Fischer et al. an office building with a gross external area per floor of less or equal to 400 m² is the most economical type of building because of the fire protection regulation (Fischer et al. 2010). Therefore, a simple design is chosen to fulfil the first-degree regulation, which have less demanding fire protection regulations and is hence more economical. A gross area per floor (GF_{floor}) of 400 m² is chosen.

This information allows calculating the number of floors in the average European office building by dividing the average gross external area ($BGF_{average}$) by the gross area per floor, see equation *(5-3)*.

$$Number\ of\ floors = \frac{BGF_{average}}{GF_{floor}} = \frac{2271\ m^2}{400\ m^2} \approx 5{,}7\ floors \qquad (5\text{-}3)$$

Table 5-2: Key data summary of the non-residential building

Construction segment	Non-residential building: office building with a commercial area		
Times	Past	Present	Future
Construction type	Non-prefabricated construction		
Construction method	Steel composite construction	Reinforced concrete skeleton construction	
Material	Steel	Reinforced concrete	
Dimensions (L x W x H)	30 m x 13,5 m x 20 m		
Number of floors	5 floors + 1 basement		
Gross floor area	~400 m²		
Office space	Cubicle offices		
Office length	4.8 m		
Storey height	3.2 m		
Headroom	~2.50		

According to Eisele and Staniek office buildings with a width of approximately 12 m are the most common because of their economical aspects like investment costs, energy consumption, operating costs, etc. (Eisele and Staniek 2005)

According to Knirsch 80.7 % of all offices in Germany are cubicle offices (Knirsch 2002). Eisele and Staniek also describe that common office building constructions have four facade grid of 1.2 m to 1.5 m between each support grid (Eisele and Staniek 2005).

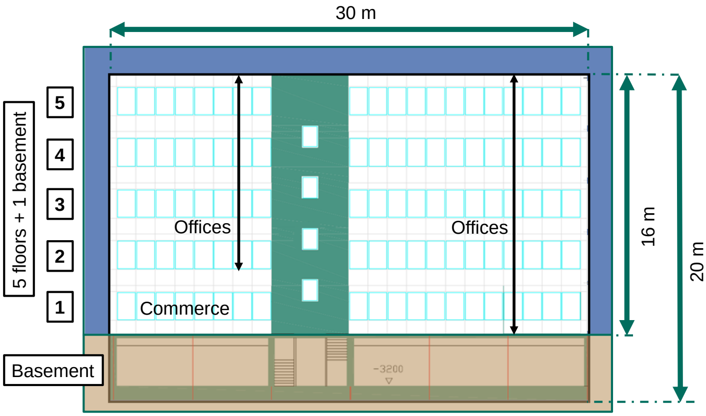


Figure 5.3: Non-residential - office building with five floors and one basement

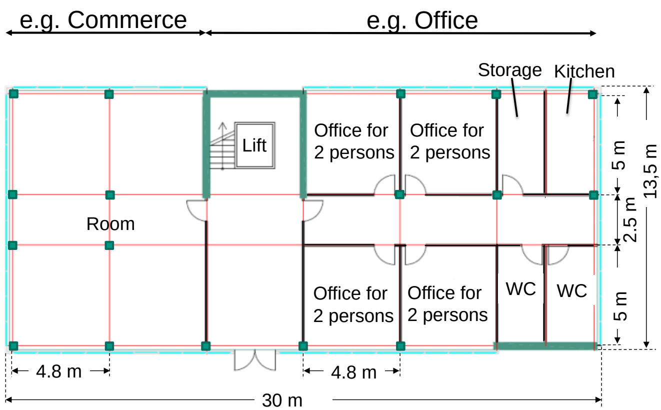


Figure 5.4: Ground floor plan of the office building

As described in Table 5-2 and Figure 5.3, an office building with five floors and one basement, meaning a length of 30 m, a width of 13.5 m and a height of 20 m is chosen as reference.

According to the guidelines for office space dimensioning, the minimum dimensions of an office for two persons are 3.6 m x 1.8 m (Eisele and Staniek 2005). Consequently, a face façade grid of 4.8 m (2 x 1.2 m) complies with the office space dimensioning guidelines. Figure 5.4 represents the floor plan of the office building.

5.2.3 Road construction

A representative type of application in civil engineering for Europe can be determined with national statistics of the three countries with the largest civil engineering sector. According to Eurostat, these countries are the United Kingdom with 20 %, Germany with 10 % and France with 10 % (Eurostat 2013). In the same statistics, it is shown that road and railways are the most relevant construction applications in the civil engineering sector in Europe (ibid.). In 2013, in Great Britain 41 % of civil engineering expenses went to the road sector (26 % into local roads and 15 % into national roads) and 34 % to the railway sector (Department for Transport 2014). Therefore it can be assumed, that in the United Kingdom, road construction, especially of local roads is a representative construction application. In Germany in 2015 the biggest revenues in the civil engineering sector were in road construction with 42 %, followed by canalisation and waste water treatment plants with 22 %, then with 11 % from rail construction, then with 4 % from bridges and tunnel construction and the remaining 21 % are from various other sectors (Statista 2015). Most construction is assumed to be for local roads because there are eighteen times more local roads than national roads in Germany (ibid.). The biggest activity share in the civil engineering sector in 2013 in France was road construction with 35 %, followed by earthmoving with 19 %, then by wastewater treatment plant, water supply and canalisation with 16 % and then with 13 % electric constructions (FNTP 2014). The remaining 16 % were for various other activities (ibid.). In conclusion, in all three representative European countries, most expenses went to road construction. The construction of a local road is chosen as a representative application.

Each country in Europe has different standards for road construction. The dimensioning of the road as a reference application is chosen to be based on

German standards. In Germany roads of the type BK32, BK10 and BK3,2 are defined as local roads (Velske et al. 2013). In the context of this work, the local road chosen is a BK10 type road. This type of road is built for different purposes like a connecting road, an industrial road, a main shopping street, a local business street, etc. (Velske et al. 2013). The exact dimensions of the BK10 road are illustrated in Figure 5.5, with dimensions of 7.5 m width and 1 km length. Popular materials for the different layers are chosen and are shown in the same figure. Except for the past scenario, an equivalent of the BK10 type was the II type. The material type and road thickness are therefore different for the past scenario.

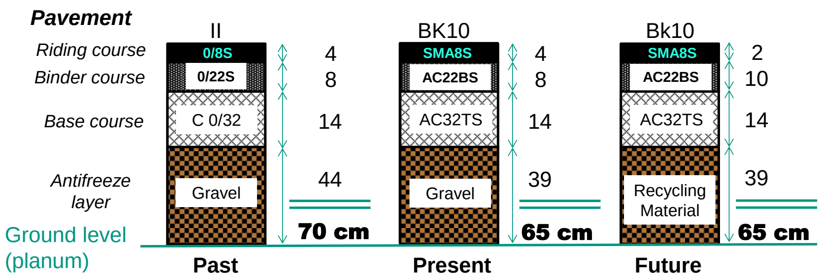
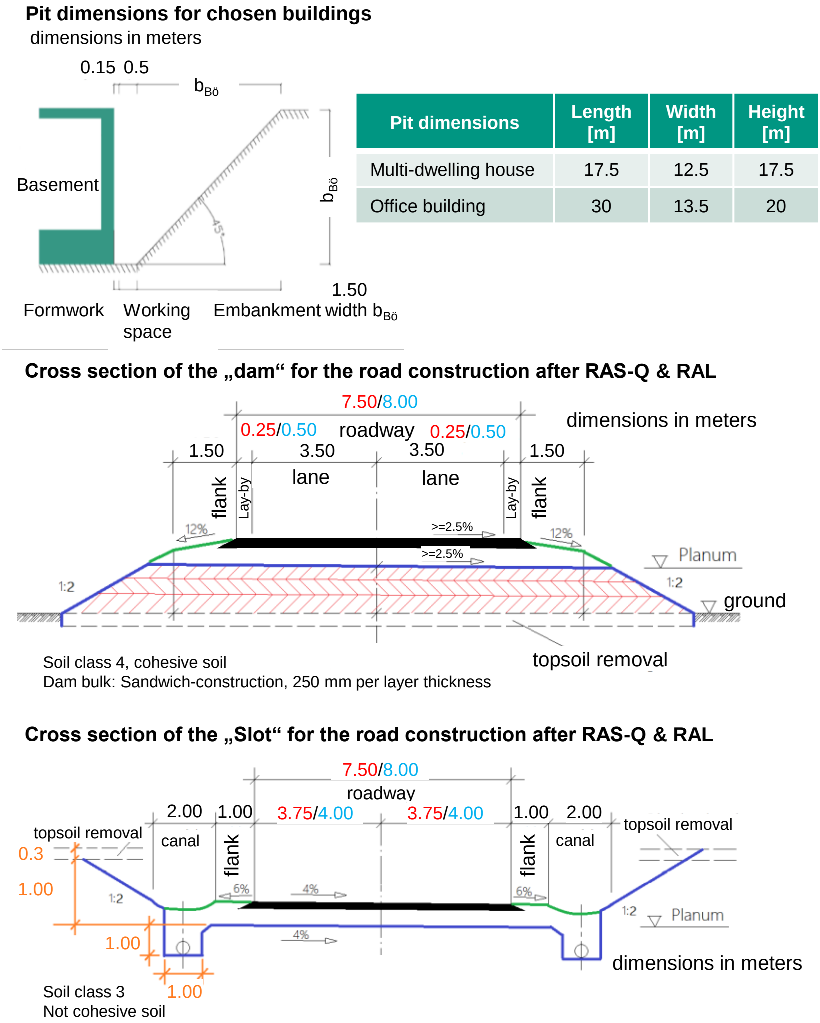


Figure 5.5: BK10 road section with its correspond materials

A survey of companies producing road equipment has indicated that the most frequent type of road construction applications in Europe are the construction of new roads and their renewal using the inlay method. This is the reason why, renewal of roads using the inlay method will also be the subject of this analysis and be chosen as the reference application. The inlay method consists of replacing old road layers with new ones (Velske et al. 2013). The chosen representative construction processes for road renewal will consist of replacing the surface, binder and base course with new ones.

5.2.4 Earthmoving



Pit dimensions	Length [m]	Width [m]	Height [m]
Multi-dwelling house	17.5	12.5	17.5
Office building	30	13.5	20

Figure 5.6: Three chosen earthmoving works with their dimensions

Earthmoving work in the construction sector is most of the time part of a bigger construction undertaking. Therefore, as the subject of analysis the earthmoving work needed for the previously chosen reference application in the building and in the road construction sector will be chosen. These needed works are pits for the building constructions as well as a dam and a slot construction for the local road, as shown in Figure 5.6.

5.2.5 Quarry

Lüttig shows in his statistics that sand and gravel followed by ashlar and hard stone are the material types most extracted in the world (Lüttig 2007). According to Hass and Popescu, these types of material are also the most extracted in Europe with a share of 61 % (Hass and Popescu 2011). These types of material can be extracted using two different methods: wet and dry extraction (Patzold et al. 2008). A statistic from Liebherr shows that 90 % of these materials used in the construction industry are from quarries. Therefore the representative application chosen will be the dry extraction of sand, gravel, ashlar and hard stone in quarries.

A quarry is defined as an open-pit mine with the objective of gaining mineral materials from natural rock deposits through cutting out, extracting and processing (Liebherr 2012). The life cycle of a quarry consists of three phases (Gehbauer and Gentes 2011). The first phase happens before operation of the quarry and consists of investigating, planning, transporting equipment, preparing access, harvesting and off-road transporting (Volvo CE 2015, p. 36). The second phase is during operation of the quarry which consists of extracting mineral materials (Gehbauer and Gentes 2011; Liebherr 2012). The last phase consists of recultivation and renaturation of the area where the quarry operation took place (Volvo CE 2015, p. 36). Phase two can have a lifetime of over 100 years (Gehbauer and Gentes 2011), therefore according to the pareto principle, the focus will lie on processes of phase two, during quarry operation.

The reference quarry chosen will have an extraction capacity of 110,000 t/year[18]. It will produce crushed material with an average diameter of

[18] This extraction capacity corresponds to the capacity of an average European quarry (Liebherr 2012).

16 to 32 mm and a density of 1450 to 1550 kg/m³ [19]. The quarry will be operated with 8 machines and the transport of the material will take place with a dump truck[20].

5.3 Representative construction application

Statistics from construction activities as well as from material extraction have permitted defining representative construction applications. These applications with their processes and sub processes are meaningful and of statistical significance for a CO_2 balance. These representative application are:

<u>Building construction</u>

- Construction of a flat with five floors and one basement
- Construction of an office building with five floors and one basement. The ground floor has an area reserved for commerce.

<u>Road construction</u>

- New construction of a road of type BK10
- Renewal of a road of type BK10

<u>Earthmoving work</u>

- Pit excavation for the flat
- Pit excavation for the office building
- Dam construction for the road of type BK10
- Slot construction for the road of type BK10

<u>Material Extraction</u>

- Quarry extracting mineral material

[19] These sizes of crushed material are sizes representative for European quarries (Volvo CE 2010).

[20] Automatic material transport with e.g. conveyor band is used for quarries with an extraction capacity of 1,000,000 to 5,000,000 t/year. In Europe, only a few quarries have such a extraction capacity. (Liebherr 2012.)

6 Influence analysis

This chapter focuses on analysing how efficiencies of 4.3 impact the total amount of CO_2e emitted from mobile machines. First, the factor influence will be verified, then the value ranges will be determined for each factor described in chapter 4. Afterwards, values for the factors in the past, present and future scenarios will be determined. An influence analysis of these factors on the example of an excavator will follow in order to determine the impact of each factor. This will permit prioritising the factors according to their influence impact. Finally, the method will be verified through its simulation in the representative scenarios defined in chapter 5. An additional simulation will take place in order to validate the consideration of CO_2e sinks destruction and new formation in the CO_2e quantification method.

6.1 Verification of the factors' influence on CO_2e emissions from mobile machines

In this subchapter, the factors' influence on the amount of CO_2e emitted by mobile machines is verified. The verification is carried out according to two procedures. All information concerning machine efficiency, which means the effects of efficiencies in the machine technology and the state of the machine's condition as well as the efficiency impact of process assistant systems, was assessed through mobile machine producers according to the Delphi method, see appendix A.1. The Delphi method consists of collecting information from the mobile machine producers through questionnaires anonymously. After the questionnaire was returned answered, an average of the values received was calculated and resend to them in order to revise the numbers and see if a mean value as consensus was still representative for their machines. The influence factor of $f_{machine\ condition}$ was complemented with information from the literature and interviews of rental companies of mobile machines. The verification of the other factors determined in chapter 4 were assessed through literature reviews.

6.1.1 Machine technology

The application of these two procedures resulted in the following findings. Applying the Delphi method, it was found that the efficiency of machine technology impacts the CO_2e emitted by mobile machines (see appendix A.1). Machine efficiency is the combined effect of engine efficiency of today's existing ECO-mode (only when it is activated during operation) and of other additional machine technologies improvements (see appendix A.1). Internal historical data from the mobile machine producers show that engines have improved over the years since 1990 (see appendix A.1). Fuel consumption or CO_2e emissions have been reduced through engine improvements up to 3 % (see appendix A.1). Operating machines in ECO-mode, a modus where the engine revolution (rpm) is reduced, can save up to 15 % on fuel or CO_2e (see appendix A.1). Through improving other machine technologies other than that of the engine or ECO-mode, it is possible to reduce fuel consumption or CO_2e emissions up to 35 % compared to the technology level of 1990 (see appendix A.1)[21]. The relation of these three factors described in equation *(4-1)* results in a range for $f_{machine\ technology}$ between 0.54 and 1.0. Where $f_{machine\ technology}$ will have the value 1.0, if no improvement in the machine technology has happened since 1990.

6.1.2 Machine condition

Likewise, according to the Delphi method, it was found that the condition of a machine influences the CO_2e amount emitted (see appendix A.1). The condition of the machine is defined by the amount of operation hours defining its age and by service regularity (see appendix A.1).

Age

A machine with regular correct maintenance and repair work, will decrease its fuel consumption over its lifespan a maximum of 10 % (see appendix A.1). Further, machines from rental companies have greater annual utilisation, a higher average horsepower rating and so a shorter lifetime than similar

[21] In some cases the ECO-mode cannot be used because the delivered power is not sufficient to fulfill the work task.

machines from private owners (Zou 2018)[22]. By assuming a linear performance deterioration, this would mean that a mobile machine exceeding its average lifetime by 3.2 times[23] would mean a greenhouse gas increase up to 32 %. The value range from f_{age} varies between 1.0 and 1.32, where the value 1.0 represents no fuel consumption increase due to age.

Service regularity

A mobile machine lacking in service regularity will consume more fuel and so emit more greenhouse gases. Some components need regular service more than others. Components with a higher service necessity were analysed on the example of a wheel loader through literature reviews and are featured in pink in Figure 6.1 below representing the power flow of a wheel loader with a diesel drive. After every 500 operating hours of a wheel loader, following components need to be replaced during service: fuel, air and oil filters as well as engine oil, hydraulic oil and gear oil. Depending on the soil class where the wheel loader is working, after approximately every 1500 operation hours, the tooth system of the bucket needs to be replaced. (Zou 2018)

In the following, the effects of these components aging or having a lack of services were analysed further through literature reviews and the results are depicted below.

The purpose of a fuel filter is to retain particles and free water from entering the engine (Tschöke et al. 2018). Particles in fuels originate from organic and mineral dusts, metallic abrasions and soot and can cause damage to the fuel injection system (ibid.). Water causes corrosion and cavitation, accelerating fatigue and aging of the components in the fuel injection system, which reduces lubricity, etc. (Tschöke et al. 2018; Nessau 1977). The consequences of a damaged fuel injection system are lower performance capability, uneven running, variation in the injection conditions like its quantity, higher engine

[22] Additionally, a survey of construction machinery manufacturers has also confirmed this statement.

[23] A wheel loader from a rental park reaches its average lifetime in approximately 5 years (Zou 2018). According to a publication from the CECE, mobile machines can be used for up to 16 years (Euromot, CECE, CEMA 2008), although new machines are typically operated at a higher number of hours per year relative to older engines. Consequently, the wheel loader would exceed its average lifetime by 3.2 times.

wear and changes in exhaust gas characteristics (Nessau 1977). All these effects combined together lead to an increase in fuel consumption (Nessau 1977) and so in greenhouse gas emissions.
Air filters for the engine filtrates particles such as dust, pollen or pollutant from the intake air before it flows into the combustion engine. This protects the engine as well as sensors like the mass air flow sensor (MAF) from wear and malfunctions. (Tschöke et al. 2018)
A polluted air filter increases the fuel consumption and reduces the maximum power of the machine. A pollution increase of 25 %, 50 % or 75 % reduces the maximum power respectively to 6.7 %, 26 % and 42 % and increases fuel consumption and thus greenhouse gas emissions by 15 %, 44 % and 80 % respectively. (Behched et al. 2011)

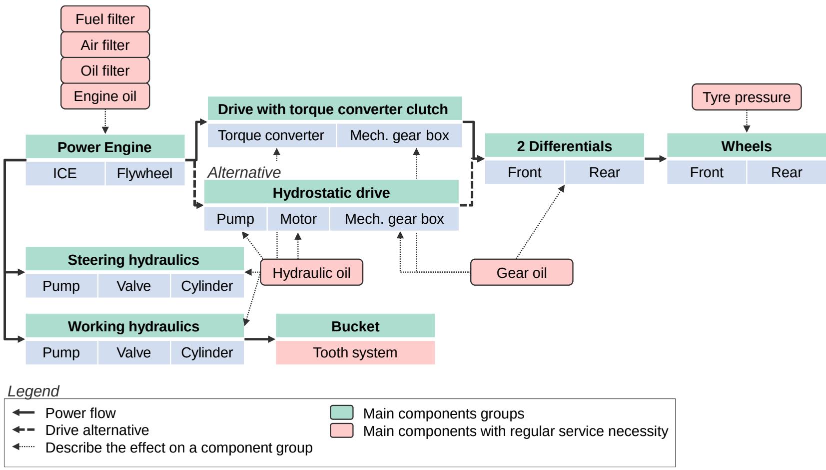


Figure 6.1: Power flow of a wheel loader

The engine oil's purpose is to reduce friction by creating a separating layer between components, sealing component gaps, cooling down components by absorbing and transporting heat loss and to remove residues and wear particles (Kunze et al. 2012b, p. 68). When oil ages it can become thinner due to lacquer-like residues, become thicker because of asphalt-like residues, get contaminated or acidified (Todsen 2012, p. 184). Murtonen and Kytö showed that by varying the viscosity degree of lubrication oil, differences in fuel consumption and in CO_2 emissions take place (Murtonen and Kytö 2004).

Too high oil viscosity results in “high-energy consumption due to loss of energy viscous drag” (Chen et al. 2018, p. 6). Contaminated oil decreases the lubrication effect and increases wear of components resulting in increased energy consumption and so in increased greenhouse gas emissions (ibid.). The wear caused by oil contamination produces a chain-reaction-of-wear resulting in oil suspended particles (Needelman and Madhavan 1988, p. 15). This can lead to higher friction as well as to the loss of compression in the piston due to the opening of the dynamic sealing surface (ibid.). These result in higher fuel consumption and so higher greenhouse gas emissions. (ibid.)

In order to reduce oil contamination, an oil filter is flanged to the engine block enabling more efficient fuel burning and thus reducing fuel consumption (Tschöke et al. 2018; Chen et al. 2018, p. 6). When the oil filter ages, more contamination enters the oil leading to oil aging, which in turn results in higher greenhouse gas emissions (see explanation above).

The functions and aging effect of gear oil is similar to the engine oil. Aging occurs through intermeshing gears crushing the long-chain of oil molecules, resulting in thinner oil which means lower oil viscosity (Anon. 2017). If the viscosity is too low, the transferable frictional power is reduced leading to fretting and increased wear and thus in increased fuel consumption and greenhouse gas emissions (Kunze et al. 2012b, p. 68; Anon. 2017)

Hydraulic oil's main purpose is to convey energy (Geimer 2018/2019, H-1). As second function, oil serves to lubricate the hydraulic control system (ibid., p.H-5). Aging of hydraulic oil due to its contamination due to particles, free water or free air causes blocking of the valve slide or fretting of the pump. This results in wear particles generating more particles (chain-reaction-of-wear). Further free air leads to local decomposition of oil molecules, small local explosions due to self-ignition and a reduction in thermal conductivity. Free water deteriorates the lubrication effect and promotes corrosion. Contaminated hydraulic oil can cause damages up to sudden component failures as well as efficiency losses due to components wear and tear. (Will and Gebhardt 2011, pp. 29–399)

Efficiency of a hydraulic system enables assessing energy use and is described through the quotient of the energy delivered and the energy supplied (Hlawitschka 1980, p. 459). Consequently, by decreasing the efficiency of the hydraulic system, fuel consumption and thus greenhouse gas emissions increases.

According to Kunze et al., a working tool is characterised as optimal if it permits the realisation of the maximum technological machine performance (Kunze et al. 2012b, p. 85). „Approximately 50 % to 60 % of all loader buckets are equipped with teeth to improve penetration and decrease cycle time" (Lukavich 1974, p. 7).

When the bucket pierces the overburden, five forces act on it: the weight force of the overburden in the bucket, the reaction force from the rocks/earth under the bucket, the reaction force from the bucket edge penetration, the friction force on the bucket surface and the reaction force of the anterosuperior soils moved by the bucket (Takahashi et al. 2006, p. 476). Due to these forces, over time, the underside of the tooth system will wear more than the top, resulting in an asymmetrical shortening of the teeth (CNH Industrial). According to Kunze et al. the cutting resistance is 25 % better with symmetrically formed teeth than with asymmetrically formed teeth (Kunze et al. 2012b, p. 29). Further long and thin teeth are to be favoured to short and wide teeth (ibid.). An impaired penetration capability due to teeth wear results in longer cycle times, higher hydraulic pressure and thus increased fuel consumption (Komatsu 2014, p. 3). Therefore, in order to replace quickly the tooth tip, the tooth is composed of two components the tooth tip and the tooth holder (Pfab 2017, p. 123). According to Zou, it is recommended for a wheel loader to replace the tooth tip every 1500 operation hours (Zou 2018, p. 61).

According to Hilgers, when the air pressure in tyres is too low, the tyre will flex more and heat up significantly. Consequently, the rolling resistance will increase and thus also fuel consumption. (Hilgers 2016, p. 47; CEMA and CECE 2011)

In summary, the literature review has shown that a lack of service regularity influences the amount of greenhouse gases emitted by mobile machines.

According to the results from using the Delphi method, a greater than 100 % lack of service inspections beyond the recommended service amount in mobile machines can increase fuel consumption and thus CO_2e emissions up to 40 % (see appendix A.1). This means that $f_{service\ regularity}$ varies between 1.0 and 1.40. Where the value 1.0 states that the machine has been under regular service and so there is no increase of fuel consumption.

Consequently, according to equation (4-2), $f_{machine\ condition}$ has a value range from 1.0 to 1.85. Where the value 1 for $f_{machine\ condition}$ means that the machine is in ideal condition.

6.1.3 Process assistant

Concerning process efficiency, the application of the Delphi method also permitted defining the range of effects from process assistant systems on the driver. Process assistant systems are different for each type of machine and have a different impact depending on the experience of the driver. For a wheel loader or excavator, process assistant systems can be a tyre pressure monitoring system, a bucket filling assist system, systems enabling semi-automatic movements, payload weighing systems, data analysis and its visualisation for the driver through visibility assistants like sensors, cameras, etc.. Process assistant systems for a paver are different. They are, for example, a repositioning and paving function system, a 3D positioning system, a communication system between truck and paver. A roller, for example, will have process assistant systems permitting measurements of the compaction degree, controlling of track and temperature as well as an automatic continuously variable amplitude system. (See appendix A.1)
Today, existing process assistant systems can increase efficiency of an expert driver up to 14 %, of a good driver up to 28 %, of a medium driver up to 48 % and of a beginner up to 72 % (see appendix A.1). Subsequently, $f_{process\ assistant}$ has a possible value range from 1.0 to 1.72. Where $f_{process\ assistant}$ takes the value 1.0 when no process assistant systems are used.

6.1.4 Construction complexity

Application of the Delphi-method permitted determining that the construction complexity influences the performance and the fuel consumption of construction machines. The construction complexity represents the combined effects of the weather influence, the available construction time and the available construction site freedom.

Weather

The weather at construction sites is characterised by temperature, wind velocity, humidity (rain/snow) and light. Al-Abbasi shows in his work that from the three weather variables: temperature, wind and humidity, temperature has the largest impact on construction trade productivities (Al-Abbasi 2014). According to the ideal gas law with a constant amount of air, when the temperature drops, the volume of air becomes smaller which means air becomes denser. Higher air density results in higher aerodynamic drag. Further, air density influences combustion behaviour in diesel engines (Hilgers 2016, p. 38). According to Cummins, every 10 °C temperature drop, increases aerodynamic drag by 2 % (Cummins MPG Guide 2012). Thus, fuel consumption will increase by 1 % for machines with a high driving share (ibid.). Further, low temperature affects the hydraulic oil in mobile machines, therefore a longer warm-up period of the machine is necessary[24]. According to Howdy Honda, warm temperatures can reduce a vehicle's fuel consumption because the engine heats up faster to an efficient temperature (Howdy Honda 2016). According to Abele, cold temperatures can decrease efficiency up to 55 % (at -25 °C). This efficiency decrease due to low temperature is similar to the effect resulting in high temperatures (Rashid 2014). According to Rashid, the efficiency can decrease up to 10 % at temperatures higher than 46 °C (ibid.). Wind velocity also affects the efficiency of construction equipment (Al-Abbasi 2014; Abele 1986). According to Abele a wind speed of 48 km/h[25] (Bft 6) decreases equipment efficiency 80-90 % (Abele 1986). The humidity degree can affect the fuel consumption of mobile machines (Abele 1986; Cummins MPG Guide 2012; Al-Abbasi 2014). In case of rain and snow, the rolling resistance increases on the tyres because they have to overcome puddles, water-filled ruts, snow on the pavement (Hilgers 2016, p. 38; Cummins MPG Guide 2012, p. 30). The resulting increased rolling resistance causes additional fuel consumption and thus increases greenhouse gas emissions (ibid.). According to Abele, light

[24] According to an interview with a site manager from a construction site.

[25] A wind speed of 48 km/h is considered to be level 6 (Bft 6) on a scale up to 12. Bft 6 is a strong wind, where large branches are in motion and umbrellas are difficult to use. (WetterKontor GmbH 2019)

snowfall and heavy snowfall decrease mobile machines' efficiency by up to 5 % and 25 %, respectively (Abele 1986). Light conditions affect efficiency on construction sites (Intergraph Corporation 2012). Reduced daylight or even night shifts increase difficulties seeing work results or picking up where the last shift left off (ibid.). Consequently, a possible value for $f_{weather}$ ranges from 0.1 to 1.0. Where 0.1 represents very bad weather like strong wind[26] and 1.0 ideal weather and so no influence on construction site efficiency.

Available construction time

The available construction time influences efficiency at construction sites. According to Ibbs and Vaughan, limited or insufficient construction time leads to the so called "acceleration" effect. Acceleration occurs at construction sites when productivity hours are increased by adding more resources, resequencing work, etc. in order to complete a work task faster than originally planned. As stated by Ibbs and Vaughan, 30 % of all construction jobs experience some form of acceleration. Four main forms of acceleration can be differentiated as follow: overtime, over manning, trade-stacking and shift work. Work which is extended beyond the standard 8 hour day and 5 day week is called overtime. According to Ibbs and Vaughan, for every 10h additional hours per week, efficiency decreases by 10 %. Over manning describes the addition of more workers to a crew than is normally needed for the task. When multiple crews work in the same space, it is called trade-stacking. Over manning combined with trade-stacking resulting in less than $100m^2$ per worker can decrease efficiency up to 40 % due to congestion and less supervision. Another acceleration form is "shift work". It consists of adding a second crew of workers whose work is performed after the primary crew. According to Ibbs and Vaughan, using less than 5 % of shift work can increase productivity up to 12 %, though above 5 % shift work, a decrease in productivity losses is observed. 40 % of shift work equals an overall efficiency loss of 15 %. In conclusion with the exception of a less than 5 % shift work increase, all forms of acceleration decrease overall project productivity

[26] According to Abele a strong wind of 48 km/h decreases equipment efficiency up to 90 % (Abele 1986).

which correspond to an increase of the overall fuel consumption and thus an increase in greenhouse gas emissions. (Ibbs and Vaughan 2015)
The value range from $f_{construction\ time}$ varies from 0.6 to 1.12. Where 0.6 represents an efficiency decrease of 40 % and 1.12 an efficiency increase of 12 %.

Available construction site freedom
According to the Delphi-method, available construction site freedom also affects the efficiency on construction time and so the amount of greenhouse gas emissions. Ok and Sinha as well as Smith agree that work space restrictions influence construction equipment productivity (Ok and Sinha 2006, p. 1033; Smith 1999, p. 133). Holt and Edwards are of the opinion that production is reduced significantly by lower-volume excavation activities due to problems with machine accessibility or working space (Holt and Edwards 2015, p. 855). Iseley and Gokhale state that for an excavator digging around obstacles like existing utilities, digging inside a trench shield, or digging in an area occupied by workers, there is a significant impact on excavator production efficiency (Iseley and Gokhale 2002, 3-10). Further, less construction site freedom also influences the logistic chain of material transport. Through necessary rearrangement of stocks or material storage outside the workplace, transport routes to pick up the material are longer (Vogt 2010).
No percentage of efficiency decrease could be found in the literature, therefore it is assumed that $f_{site\ freedom}$ has a percentage decrease of maximum 10 %. Consequently, $f_{site\ freedom}$ will range from 0.9 to 1.0, where 1.0 represents no workspace restrictions.

Consequently, according to equation (4-3), $f_{constr.\ complexity}$ has a value range from 0.05 to 1.12, where the values 0.05 and 1.12 for $f_{constr.\ complexity}$ mean that the machine has an efficiency decrease of 95 % and an efficiency increase of 12 %, respectively.

6.1.5 Construction site organisation

One factor influencing process efficiency is the effective construction site organisation. Construction site organisation describes the combined effect of construction site planning as well as of the selection of type and size of the construction equipment. Through effective planning, time can be saved and construction productivity can increase. One approach to improved planning is called “Lean construction”. The aim of lean construction is “to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value” (Koskela et al. 2002, p. 211). According to Locatelli et al., lean construction can save about 20-30 % time and increase construction productivity about the same amount (Locatelli et al. 2013, p. 780). The main differences between conventional construction planning and lean construction are shown in Table 6-1.

Table 6-1: Main differences between conventional planning and lean construction (Bajjou et al. 2017)

	Conventional Planning	Lean Construction
Idea	Focuses on value adding activities	Focuses on value adding activities & non-value adding activities
	Lack of waste elimination	Identification & elimination of waste
	Push strategy	Pull strategy
Planning method	Lack of collaboration	Collaboration & sharing of multilateral issues
	Rigid hierarchical organisational structure Planning, steering and coordination by the project manager	Planning, steering and coordination with all involved
	Absence of performance indicators	Constant controlling of construction performance
	Contractual relationship working with penalties	Seeking to solve problems and find effective solutions instead of working with penalties
Site planning	Poor organisation	Organisation after 5S method
	Lack of visual management	Visual management

Contrary to conventional planning, lean construction not only focuses on value adding activities but also on non-value adding activities. In this way waste of material, time and effort can be identified and eliminated. Conventional planning is based on a push strategy, meaning that the project manager realises the construction plan based on project information and the targeted objectives without considering the construction site or the construction companies. Lean construction, on the other hand consists of a pull system.

This means that the construction plan of the project manager is arranged according to the opinions of each foreman representing a construction company. The project plan is then verified again two to eight weeks before each construction task starts. Additionally, a weekly work plan is elaborated one week before execution in order to engage all stakeholders on the activities to fulfil. Lean construction seeks to solve problems with effective solutions instead of focusing on finding a responsible entity to penalise for each timeout. A construction site run according to the lean construction principle will be organised according to the 5S method (sort, set in order, shine, standardise, sustain and self-discipline) and have visualisation of information through billboards, security signs, etc. (Bajjou et al. 2017)

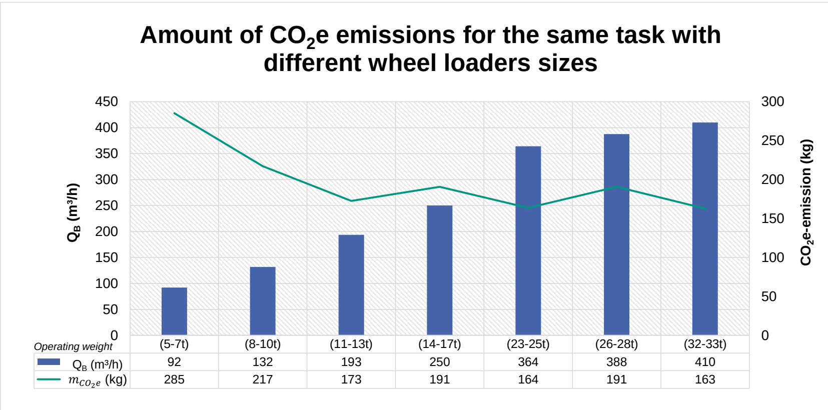


Figure 6.2: Comparison of greenhouse gas emissions from wheel loaders with different sizes for the same task (Processing of 1500m³ earth material)

Also, a part of construction organisation is the choice of the right construction machine for the construction task. Waris et al. have listed 38 criteria found in literature to take into account when choosing the right construction machine (Waris et al. 2014, p. 100). They are categorised according to socio-economic, engineering and environmental aspects (ibid.). When choosing the right construction machine for the task, not only the criteria have to be considered but also if the machine needed at the moment is available for the considered construction task. In the context of this thesis, the amount of greenhouse gas emissions from mobile machines is the main criteria on which to focus. In Figure 6.2, the amount of greenhouse gas emissions for different sizes of wheel loaders for a same task are compared. The Figure 6.2 shows that an undersized machine for a specific task will consume in total more than the right machine size and can therefore increase greenhouse gas emissions up to 74 %. Additionally, the right machine can reduce the working time up to 75 %. Frank et al. confirm that an undersized or oversized machine affect the fuel efficiency and productivity (Frank et al. 2012a, p. 1).

Depending on the construction site organisation greenhouse gas emissions can increase or decrease. An efficient construction site organisation will reduce the number of processes necessary and decrease idle time. The factor $f_{site\ orga.}$ represents time efficiency due to less idle time. During measurement of machines on construction sites, Lewis et al. found that idle time can take up to 68 % of total construction time[27] (Lewis et al. 2012b, p. 35). Consequently, the factor $f_{site\ orga.}$ can take the values 0 to 0.68. Where 0 represents a perfect construction site organisation and therefore no avoidable idle time.

6.1.6 Unavoidable idle

The factor unavoidable idle was noted during construction site observation in April 2017 in Karlsruhe, where in order to hold the temperature of the paving screed, idle time was necessary. According to the United States Environmental Protection Agency, idle time is necessary for some process realisations like for “controlling cargo temperature, operating a lift, crane, pump, drill, hoist, mixer (such as a ready mix concrete truck) or other auxiliary equipment [or for] providing mechanical extension to perform work functions for which the vehicle was designed” (EPA 2006). Idle time can be necessary for safety purposes like controlling operating order and conditions or operating the defroster, heater, air conditioners or for “testing, servicing, repairing, or diagnostic purposes” (ibid.). Unavoidable idle time means the engine is switched on, the machine is not executing work but this idle time is necessary

[27] The total construction time is defined by the sum of idle and working time. Driving for construction site preparation is not considered.

for a fluid unhindered operation at construction sites. A switched on engine consumes fuel and so influences the total greenhouse gas emissions during construction.
No information was discovered about the maximum or average unavoidable idle time at construction sites. Therefore, based on the machine measurement by Lewis et al., the maximum idle time of 68 % of the total time is taken as a reference. Further, according to equation *(4-25)*, the sum of $f_{site\ orga.}$ and $f_{idle\ unavoidable}$ is maximum 1. Consequently, unavoidable idle can reach from 0 to 0.68, if $f_{site\ orga.} + f_{idle\ unavoidable}$ is below or equal 1. Where 0 states that no unavoidable idle time occurred during construction.

6.1.7 Driver

A factor from the category operation efficiency is the driver as a human being. Frank et al. compared the performance and fuel consumption of 80 wheel loaders operators (Frank et al. 2012a). The operators had to drive 20 min during different cycles under the same conditions (same machine with the same equipment, same bucket, same tyres and same calibrated gravel pile) (ibid.). The measurement of 80 operators under the same conditions enabled isolating the operator’s behaviour as a unique variable parameter. The results of the measurements showed that the performance and thus the fuel consumption varies depending on the operator. The novice operators who had driven a wheel loader between two to ten hours had the lowest performance (Frank et al. 2012a; Frank et al. 2012b; Stec 9/7/2016). Average and expert operators were in a similar range concerning performance and fuel consumption (ibid.). The lowest value compared to the best value of expert drivers had a difference of performance and fuel consumption of 70 % and 43 %, respectively (ibid.). Frank et al. demonstrated through their experiment that the operators' behaviour influenced fuel consumption and thus greenhouse gas emissions of construction machines (Frank et al. 2012a). The experiment also showed that the experience of an operator is not the only factor influencing the operator’s behaviour.
An experiment by Voigt et al. came to the same conclusion. They analysed the simultaneous degree of an operator, which means the ability to manage as many cylinders as possible during an excavation cycle with an excavator.

Seven test persons from apprenticeship year 1 to 3 were examined. It was found out that operators with 3 years of experience had a higher simultaneous degree with a shorter cycle time. Only one operator with one year of experience had the same results as operators with 3 years of experience. This experiment showed that the amount of experience influences the performance of an operator, but it is not the only influencing factor. (Voigt et al. 2012)
According to the Delphi method, three main factors influence the operators' behaviour: the physical and mental state of the operator, the workplace and working environment as well as the driver's experience.

Physical and mental state of the operator
The performance of the operator is subject to fluctuations for different persons but also for an individual (Schlick et al. 2018, p. 60). Zülch states that the performance range of a person depends on their performance ability and readiness (Zülch 2012). One source for the fluctuation influencing performance ability is the person’s unique characteristics and basic abilities like gender, age or physical constitution (ibid.). Another source is their knowledge and skills which is based on their basic educational training, their experience and their driver training courses. This source will be discussed in more depth in subchapter “driver experience”. Disposition and motivation of an operator are the fluctuation sources for an operator's performance readiness (Zülch 2012). The disposition of an operator is defined by their daily rhythm, physical condition and fatigue due to the workplace and working environment. Graf calls the operator's rhythm over 24 hours the physiological work curve. (Schlick et al. 2018, p. 108)
Figure 6.3 shows that a human’s performance can be subdivided into different areas and is strongly linked to the respective state of motivation. The area of involuntary performance describes the performance that is automatically consumed for basic vital functions such as breathing, circulation and digestion as well as actions such as running, speaking and reading. Also, long trained tasks needing a low activity level like driving a car in simple traffic situations can be part of this involuntary performance area. (Schmauder 2005, p. 14)
The second area is the available capacity of a human according to their will, available without any particular deliberate effort (Schmauder 2005, p. 14).

This second area is limited by the physiological work curve. The physiological work curve[28] shows that the human performance is not constant over 24 hours.

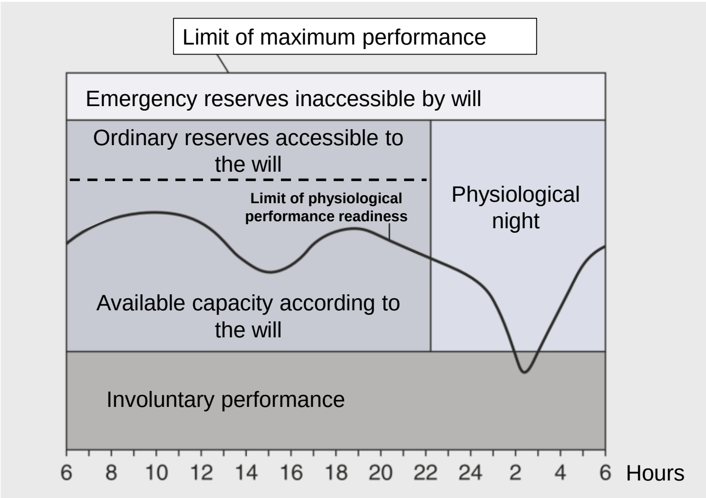


Figure 6.3: Physiological work curve over 24 hours (based on Schlick et al. 2018, p. 108)

The performance peak of a human is reached between 9 and 11 o'clock. The performance then decreases to a minimum around 1 to 3 o'clock in the afternoon. After 3 o'clock in the afternoon the performance increases until reaching another maximum (half as high as the maximum in the morning) in the evening (Zülch 2012). Then, the performance decreases continuously until reaching the lowest point between 2 and 4 o'clock in the morning. If the performance requirement of the work system lies above this area, the person can use his ordinary reserve. However, it will lead to faster fatigue and negatively affect his motivation (Schmauder 2005, p. 14). Beyond this performance area, a human has limited emergency reserves. They can become accessible in unusual situations for a short time (ibid.).

[28] The physiological work curve is based on average values of data and so may vary for each individual.

The second element defining the disposition of an operator is their physical condition which is unique for each individual and is based on the person's history.

The third element is fatigue. Zieschang and Müller-Gethmann have measured the heart rate of excavator operators during operation in order to assess the work strain. They have measured that the heart rate per minute of an excavator operator during operation varies between 71.4 to 95.1 (Zieschang and Müller-Gethmann 2004, p. 84). This heart rate corresponds to the heart rate of a human being driving a car (Mell 2005, p. 60). According to Mells classification, driving a car does not strain the driver (ibid.). Further, Zieschang and Müller-Gethmann show in a second type of heart rate measurements of excavator drivers that the heart rate stays the same for all operators although the difficulty degree of the operations varies from simple, somewhat difficult, difficult to very difficult (Zieschang and Müller-Gethmann 2004, pp. 84–85). These heart rate measurements demonstrate that operating mobile construction machines is not considered to be a physical activity. Therefore, mobile machine operator's fatigue is not caused by physical strain from operation.

Fatigue can also be caused by the workplace and working environment. This aspect is discussed further later on.

The motivation of an operator is of a psychological nature and will therefore be discussed briefly. The focus will lay on the psychological strain affecting the motivation of the operator. The motivation of an operator is linked to their satisfaction level (see Maslow's hierarchy of need) and wellbeing. The motivation of an operator co-defining their performance readiness is divided into their mood, their social relationships, their attitude due to the work assignment as well as to the workplace and working environment. The mood of a person is an overall state of "general [long-lasting] feeling, not a reaction to a particular situation" (Thagard 2018). The reasons for good or bad moods are complex (ibid.). Social relationships reflect the working atmosphere and personnel management (Brixel 2018, p. 62). An employee satisfied with their superior and superior's leadership style will tend to be satisfied with their workplace (ibid.). Good social relationships with their colleagues will support the operator who in turn can cope better with the task at hand, leading to a well-being feeling and making them more stress resistant (ibid.).

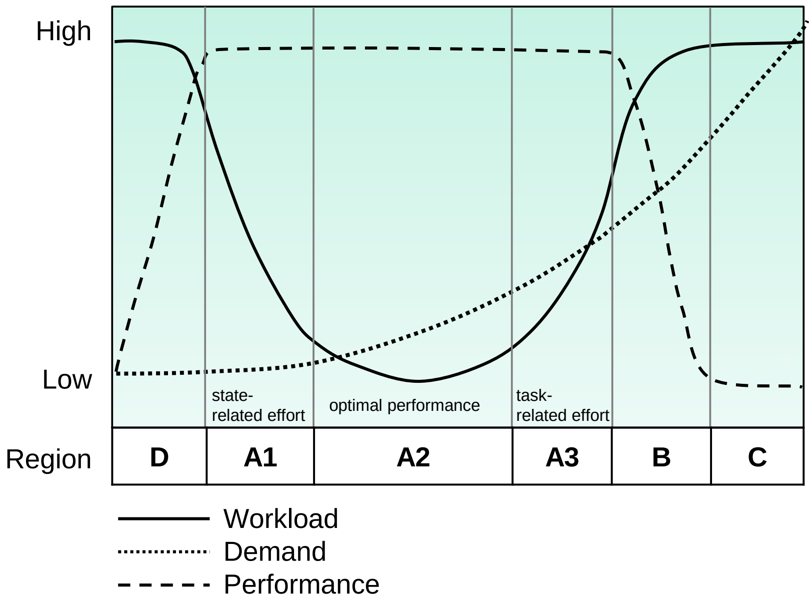


Figure 6.4: Six performance regions of an operator depending on demand and workload (based on Waard 1996, p. 24)

The third element is the attitude due to the work assignment. Waard analysed in his dissertation a drivers' mental workload and shows the relation between demand, workload and performance. He defines six possible performance states for the driver as in Figure 6.4. The first region is called deactivation (D) because of e.g. monotony. In this region the work itself is not particularly demanding but the workload is too high for the operator. Consequently, the operator will have low performance. The second region is called A1. In A1, the work demand increases, the workload decreases. The workload is not too high and the demand not too low for the operator, so that he can counteract the symptoms of deactivation with a state-related effort. The operator can with effort maintain high performance. In the third region A2, the workload is adapted to the operator, he can easily cope with increased task demands without effort. Consequently the performance is high. In the following region A3, the workload and the demand increases so that the operator can only maintain high performance with task related effort. Region

A1 and A3 can be maintained by an operator only for a limited time. Therefore region A2 is recommended for any workplace. The fifth region B is when the operator can no longer compensate for the increased workload and increased demand through a task related effort. Consequently, the performance of the operator decreases until reaching a minimum in phase C. In phase C, the demand continues to increase, the workload is too high for the operator so that the performance remains at a minimum level. (Waard 1996, pp. 21–24)
Waard has shown that the attitude due to the work assignment which corresponds to the possible performance of an operator is influenced by the task demand and the amount of workload.

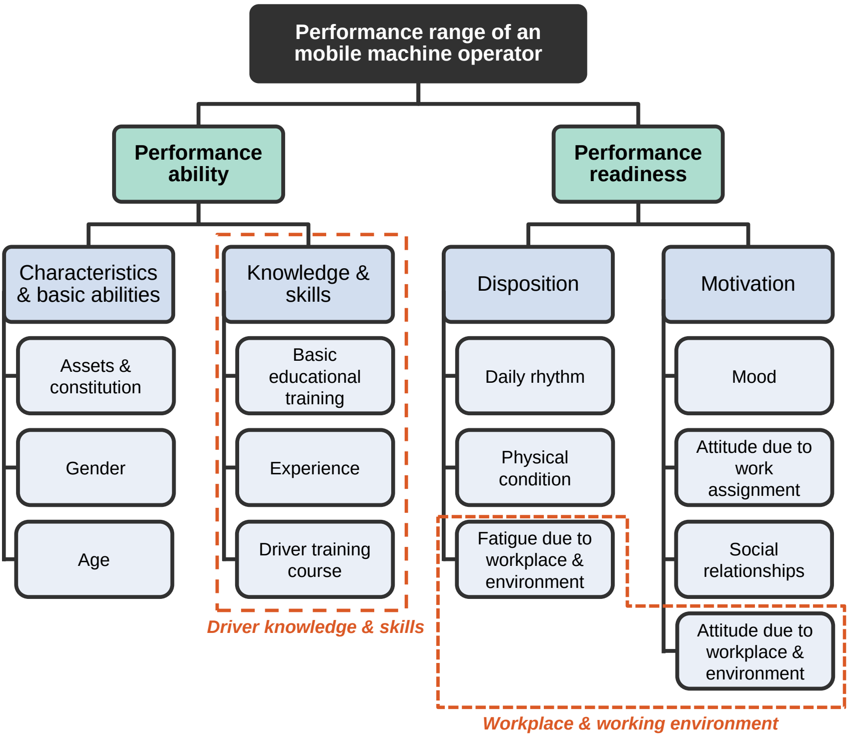


Figure 6.5: The performance range of a mobile machine operator (based on Zülch 2012)

Figure 6.5 shows the elements defining the performance range of a mobile machine operator. The element “attitude due to the workplace and working environment” is further discussed in the next paragraph.

Workplace & working environment

The workplace and working environment is another factor influencing the operator’s behaviour. The workplace influence is characterised by its ergonomics (Bullinger 1994, pp. 4–5) as well as by the view quality from the cabin. Ergonomics are defined by production ergonomics, focusing on reducing the strain of the employee from the workplace and the product ergonomics focusing on user-friendly objects in the workplace (Bubb et al. 2015, p. 19). For an ergonomic design of the workplace, knowledge of the human body (anatomy and anthropometry[29]) is necessary. In order to have ergonomic gripping and foot space as well as body supports in a workplace, the different body sizes of the population need to be taken into account (Bubb et al. 2015, p. 19). In an ergonomical workplace for 95 % of the population, the design of the inner dimensions representing the space in a cabin of the construction equipment, should accommodate the largest person within the population (dimensions of the 95th percentile of the male population) (Heine 2018). Additionally, external dimensions which represent accessibility dimensions in the construction machine cabin should be designed for the smallest person of the population (dimensions of the 5th percentile of the female population) (ibid.). For an ergonomic workplace adapted to the driver, technical solutions exist for adjusting the seat, the armrest, backrest, the steering column as well as the operating levers (Kunze 2010). Non-ergonomical objects in the workplace like e.g. non-ergonomically designed handgrips can lead to driver fatigue (Zieschang and Müller-Gethmann 2004, p. 91).

Examples of objects lacking in product ergonomics are some controls where the index finger as well as the thumbs are not within reach, or on the contrary are within the range of the digit's resting position (Zieschang and Müller-Gethmann 2004, p. 88). These are examples of non user-friendly objects

[29] Anthropometry is the scientific study of measures, measure ratios and measurements of the human body (body dimensions, movements, masses, forces) (Heine 2018).

resulting in unintentional operation because controls are not reached on time or because they are unintentionally operated (ibid.).
The view quality in the cabin of a construction machine is of great importance because it provides 90 % of the information needed by the operator to steer the machine (Böser et al. 2011, p. 19). Indeed, Figure 4.4 in chapter 4 shows the relation of the operator and the machine forming together a control loop system. The requirements for visibility conditions are defined for earthmoving machines in ISO 500:2017 (ISO 5006:2017 (E) 2017). The view quality is affected by the quality of the interior view on operating elements and displays and of the exterior view on working tools and on the environment (Hoske et al. 2010). The view quality is therefore influenced by the cabin design and its ergonomics as well as by the working environment (glare due to sunrise or sunset, fog, etc.) (ibid., p.°530). According to Kunze and Schmauder compensation movements of the machine operator indicate unfavourable visual conditions (Kunze et al. 2012a, p. 12). Whereby a distinction must be made between beginners and advanced drivers (ibid.). An advanced driver shows a larger movement dynamic than a beginner (ibid.). The reason is that a beginner is in the same operation mode he learned to be during his driving lessons where no obstacles were in the back area (Brixel 2018, p. 40). On the contrary, due to his higher sense of security and his experience, the advanced driver automatically compensates for movements if the view is not sufficient (ibid.). Kunze and Schmauder found out through the movement dynamic of the drivers that the visibility conditions are worse in a larger construction machine than in a small one (Kunze et al. 2012a, p. 13). According to Hoske et al. insufficient visibility conditions lead to fatigue of the driver (Hoske et al. 2010, p. 531).

The working environment is characterised by the effects of climate, noise and vibrations on the driver as well as light exposure. Climate is one of the most influencing working environmental factors, as operators are exposed to it in most workplaces (Drobek 2003, p. 38). The effect of climate on the operator is determined by the following four climate parameters: air temperature, air humidity, wind speed, heat radiation and following personal parameters: work difficulty and clothing (ibid). Where the effective temperature is defined by the air temperature, air humidity and wind speed (Merkel and

Schmauder 2012, p. 95). According to Senouci et al., of the factors temperature, air humidity and wind speed, temperature has the highest impact on productivity of construction workers (Senouci et al. 2018, p. 48). This was analysed in four different trades: plaster work, block work, ceramic tile work, and concrete shuttering work (ibid.). The analysis showed that the level of impact on productivity depends on the trade type, but each trade shows a similar curve in terms of productivity decrease due to temperature increase (ibid., pp. 40-41). This means that high temperatures affect the productivity while air humidity and air wind velocity have less influence. According to an experiment on workers in south African mines, they can keep their performance with increasing heart rate up to 28.5 °C (Wenzel and Piekarski 1980, p. 93). At over 28.5 °C the heart rate does not change anymore but performance is reduced (ibid). At a temperature of 35 °C, the performance is reduced by 50 % (ibid). Another study analysed the psychological and psychophysical activities of widely undressed men during increasing effective temperature. It was found that temperatures above 28 °C decrease the performance of reaction rates, sensory perceptions, calculation skills, numerical control and sensorimotor coordination (ibid., p. 116). An experiment on radio operators showed that the average number of errors during three-hour recordings of radio messages by increasing effective the temperature (26 °C-36 °C) varies in dependence on the experience and knowledge of the operator (ibid., p. 117). Expert operators had the lowest number of errors because they could, up to a certain temperature, compensate for performance reduction from heat stress with experience and knowledge (ibid.). Another experiment from the US military showed that cold temperatures or snowfall also affect the performance of workers (Abele 1986). At -40 °C, the efficiency of manual task activities decreases by up to 90 % and by heavy snowfall up to 60 % (ibid.). These studies show how heat and cold stress can affect activities of a physical nature but also of psychological and psycho-physical nature like reaction rates and sensory perceptions necessary for machine operators. Zülch and Kiparski hold the opinion that uncomfortable climates reduce the motivation of the operator resulting in a performance reduction. An experiment on 1,300 persons wearing the same clothes and doing the same tasks showed that an uncomfortable climate is defined differently by each individual (Wenzel and Piekarski 1980). According to Yi and Chan study, the age of the person also influences a person’s performance (Yi and Chan 2017).

Noise is also a factor influencing the workplace. According to Zülch and Kiparski, there is no unanimous definition of noise (Zülch et al. 1999, p. 70).

Table 6-2: The yearly noise exposure level for machine operators in different construction sectors (SUVA 2018)

Working sector of the machine operators	Yearly noise exposure level L_{EX}
Building construction	75-83 dB(A)
Trench construction	80-86 dB(A)
Road construction	83-90 dB(A)
Concrete deconstruction & renovation	83-90 dB(A)
Foundation construction	83-86 dB(A)
Underground mining	83-90 dB(A)
Material dismantling & material processing	83-95 dB(A)

In general, noise is defined as sounds that lead to impairment of health, of work safety or of performance (Zülch et al. 1999, p. 70). The sound level is the ratio of the sound intensity relative to the hearing threshold[30] (ibid., p. 71). It has the unit Decibel (dB) (ibid). The exposure level describes the sound impact on humans (Adolph et al. 2016, 2.7_3 -2.7_21). It is calculated by the values of the emissions and the exposure time (ibid.). The daily noise exposure level is consequently the noise level experienced by humans during an eight hour shift (ibid.). According to the Directive 2003/10/EC of the European Parliament and of the Council, the daily noise exposure level ($L_{EX,8h}$) limit for a worker is 87 dB(A) and for the peak sound limit is 140 dB(C) (Directive 2003/10/EC 2003). From a daily exposure value of 80 dB(A), protective gear must be provided for the worker, which the worker can wear on a voluntary basis (ibid.). The hearing protectors as well as regular health check-ups are mandatory from a daily exposure value of

[30] The hearing threshold is defined as the value at which the human ear begins to perceive a sound event (Zülch et al. 1999, p. 73).

85 dB(A) or higher (ibid.). Table 6-2 shows, that construction machine operators have a high noise exposure level annually.
According to SUVA, depending on the attachment, an excavator has a typical continuous sound level of a noise source ($L_{Aeq,T}$) between 83-95 dB(A), a roller between 80-86 dB(A) and a paver of 90 dB(A) (SUVA 2018). According to equation *(6-1)* from Grewer (Adolph et al. 2016, 2.7_3 -2.7_21), it means that a machine operator is allowed to drive a paver without hearing protection max. 2.53 h per day, which is unrealistic.

$$L_{EX,8h} = L_{Aeq,T} + 10\lg(\frac{T}{T_r}) \qquad (6\text{-}1)$$

$L_{EX,8h}$ in equation *(6-1)* stands for the daily noise exposure level (8h shift), T for the time of exposure and T_r for the reference assessment time corresponding to 8h (Adolph et al. 2016, 2.7_3 -2.7_21). Based on this calculation example and from Table 6-2, it becomes clear, that machine operators work in noisy conditions. A survey from the Federal Institute for Occupational Safety and Health and Occupational Medicine found that out of 4,817 persons often working under noisy conditions, 51 % feels strained because of the noise. According to the professions of those surveyed, it can be assumed that 42 %[31] are in contact with mobile machines (Wittig et al. 2013). According to Gusky noise strain is not caused by the noise itself but rather by the nuisance it causes (Zülch et al. 1999, p. 75). The effects of noise on people's health, well-being and performance can be numerous and is also felt differently depending on the individual (Zülch et al. 1999). In summary, construction machine operators are influenced and affected by noise, especially because the daily noise exposure level is exceeded most of the time. Noise strains the operator and can therefore lead to performance reduction.

Another aspect characterizing the working environment and so influencing the workplace are vibrations. Vibration is any mechanical oscillation trans-

[31] 2,027 out of 20,036 persons surveyed work in professions in agriculture, forestry, gardening, mines, mineral mines, mineral processing, stone workers, manufacturing of building materials, building and civil engineering and traffic occupations. It has been assumed, that these 2,027 persons work with mobile machines and responded that they often work under noisy conditions.

mitted to the human body by objects and which can lead to a direct or indirect risk to the safety and health of workers. This includes in particular mechanical oscillation to the human hand-arm system and to the whole body (LärmVibrationsArbSchV 2007, p. 3). Mechanical oscillations are transferred into the human body, when they are in contact with oscillating surfaces (VDI 2057 2017, p. 10). The vibration exposure is characterised by „the amplitude, frequency (spectrum), direction of the vibrations with respect to the individual and to gravity, the point of vibration transfer to the body, and the duration of the exposure” (VDI 2057 2017, p. 4). The vibration transfer surfaces for a seated person are the buttocks, feet, and possibly the back of a person (ibid.). To label the direction of vibration, a coordinate system l = {x, y, z} related to the human being and the point of vibration transfer is used, like in Figure 6.6 (ibid.).

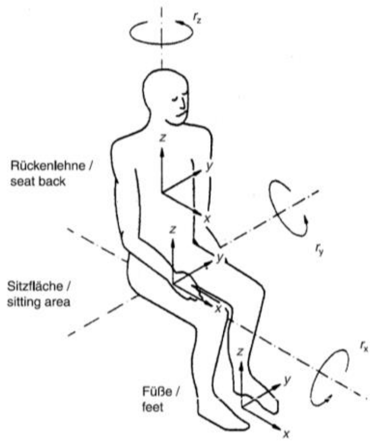


Figure 6.6: The vibration transfer surfaces for a seated person with its coordinate system (VDI 2057 2017, p. 11)

According to the European Directive 2002/44/EC the daily exposure limit value standardised to an eight hour reference period for a worker shall not be over 5 m/s² and over 1.15 m/s² for hand-arm vibration and for whole body vibration, respectively (Directive 2002/44/EC 2002). The daily vibration exposure action value standardised to an eight hour reference period shall not be over 2.5 m/s² and over 0.5 m/s² for hand-arm vibration and for whole body

vibration, respectively (ibid.). Merkel and Schmauder state that the vibration of the whole body in z-direction is limited to 0.8 m/s² by law (Merkel and Schmauder 2012, p. 76).
VDI 2057 states that operators of mobile construction machines are affected by whole-body vibrations (VDI 2057 2017, p. 4). In general, if the frequency-weighted acceleration in z direction during an 8 hour working shift ($a_{w(8)z}$) is below 0.3 m/s², there is likely no effect on mobile machines operators' performance during this time (ibid., p. 31). The following Figure 6.7 shows vibration measurements of typical mobile machines. When assuming that the machine operator works eight hours a day on the machine, then the mean value of the vibration acceleration represented by the black line in the blue field, equals the vibration exposure limit value. The measurements show that some machines like the wheel loader or the tractor exceed the allowed daily vibration exposure limit value for an eight hour period. All mean values of $a_{w(8)z}$ of the analysed mobile machines are over 0.3 m/s². For this reason, it can be assumed that vibration in mobile machines reduce operators' performance. Further, the survey from the Federal Institute for Occupational Safety and Health and Occupational Medicine found that out of 867 persons frequently working with vibrations, 53.6 % felt strained because of it (Wittig et al. 2013, p. 23). According to the professions of those surveyed, it can be assumed that all of the 867 persons work with mobile machines[32] (ibid.). According to the VDI 2057, individual factors like type of physique, constitution, age, sex, disposition and motivation influence the effects of vibration on the human being (VDI 2057 2017, p. 4). “As far as the physiological effects are concerned, there may exist large inter-individual variations. Whole-body vibrations may impair general wellbeing, influence human performance, and/or be a risk to health and safety. Low-frequency vibrations of the body with frequencies below 0.5 Hz may be the cause of different types of kinetosis (motion sickness, sea sickness)” (ibid., p. 3). When the physiological and psychological condition of the operator is affected due to vibration, it is called indirect disturbances (ibid., p. 30). Direct disturbance due to vibration occur when sensory information obtained at the human-machine interface are compromised (ibid.). In conclusion, vibrations can

[32] See explanation in footnote 31

cause direct and indirect disturbances affecting the performance of the operator. Bös agrees with the performance reduction of the operator due to vibration and explains that the reason is an accelerated fatigue due to the additional muscle work necessary to stabilize the body during vibrations (Bös 2015, p. 37). In summary, construction machine operators are always working with vibration, which can reduce the operator's performance. The amount of performance reduction depends on the vibration exposure and the operator himself.

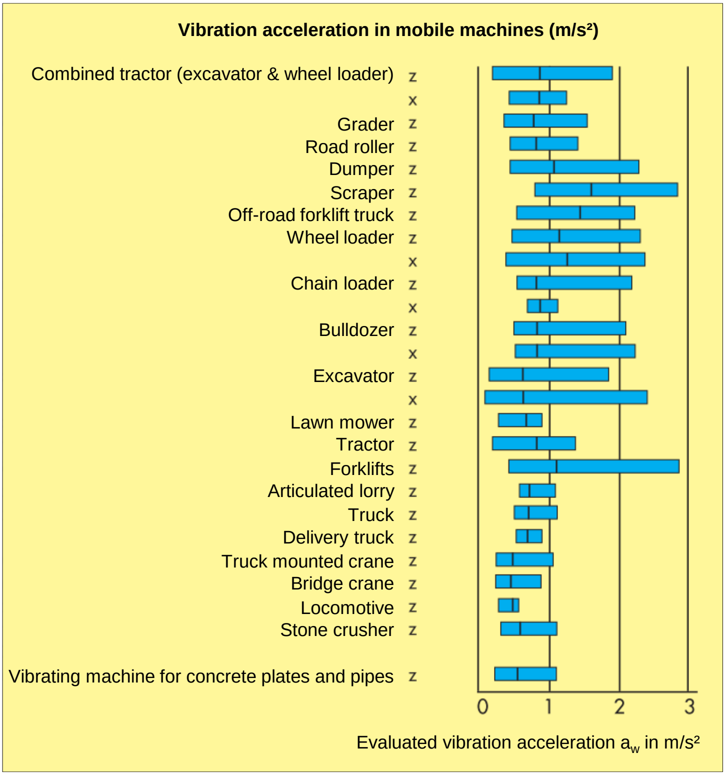


Figure 6.7: Measurements of vibration acceleration in mobile machines (Melzig-Thiel et al. 2001, p. 8)

Due to the high demands on visibility in construction machinery, light plays an important role. Construction machine operators in Germany in general work from 7:00 to 18:00. During this time, depending on the season and the weather, they are exposed to different light levels throughout the day. Thanks to the light, they can assess optical information (Zülch et al. 1999, p. 128). According to Zülch, light can influence the human being biologically, psychologically and emotionally (ibid.). This means that the human being is decisively influenced by the light level (ibid.). Böcker states that the visual acuity increases with increasing illumination sharpness (ibid., p. 119). Furthermore, he argues that age also influences the visual acuity of a person (ibid.). Older persons will have a higher need for light for the same visual acuity (ibid.). It is not unusual that a machine operator is exposed to dazzle from sunlight[33]. A distinction can be made between physiological glare and psychological glare (ibid., p. 125). Physiological glare is caused by looking directly into the sun, leading to a scattering effect within the eye overlapping objects in the visual space of the machine operators with a veil (ibid.). This results in a reduction of the visual performance of the operator (ibid.). Psychological glare causes the operator an unpleasant sensation resulting in a performance reduction over prolonged exposure (ibid.). In summary, not enough light or dazzle from sunlight can reduce the performance of an operator.

Driver knowledge & skills

Driver experience represents the machine operator's knowledge and skills. The knowledge and skills of an operator is the combined result of their basic educational training, their experience and their driver training course (see Figure 6.5).

Concerning the basic educational training of a construction equipment operator, there is for e.g. in Germany a legally regulated apprenticeship as operator, but it is not required by law to have such an apprenticeship education to drive mobile construction machines. This means that a driving licence and instructions are sufficient in order to operate a mobile machine. Depending of the machine size, a car driving licence may not be enough and rather a truck driving licence will be necessary. Instructions for mobile machines can also be given through a training course. Currently, there is a vast range of

[33] Sunrise or sunset

different training courses and certificates for construction machine operators, ranging from half-day courses to 6 week events. In conclusion the basic educational training varies from one operator to another. (Leisering 2013)
Experiments from Frank et al. as well as from Voigt et al. [34] demonstrate that the operators' performance, their fuel consumption and thus the amount of greenhouse gas emissions from mobile construction machines are influenced by their amount of experience (Frank et al. 2012b; Voigt et al. 2012). Wenzel and Pierkarski show that experience helps maintain high performance even during challenging tasks (Wenzel and Piekarski 1980, p. 117). According to the United States Environment Protection Agency, driver experience influences fuel consumption and greenhouse gas emissions (EPA 2009; cf. Frank et al. 2012a). An operator, for example, who excavates a slope in two stages will be able to save up to 8 % fuel compared to a slope excavation in one motion (EPA 2009). Various other literature agrees with the theory that driver experience influences the amount of greenhouse gas emissions (Kazaz et al. 2008; Barati and Shen 2017; CEMA and CECE 2011; Dai et al. 2009; Fan 2017).
As seen in the previous two paragraphs, the basic educational training as well as the amount of experience is different for each operator. According to Frank et al. the "traditional way to address the fuel efficiency and productivity difference due to operator behaviour is operator training" (Frank et al. 2012a, p. 1). An operator's training can consist of a person coaching the machine driver a certain number of days, providing tips and tricks to increase fuel efficiency and productivity (ibid.). Alternatively, it can be taught through a training tool, theoretically in a room or manuals can be distributed to the operators where they can find information on how to operate more efficiently (Frank et al. 2012a; Frank et al. 2012b). In summary, operator training can reduce greenhouse gas emissions, since the operator learns how to drive the mobile construction machine most effectively in terms of fuel consumption. Due to the different basic educational trainings and the different experiences of each operator, an effective driver training is the only lever possible to influence the knowledge and skills of an operator.

[34] See experiment description in the introduction part of 6.1.7 Driver.

The machine operator is not formally describable in the totality of his characteristics and abilities (Voigt et al. 2012). The diversity of individuals, the ability of humans to constantly adapt their behaviour to new and unknown situations as well as the further development and acquisition of skills through learning prove that an operator's performance is not constant.
When the operator is exposed to early fatigue or strain, it results in a performance reduction (Bullinger 1994, p. 69; Kauffeld 2014, p. 253). Additionally, Schmid found that the first symptoms of driver fatigue are unwillingness to work and inhibition of will (Schmid 1961, p. 11). Over time, the effect of these symptoms become stronger (ibid.). Operating errors or performance reduction of the operator result in longer required operating time of the machines for the same work task (cf. Hoffmann et al. 2011). Longer operating time due to inefficient machine operation increases the total fuel consumption and so the amount of greenhouse gas emissions (cf. Sturm 2015, p. 104). In conclusion, operator performance reductions lead to increased fuel consumption and so to increased greenhouse gas emissions of mobile machines (cf. Frank et al. 2012a).

According to the literature review $f_{workplace\&working\ environment}$ can take the value between 0.1 and to 1.0. Where 0.1 represents an efficiency decrease of 90 % due to extreme weather conditions. The value 1 represents ideal workplace and working environment conditions.
During the experiment of Frank et al., all operators had the same workplace and working environment conditions (Frank et al. 2012a). Therefore, the efficiency decrease in this experiment is only influenced by the factors $f_{physical\&mental\ state}$ and $f_{driver\ experience}$. No workplace or working environment influence means $f_{workplace\&working\ environment}$ equals 1. According to equation (4-4), 1 multiplied by $f_{physical\&mental\ state}$ and with $f_{driver\ experience}$ results in the minimum value 0.3 (efficiency decrease of 70 %). By assuming the same weighting of the factors for $f_{physical\&mental\ state}$ and $f_{driver\ experience}$, these factors can take a minimum value of 0.55. No influence of these factors, means they have the value 1.0. Consequently, f_{driver} will have a value between 0.03 to 1.0.

6.1.8 Stop & Go

The factor $f_{stop\&go}$represents unnecessary idling e.g. "when trucks wait for extended periods of time to load or unload, or when equipment that is not being used is left on, such as to maintain heating or cooling for driver comfort. Reduced idling reduces fuel consumption […] and GHG emissions." (EPA 2009)

Different levels of idling exists and are called high, low and adapted[35] (cf. EPA 2009, p. 13). According to the construction machine manufacturers, high idle occurs some seconds, contrary to low idle which can last many hours[36]. Adapted idle is an idle which automatically adapts its level to the load[37]. According to the manufacturers, construction machines with such adapted idling are rare (ibid.). Therefore, the focus will only lie on unnecessary low idling of mobile construction machines.

According to the EPA, in the U.S., low idling is typically restricted to 3-10 minutes (EPA 2009, p. 13). On the contrary, the EU do not have such idling restrictions[38].

Idle time accelerates engine wear. The EPA states that "each hour of idling eliminated can save as much as 2 hours of engine life." The lack of heat for proper combustion during idling of an engine is the reason "deposits will form over time on the piston and cylinder walls" as well as contaminate the oil. The additional friction due to the contamination will accelerate engine wear. (EPA 2009, p. 13)

Idle time measurements of different construction machines from Lewis show that the percentage of idle time during operation time varies. For bulldozers, graders, wheel loaders, excavators and trucks, idle time can reach up to 35 %, 41 %, 55 %, 39 % and 68 % of the total operation time, respectively. (Lewis et al. 2012b, p. 35)

Idle time can be reduced or eliminated if the machine operator switches off the engine when the machine is not working. Alternatively, the same effect

[35] According to the experts of the Delphi method.
[36] According to the experts of the Delphi method.
[37] According to the experts of the Delphi method.
[38] According to the experts of the Delphi method.

can be reached by an automatic function switching off the engine. Consequently $f_{stop\&go}$ can take the values 0 to 1. Where 0 means the engine is always switched off and therefore the machine is in a standstill state. The value 1 means that the machine is always switched on.

6.1.9 Energy carrier with their respective greenhouse gas emissions

Table 6-3: Different energy carriers from fossil sources (grey colour) and from renewable sources (blue colour) (Edwards et al. 2014b; Ays et al. 2018a; Wu 2018; Weberbeck et al. 2016; Stan 2015, p. 206)

Energy Carrier (source)	Greenhouse gas emissions – WTW [g CO_2e/ MJ]
Hydrogen (EU-mix)	226.3
Electricity (EU-Mix, low voltage)	150.1
Methanol (natural gas)	94.0 to 101.3
DME (natural gas)	89.3 to 97.7
Diesel (crude oil from typical EU supply)	88.6
Gasoline (crude oil from typical EU supply)	87.1
Ethanol (wheat, sugar cane, maize corn, sugar beet, EU mix barley grain)	9.2 to 86.0
Liquefied methane (natural gas per sea transport)	74.5
LPG (natural gas)	73.7
CNG (EU-mix per pipeline)	69.3
Biodiesel (rapeseed, sunflower, soy beans, palm oil, waste cooking oil, tallow oil)	13.8 to 62.6
$OME_{5\text{-}6}$ (natural gas)	45.9
CBG (wet manure, waste, maize)	-69.9 to 40.8
Liquefied methane (biomass)	32.0
$OME_{5\text{-}6}$ (tree biomass)	17.76
Liquefied methane (SNG - wind energy)	13.0
Hydrogen (wind energy)*	4.2
Electricity (wind energy)*	0

* Electricity from wind turbines is energy and emissions - free (energy and emissions related to construction and maintenance are not considered)

Currently most nonroad (off-highway) mobile machinery use diesel as their energy carrier (EPA 2009, p. 5). On-highway mobile machines may drive with diesel, gasoline, electricity or other fuels like LPG and CNG (EPA 2010c, p. 10, 2009, p. 5).

During combustion of diesel, only the CO_2 gases emitted are considered greenhouse gas emissions (Edwards et al. 2014b). Consequently the CO_2 amount emitted during the combustion is equivalent to the emitted CO_2e amount. By using alternative energy carriers to diesel, the total amount of greenhouse gas emissions can vary. Table 6-3 shows an example of alternative energy carriers with their respective greenhouse gas emissions, corresponding to the total amount of CO_2e emissions during production and combustion of the energy carrier (well to wheel analysis). According to 4.3.4, by choosing an alternative energy carrier for mobile machines the calorific value, the gravimetric and the volumetric energy densities have to be considered.

Table 6-4: Greenhouse gas emissions of liquid energy carriers from fossil source (grey colour) and from renewable sources (blue colour) (Edwards et al. 2014a, 2014b; Geimer and Ays 2014; Wu 2018; Weberbeck et al. 2016; Stan 2015, p. 206)

Energy Carrier (source)	Greenhouse gas emissions – WTW [kg CO_2e/ l energy carrier]
Diesel	3.18
Gasoline	2.80
OME_5 (natural gas)	2.72
Liquid hydrogen (EU-mix)	1.93
Biodiesel (methyl ester)	1.87
DME (natural gas)	1.86
Methanol (natural gas)	1.60
Ethanol (wheat)	1.38
Liquefied methane (fossil)	1.38
Liquefied methane (biomass)	0.59
$OME_{5\text{-}6}$ (tree biomass)	0.53
Liquid hydrogen (wind energy)	0.04

In Table 6-4 some of the energy carriers in kg CO_2e per litre energy carrier are represented. Through this table, it becomes clear that by considering the density and calorific value of the energy carrier, the order with the lowest greenhouse gas emissions can vary. Consequently the factor $f_{CO_2e/energy\ carrier}$ will take a value within the interval [0.04; 3.18].

6.1.10 CO_2e capture and storage

CO_2 capture and storage already exists in the power plant industry. Technologies are classified according to three concepts: pre-combustion, oxyfuel and post-combustion processes. Pre-combustion is characterised by capturing CO_2 before combustion take places. In an oxyfuel concept, the combustion takes place with pure oxygen (O_2) instead of air, which comprises not only oxygen but also e.g. nitrogen. Post-combustion processes separate and store CO_2 from the exhaust gas, after the combustion process. (Jonker 2017, p. 3)
The literature reviews about CO_2 separation and capturing systems has shown that depending on the separation process, the CO_2 separation rate goes from 30 to 99 %. Consequently, the factor f_{CCS} will take a value within the interval [0.3; 0.99]. All existing CO_2 separation processes found in literature are summarised in Table 6-5. In blue are all possible pre-combustion processes, in yellow the possible oxy-combustion process and in colour latte all possible post-combustion processes.

Table 6-5: Possible CO_2 separation processes (Jonker 2017; Fischedick et al. 2015; Masala et al. 2017; Moshoeshoe et al. 2017; Zarghampoor et al. 2017; Castellania et al. 2012; Liu and Landskron 2017)

CO_2-Capture	Process principle	Pre-combustion capture	Oxy-combustion capture	Post-combustion capture				
	Chemical absorption	Amines	Absorption with amino acid salts	Sulfinol process	Alkaline solutions	Carbonates	Ionic liquids	Chilled ammonia-process
	Physical absorption	Selexol process	Rectisol process	Fluorine process	Purisol process			
	Gas-solid reactions	CaO	MgO	FeO				
	Adsorption	Activated carbon	Zeolites	Metal-organic frameworks	Super capacitive swing adsorption			
	Cryogen	Condensations						
	Membrane	Organic membrane	Ceramic membrane					
	Natural binding	Mineralisation	Algae	Plants				
	Hydrate-based gas separation	H_2O & Additive						

6.2 Range determination for each factor

In the previous subchapter, it was demonstrated that the factors chosen in chapter 4 for equations (4-25) and (4-26), have an influence on the amount of greenhouse gas emissions of mobile construction machines. At the same time, it was possible to determine the range of values these factors can take. In this subchapter all these factors with the range value they can take are summarised in Table 6-6.

Table 6-6: Value range of all factors used for calculating the amount of CO_2e from mobile machines

Influencing factors			Value range
Machine Efficiency	$f_{machine\ technology}$	f_{engine}	[0.97; 1.03]
		f_{eco}	[0.85; 1.00]
		$f_{significant\ improvement}$	[0.65; 1.00]
	$f_{machine\ condition}$	f_{age}	[1.00; 1.32]
		$f_{service\ regularity}$	[1.00; 1.40]
Process Efficiency	$f_{site\ orga.}$*		[0; 0.68]
	$f_{idle\ unavoidable}$*		[0; 0.68]
	$f_{process\ assistant}$		[1.00; 1.72]
	$f_{constr.\ complexity}$	$f_{weather}$	[0.10; 1.00]
		$f_{construction\ time}$	[0.60; 1.12]
		$f_{site\ freedom}$	[0.90; 1.00]
Energy Source	$f_{CO_2e/energy\ carrier}$		[0.04; 3.18]
Operation Efficiency	f_{driver}	$f_{physical\&mental\ state}$	[0.55; 1.00]
		$f_{knowledge\&skills}$	[0.55; 1.00]
		$f_{workplace\&working\ environment}$	[0.10; 1.00]
	$f_{stop\&go}$		[0; 1.00]
CO_2e Capture & Storage	f_{CCS}		[0.30; 0.99]

* On the condition that: $0 \leq f_{site\ orga.} + f_{idle\ unavoidable} \leq 1$

6.3 Values for past and present and future scenarios

In this subchapter values are determined for the simulation of the past present and near future. The past scenario represents the situation on construction sites around 1990, the present scenario around 2014 and the near future scenario around 2020.

The engine of construction machines in the past scenario had stage I, in the present scenario stage IIIA and in the near future scenario stage IV[39]. These correspond for f_{engine} to the values 1.0, 1.03 and 1.0, respectively. In the past, ECO-mode didn't exist, therefore f_{eco} corresponds to 1.0. In the present and near future ECO-mode is available in all construction machines in Europe. Consequently, f_{eco} for the present and near future is 0.88[40]. According to definition, significant improvements in construction machines did not exist in the past. $f_{significant\ improvement}$ had the value 1.0 in the past. In the present, the average effect due to improvements corresponds to 0.85 and in the future it will correspond to 0.75 (see appendix A.1). In summary, $f_{machine\ technology}$ will for the past, present and near future scenarios have the values 1.0, 0.76 and 0.66, respectively.

For the past and present scenario, it is being assumed that the service regularity recommended by the machine manufacturers is being exceeded by 20 %. Therefore $f_{service\ regularity}$ will have the value 1.04, corresponding to the average effect determined through the expert survey (see appendix A.1). In the near future, machines will have assistant systems reminding machine operators to perform services. Further, operators as well as responsible persons from the construction industry are aware of the negative effect on production through poor machine maintenance. It's being assumed that in the future scenario service regularity is very good, which means $f_{service\ regularity}$ equals 1.0. Concerning the age of the machines, it's being

[39] In the near future scenario of 2020, machine generation of 2015-2016 are taken as reference because it takes approximately 5 years until machine generations are state of the art on European construction sites, see 4.1.

[40] This values corresponds to the average effect determined by industry through the expert survey according to the Delphi method (see appendix A.1).

presumed for past, present and near future scenarios that the machines have reached half of their average lifetime ($f_{age} = 1.05$). This means, $f_{machine\ condition}$ will for past, present and future scenarios have the values 1.09, 1.09 and 1.05, respectively.
In equations (4-25) and (4-26) the factor construction site organisation affects only idle time. In the past, construction machine engines were not switched off when they were not working. Further, the construction site organisation took place before beginning construction and was not constantly adapted to the current construction situation like in a lean construction organisation. Therefore, for the past scenario $f_{site\ orga.}$ will take the minimum value of 0.68. In the present scenario, better organisation at construction sites, e.g. lean principles are becoming more common. Therefore, $f_{site\ orga.}$ will have the value 0.34. In the near future scenario, 80 % of perfect organisation is reached, therefore $f_{site\ orga.}$ will have the value 0.06 [41].
Idle time necessary for construction processes is called unavoidable idle. For the past scenario, it is assumed that engines are linked with the machine task and they need to be switched on a high amount of the time. In the present scenario a better decoupling of engine and machine tasks is possible. In the near future the necessary amount of unavoidable idle time on construction sites will be very low. Further, the sum of $f_{site\ orga.}$ and $f_{idle\ unavoidable}$ should maximally be below one. Therefore, $f_{idle\ unavoidable}$ will have the values 0.31, 0.16 and 0.07, respectively for the past, present and future scenarios.
The effect of process assistant systems increase the production efficiency depending on the type of operator. For the past scenario, no assistant systems existed, for the present scenario, some assistant systems are available and in the near future scenario all assistant systems available today on the market will be implemented in the machine. Therefore $f_{process\ assistant}$ will have the value 1.0, 1.18 and 1.41, respectively for the past, present and near future scenarios.
The construction complexity is the effect from the weather, the available construction time and the available construction freedom. For the weather,

[41] $(1 - 0.68) \times 0.2 = 0.06$

ideal conditions are assumed in the past and present scenarios. The near future is connoted with some slight effects due to the global warming. Therefore $f_{weather}$ equals 1.0 for past and present scenarios and 0.95 for near future scenarios. Construction stop due to the cold season in the winter forces employees from the construction industry to accumulate overtime working hours during the other seasons. Therefore, an overtime of max. 10 h/week is assumed for all scenarios, which correspond to 0.9 for $f_{construction\ time}$. The available construction freedom is expected to be ideal in the past and present scenarios. In the near future scenario, because of the population growth over the years, construction takes place in populated areas to make areas denser. Therefore $f_{site\ freedom}$ the past and the current value of 1.0 is expected to drop to 0.9 for the near future scenario. In summary, $f_{constr.\ complexity}$ will have the values 0.9, 0.9 and 0.77, respectively for the past, present and future scenario.

In the past, present and near future, construction machines had and will be working with diesel. Therefore, $f_{CO_2e/energy\ carrier}$ will have the value 3.18, which corresponds to the conversion factor from a litre of diesel in CO_2e emissions.

The factor f_{driver} is the combined effect of the driver's physical and mental state, the workplace and working environment influences and the driver's skills, consisting of its experience and training courses. For the scenarios, it is being assumed that the driver has an ideal physical and mental state. This means, $f_{physical\&mental\ state}$ will have the value 1.0. In the past, not all machines had a cabin that could be closed so the working environment affected the driver. In the present, cabins which can be closed are state of the art, though the workplace still lacks good ergonomics. In the near future scenario, cabins are improved but still not ideal. Consequently, $f_{workplace\&working\ environment}$ will have the values 0.55, 0.78 and 0.89, respectively for the past, present and near future scenarios. In all three scenarios, training courses for drivers to improve fuel consumption are not effective enough to make a difference at construction sites. In the past scenario, the driver was an expert. In the present scenario the driver is good. The construction industry has more and more difficulties finding good drivers for construction machines, therefore a medium driver is assumed for the near future scenario. This means, $f_{knowledge\&skills}$ will have the values 0.92, 0.83 and 0.77, respectively for past, present and near future scenarios. In summary, f_{driver} will have for the past, present and future scenarios the values 0.51, 0.64 and 0.68, respectively.

Table 6-7: Factor values for past, present and near future scenarios

Influencing factors			Past	Present	Near future
Machine Efficiency	$f_{machine\ technology}$	f_{engine}	1.00	1.03	1.00
		f_{eco}	1.00	0.88	0.88
		$f_{significant\ improvement}$	1.00	0.85	0.75
	$f_{machine\ condition}$	f_{age}	1.05	1.05	1.05
		$f_{service\ regularity}$	1.04	1.04	1.00
Process Efficiency	$f_{site\ orga.}$		0.68	0.34	0.06
	$f_{idle\ unavoidable}$		0.31	0.16	0.07
	$f_{process\ assistant}$		1.00	1.18	1.41
	$f_{constr.\ complexity}$	$f_{weather}$	1.00	1.00	0.95
		$f_{construction\ time}$	0.90	0.90	0.90
		$f_{site\ freedom}$	1.00	1.00	0.90
Energy Source	$f_{CO_2e/energy\ carrier}$		3.18	3.18	3.18
Operation Efficiency	f_{driver}	$f_{physical\&mental\ state}$	1.00	1.00	1.00
		$f_{knowledge\&skills}$	0.92	0.83	0.77
		$f_{workplace\&working\ environment}$	0.55	0.78	0.89
	$f_{stop\&go}$		1.00	1.00	0.20
CO_2e Capture & Storage	f_{CCS}		0	0	0

In the past and present, drivers were not sensitised to fuel consumption during idle, therefore the engine was switched on the whole day. The factor $f_{stop\&go}$ will have the value 1 for such driver behaviour. In the near future scenario, all machines will have a stop and go function, which means the engine switches off automatically after 3 minutes of no working. Due to this automatic function, drivers will no longer switch off their engines manually. Consequently, for the near future, $f_{stop\&go}$ will have the value 0.20.

In the past, present and near future, no construction machine exists with a carbon capture and storage system. Therefore, the factor f_{CCS} will have the value of zero.
The values for the factors are summarised in Table 6-7.

In further future scenarios[42], it can be assumed that carbon capture and storage systems for mobile machines will be developed. Additionally, construction machines will continue to improve in such a way that the driver as a human being will not have to work constantly or in a forced rhythm. In Table 6-8 the different mechanisation steps of a mobile machine are shown. In the future, fully automated working systems (fully autonomous) will be state of the art. With fully automated machines, one "driver" can monitor several machines from a central location. The "control of the result" function is detached from monitoring and is purely concerned with the observation, evaluation and control of the work result (Ays et al. 2018b). In such a scenario the driver will have no influence anymore on the construction result, and so f_{driver} will have the value 1.0.

[42] The described further future scenarios are the author's expectations.

Table 6-8: Different stages of mechanisation steps for a mobile machine (based on Ays et al. 2018b)

Subfunctions of a mobile machine			Technological stage of a mobile machine						
			Manual work system	Mechanised work system	Work system with assistant systems	Partial automated work system	Highly automated work system (semi-autonomous)	Fully automated work system (fully autonomous)	Ideal process
Subfunctions of a mobile machine	Impacting	Driving Working	Human	Technique	Technique	Technique	Technique	Technique	Technique
	Steering	Driving Working	Human	Human	Human	Technique Human	Technique	Technique	Technique
	Monitoring	Driving Working	Human	Human	Human	Human	Human	Human	Technique
Control of the result		/ Working	Human	Human	Human	Human	Human	Technique	Technique

6.4 Factor influence analysis

In order to better understand the factors of Table 6-7 and their value range on how they affect the amount of greenhouse gas emissions, a factor influence analysis is performed on the example of a 27 t excavator. For the excavator, the parameter values from Table 6-9 were chosen for reference.

By varying the factors into their respective value ranges between their minimum and maximum value, the maximum difference of the amount of greenhouse gas emissions can be seen in Table 6-10. The analysis has shown that the weather ($f_{weather}$) is the factor with the biggest potential to influence the total greenhouse gas emissions of a mobile construction machine. Indirectly, bad weather also affects the driver through the factor $f_{workplace\&working\ environment}$. Consequently the driver will not be able to be as effective as possible in driving the machine and will so emit more greenhouse gas emissions with it. The factor $f_{workplace\&working\ environment}$ thus has the second biggest potential in influencing the total greenhouse gas emissions of a mobile construction machine. In order to reduce the total greenhouse gas emissions due to this factor, the strain on the driver because of the workplace and the working environment has to be reduced. It is therefore important to pay attention to good workplace ergonomics and isolate the driver from working environment influences like weather, noise, vibrations, etc.

The third factor with the highest influence potential on greenhouse gas emissions is the energy carrier. In 6.1.9, different energy carriers are compared with diesel. The CO_2e emissions can easily increase when instead of conventional diesel a different energy carrier is used which is not produced in a sustainable way.

The factor influence analysis shows that the engine influence (f_{engine}) and a stop & go functionality or a conscious driver switching off his/her machine when it is not needed ($f_{stop\&go}$) are the factors with the lowest impact of the CO_2e amount emitted by mobile construction machines.

Table 6-9: Parameter values chosen for the influence analysis of an excavator.

Influencing factors			Values
Excavator data	Material volume $V_{material}$		1,500 m³
	Basic performance of the excavator Q_B		193 m³/h
	Consideration of unforeseeable events f_{ui}		1
	Fuel consumption during working time b_m		31.9 l/h
	Fuel consumption during idle time b_{idle}		3.0 l/h
Machine Efficiency	$f_{machine\ technology}$	f_{engine}	1.03
		f_{eco}	0.88
		$f_{significant\ improvement}$	0.85
	$f_{machine\ condition}$	f_{age}	1.05
		$f_{service\ regularity}$	1.04
Process Efficiency	$f_{site\ orga.}$		0.34
	$f_{idle\ unavoidable}$		0.16
	$f_{process\ assistant}$		1.18
	$f_{constr.\ complexity}$	$f_{weather}$	1.00
		$f_{construction\ time}$	0.90
		$f_{site\ freedom}$	1.00
Energy Source	$f_{CO_2e/energy\ carrier}$		3.18
Operation Efficiency	f_{driver}	$f_{physical\&mental\ state}$	1.00
		$f_{knowledge\&skills}$	0.83
		$f_{workplace\&working\ environment}$	0.78
	$f_{stop\&go}$		1.00
CO_2e Capture & Storage	f_{CCS}		0

Table 6-10: Impact importance of the factors influencing the greenhouse gas emissions of mobile construction machines

Impact importance	Factors	Potential for change in kg CO_2e
1	$f_{weather}$	9,635
2	$f_{workplace\&working\ environment}$	7,467
3	$f_{CO_2e/energy\ carrier}$	2,474
4	f_{CCS}	1,060
5	$f_{physical\&mental\ state}$	876
6	$f_{construction\ time}$	746
7	$f_{knowledge\&skills}$	727
8	$f_{site\ orga.}$	550
9	$f_{process\ assistant}$	528
10	$f_{idle\ unavoidable}$	515
11	$f_{significant\ improvement}$	398
12	$f_{service\ regularity}$	370
13	f_{age}	321
14	f_{eco}	165
15	$f_{site\ freedom}$	119
16	f_{engine}	56
17	$f_{stop\&go}$	54

6.5 Simulation of representative applications

In this subchapter, the CO_2e quantification method is applied for the representative construction applications described in chapter 5. For the application of each scenario period: past, present and future, the construction material, the construction process and the construction machine are being considered. The assumptions used for the simulation periods are described in 6.3 and intermediate results are shown in appendix A.2.

6.5.1 Building construction

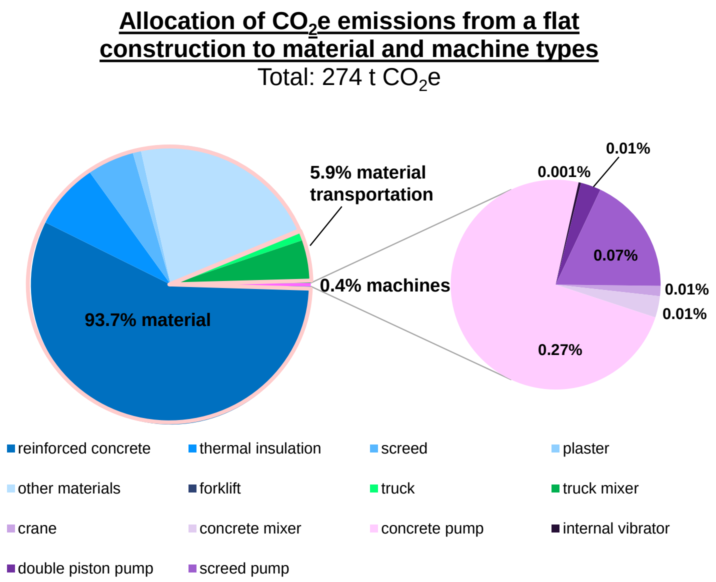


Figure 6.8: Allocation of CO_2e emissions to material and machine types from a flat construction (present scenario)

By applying the quantification method for each sub process for the construction of a flat with reinforced concrete, the total amount of CO_2e emissions during construction can be quantified. The results show that 93.7 % of the total CO_2e emissions are emitted during material production, 5.9 % during material transportation and 0.4 % for other machines. The respective emitters are shown in Figure 6.8.

By applying the quantification method for the same application in the times past, present and future with the construction design described in 5.2.1 and construction conditions described in 6.3, the CO_2e emission development over time for the construction of the flat can be quantified. The results are shown in Figure 6.9. A CO_2e reduction of 13 % is reached in the present scenario and a reduction of 10 % is reached in the near future scenario compared to 1990 (past). For the future scenario, a construction with sand lime brick is assumed instead of a reinforced concrete construction like in the present scenario. According to the quantification, greenhouse gas emissions for a sand lime brick construction is higher than for a reinforced concrete construction.

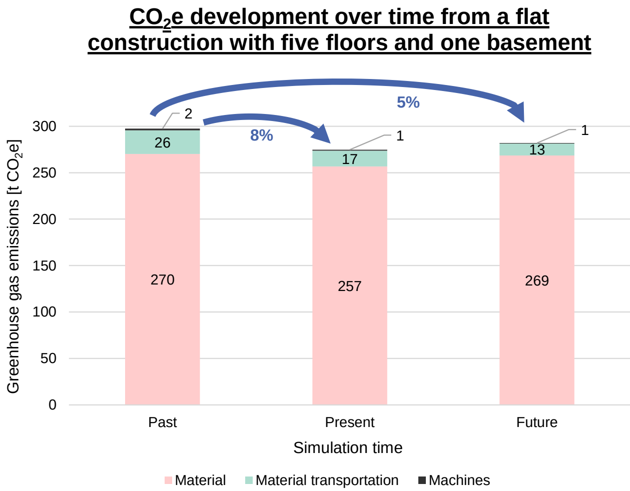


Figure 6.9: CO_2e emission development over time from a flat construction

Applying the quantification method for each sub process for the construction of an office building with five floors and one basement, where the ground floor has an area reserved for a commerce results in the CO_2e emission distribution of Figure 6.10. 96.4 % of the total emissions of 776 t CO_2e are from the material production, 3.4 % from material transportation and 0.2 % for machines working at the construction site.

The application of the CO_2e quantification method for an office building in the times past, present and future with the construction design described in 5.2.1 and construction conditions described in 6.3, is shown in Figure 6.11. A CO_2e reduction of 19 % is reached in the present scenario and a reduction of 18 % is reached in the near future scenario compared to 1990 (past).

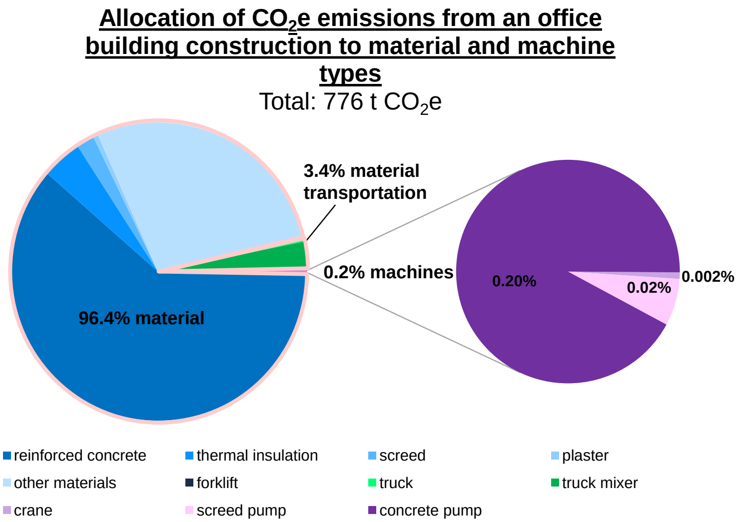


Figure 6.10: Allocation of CO_2e emissions from an office building construction to material and machine types (present scenario)

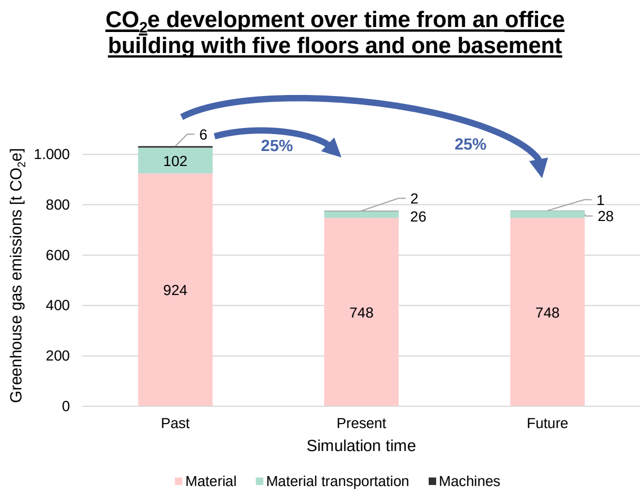


Figure 6.11: CO_2e emission development over time from an office building construction

For the future scenario, the concrete truck mixers need in total less time for a period of circulation consisting of: loading, driving loaded, unloading, driving back empty and truck rotation time. In order to have the minimum standstill time possible, in the future scenario because of the shorter circulation time, four truck mixers will be used instead of three. An additional truck mixer results in an increase in CO_2e emissions for the future scenario compared to the present scenario.

6.5.2 Road construction

The CO_2e quantification method was also applied to the construction of a road of BK10 type described in Figure 5.5. The biggest CO_2e amount is emitted during material production with 82.0 %, then with 16.5 % from material transportation and 1.5 % from construction machines (see Figure 6.12). By comparing the CO_2e quantification results for the times past, present and future, a reduction of 24 % is already reached and a reduction of 39 % is expected in the near future (see Figure 6.13). The reduction results from the assumptions taken in 6.3 and through the effect combination of a different road dimensioning regulation and improvements in material production using less energy and more recycling material.

The CO_2e quantification method was also applied for a BK10 road renewal. Using the inlay method for road renewal, the resulting CO_2e emitter's distribution is shown in Figure 6.14. 79.6 % of the total CO_2e amount for this construction is emitted through material production, 18.4 % through material transportation and 2.0 % through construction machines (see Figure 6.14). In comparison to the past, the present has reached a CO_2e reduction of 24 % and a reduction of 34 % is expected in the near future.

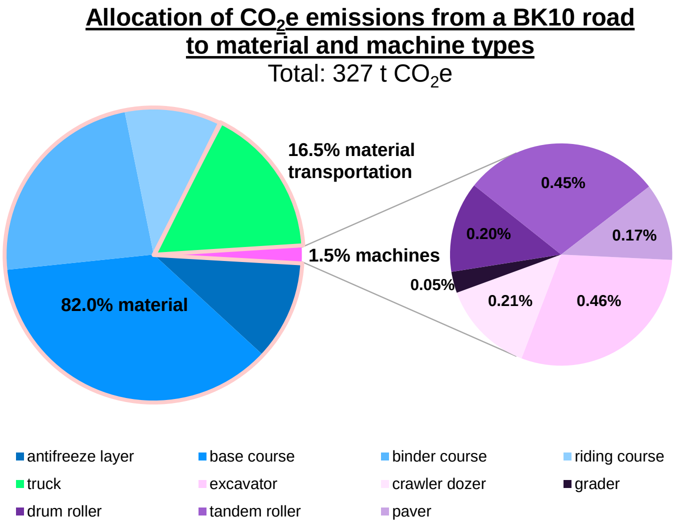


Figure 6.12: Allocation of CO_2e emissions from the Bk10 road construction to material and machine types (present scenario)

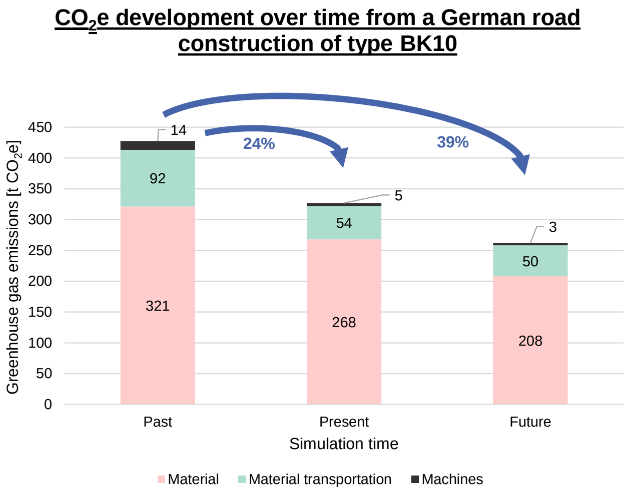


Figure 6.13: CO_2e development over time from a road construction of type BK10

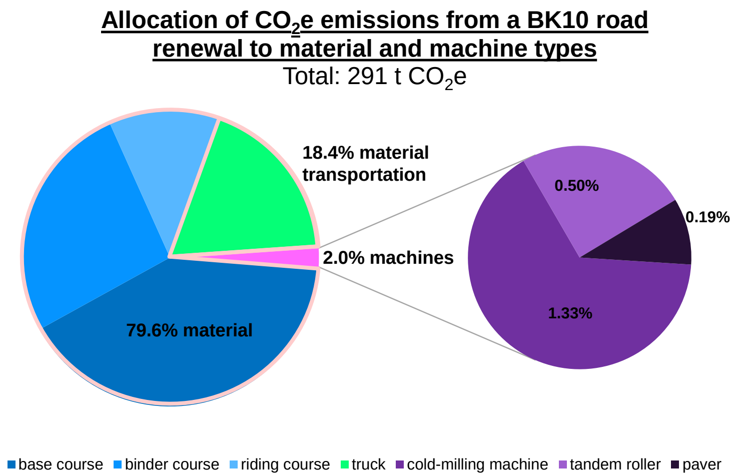


Figure 6.14: Allocation of CO_2e emissions from a BK10 road renewal to material and machine types (present scenario)

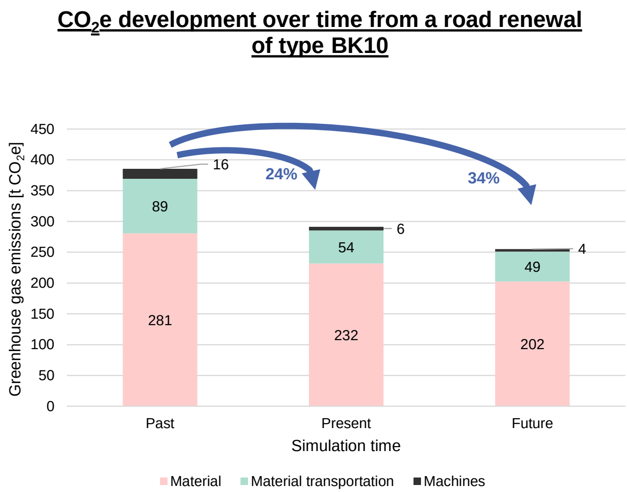


Figure 6.15: CO_2e development over time from a road renewal of type BK10

6.5.3 Earthmoving work

The CO_2e emission sources distribution from a pit excavation for the flat or the office building is similar. 93.0 % to 93.2 % are emitted for material transportation and 6.8 % to 7.0 % are emitted by the construction machines. In these two applications, no material production takes place. The analyses over time show that compared to the past, in the present, a CO_2e reduction of 44 % was reached and a reduction of 47 % is expected in the near future. The respective results over time are shown in Figure 6.16 and in Figure 6.17. These reductions are based on the assumptions made in 6.3 and are mainly influenced by the assumption about the global warming and the workplace improvements.

Two earthmoving applications were chosen for the BK10 road. The first consists in building the road on a dam. The CO_2e quantification for the dam construction is shown in Figure 6.18. For the dam, materials like sand, clay and lime are needed. All three materials don't emit as much CO_2e as reinforced concrete. Therefore, the biggest CO_2e emission share comes from material transportation with 79.8 %. In the slot construction application for a BK10 road, on both sides a reinforced concrete pipe is installed in order to evacuate water. The use of reinforced concrete increases the amount of CO_2e emission from the material. The resulting respective CO_2e emitters share is shown in Figure 6.20. The CO_2e emissions reduction over time of the dam and slot construction application shown in Figure 6.19 and Figure 6.21 are due to the assumptions defined in 6.3.

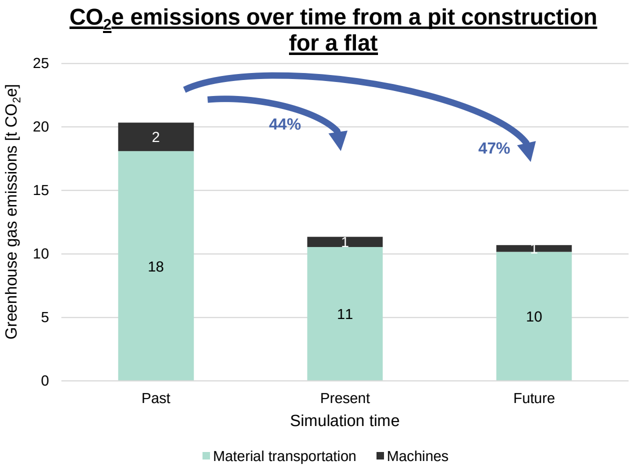


Figure 6.16: CO_2e emissions over time from a pit construction for a flat

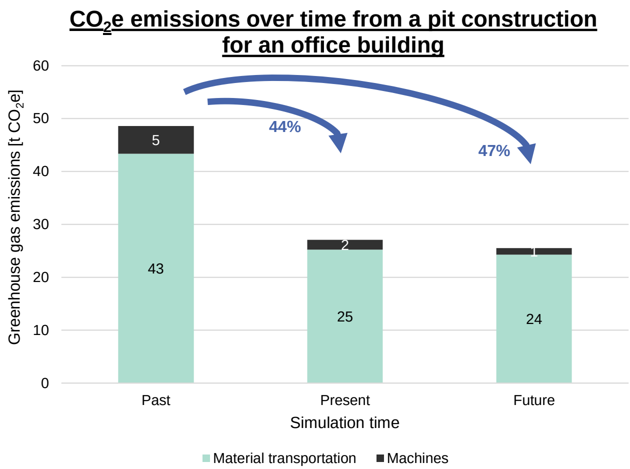


Figure 6.17: CO_2e emissions over time from a pit construction for an office building

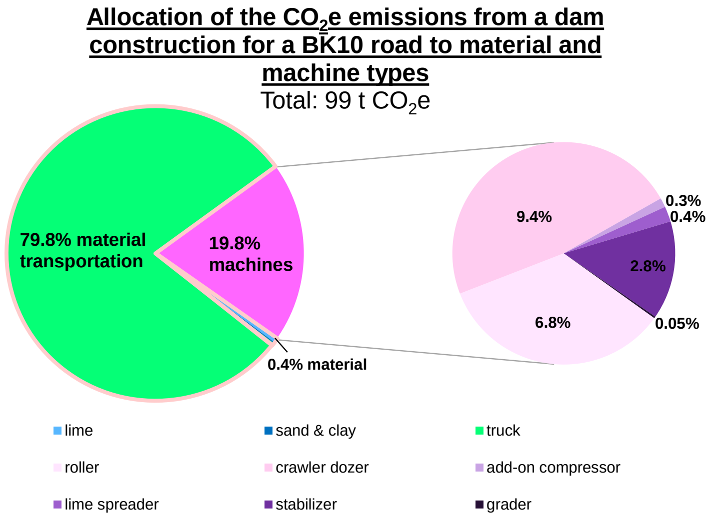


Figure 6.18: Allocation of the CO_2e emissions from a dam construction for a BK10 road to material and machine types (present scenario)

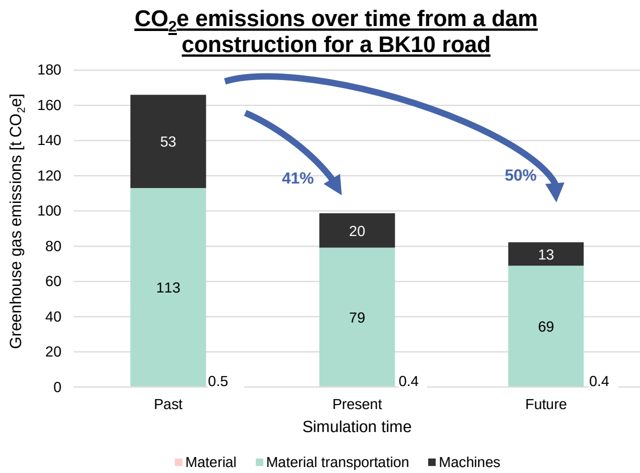


Figure 6.19: CO_2e emissions over time from a dam construction for a BK10 road

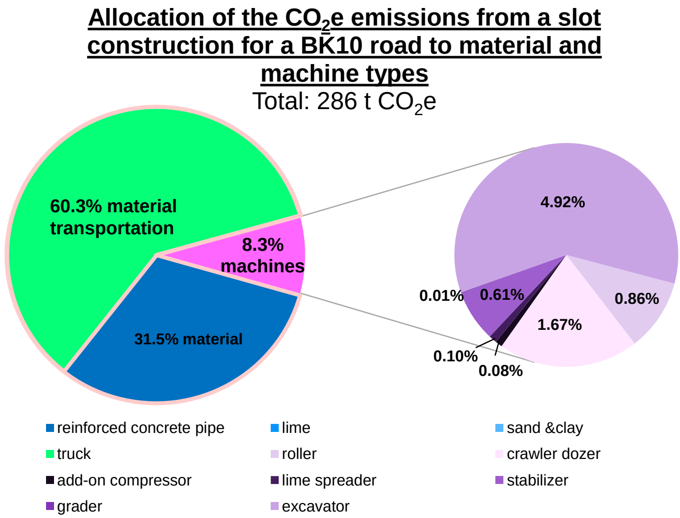


Figure 6.20: Allocation of CO_2e emissions from a slot construction for a BK10 road to material and machine types (present scenario)

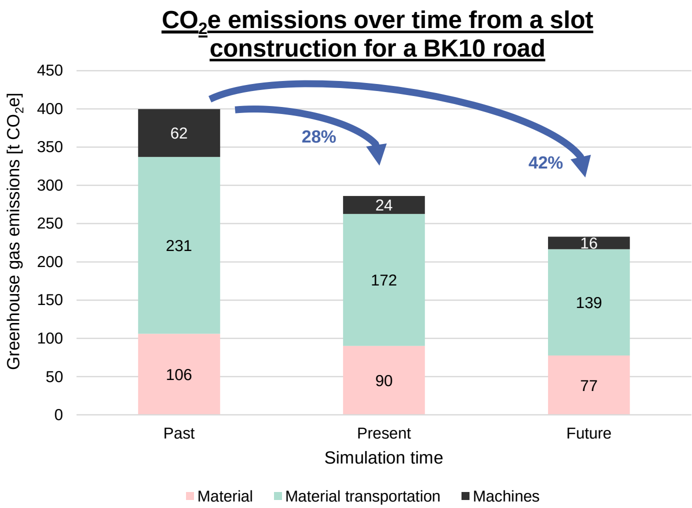


Figure 6.21: CO_2e emissions over time from a slot construction for a BK10 road

6.5.4 Material Extraction

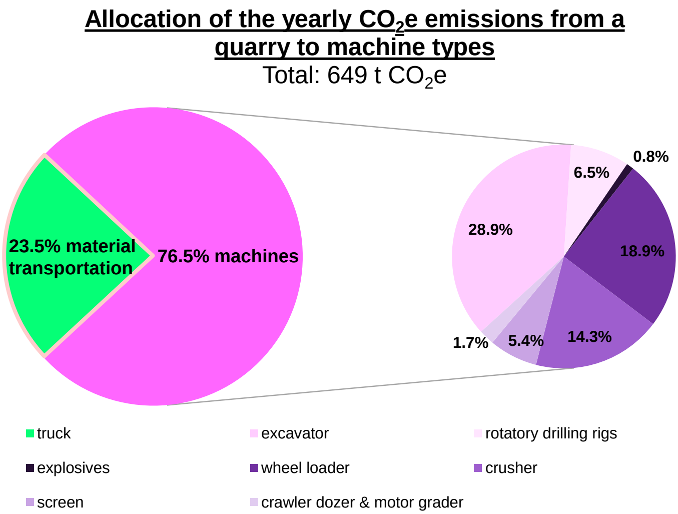


Figure 6.22: Allocation of the yearly CO_2e emissions from a quarry (present scenario)

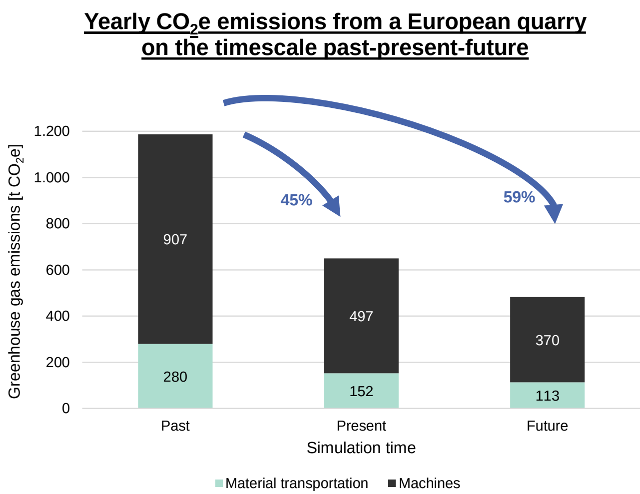


Figure 6.23: CO_2e emissions development over time from a quarry

The explosives used in a quarry are treated for the simulation like a machine. Therefore, only the CO_2e amount emitted during an explosion are considered and not the CO_2e emissions emitted during their production.
The application of the CO_2e quantification method on a quarry shows that the biggest share comes from machines used in the quarry with 76.5 %. 28.9 % of these greenhouse gas emissions come from excavators (see Figure 6.22). Over time, with the assumptions defined in 6.3, a CO_2e reduction of 45 % is reached in the present scenario and a reduction of 59 % is quantified in the near future scenario.

In summary, the largest amount of CO_2e emissions based on these representative construction applications are emitted during an office building construction with 776 t CO_2e where 96.4 % are emitted during material production. The quarry is the second biggest CO_2e emitter with 5.9 kg CO_2e /t from the extracted granulate and 76.5 % from the construction machines. The application with the lowest greenhouse gas emissions is the construction of pits without special foundation work. In these two constructions of pits, the greatest amount of CO_2e originates from material transportation. Depending on the assumptions made for the past, present and future scenario different CO_2e reductions are reached. According to the assumptions from 6.3, for the representative construction applications, CO_2e reductions over the timescale past-present-future vary. Compared to the past scenario (1990), the present scenario reaches a CO_2e reduction between 13 % and 45 % and the near future scenario between 10 % and 59 %.

6.6 Simulation: Quantification of CO_2e emissions due to destruction and new formation of CO_2e sinks from a BK10 road

Two simulations are carried out using the example of a BK10 road construction to investigate the influence of the destruction and the new formation of CO_2e sinks. The data from the previous projects are used as a reference. The BK10 road under consideration is 1 km long and 7.5 m wide and is built on a dam. The original vegetation is assumed to be grassland for simulation 1 and a forest for simulation 2.

The data assumed for the simulation are summarised in Table 6-11. The total CO_2e amount emitted during a BK10 road construction on a dam foundation equals 426 t CO_2e and a total of 1,591 t CO_2e with four road renewals over a period of 30 years.

Table 6-11: Data assumptions for the simulation of CO2e sinks destruction and formation

Data chosen for the simulation	
Construction area A_{con}	20.000 m²
Restoration area A_{ser}	12.500 m²
Construction time t_{con}	0.04 year (15 days)
Road life cycle t_{ser}	30 year
CO_2e emissions during material production	268 t CO_2e
CO_2e emissions during material transportation	54 t CO_2e
CO_2e emissions from machines	5 t CO_2e
CO_2e emissions through road renewal	291 t CO_2e
Number of renewal processes in 30 years	4

Table 6-12 shows the results of both simulations by applying equation *(4-40)* from chapter 4.4.

By limiting the system boundary on the construction period, the amount of additional CO_2e in the atmosphere due to CO_2e sinks destruction equals 13 %. The results are shown in Figure 6.24.

Taking the whole road life cycle into account as the system boundary, the amount of additional CO_2e in the atmosphere due to CO_2e sinks destruction equals 5 % for simulation 1 (grassland as reference vegetation) and 10 % for simulation 2 (forest as reference vegetation) (see Figure 6.25).

Table 6-12: Results of the simulation with reference vegetation grassland for simulation 1 and forest for simulation 2

Components				Simulation 1		Simulation 2	
Reference vegetation				Grassland		Forest	
Losses	Construction time T_{con}	Vegetation clearing		0.16 t CO_2e		0.30 t CO_2e	
		Ground movement of the topsoil	Losses	0.06 t CO_2e		0.06 t CO_2e	
			Flux	61.76 t CO_2e		61.76 t CO_2e	
		Sum		62 t CO_2e	13%	62 t CO_2e	13%
	Life time t_{ser}	Vegetation clearing		45 t CO_2e		81 t CO_2e	
		Ground movement of the topsoil		16 t CO_2e		16 t CO_2e	
Gains		Initial, rapid gains in CO_2e sinks through replanting		41 t CO_2e		41 t CO_2e	
		Slow gains in CO_2e sinks through replanting		0 t CO_2e		-60 t CO_2e	
		Sum		20 t CO_2e		116 t CO_2e	
Total greenhouse gas emissions				82 t CO_2e	5%	178 t CO_2e	10%

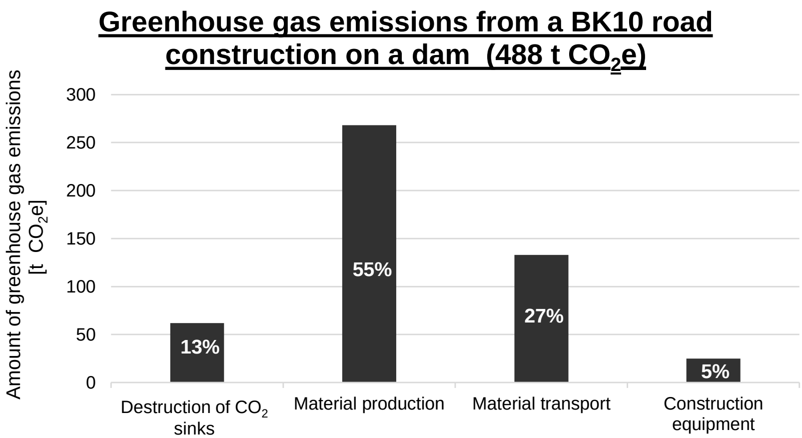


Figure 6.24: CO_2e emissions from a road construction considering the destruction of CO_2e sinks

These two simulations based on a BK10 road construction showed that the destruction and new formation of CO_2e sinks can produce a non-negligible amount of CO_2e emissions. Depending on the system boundaries, the proportion of total greenhouse gas emissions for this BK10 road construction is between 5 % and 13 %. Though, these CO_2e emissions can be reduced or compensated for by applying selected measures during the restoration process of CO_2e sinks. An example of measures from the construction of a BK10 road is shown in Figure 6.26.

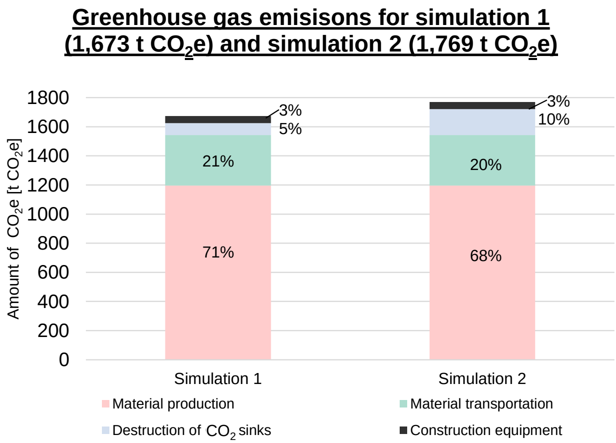
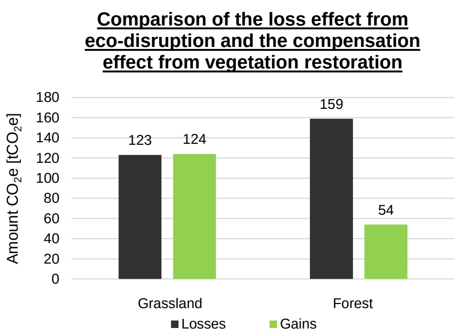


Figure 6.25: CO_2e emissions distribution from the construction of a BK10 road on a dam for the system boundary of 30 years



Measures for gain increases:

- Multi-layer planting
- Planting of species with higher sequestration (shrub areas: 0.58 kg $CO_2.m^2.year^{-1}$)
- Enlarged planting areas due to hills and slopes (15 %)
- Reduced space consumption in urbanisation

Figure 6.26: Comparison of the loss effect from eco-disruption and the compensation effect from restoration on a BK10 road (Chen 2019b)

6.7 Discussion about the verification process

This chapter focuses mainly on verifying the CO_2e quantification method developed in chapter 4. The literature research in 6.1 showed that the right

CO_2e factors were chosen influencing the total amount of CO_2e on construction processes. In 6.2, the range of values these factors can take was determined, enabling defining the correct values for the times past, present and near future in 6.3. The values valid for the time "present" were then used on an excavator allowing to show the CO_2e influence potential of each factor. Further, through the CO_2e quantification of the representative construction applications defined in 5, it was possible to show that the same method is applicable in the different construction sectors and so fulfils the research gap G5.

Table 6-13: Result examples of CO_2e reduction by varying only one pillar

CO_2e reduction potential	Result examples
Machine efficiency	e.g. dam construction application: machine efficiency reduced the total CO_2e amount by 3.5%
Process efficiency	e.g. road renewal process: overlay construction instead of inlay process reduced the total CO_2e amount by 30%
Operation efficiency	e.g. dam construction: no standstill time and perfect driver can reduce the total CO_2e amount by 36%
Energy sources	e.g. dam construction: instead of diesel, liquefied synthetic methane is used and can reduce the total CO_2e amount by 91%
Material efficiency	e.g. flat construction with wood instead of reinforced concrete can reduce the CO_2e amount by 108%*
CO_2e capture & storage	e.g. quarry: when 99% of CO_2 directly emitted by machines are captured and stored then a CO_2e reduction of 82% can be reached

*If wood material is assumed to be equal to 0 instead of -632 kg CO_2e/m^3 then the CO_2e reduction equals 95%

By applying the method on a construction application, not only the effects of machine efficiency are modelled but of all six potential groups defined in 4.4. Effects for each of the six pillars can be quantified through this method. Influence examples for each pillar are given in Table 6-13. This fulfils the defined research gaps G1, G3, G4 and G6.

Each CO_2e quantification took place for all three time periods past, present and near future. This shows that the method is applicable over different time periods and so permits quantifying the CO_2e reduction reached up until now and the expected reduction in the near future (research gap G2).

Finally, the simulation in 6.6 enables understanding why CO_2e sinks destructions and new formations need to be considered in the method. Depending on the construction application, they can have a considerable effect on the total amount of CO_2e emitted during a construction process.

In summary, through the simulations in this chapter, it was possible to prove that the method is an essential tool in order to understand and simulate the effects of possible measures in order to reduce CO_2e emissions in construction processes (need N4).

7 Validation of the CO_2e quantification method

In chapter 4, a CO_2e quantification method has been developed that breaks down a construction application into processes. For each process the CO_2e emissions are quantified and the sum results in the total CO_2e emissions for the application. This part of the method could be verified through the simulation work on representative applications in 6.5.

Further in 6.5, it was possible to verify that the loss of CO_2e sinks due to vegetation clearance and soil movement before construction work is essential to be considered in the CO_2e quantification method. In case the application to quantify goes beyond the construction time and also considers the maintenance work of the construction product over its lifecycle, it is important to consider the CO_2e effects due to vegetation restoration after construction work. A validation process for the CO_2e quantification method of this part is not necessary here because the values used for the CO_2e quantification for this part are from existing literature and are thus already validated.

The part for the quantification of CO_2e emitted during material production also need not be validated. The data is based on accredited databases like Ökobaudat, Probas, Ecoinvent and thus do not require validation (Ökobaudat 2013; Ecoinvent 2007; ProBas 2015).

The CO_2e emitted during material transport focuses on CO_2e emissions emitted by transport vehicles like heavy-duty trucks. The CO_2e emission for material transport is based on the performance calculation of Hoffmann et al. and the fuel consumption is based on the specific fuel consumption chosen with 190 g/kWh for the past scenario (Hoffmann et al. 2011). In the present and future scenario an efficiency is assumed according to the values chosen in 6.3. Therefore, the CO_2e quantification for heavy-duty trucks are only an approximation. In this work, the focus does not lie on trucks, therefore a validation for the truck formula is unnecessary. For a validated method, the VECTO-tool can be consulted.

The CO_2e emitted from construction machines during construction applications has not yet been validated. Therefore, the following chapter will focus on its validation, which is equivalent to the validation of equations *(4-14*) or

(4-25) and *(4-26)*. According to the Pareto principle, the method has to quantify 80 % of the CO_2e emissions related to construction machines.

7.1 Equipment and instrumentation

In order to validate the part of quantifying the CO_2e emissions from mobile construction machines interviews, observations and measurements were carried out at two construction sites in Germany. The first construction site doing canal construction took place in Ludwigsburg. The second construction site, road construction, took place in Mannheim. The validation of the construction site in Ludwigsburg took place based on an excavator and on one single drum roller. The specific data for these machines are described in Figure 7.1. The validation at the construction site in Mannheim took place based on two pavers and two asphalt tandem rollers, described in Figure 7.2.

Machine: Excavator
Engine: Volvo D8J
Max. performance: 160 kW
Exhaust gas stage: stage IV (Tier 4f)
Machine weight: 29 t
Year of production: 2016

Attachment used with the excavators:

- Universal bucket with a filling quantity of 0.8 m³
- Grading bucket with a filling capacity of 1.6 m³.
- Gripper with a filling quantity of 1.2 m³
- Add-on compressor: Ammann APA 1000
- Universal bucket with a filling quantity of 2.1 m³
- Grading bucket with a filling capacity of 2.5 m³


Machine: Single drum roller Engine: Kubota V3307CR-T Max. performance: 55 kW Exhaust gas stage: stage IV (Tier 4f) Machine weight: 8 t Year of production: 2015 Effective width: 1686 mm

Figure 7.1: Excavator and single drum roller used in Ludwigsburg

	
Machine: Road paver A Engine: Volvo D8H Max. performance: 200 kW Exhaust gas stage: stage IIIB (Tier 4i) Machine weight:17 t Year of production: 2017 Paving width: 2.5-13m	Machine: Road paver B Engine: Cummins QSB6.7-C164 Max. performance: 125 kW Exhaust gas stage: stage IV (Tier 4f) Machine weight: 22 t Year of production: 2017 Paving width: 3.0-9.0m

	
Machine: Tandem roller A Engine: Deutz Max. performance: 74 kW Exhaust gas stage: stage IV (Tier 4f) Machine weight: 9.5 t Year of production: 2018 Effective width: 1686 mm Picture source: (Bomag GmbH 2015)	Machine: Tandem roller B Engine: Kubota Max. performance: 55 kW Exhaust gas stage: stage IIIb (Tier 4f) Machine weight: 7 t Year of production: 2018 Effective width: 1500 mm

Figure 7.2: Pavers and tandem rollers used in Mannheim

In order to determine the amount of greenhouse gas emissions emitted, the fuel consumption of the machines needed to be assessed. A CANBUS reading device was installed on the machines with a CANBUS protocol J1939. For the other machines, the fuel consumption was determined through refuelling. The fuel tank is refilled in the morning and again in the evening after the construction work. The amount of fuel refilled represents the daily fuel consumption.

In order to evaluate the workplace ergonomics and the view quality out of the machine, cabin measures were taken from the cabin. Every part of the cabin, which can be adjusted, was moved from the minimum to the maximum position in order to assess if the ergonomics was acceptable for the drivers anthropometry. The influence of ergonomics on the machine operator is very dependent on how he himself evaluated the comfort of the machine. Therefore, the information measured was complemented with the answers the driver gave in a survey at the end of the working day. The view quality out of the cabin was assessed based on ISO 500:2017 and their revisions 5006:2006 to 5006:2017 (Brixel 2018). Following assessing, a procedure was applied: a person walks with an object at 1.2 m from the ground around the machine at a distance of 1 m from the construction machine. Another person sat in the cabin and assessed the blind spots where the object carried by the person could not be seen by the driver with mirrors nor with the camera installed in the machine. An exemplary result of such an assessment is shown for the excavator in Figure 7.3.

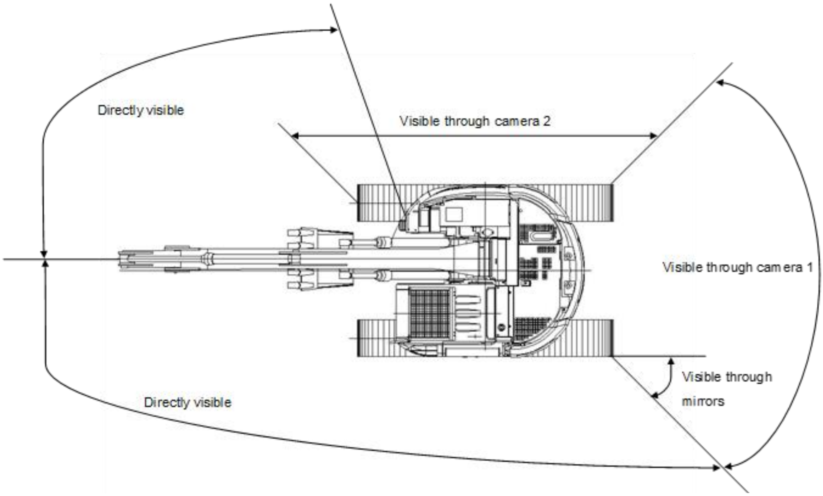


Figure 7.3: Exemplary result of a view quality assessment

The multi measuring device was used to measure the temperature, humidity, noise and light exposure of the workplace. Additionally, a d2 test was conducted with the drivers of the observed mobile machines in order to assess the concentration level of the day. A vibration measurement device was used to assess the vibrations exposure on the driver in the mobile machine cabin. At the end of the construction day, the workers and drivers were asked to answer a survey. There, the questions of the survey aimed to define their background, workplace ergonomics, performance of the day, disturbances of the day, etc.

In the following Table 7-1 and Table 7-2, the exact procedure is summarised on how the factors from equation (4-25) and *(4-26*) are recorded and determined.

Table 7-1: Investigation procedure to determine the factors from machine and process efficiency

Influencing factors			Investigation procedure
Machine Efficiency	$f_{machine\ technology}$	f_{engine}	1. The exhaust stage of the engine is taken from the technical data sheet of the machine. 2. The value is defined with the expert survey.
		f_{eco}	1. Observation and questioning at the construction site as to whether and for how long the Eco-mode was in use 2. The value is defined with the expert survey.
		$f_{significant\ improvement}$	1. Information from observation, questioning and from the technical data sheet of the machine. 2. The value is defined with the expert survey.
	$f_{machine\ condition}$	f_{age}	1. The year of production is taken from the data plaque on the machine 2. The value is defined with the expert survey.
		$f_{service\ regularity}$	1. Determination through survey, when the last service was carried out and what was done in the process. 2. The value is defined with the expert survey.
Process Efficiency	$f_{site\ orga.}$		Value is determined based on observations of the site and questioning of the workers
	$f_{idle\ unavoidable}$		Value is determined based on observations of the site and questioning of the workers
	$f_{process\ assistant}$		1. Information from observation, questioning and from the technical data sheet of the machine. 2. The value is defined with the expert survey.
	$f_{constr.\ complexity}$	$f_{weather}$	Value is determined based on observations and measurements from the multi measuring device
		$f_{construction\ time}$	Value is determined based on observations of the site and questioning of the workers
		$f_{site\ freedom}$	Value is determined based on observations of the site and questioning of the workers

Table 7-2: Investigation procedure to determine the factors from energy source, operation efficiency and CO_2e capture and storage

Influencing factors			Investigation procedure
Energy Source	$f_{CO_2e/energy\ carrier}$		1. Questioning the drivers about the fuel type 2. Value is calculated based on data from literature
Operation Efficiency	f_{driver}	$f_{physical\&mental\ state}$	Value is determined based on observations of the site, questioning of the workers and the d2 test
		$f_{knowledge\&skills}$	Value is determined based on observations of the site and questioning of the workers
		$f_{workplace\&working\ environment}$	1. Ergonomics: Measurements of the adjustability of parts in the cabin View from the cabin: assessment based on ISO 500:2017 (see description above) Weather: Value is determined with observations and measurements with the multi measurement device Noise: Value is determined with the multi measuring device Vibrations: The value is determined with the vibration measuring instrument 2. Based on the assessed information in 1. a representative value for the factor is chosen based on the information found in the literature (see 6.1)
	$f_{stop\&go}$		Value is determined based on observations
CO_2e Capture & Storage	f_{CCS}		Value is determined based on questioning and the data sheet of the CCS device. (This device does not exist yet)

7.2 Results

This part 7.2, compares the results determined based on data from the construction sites in Ludwigsburg and Mannheim with the theoretical result determined using the CO_2e quantification method.

7.2.1 Excavator

First, the results concerning the construction site in Ludwigsburg will be analysed. On the fourteenth of December 2018, the excavator was observed during the whole morning. An extract of the observation notes are shown in the following table.

Table 7-3: Extract of the excavator observation notes, taken on 14/12/2018

Time	Duration [min]	Machine status	Bucket volume/ type	Material type: Amount of buckets moved	Driver distance [m]	Task
7:00	38	idling	-	-	-	-
7:38	6	working	-	-	250	driving
7:44	3	working	-	-	100	driving
7:47	6	working	1,6m³	earth:15	-	digging
7:53	12	working	1,6m³	earth:22	15	digging
8:05	1	idling	-	-	-	-
8:06	5	working	1,6m³	earth:4	-	digging
8:11	2	working	1,6m³	earth:2	-	digging
8:13	9	working	1,6m³	earth:16	30	digging
8:22	2	idling	-	-	-	-
8:24	10	working	1,6m³	earth:16	-	digging
8:34	46	standstill	-	-	-	-
9:20	8	working	-	-	340	driving
9:28	3	working	gripper	splinter:1	130	driving & material transport & canal filling
9:31	3	idling	-	-	-	-
9:34	4	working	gripper	splinter:1	260	driving & material transport
9:38	7	idling	-	-	-	-
9:45	2	working	gripper			canal filling
9:47	4	working	gripper	splinter:1	260	driving & material transport & canal filling
9:51	2	working	gripper	earth:2	10	canal filling
9:53	9	idling	-	-	-	-
10:02	6	working	gripper	earth:7	4	canal filling
10:08	6	idling	-	-	-	-
10:14	3	working	gripper	earth:9		canal filling
10:17	2	idling	-	-	-	-
10:19	4	working	Add-on compressor			compacting
10:23	2	working	gripper	earth:1	10	canal filling
10:25	1	working	Add-on compressor			compacting
10:26	3	working	gripper	splinter:1	75	driving & material transport
10:29	6	idling	-	-	-	-
10:35	25	standstill	-	-	-	-
11:00	1	working	gripper	-	-	canal filling
11:01	2	idling	-	-	-	-
11:03	1	working	gripper			canal filling
11:04	4	working	gripper	splinter:1	90	driving & material transport & canal filling
11:08	7	working	gripper	splinter:1	200	driving & material transport & canal filling
11:15	2	working	gripper	earth:2	10	canal filling
11:17	2	working	gripper	earth:1	5	canal filling
11:19	8	idling	-	-	-	-
11:27	1	working	Add-on compressor	-	-	compacting
11:28	4	working	gripper	earth:8	-	canal filling
11:32	4	working	Add-on compressor	-	-	compacting
11:36	5	working	1,6m³	earth:5	25	canal filling
11:41	2	working	1,6m³	earth:3		canal filling
11:43	8	working	Add-on compressor	-	-	compacting
11:51	9	working	-	-	-	driving
12:00	-	standstill	-	-	-	-

<u>Practical approach</u>

The total fuel consumption of the excavator on 14/12/2018 was 50 l of diesel, which is equivalent to 159 kg CO_2e. The Table 7-3 shows that five different processes are carried out with the excavator: digging, filling the canal, compacting, idling and driving. From the observation notes, it can be calculated that the excavator was idling for a total of 1.71 h, working for 1.36 h, driving for 0.75 h and at a standstill for 25 min. Driving times are not taken into account, since driving in the CO_2e quantification method is regarded as preparatory work and is not considered according to the system boundary. Therefore, fuel consumption from driving needs to be subtracted from the total fuel consumption of the morning. The fuel consumption of the excavator of 16.3 l/h is assumed for driving[43]. A driving time of 0.75 h therefore corresponds to a fuel consumption of 12.2 l diesel.

Additionally, the process of compaction with an excavator will not be validated in this thesis, because of missing data about the basic performance. Therefore, the fuel consumption during compacting also needs to be subtracted from total fuel consumption on the observed morning. The fuel consumption during compaction is calculated using the Ammann APA1000 add-on compactor data sheet. The data sheet states that the attached compressor requires a pressure of 250 bar and a hydraulic oil volume flow of 150 l/min for compression. The required power requirement for the excavator is therefore 62.5 kW. This corresponds to 56 % of the maximum excavator output. The approximate fuel consumption during compaction is calculated using the cross product. At maximum output, the excavator consumes 36.4 l/h, 56 % of maximum output corresponds to 20.32 l/h. A compression time of 0.30 h means a fuel consumption of 6.1 l diesel or 19.38 kg CO_2e.

The fuel consumption can be calculated for the respective processes to be validated. The sum of the fuel consumption for each process should correspond to 31.7 l diesel or 101 kg CO_2e. Table 7-4 summarises the respective fuel consumption of the various construction processes. The processes in pink correspond to the processes which will be validated using the CO_2e quantification method.

[43] An 103 kW excavator consuming during driving modus 10.5 l/h is used as a referenced.

Table 7-4: Summary of excavator fuel consumption in Ludwigsburg for its respective construction processes, 14/12/2018.

Process		Time	Fuel consumption	CO_2e emissions
1	Digging	0.73 h	**31,7 l**	**101 kg**
2	Filling the canal	0.33 h		
3	Idling	1.71 h		
4	Compacting	0.30 h	6,1 l	19 kg
5	Driving	0.75 h	12,2 l	39 kg
6	Standstill	1.18 h	0 l	0 kg
		Total	**50 l**	**159 kg CO_2e**

Theoretical approach

The theoretical approach consists of applying the CO_2e quantification method from mobile construction machines during the construction application for the excavator. First, the basic performance of the excavator for the processes “digging” and “filling the canal” will be calculated with equation *(4-27)*. During the digging process, a bucket was used with a capacity of 1.6 m³. For the filling process, a bucket and a gripper were used with 1.6 m³ and 1.2 m³ capacity, respectively. The other parameters were determined according to Hoffmann et al. The load factor was determined based on the decompaction factor, which describes the soil type and the filling factor describes how the bucket is filled. In Ludwigsburg, the soil moved during digging is of type 6, an easily detachable rock in loose bedding, therefore according to Hoffmann et al. the decompaction factor corresponds to 1.00 (Hoffmann et al. 2011, pp. 717–788). During the filling process of the canal, gravel and sand are used, corresponding to the soil type 3 “easily removable soil types with soft bedding” (ibid.). The decompaction factor for the process “filling the canal” corresponds to 1.00 (ibid.). According to Hoffmann et al., a filled bucket of detachable rock in loose bedding and a filled bucket with sand and gravel correspond to a filling factor of 0.95 and 1.13, respectively. Consequently, the load factor will correspond to 0.95 for the “digging” process and 1.13 for the process "filling the canal”. According to Hoffmann et al., the cycle criterion for a bucket of 1.6 m³ corresponds to 202 h^{-1} and for a bucket of 1.2 m³ to 175 h^{-1}(ibid.). During the “digging” process, the pivoting angle is 90° which corresponds to a factor f_1 equal to 1.00. During the process

“filling the canal”, the pivoting angle is 105°, corresponding to f_1 equal to 0.98 (ibid.). The digging depth during the “digging” process is 2 m, corresponding to f_2 equal to 0.95 (ibid.). During the process “filling the canal” the material is distributed into the canal without lowering the boom of the excavator, therefore f_2 will be equal to 1.00 (ibid.). Emptying the bucket after digging takes place in an untargeted way, therefore f_3 is equal to 1.00 (ibid.). On the contrary, during the process “filling the canal”, the emptying takes place in a targeted way so that only the canal is filled with the material. Therefore, for this process f_3 takes the value 0.83 (ibid.). Digging with the excavator takes place in an unbuilt trench, therefore f_4 takes the value 0.90 (ibid.). Filling the canal is considered as an obstacle-free work and therefore f_4 takes the value 1.00 (ibid.).
The values for the respective parameters are summarised in Table 7-5 and result in a basic performance of 223 m³/h for the processes “digging”. For the processes “filling the canal” 227 m³/h and 257 m³/h are calculated as the basic performance.

Table 7-5: The basic performance of the excavator in Ludwigsburg on 14/12/2018 for the processes digging and filling

Process	V_R	f_L	n	f_1	f_2	f_3	f_4	Q_B
Digging	1.6 m³	0.95	175 h⁻¹	1	0.95	1	0.9	**227 m³/h**
Filling 1	1.2 m³	1.13	202 h⁻¹	0.98	1	0.83	1	**223 m³/h**
Filling 2	1.6 m³	1.13	175 h⁻¹	0.98	1	0.83	1	**257 m³/h**

The datasheet of the machine, machine operator surveys, construction site observations, measurements with the multi measuring device and the vibration measuring device permitted defining the values for the factors determined in chapter 4. The excavator has an engine with an exhaust after-treatment system stage IV ($f_{engine} = 1.00$), driving in the ECO-mode ($f_{eco} = 0.88$) and has different other significant improvement technologies corresponding to a fuel consumption reduction of 13 % ($f_{significant\ improvement} = 0.87$). The excavator is 2 years old ($f_{age} = 1.05$) and is subject to regular service maintenance work ($f_{service\ regularity} = 1.00$). No observed idle time was considered unavoidable for the construction processes ($f_{idle\ unavoidable} = 0$). Time recordings of the idle time compared to the total active time of the machine shows that the construction site organisation is good ($f_{site\ orga.} = 0.58$). The calculation of the value of $f_{site\ orga.}$ is described in equation (7-1)[44].

$$f_{site\ orga.} = \frac{t_{total} - t_{working} + t_{idle\ unavoidable}}{t_{total}} = \frac{t_{standstill} + t_{idle}}{t_{total}} = \frac{1.18 + 1.71}{5} = 0.58 \qquad (7\text{-}1)$$

The operator is considered to be a good driver ($f_{knowledge\&skills} = 0.83$) and can therefore profit to a certain degree from the advantages of the process assistant systems integrated in the excavator such as the bucket filling assist system, semi-automatic movements and visibility assistants ($f_{process\ assistant} = 1.09$). On this day, the weather conditions were good (effective weather temperature of below -5 °C and average wind speed of 1.20 m/s), the available construction time and construction site freedom were ideal ($f_{weather} = 0.98$; $f_{construction\ time} = 1.00$; $f_{site\ freedom} = 1.00$). During the whole work task, the excavator drove with diesel ($f_{CO_2e/energy\ carrier} = 3.18\ \text{kg}\ CO_2\text{e/l diesel}$). The d2-concentration test resulted in a concentration performance (KL) of 103, which is equivalent to $f_{physical\&mental\ state}$ of 0.89, see equation *(7-2)*.

$$f_{physical\&mental\ state} = 1 - (1 - 0.55) \times \frac{114 - KL}{114 - 70} \qquad (7\text{-}2)$$

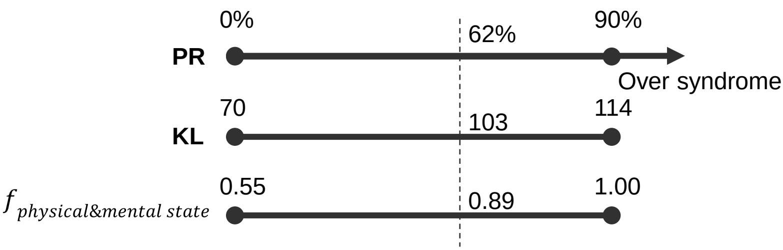


Figure 7.4: Schematic representation of the calculation of $f_{physical\&mental\ state}$

Equation *(7-2)* is derived from Figure 7.4. According to Brickenkampp et al. a normal person has a percentile rank of concentration between 0 % to 90 %.

[44] $t_{total} = t_{working} + t_{standstill} + t_{idle} = t_{working} + f_{site\ orga.} \times t_{total} + f_{idle\ unavoidable} \times t_{total}$

Over 90 % is characterised as over syndrome. According to the evaluation table of the d2 test, a percentile rank of 0 % and 90 % is equivalent to a KL of 70 and 114, respectively. According to 6.2, $f_{physical\&mental\ state}$ varies between 0.55 and 1.00. (Brickenkamp et al. 2010)

Table 7-6: Values for the influencing factors of the excavator on 14/12/2018

Influencing factors			Value
Machine efficiency	$f_{machine\ technology}$	f_{engine}	1.00
		f_{eco}	0.88
		$f_{significant\ improvement}$	0.87
	$f_{machine\ condition}$	f_{age}	1.05
		$f_{service\ regularity}$	1.00
Process efficiency	$f_{site\ orga.}$		0.58
	$f_{idle\ unavoidable}$		0
	$f_{process\ assistant}$		1.09
	$f_{constr.\ complexity}$	$f_{weather}$	0.98
		$f_{construction\ time}$	1.00
		$f_{site\ freedom}$	1.00
Energy Sources	$f_{CO_2e/energy\ carrier}$		3.18 [kg CO_2e/l diesel]
Operation efficiency	f_{driver}	$f_{physical\&mental\ state}$	0.89
		$f_{knowledge\&skills}$	0.83
		$f_{workplace\&working\ environment}$	1.00
	$f_{stop\&go}$		0.59
CO_2e Capture & Storage	f_{CCS}		0

Noise measurements and vibration measurements were under the lower limit value. The light state and the view from the cabin were assessed to be very good. Therefore $f_{workplace\&working\ environment}$ has the value 1.00. Based on the time recordings, $f_{stop\&go}$ can be calculated according to equation (7-3) and is equal to 0.59. The excavator was not equipped with a CO_2e capture and storage system ($f_{CCS} = 0$).

$$f_{stop\&go} = 1 - \frac{t_{standstill}}{t_{standstill} + t_{idle}} \tag{7-3}$$

In Table 7-6 all values from the influencing factors on the CO_2e amount emitted are summarised.

By inserting the factor values in *(4-25)*, the following fuel consumption and CO_2e emissions in Table 7-7 are calculated for the processes “digging” and “filling the canal”.

Table 7-7: Fuel consumption and CO_2e emissions for the processes “digging” and “filling the canal”

Process	$V_{material}$ [m³]	Q_B [m³/h]	$t_{working}$ [h]	b_m [l/h]	f_{ui}	B [l diesel]	m_{CO_2e} [kg CO_2e]
Digging	120	227	0.67	36.41	1	19.5	62
Filling 1	43	223	0.06	36.41	1	7.2	23
Filling 2	13	257	0.25	36.41	1	1.8	6
Total						**28.6**	**91**

The process idling is being calculated in Table 7-8.

Table 7-8: Fuel consumption and CO_2e emissions for the processes “idling”

Process	$f_{stop\&go}$	$f_{site\ orga.}$	t_{total} [h]	t_{idle} [h]	b_{idle} [l/h]	B_{idle} [l diesel]	m_{CO_2e} [kg CO_2e]
Idling	0.59	0.58	5	1.71	2.7	4.6	15
Total						**4.6**	**15**

These four processes result in a total fuel consumption of 33.2 l diesel and a total of 106 kg of CO_2e[45].

Practical vs. theoretical approach

In Table 7-9, the results from the measurements on the construction site (practical approach) are compared to the results determined by using the quantification equation *(4-25)* (theoretical approach). The factor f_{price/CO_2e} used for the calculation of climate costs of the additionally emitted CO_2e $C_{CO_2e,T}$ has the value of 30 € per ton CO_2e emitted (OECD 2018). The differ-

[45] By multiplying the fuel consumption with 3.18 kg CO_2e/l diesel

ence between the practical and theoretical approach are within the acceptable range of 20 % (according to the Pareto principle).

Table 7-9: Comparison of the practical and theoretical approach of the excavator on 14/12/2018

	B [l diesel]	m_{CO_2e} [kg CO_2e]	$C_{CO_2e,T}$ [€]
Practical approach	31.73	101	3.03
Theoretical approach	33.18	106	3.17
Difference	1.45 l diesel	5 kg CO_2e	0.14 €
	+5%		

According to the factor determination, only $f_{weather}$ has a variation potential between 0.96 and 0.98 according to the efficiency diagram from Abele (Abele 1986). Such a variation consequently leads to a different variation range for the excavator of +5 % to +6 %. This difference is within the acceptable range.

According to the same procedures were determined, the fuel consumption and CO_2e amount emitted by the excavator on 27/11/2018 during construction (practical approach). These results were compared to the calculated amounts with equation *(4-25)* (theoretical approach). The comparison results are shown in the following Table 7-10. Also in this case, the difference between the practical and theoretical approach are within the acceptable range.

Table 7-10: Comparison of the practical and theoretical approach of the excavator on 27/11/2018

	B [l diesel]	m_{CO_2e} [kg CO_2e]	$C_{CO_2e,T}$ [€]
Practical approach	93.96	299	8.96
Theoretical approach	93.21	296	8.89
Difference	0.75 l diesel	3 kg CO_2e	0.07 €
	-1%		

According to the factor determination, $f_{weather}$ has a variation potential between 0.98 and 0.998 according to the efficiency diagram from Abele (Abele 1986). Further, due to the temperature sensation in the cab by the driver, $f_{workplace\&working\ environment}$ may vary between 0.92 to 0.97. Such a variation consequently leads to a different variation range for the excavator of -1 % to -6 %. This difference is within the acceptable range.

7.2.2 Single drum roller

On 27/11/2018 as well as on 14/12/2018 the evaluation of the collected data from the single drum roller in Ludwigsburg was done according to the same principle. Contrary to the excavator, a CANBUS reading device could be installed on the single drum roller. This made it possible to record the signals available on the BUS like velocity, fuel consumption and engine speed during the observation time.

On 27/11/2018, the roller was in use for 28 min. 8 minutes of this time was driving the single drum roller in and out of the construction site. Driving is regarded as preparatory work in the CO_2e quantification method and is according to the system boundary not taken into account. The process to be validated therefore consists of 20 min, from 16:22 to 16:42. In Table 7-11 the observation notes complemented with the recorded data from the CANBUS readout device are shown.

Table 7-11: Single drum roller observation notes complemented with recorded data from the CANBUS readout device, taken on 27/11/2018

Time	Duration [h]	Machine status	Distance forward [m]	Distance backwards [m]	v [m/h]
16:21	0.03	driving			
16:22:51	0.28	compacting		52	1687
16:24:42		compacting	52		1687
16:26:33		compacting		52	1642
16:28:24		compacting	52		1687
16:30:15		compacting		52	1733
16:32:06		compacting	52		1783
16:33:57		compacting		52	1671
16:35:48		compacting	52		1717
		compacting & turning	22	52	2018
16:38	0.06	idling	-	-	-
16:42	0.12	driving	100	90	1900
16:49	-	standstill	-	-	-

Practical approach

From the notes, it can be seen that $t_{working}$ lasted 0.28 h and t_{idle} 0.06 h. The fuel consumption during compacting and idling could be recorded with the CANBUS readout device. The fuel consumption while idling corresponded to 0.07 l diesel with a b_{idle} of 1.1 l/h. The total fuel consumption during the compacting process was 2.06 l diesel. This corresponds to a total fuel consumption of 2.13 l or 7 kg CO_2e. Table 7-12 summarises the respective fuel consumptions and CO_2e emissions. The processes in pink correspond to the processes which will be validated with the CO_2e quantification method.

Table 7-12: Summary of the fuel consumption of the single drum roller in Ludwigsburg 27/11/2018

Process		Time	Fuel consumption	CO_2e emissions
1	Compacting	0.28 h	2.06 l	6.6 kg
2	Idling	0.06 h	0.07 l	0.2 kg
3	Standstill	0 h	0 l	0 kg
		Total	**2.13 l**	**7 kg CO_2e**

Theoretical approach

Also here the theoretical approach consists of applying the CO_2e quantification method from mobile construction machines during the construction application for rollers. First, the basic performance of the single drum roller will be calculated with equation *(4-29)*. The velocity on the construction site was measured with the CANBUS readout device and corresponded to 1,741 m/h on average. Four passages of the single drum roller took place during this compaction process. According to the datasheet of the machine, the effective working width was 1.7 m. Consequently, the basic performance of this machine on this day equalled 550 m²/h (see Table 7-13).

Table 7-13: The basic performance of the single drum roller in Ludwigsburg on 27/11/2018

Process	b_{eff}	v	z	Q_B
Compacting	1.7 m	1,741 m/h	4	**550 m²/h**

The datasheet of the machine, machine operator surveys, construction site observations, measurements with the multi measuring device and the vibration measuring device permitted defining the values for the factors determined in chapter 4. The single drum roller has an engine with an exhaust after-treatment system stage IV ($f_{engine} = 1.00$), driving in ECO-mode ($f_{eco} = 0.87$) and has different other significant improvement technologies corresponding to a fuel consumption reduction of 35 % ($f_{significant\ improvement} = 0.65$). The roller is 3 years old ($f_{age} = 1.05$) and is subject to regular service maintenance work ($f_{service\ regularity} = 1.00$). Time recordings of idling time compared to the total active time of the machine shows that the construction site organisation is very good ($f_{site\ orga.} = 0.18$). The calculation of the value of $f_{site\ orga.}$ is described in equation (7-4).

$$f_{site\ orga.} = \frac{t_{idling}}{t_{compacting} + t_{idling}} = 0.18 \qquad (7\text{-}4)$$

No observed idle time was considered unavoidable for the construction processes ($f_{idle\ unavoidable} = 0$). The operator is considered to be a good driver ($f_{knowledge\&skills} = 0.83$) and can therefore profit to a certain degree from the advantages of the process assistant systems integrated in the roller such as the measurement of the compaction degree and the automatic continuously variable amplitude system ($f_{process\ assistant} = 1.23$). On this day the weather conditions (effective weather temperature -0.50 °C and average wind speed of 0.95 m/s), the available construction time and construction site freedom were ideal ($f_{weather} = 1.00$; $f_{construction\ time} = 1.00$; $f_{site\ freedom} = 1.00$). During the whole work task, the single drum roller drove with diesel ($f_{CO_2e/energy\ carrier} = 3.18\ \text{kg}\ \text{CO}_2\text{e/l diesel}$). The compacting process was on that day the last construction task of the worker. $f_{physical\&mental\ state}$ is therefore considered to be equal to 0.99. Noise measurements and vibration measurements were under the lower limit value. The light state and the view from the cabin were not optimal because the sun was already down and so it was dark. Therefore $f_{workplace\&working\ environment}$ has the value 0.97. Based on the time recordings, no standstill time took place. $f_{stop\&go}$ is therefore equal 1.00. The single

drum roller was not equipped with a CO_2e capture and storage system ($f_{CCS} = 0$).
In the following Table 7-14 all values of the influencing factors on the CO_2e amount emitted by the single drum roller are summarised.

Table 7-14: Values for the influencing factors of the single drum roller on 27/11/2018

Influencing factors			Value
Machine efficiency	$f_{machine\ technology}$	f_{engine}	1.00
		f_{eco}	0.87
		$f_{significant\ improvement}$	0.66
	$f_{machine\ condition}$	f_{age}	1.05
		$f_{service\ regularity}$	1.00
Process efficiency	$f_{site\ orga.}$		0.18
	$f_{idle\ unavoidable}$		0
	$f_{process\ assistant}$		1.23
	$f_{constr.\ complexity}$	$f_{weather}$	1.00
		$f_{construction\ time}$	1.00
		$f_{site\ freedom}$	1.00
Energy Sources	$f_{CO_2e/energy\ carrier}$		3.18 [kg CO_2e/l diesel]
Operation efficiency	f_{driver}	$f_{physical\&mental\ state}$	0.99
		$f_{knowledge\&skills}$	0.83
		$f_{workplace\&working\ environment}$	0.97
	$f_{stop\&go}$		1.00
CO_2e Capture & Storage	f_{CCS}		0

By inserting the factor values in equation *(4-25)*, the following fuel consumption and CO_2e emissions in Table 7-15 are calculated for the work processes of the single drum roller.

Table 7-15: Fuel consumption and CO_2e emissions for the single drum roller

Process	$V_{material}$ [m²]	Q_B [m²/h]	$t_{working}$ [h]	t_{idle} [h]	b_m [l/h]	b_{idle} [l/h]	f_{ui}	B [l diesel]	m_{CO_2e} [kg CO_2e]
Compacting + idle	152	550	0.28	0.06	12.7	1.6	1	2.2	7

Practical vs. theoretical approach

In Table 7-16, the results from the measurements at the construction site (practical approach) are compared to the results determined by using the quantification equation *(4-25)* (theoretical approach). The factor f_{price/CO_2e} used for the calculation of climate costs of the additionally emitted CO_2e $C_{CO_2e,T}$ has the value of 30 € per ton CO_2e emitted (OECD 2018). The difference of 5 % between the practical and theoretical approach is within are within the acceptable range of 20 % (according to the Pareto principle).

Table 7-16: Comparison of the practical and theoretical approach for the single drum roller on 27/11/2018

	B [l diesel]	m_{CO_2e} [kg CO_2e]	$C_{CO_2e,T}$ [€]
Practical approach	2.1	7	0.20
Theoretical approach	2.2	7	0.21
Difference	0.1 l diesel	0 kg CO_2e	0.01 €
	+5%		

According to the observation at the construction site $f_{physical\&mental\ state}$ and $f_{workplace\&working\ environment}$ are the only factors in the quantification method that can vary between 0.90 to 1.00 and 0.95 to 1.00, respectively. Consequently the difference between the practical and theoretical approach can vary between +5 % to +17 %.

According to the same procedure, the fuel consumption and CO_2e amount emitted by the single drum roller on 14/12/2018 during construction were determined (practical approach). These results were compared to the calculated amounts with equation *(4-25)* (theoretical approach). The comparison results are shown in the following Table 7-10. Also in this case, the difference of 10 % between the practical and theoretical approach is within the acceptable range.

According to the observation at the construction site, no factors are variable. Therefore, no analysis to calculate the possible difference variation is needed. According to the equation (4-25) and (4-26), the fuel consumption at idle ($b_{idle,r}$) is the general fuel consumption for machine r, in this case the single drum roller. If instead of $b_{idle,r}$ the fuel consumption at idle for elementary process α would be used ($b_{idle,\alpha,r}$) then the difference would be 3 %.

Table 7-17: Comparison of the practical and theoretical approach for the single drum roller on 14/12/2018

	B [l diesel]	m_{CO_2e} [kg CO_2e]	$C_{CO_2e,T}$ [€]
Practical approach	**15.6**	**49**	**1.48**
Theoretical approach	**17.2**	**55**	**1,64**
Difference	**1.6 l diesel**	**6 kg CO_2e**	**0.15 €**
	+10%		

7.2.3 Road pavers

In Mannheim, on 12/12/2019, the two pavers described in Figure 7.2 were observed. The pavers could not be equipped with a CANBUS readout device. The total fuel consumption was therefore determined through refuelling before and after the work task. Three processes were observed for both road pavers: idling, driving and asphalt laying. The process “driving” is regarded as preparatory work in the CO_2e quantification method and is according to the system boundary not taken into account. The process to be validated therefore consists of “idling” and “asphalt laying”.

Practical approach

The road paver A was active 11.88 h and consumed 148 l of diesel, the road paver B was active 8.18 h and consumed 49 l diesel. This corresponds to an emitted greenhouse gas emission quantity of 471 kg CO_2e for road paver A and 156 kg CO_2e for road paver B. The fuel consumption and respective CO_2e emissions of the process “driving” must be deducted from the total measured fuel consumption and total emitted CO_2e. Fuel consumption from driving was estimated at 22.40 l/h for road paver A and 14 l/h for road paver B based on the machine manufacturers data. The process "driving" consisted of driving interrupted by idle time. The respective fuel consumption and greenhouse gas emissions are calculated in Table 7-18.

Table 7-18: Quantity of greenhouse gas emissions from road pavers during the "driving" process

Machine	Process: Driving	$t_{driving}$ [h]	$b_{driving}$ [l/h]	t_{idle} [h]	b_{idle} [l/h]	B [l]	m_{CO_2e} [kg CO_2e]
Paver A	driving + idle	0.62	22.40	2.52	4.05	24.0	76
Paver B	driving + idle	0.65	14	5.93	4.05	33.1	105

The deduction of the process "driving" results in a fuel consumption of 124 l diesel and an emission quantity of 394 kg CO_2e for the road paver A and in a fuel consumption of 16 l diesel and 50 kg CO_2e for the road paver B (see Table 7-19).

Table 7-19: Fuel consumption and greenhouse gas emissions emitted by the pavers on 12/12/2019

Machine	Process to validate	Fuel consumption	CO_2e emissions
Paver A	asphalt laying + idle	124 l	394 kg CO_2e
Paver B	asphalt laying + idle	16 l	50 kg CO_2e

<u>Theoretical approach</u>

The theoretical approach consists of applying the CO_2e quantification method from mobile construction machines during the construction application for pavers. First, the basic performance of the road pavers will be calculated with equation *(4-28)*. The working width b' is determined based on the data sheets of the two pavers. The layer height of the material is determined with measurements made at the construction site. The recommended velocities from the company Vögele are chosen for the calculation (Vögele). The respective values chosen for the parameters as well as the resulting basic performance are described in Table 7-20.

Table 7-20: Basic performance calculation for paver A and paver B

Machine	Times	b_{eff} [m]	v [m/h]	h [m]	Q_B [m²/h]
Paver A	morning	6.15	300	0.10	185
	at noon	5.00	360	0.04	72
	afternoon	6.15	360	0.06	133
Paver B	morning	4	360	0.04	58
	at noon	5	360	0.04	72

The datasheet of the machine, machine operator surveys, construction site observations and measurements with the multi measuring device permitted defining the values for the factors determined in chapter 4. The road paver A and B have an engine with an exhaust after-treatment system of stage IIIB (f_{engine} = 1.03) and stage IV, respectively (f_{engine} = 1.00). Paver A works in ECO-mode (f_{eco} = 0.85), paver B in the regular mode (f_{eco} = 1.00). For both pavers, a fuel consumption reduction of 12 % ($f_{significant\ improvement}$ = 0.88) is assumed due to other significant improvement technologies such as ECO-mode and the engine technology. Both pavers are 2 years old (f_{age} = 1.04) and are subject to regular service maintenance work ($f_{service\ regularity}$ = 1.00). Time recordings of idling time compared to the total active time of the machine shows that the construction site organisation is from medium to good depending on the time of day. By applying equation (7-5)[46], paver A has a $f_{site\ orga.}$ of 0.71 in the morning, of 0.64 at noon and of 0.47 in the afternoon.

Paver B has a $f_{site\ orga.}$ of 0.81 in the morning and of 0.46 at noon.

$$f_{site\ orga.} = \frac{t_{total} - t_{working} + t_{idle\ unavoidable}}{t_{total}} = \frac{t_{standstill} + t_{idle} - t_{idle\ unavoidable}}{t_{total}} \qquad (7\text{-}5)$$

On 12/12/2018 the temperature in Mannheim varied between mornings and at noon and afternoons. The average effective temperature was -1.25 °C in the morning with an average wind speed of 0.45 m/s. At noon and in the afternoon the average effective temperature was 1.75 °C with an average wind

[46] See footnote 44

speed of 1.02 m/s. Consequently, for $f_{weather}$, a value of 0.99 is assumed for work during the morning and a value of 1.00 for work at noon and in the afternoon (according to the efficiency diagram from Abele) (Abele 1986). An unavoidable idle time of 30 min is being assumed for paver A in the morning in order to heat the screed to the right temperature ($f_{idle\ unavoidable} = 0.10$). The heating time of the screed for paver B is considered to have happened during the process "driving" and therefore is considered in the analysed process as non existing ($f_{idle\ unavoidable} = 0$). Both operators are considered to be expert drivers ($f_{knowledge\&skills} = 0.92$) and work as efficiently as the process assistant systems integrated in the paver ($f_{process\ assistant} = 1.00$). The available construction site freedom was somewhat restricted by the other construction crews ($f_{site\ freedom} = 0.95$). The available construction time was ideal in the morning ($f_{construction\ time} = 1.00$), at noon somewhat limited due to parallel working of paver A and paver B and ($f_{construction\ time} = 0.90$) and in the afternoon paver A was hurrying up to finish the work on time ($f_{construction\ time} = 0.85$). However, the paver A crew had to work overtime until 18:30. Both crews were travel teams, sleeping in hotels and travelling from one town to another. Therefore, for $f_{physical\&mental\ state}$ the value of 0.84 is chosen. The daily noise exposure level for the driver of paver A equalled $L_{EX,8h} = 79.04\ dB(A)$ and for paver B equalled $L_{EX,8h} = 77.28\ dB(A)$, which are both below the lower limit value of 80 dB. Paver A started in the morning, when the sun had not yet risen. The temperature in the cabin was not assessed to be unpleasant by the driver. The light state and the view from the cabin were assessed to be ideal for paver B. Therefore, $f_{workplace\&working\ environment}$ has the value 0.97 for paver A and 1.00 for paver B.

During the whole work task, the pavers drove with diesel ($f_{CO_2e/energy\ carrier} = 3.18\ \text{kg}\ \text{CO}_2\text{e/l diesel}$). No standstill time was observed, therefore $f_{stop\&go}$ equals 1.00. In the following Table 7-21 all values of the influencing factors on the CO_2e amount emitted by both pavers are summarised.

Table 7-21: Values for the influencing factors of paver A and paver B on 12/12/2018

Influencing factors		Paver A			Paver B	
		Morning	At noon	Afternoon	Morning	At noon
Machine efficiency	f_{engine}	1.03			1.00	
	f_{eco}	0.85			1.00	
	$f_{significant\ improvement}$	0.88			0.88	
	f_{age}	1.04			1.04	
	$f_{service\ regularity}$	1.00			1.00	
Process efficiency	$f_{site\ orga.}$	0.71	0.64	0.47	0.81	0.46
	$f_{idle\ unavoidable}$	0.10	0		0	
	$f_{process\ assistant}$	1.00			1.00	
	$f_{weather}$	0.99	1.00		0.99	1.00
	$f_{construction\ time}$	1.00	0.90	0.85	1.00	0.90
	$f_{site\ freedom}$	0.95			0.95	
Energy Sources	$f_{CO_2e/energy\ carrier}$	3.18 [kg CO_2e/l diesel]			3.18 [kg CO_2e/l diesel]	
Operation efficiency	$f_{physical\&mental\ state}$	0.84			0.84	
	$f_{knowledge\&skills}$	0.92			0.92	
	$f_{workplace\&working\ environment}$	0.97			1.00	
	$f_{stop\&go}$	1.00			1.00	
CO_2e Capture & Storage	f_{CCS}	0			0	

By inserting the factor values in equation *(4-25)*, the following fuel consumption and CO_2e emissions in Table 7-22 are calculated for the work processes of both pavers.

Table 7-22: Fuel consumption and CO_2e emissions for both pavers

Machine	Times	$V_{material}$ [m³]	Q_B [m³/h]	b_m [l/h]	b_{idle} [l/h]	f_{ui}	B [l Diesel]	m_{CO_2e} [kg CO_2e]
Paver A	morning	125.77	185	46.71	4.05	1	53.3	169
	at noon	23.00	72	46.71	4.05	1	22.2	71
	afternoon	101.48	133	46.71	4.05	1	51.8	165
						Total	127.3	405
Paver B	morning	4.96	58	20.40	4.05	1	4.4	14
	at noon	23.2	72	20.40	4.05	1	11.4	36
						Total	15.9	50

<u>Practical vs. theoretical approach</u>

In Table 7-23, the results from the measurements at the construction site (practical approach) are compared to the results determined by using the quantification equation *(4-25)* (theoretical approach). The factor f_{price/CO_2e} used for the calculation of climate costs of the additionally emitted CO_2e $C_{CO_2e,T}$ has the value of 30 € per ton CO_2e emitted (OECD 2018). The difference between the practical and theoretical approach is +3 % for paver A and 0% for paver B. The results are therefore within the acceptable range of 20 % (according to the Pareto principle).

Table 7-23: Comparison of the practical and theoretical approach for both pavers on the 12/12/2018

Machine	Approach	B [l Diesel]	m_{CO_2e} [kg CO_2e]	$C_{CO_2e,T}$ [€]
Paver A	Practical	124.0	394	11.83
	Theoretical	127.2	405	12.14
	Difference	3.3 l Diesel	10.35 kg CO_2e	0.31 €
		+3%		
Paver B	Practical	15.9	50	1.51
	Theoretical	15.9	50	1.51
	Difference	0.01 l Diesel	0.03 kg CO_2e	0.00 €
		0%		

According to the factors determination, for Paver A following factors were estimated according to the observations at the construction site: $f_{weather}$, $f_{construction\ time}$, $f_{site\ freedom}$, $f_{physical\&mental\ state}$ and

$f_{workplace\&working\ environment}$. According to Abele, $f_{weather}$ could take a value between 0.98 and 0.99 in the morning (Abele 1986). According to Ibbs and Vaughan, $f_{construction\ time}$ could take a value between 0.84 and 1.0 (Ibbs and Vaughan 2015). According to the value range definition of $f_{site\ freedom}$, the value can vary between 0.90 and 1.00. According to the construction site observations, $f_{physical\&mental\ state}$ could take a value between 0.80 and 0.90. For the factor $f_{workplace\&working\ environment}$ a value range of 0.95 to 1.00 is assumed for paver A. The factor variations results in a different variation range of +3 % and -19 %. Also this difference range is acceptable.

For Paver B following factors were estimated according to construction site observations: $f_{weather}$ and $f_{construction\ time}$. $f_{weather}$ could also take a value between 0.98 and 0.99 in the morning according to Abele (Abele 1986). For $f_{construction\ time}$, the estimated range would be between 0.84 and 1.02 (Ibbs and Vaughan 2015). Consequently the difference between practical and theoretical value for paver B would be between negligible and 9 %. Also this difference is in the acceptable range.

7.2.4 Tandem roller

In Mannheim, two tandem rollers were observed and data was recorded according to the same procedure like the single drum roller in Ludwigsburg. On both tandem rollers, a CANBUS readout device was implemented.

<u>Practical approach</u>

From observation notes and from data recorded with the CANBUS readout device on 12/12/2018, compacting, idling and standstill times were recorded. Their respective fuel consumption as well as CO_2e emissions are summarised in Table 7-24. The processes in pink corresponds to the processes which will be validated using the CO_2e quantification method.

Table 7-24: Summary of the fuel consumption of both tandem rollers in Mannheim on 12/12/2018

Machine	Process		Time	Fuel consumption	CO_2e emissions
Tandem roller A	1	Compacting	1.71 h	12.33 l	39 kg
	2	Idling	0.36 h	0.50 l	2 kg
	3	Standstill	0.19 h	0 l	0 kg
			Total	12.83 l	41 kg CO_2e
Tandem roller B	1	Compacting	2.23 h	16.53 l	53 kg
	2	Idling	0.07 h	0.08 l	0.2 kg
	3	Standstill	0 h	0 l	0 kg
			Total	16.53 l	53 kg CO_2e

Theoretical approach

For the theoretical approach, first, the basic performance of the tandem rollers will be calculated, then the influence factors for the application of the CO_2e quantification method for mobile construction machines will be determined. Finally, by inserting the values of the factors in equation *(4-25)*, the CO_2e emitted by both tandem rollers will be calculated.

For the basic performance of both rollers, the effective width was determined with the datasheet of the machine, the velocity was calculated by dividing the observed working length by the recorded total working time at the construction site. Four passages of the tandem rollers took place during the process compacting. Consequently, the basic performance of these tandem rollers on this day were 822.79 m²/h and 540.60 m²/h for tandem roller A and tandem roller B, respectively (see Table 7-25).

Table 7-25: The basic performance of both tandem rollers in Mannheim on 12/12/2019

Process	b_{eff} [m]	v [m/h]	z	Q_B [m²/h]
Compacting with tandem roller A	1.7	2612	4	**823**
Compacting with tandem roller B	1.5	1922	4	**541**

The datasheet of the machine, machine operator surveys, construction site observations, measurements with the multi measuring device permitted defining the values for the factors determined in chapter 4.

Tandem roller A has an engine with an exhaust after-treatment system stage IV ($f_{engine} = 1.00$) and tandem roller B with an exhaust after-treatment system stage IIIB ($f_{engine} = 1.03$). Both rollers drive in ECO-mode ($f_{eco} = 0.87$) and have further significant improvement technologies implemented in the machines, corresponding to a fuel consumption reduction of 35 % ($f_{significant\ improvement} = 0.65$). Both rollers are from 2018 ($f_{age} = 1.00$) and are subject to regular service maintenance ($f_{service\ regularity} = 1.00$).

No observed idling time was considered unavoidable for the construction processes ($f_{idle\ unavoidable} = 0$). Time recordings of idling time compared to the total active time of the machine shows that the construction site organisation is good to very good concerning the tandem rollers. For tandem roller A $f_{site\ orga.}$ equals 0.24 and for tandem roller B 0.03. The calculation of the value of $f_{site\ orga.}$ is described in equation (7-4)[47].

$$f_{site\ orga.} = \frac{t_{total} - t_{working} + t_{idle\ unavoidable}}{t_{total}} = \frac{t_{idle} + t_{standstill} - t_{idle\ unavoidable}}{t_{total}} \quad (7\text{-}6)$$

The operator is considered to be an expert driver ($f_{knowledge\&skills} = 0.92$) and can therefore profit to a certain degree from the advantages of the process assistant systems integrated in the rollers, such as the measurement of the compaction degree and the automatic continuously variable amplitude system ($f_{process\ assistant} = 1.14$). On this day, the weather conditions for the rollers was ideal (average effective temperature 0.25 °C and average wind speed of 0.74 m/s); both crews were slightly pressured to finish the work within 3 days, the construction site freedom was limited by the other roller working in parallel on the same asphalt area ($f_{weather} = 1.00$; $f_{construction\ time} = 0.90$; $f_{site\ freedom} = 0.95$). During the whole work task the excavator drove with diesel ($f_{CO_2e/energy\ carrier} = 3.18\ \mathrm{kg\ CO_2e/l\ diesel}$). No concentration

[47] See footnote 44

tests for both drivers were undertaken. The physical and mental state of the tandem roller drivers were assumed to be ideal ($f_{physical\&mental\ state}$ = 1.00). Noise measurements were under the lower limit value. The light state and the view from the cabin were optimal ($f_{workplace\&working\ environment}$ = 1.00). Based on the time recordings, only for tandem roller A was standstill time recorded. According to equation (7-3) $f_{stop\&go}$ equals 0.65 for tandem roller A and 1.00 for tandem roller B. Neither tandem roller was equipped with a CO_2e capture and storage system ($f_{CCS} = 0$).

Table 7-26: Values for the influencing factors of tandem roller A and B on 12/12/2018

Influencing factor values			Tandem roller A	Tandem roller B
Machine efficiency	$f_{machine\ technology}$	f_{engine}	1.00	1.03
		f_{eco}	0.87	0.87
		$f_{significant\ improvement}$	0.65	0.65
	$f_{machine\ condition}$	f_{age}	1.00	1.00
		$f_{service\ regularity}$	1.00	1.00
Process efficiency	$f_{site\ orga.}$		0.24	0.03
	$f_{idle\ unavoidable}$		0	0
	$f_{process\ assistant}$		1.14	
	$f_{constr.\ complexity}$	$f_{weather}$	1.00	
		$f_{construction\ time}$	0.90	
		$f_{site\ freedom}$	0.95	
Energy Sources	$f_{CO_2e/energy\ carrier}$		3.18 kg CO_2e/l diesel	
Operation efficiency	f_{driver}	$f_{physical\&mental\ state}$	1.00	
		$f_{knowledge\&skills}$	0.92	
		$f_{workplace\&working\ environment}$	1.00	
	$f_{stop\&go}$		0.65	1.00
CO_2e Capture & Storage	f_{CCS}		0	0

In Table 7-26 all values of the influencing factors on the CO_2e amount emitted by both tandem rollers are summarised.

Table 7-27: Fuel consumption and CO_2e emissions for both tandem rollers

Process Compacting + idle	$V_{material}$ [m²]	Q_B [m²/h]	$t_{working}$ [h]	t_{idle} [h]	b_m [l/h]	b_{idle} [l/h]	f_{ui}	B [l diesel]	m_{CO_2e} [kg CO_2e]
Tandem roller A	1,306	823	1.71	0.36	12.7	1.6	1.00	13.3	42
Tandem roller B	1,069	541	2.23	0.07	12.7	1.6	1.00	16.4	52

By inserting the factor values in equation *(4-25)*, the following fuel consumption and CO_2e emissions in Table 7-27 are calculated for the work processes of both tandem rollers.

<u>Practical vs. theoretical approach</u>

In Table 7-28, the results from the measurements on the construction site (practical approach) are compared to the results determined by using the quantification equation *(4-25)* (theoretical approach). The factor f_{price/CO_2e} used for the calculation of climate costs of the additionally emitted CO_2e $C_{CO_2e,T}$ has the value of 30 € per ton CO_2e emitted (OECD 2018). The difference between the practical and theoretical approach of +4 % and -1 % are within the acceptable range of 20 % (according to the Pareto principle).

The factor determination for these two observed tandem rollers enable a factor variation for $f_{construction\ time}$ and $f_{site\ freedom}$ between 0.84 to 1.02 and 0.90 to 1.00, respectively. The resulting difference range for tandem roller A varies between 4 % and 17 %. The resulting difference range for tandem roller B varies between 1 % and 17 %. Both difference ranges are acceptable.

Table 7-28: Comparison of the practical and theoretical approach for both pavers on 12/12/2018

Machine	Approach	B [l Diesel]	m_{CO_2e} [kg CO_2e]	$(m_{CO_2e})_{in\,€}$ [€]
Tandem roller A	Practical	12.8	41	1.22
	Theoretical	13.3	42	1.27
	Difference	0.5 l Diesel	1.52 kg CO_2e	0.05 €
			+4%	
Tandem roller B	Practical	16.6	53	1.58
	Theoretical	16.4	52	1.57
	Difference	0.18 l Diesel	0.6 kg CO_2e	0.02 €
			-1%	

7.3 Discussion

The CO_2e amount emitted at the construction sites in Ludwigsburg and Mannheim were comparable to the theoretical results quantified using the developed quantification method of CO_2e emitted by construction machines during their construction application. According to the Pareto principle, the method should at least consider 80 % of the CO_2e emissions emitted by each sub process. A difference in the theoretical and practical approach ranging between negligible and 10 % were found. This difference range is below the maximum acceptable range of 20 % (Pareto principle). This result is better than the result obtained using the Lewis Method, where only 5 of 18 machines had a difference below 20 % or the results obtained with the NONROAD model, where all 18 analysed machines had a difference above 60 % (Heidari and Marr 2015).

Contrary to the NONROAD–Model (see p. 14), the focus on the developed CO_2e quantification method does not only lie on the engine of the construction machine. The developed method considers the different types of construction processes. Further, contrary to the EMEP/EEA Air pollutant Emission Inventory Guidebook (see p. 18), the method considers not only wear on the engine but wear on the whole machine. A state differentiation is possible between a privately owned and rental machines. Accordingly, the method closes the defined research gap G1 by not only focusing on the engine but considering the whole machine.

Differently to the Swiss non-road Database (see p. 22) or analysed tools for construction equipment (see p. 26), the developed method considers the construction process and machine operation and so takes into account effects of possible efficiencies in these fields. Additionally, by not mixing up working time with idle time, the model gains in accuracy relative to reality. Ergo, the method also closes the defined research gap G4 by considering the construction operation and differentiating idling and working time.

During the validation method in Ludwigsburg and Mannheim, the same method was used for different machine types such as the excavator, single drum roller, road pavers and tandem rollers. Also the same method was used for two different construction applications: in canal construction, being part of earthmoving and in road construction. The difference between reality and the theoretical approach being in the acceptable range, showed that the method is valid for different machine types and different construction applications and thus fulfils the defined research gap G5.

In addition, the method considers not only the amount of CO_2 emissions but the total amount of greenhouse gases emitted by taking into account the production and consumption of fuel. As a result, the method also bridges the defined research gap G7.

In conclusion, the validation process at construction sites in Ludwigsburg and Mannheim was able to show that the developed quantification method of CO_2e emitted by construction machines during their construction application is valid and bridges the defined research gaps G1, G4, G5 and G7.

Nevertheless, the validation process was only made possible through the cooperation of construction industries and construction machine producers. This shows that need N3, cooperation of industries are essential in order to reach the climate goals set by the government.

The system boundary of the method states that the process “driving” of the machine to the construction place is regarded as preparatory work and therefore neglected. The observation at the construction sites showed that “driving” occurs on a regular basis and can even occur several times a day. “Driving” is strongly dependent on construction site organisation and the machine operator’s behaviour. In order to better understand the effect of “driving” on the total amount of CO_2e emissions emitted, further examinations and research work are recommended.

8 Transformation of mobile construction machines into zero greenhouse gas emitters

This chapter focuses on measures derived from the previous chapter resulting in reducing or eliminating CO_2e emissions from mobile construction machines during their construction applications.
The developed CO_2e quantification method permitted identifying the factors influencing the amount of CO_2e emissions emitted by construction machines during their construction applications. The impact importance of these factors is shown in Table 6-10 from chapter 6.4. In third place, the largest impact on the amount of CO_2e emissions is held by the factor $f_{CO_2e/energy\ carrier}$. That is the reason why the focus will lie on finding an adequate alternative energy carrier for mobile machines in order to reduce their climate impact. By combining the adequate alternative energy carrier with the adequate primary energy converter, it is further possible to reduce the amount of emitted greenhouse gas emissions. Finally, in order to reach zero emissions, two concepts on how a carbon capture system for mobile machines could look will be described. The chapter will end with a short discussion about the sustainability aspects of mobile machines.

8.1 Adequate alternative energy carrier

In order to ensure freedom of movements, a mobile machine must be able to store a certain amount of energy so that its respective working process does not have to be interrupted (Ays et al. 2017, pp. 126–127). For an adequate alternative energy carrier, different energy carriers are compared to each other in Table 8-1. For comparison, a mobile machine with a tank volume of 500 l is taken as a reference. Additionally, an internal combustion engine with an efficiency of 34 % is assumed for all analysed energy carriers except for the lithium-air battery. For the lithium-air battery combined with an electric motor, an efficiency of 80 % is being assumed.

Table 8-1: Comparison of different energy carriers with a usable energy amount of 6,067 MJ (based on Geimer and Ays 2014; Wu 2018)

Energy carrier	Energy content [MJ/kg]	Mass [kg]	Volume [l]
Diesel	43	415	500
Gasoline	44	407	543
Lithium-air battery	0.5-1.6	4,150 – 12,450	3,125
Hydrogen (-200°C, 1 bar)	120	149	16,523
Hydrogen (25°C, 700 bar)	120	149	3,718
Liquefied hydrogen (-253°C, 1 bar)	120	149	2,094
Ethanol	26	686	874
Dimethyl ether (DME, 20°C, 0,5 bar)	31	576	859
Oxymethylene ether (OME_{3-6})	18.8	949	887
Methane (0°C, 200 bar)	50	357	2,531
Liquefied methane (-167°C, 1 bar)	50	357	854

The analysis shows that hydrogen has the lowest gravimetric energy density but a high volumetric energy density. By using hydrogen, many components in the machine would have to be replaced with hydrogen-resistant materials, since hydrogen reduces the strength, ductility and service life of many metallic materials (Fraunhofer IWM 2018). Further, lithium-air batteries are heavy and need a lot of space[48] and are therefore considered inadequate for mobile machines with an energy disposal of 6,067 MJ or more. By considering the calorific value as well as the gravimetric and volumetric energy densities of the energy carrier, liquefied methane is the most promising option as alternative fuel to diesel. Although liquefied methane has a similar volume to ethanol, dimethyl ether or oxymethylene ether, it is lighter.

[48] 4,150-12,450 kg and 3.1 m^3 for a lithium-air battery machine with an energy disposal of 6,067 MJ.

Alternative energy carriers have different compositions and manufacturing processes than fossil diesel and can therefore influence the greenhouse gases emitted by mobile machines. Biomass has absorbed CO_2 emissions from the atmosphere during its growth. Therefore, if biomass is used for the production of the alternative energy carrier, the conversion of chemical energy into mechanical energy, i.e. during internal combustion of this energy carrier, it is assessed as climate-neutral (Edwards et al. 2014b). The amount of CO_2 absorbed is assumed to be equal to the amount emitted (ibid.). Equally, if the primary energy converter uses energy carriers produced synthetically with wind energy from emitted CO_2 emissions from e.g. power plants, then the conversion process is considered climate-neutral (ibid.). In summary, if the well-to-wheel cycle[49] corresponds to a closed CO_2 cycle, then the mobile machine can be described as climate-neutral.

A second analysis takes place in Table 8-2 by comparing the total amount of greenhouse gas emissions (well-to-wheel-analysis[50]) of the liquefied energy carriers from Table 8-1.
The most climate friendly alternative energy carrier to diesel is liquefied hydrogen under the condition that it is produced with CO_2 emitted from power plants and electric energy produced with wind turbines. If liquefied hydrogen is produced with the current EU-Mix electricity, then the energy carrier hydrogen becomes the worst alternative with the biggest climate impact of the analysed energy carriers. By considering the calorific value, the gravimetric and volumetric energy density as well as the amount of emitted CO_2e emissions, OME from Biomass and liquefied methane are the two most promising alternative energy carriers for mobile machines.

[49] The well-to-wheel cycle consider the production as well as the combustion of an energy carrier.

[50] The well-to-wheel analysis takes into account the greenhouse gas emissions emitted during production and during fuel consumption by the primary energy carrier.

Table 8-2: Comparison of alternative energy carriers with their CO_2e emissions (based on Edwards et al. 2014b; Wu 2018)

Energy carrier	$f_{CO_2e/energy\ carrier}$ [kg CO_2e/l energy carrier]	Energy content [MJ/kg]	Mass [kg]	Volume [L]	CO_2e emissions [kg CO_2e]
Diesel	3.18	43	415	500	1,590
Gasoline	2.80	44	407	543	1,520
Liquefied Hydrogen (-253°C, 1 bar)	EU-Mix: 1.93	120	149	2.094	4,041
	Wind-energy: 0.04				84
Ethanol	Wheat: 1.38	26	686	874	1,206
Dimethyl ether (DME, 20°C, 0,5 bar)	Natural gas: 1.86	31	576	859	1,598
Oxymethylene ether (OME $_{3-6}$)	Natural gas: 2.72	18,8	949	887	2,413
	Tree biomass: 0.53				470
Liquefied methane (-167°C, 1 bar)	Natural gas: 1.54	50	357	854	1,315
	Biogas: 0.66				564
	Synthetic: 0.27				231

OME is the short form of oxygen-containing oligomeric oxymethylene ethers [CH_3O-(CH_2O-)$_n$$CH_3$] (Wu et al. 2019). It is considered a further developed fuel form of the toxic and at ambient temperatures high vapour pressured dimethyl ether (DME) or methanol (Maus and Jacob 2014). On the contrary, OME, is a non-toxic and colourless liquid fuel (Wu et al. 2019). The physical properties of the individual OME_n ($n \geq 1$) depend on their chain length (ibid.). Sustainable OME is a possible fuel alternative or can be used as a diesel additive for mobile machines in order to reduce greenhouse gas emissions (up to 70 % with pure OME from biomass). However, due to the limited availability of sustainable OME, only an admixture in diesel is currently an option for reducing pollutants and CO_2e (Wu et al. 2019).

Liquefied methane, also called LNG (liquefied natural gas) can be from fossil, biogenic or synthetic sources. Liquefied methane is a colourless and odourless energy carrier. Its composition and calorific value is defined according to the DIN 51624 norm. Liquefied methane has to be composed of at least 75 % of methane. A distinction is made between L-gas (low) with a calorific value of 39-46 MJ/kg and H-gas (high) with a minimum of

46 MJ/kg. The exact composition defines the energy carrier’s properties which have an energy density between 430 kg/m³ up to 470 kg/m³ and a liquefied storage at -166°C to -157°C. (Ays et al. 2017)
Liquefied methane is an alternative energy carrier for mobile machines and can reduce greenhouse gas emissions up to 85 %. A possible methane infrastructure is already available with the natural gas network throughout Europe. Only methane liquefiers need to be installed to complete the infrastructure for liquefied methane. Through EU initiatives like „LNG Blue Corridors Project" or "Trans-European Networks", the liquefied methane network is developed and expanding. Additionally, Germany has the largest natural gas storage capacities in the EU and the fourth largest in the world. (Engelmann et al. 11/20/2018; Ays et al. 2017)

8.2 Adequate combination of energy carriers and primary energy converters

In this subchapter, the two primary energy converters further analysed using alternative energy carriers are the internal combustion engine and the fuel cell. First, four different concept combinations will be explained: OME combined with an internal combustion engine, liquefied methane combined with an internal combustion engine, liquefied methane combined with a fuel cell and liquefied hydrogen combined with a fuel cell. Then the subchapter will end with comparing weight, volume and amount of CO_2e emissions of the conventional diesel-internal combustion engine combination with the four concepts presented before.

8.2.1 Oxymethylene ethers & internal combustion engine

By designing an oxymethylene ether (OME) power train concept for mobile machines, the first step is to decide if OME will be used as a pure fuel or as a diesel fuel additive. Different mixture ratios exist for $OME_{3\text{-}6}$[51] as an additive

[51] For the energy carrier $OME_{3\text{-}6}$, the numbers“3-6” describe its chain length, which defines its physical properties.

to diesel. As shown in Table 8-2, the lower energy density of pure OME_{3-6} requires 1.7 times as much installation space and weighs 2.3 times more than a diesel tank. As a result, for machines that have short working shifts or can be fuelled several times per shift, pure OME can be used despite the lower energy density. On the other hand, for machines where installation space is limited and where fuelling during working shift is unwanted, OME_{3-6} diesel mixture is recommended. Due to the high oxygen content (42-49 wt. %) of OME, an adapted injection system is needed. Two injection systems are available: the cam-operated injection system and the common rail injection system. The compacted construction of the cam-operated injection system is favourable in small machines where installation space is limited. For machines with high driving power, an effective combustion is possible with the common-rail injection system because of its high flexibility in positioning and quantity of the injection. The absence of soot formation when using pure OME_{3-6} permits running the internal combustion engine at an air-fuel ratio of $\lambda = 1$. On the other hand, engines running with OME_{3-6} diesel mixture can only be operated like conventional diesel engines at $\lambda > 1.2$. When using pure OME as energy carrier, no Diesel Particulate Filter (DPF) is necessary because of the absence of soot formation. In stoichiometric operation ($\lambda = 1$) a three-way-catalyst (TWC) can be used. (Wu et al. 2019)

In case of an OME_{3-6} diesel mixture as energy carrier, a "standard" exhaust after-treatment system is needed, composed of a Diesel Oxidation Catalyst (DOC) combined with a Diesel Particulate Filter (DPF) and a Selective Catalytic Reduction (SCR). In Figure 8.1, an example of a drive train powered with pure OME fuel is illustrated for mobile construction machines. For this concept, the maximum tank capacity is chosen so that the longest possible operating time per working shift is reached. In fact, it is not unusual that construction machines are operated in 2 or 3 shifts. An increase of weight due to the use of pure OME_{3-6} is acceptable for construction machines that hardly drive or drive slowly. For machines driving frequently or at high speed, the increased weight needs to be evaluated according to their working cycles and applications. For high efficiency, the common-rail injection system and an air-fuel ratio of $\lambda \geq 1.2$ are chosen. This implies the use of an exhaust after-treatment system consisting of a DOC and an SCR. (Wu et al. 2019)

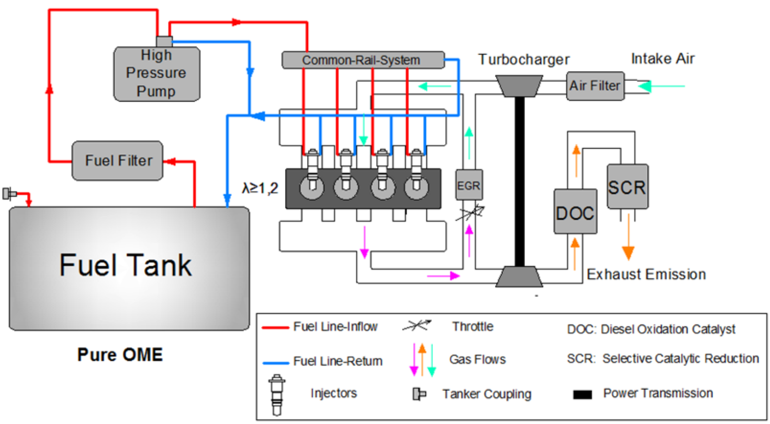


Figure 8.1: Exemplary drive train of a mobile construction machine driving with pure OME (Wu et al. 2019)

8.2.2 Liquefied methane & internal combustion engine

Liquefied methane is stored at -166°C to -157°C and therefore needs a special tank with a multi-layered vacuum insulation. The temperature difference between the interior of the tank and exterior causes heat inflows into the tanks. This leads to a constant evaporation of the energy carrier, also referred to as “boil-off gas”. The tanks are designed so that no boil-off gas is released until a maximum permissible pressure level is reached. Consequently, liquefied methane tanks have 1.6 to 2.9 times the weight and at least twice the construction volume of diesel tanks per energy content. Three main combustion processes are differentiated for liquefied methane: the Otto process, the diesel-gas process and the gas-diesel process. In the Otto process, liquefied methane without additional fuel is burned in the combustion process. Further, this process produces up to 3 dB(A) less noise than diesel engines. Most of the time, diesel-gas and gas-diesel processes require diesel fuel for operation in addition to liquefied methane. The diesel-gas process, also referred to as a dual-fuel process, has a gas fraction of about 60-80 %. While the gas-diesel process also called HPDI (high-pressure direct injection) process has a gas fraction above 90 %. The efficiency and power density of the gas-diesel engine corresponds to that of a diesel engine. The current exhaust emission regulation demands the same exhaust gas cleaning system used in diesel engines. Depending on exhaust emission regulations, in the Otto process a three-way catalytic converter can be sufficient. (Weberbeck et al. 2016)

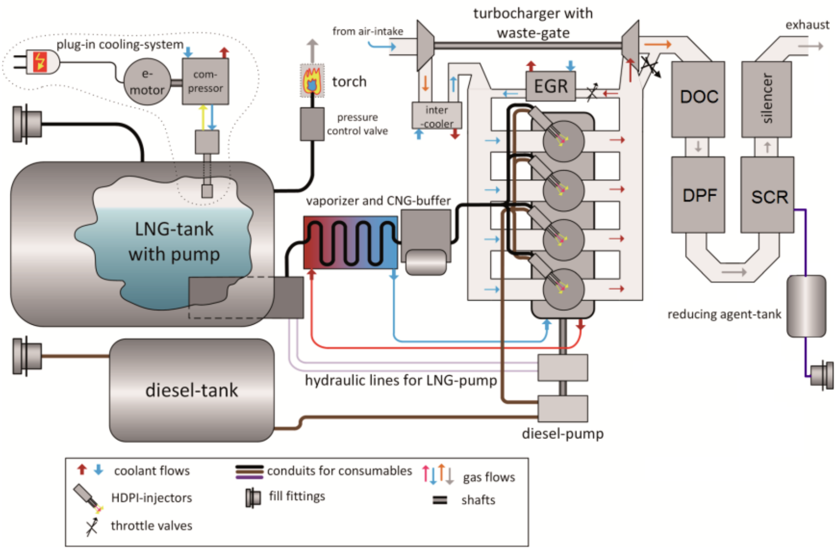


Figure 8.2: Exemplary drive train of a mobile construction machine driving with a gas-diesel process (HPDI) and liquefied methane (based on Weberbeck et al. 2016)

In Figure 8.2, an exemplary drive train for a mobile construction machine is shown. For this concept, a gas-diesel process (HPDI) for a high power supply, a large tank capacity in order to maximise operating without interruptions and a tank cooling system are chosen. The tank cooling system is operated with an electric cooling system. Alternatively, a cooling system driven with boil-off gas could be envisaged. Machines with an electric system should be equipped with a torch to burn off gas in case of downtimes without electric power supply. Also here, a potential weight gain in machines hardly driving or driving very slowly are acceptable. For machines driving frequently or at high speed, the increased weight needs to be evaluated in each case according to their working cycles and applications. (Weberbeck et al. 2016)

8.2.3 Liquefied methane & fuel cells

A fuel cell converts the chemical energy into electricity. It is a compact technology, emitting no noise, having no moving parts and producing no vibrations. Additionally, the electrical efficiency[52] of the fuel cell can reach 50-65 % (Ivers-Tiffée 2017/2018). The total efficiency[53] of the fuel cell can reach over 80 % (Ivers-Tiffée 2017/2018). In Figure 8.3 an exemplary drive train powered with liquefied methane is shown for a mobile construction machine. It is composed of a PEMFC as the fuel cell because of its high energy density and efficiency and of a lithium-ion battery because of its high energy density. In Figure 8.3, the range-extender drive concept is chosen so that load fluctuations impact the fuel cell as little as possible and thus handing this off to the battery.

In this concept, liquefied methane flows through a heat exchanger in order to enter an external reformer in a gaseous state. There two reactions take place: the steam reforming process and the water gas shift reaction. In the first reaction, methane reacts with the water vapour to produce syngas or synthesis gas which consists of hydrogen (H_2) and carbon monoxide (CO). The second reaction serves to increase hydrogen production. Both reactions are described in (8-1) and (8-2). (Ays and Geimer 2019)

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad \Delta H° = 206 kJ.mol^{-1} \qquad \text{(8-1)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta H° = -41\ kJ.mol^{-1} \qquad \text{(8-2)}$$

Hydrogen (H_2) flows into the fuel cell in order to produce electricity for the traction drive. For efficient use of the chemically bound energy, a burner is located directly after the fuel cell. It burns the residual gases left in the exhaust gas leaving the fuel cell. The heat produced thereby is then recuperated and used for the heat exchangers, reformer and H_2O separator. The exhaust gas is composed of O_2, CO_2 and because of the residual gas burner very low levels (<10 ppm) of CO and NO_x. (Ays and Geimer 2019)

---

52 $\eta_{electrical} = \frac{electrical\ energy}{chemical\ energy}$

53 The total efficiency of a fuel cell system: $\eta_{total} = \eta_{electrical} + \eta_{thermal}$ with $\eta_{thermal} = \frac{useful\ heat\ recovered}{chemical\ energy\ of\ the\ fuel}$

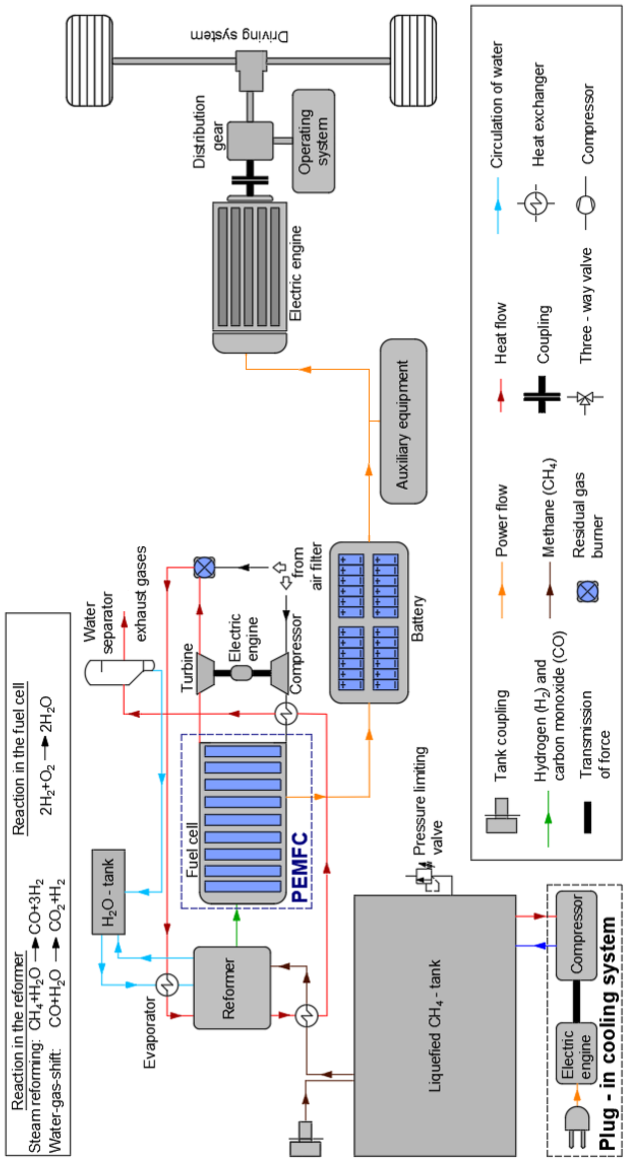


Figure 8.3: Exemplary liquefied methane and fuel cell drive train for mobile construction machines

8.2.4 Liquefied hydrogen & fuel cells

Even if it was shown in subchapter 8.1 that hydrogen in gas form or in liquid form is not an interesting solution for mobile construction machines, a general predesign of a possible drive train takes place because of its current popularity with companies and the media. It combines liquefied hydrogen with a fuel cell and a battery similar to the fuel cell drive train with liquefied methane presented before. In the tanks, hydrogen is stored in liquid form, therefore no reformer is needed. Consequently, the weight and volume of the reformer is subtracted as well as the efficiency decrease because the reformer is omitted.

8.2.5 Comparison

For comparison, the four concepts are applied to an excavator of 30 t with an energy output of 6,340 MJ. An efficiency of 34 % is assumed for the internal combustion engine, of 50 % for the fuel cell system, of 75 % for the reformer and of 90 % for the electric engine. The respective weight and volume for the main components of the five drive trains are calculated in Table 8-3.
In the calculations, the weight and volume of the fuel, tank, primary energy converter and exhaust after-treatment system are considered. For the OME concept combined with an internal combustion engine (ICE), the exhaust after-treatment system has no DPF. For the concept combining liquefied methane with an ICE, the whole energy is supplied by the energy carrier liquefied methane and no diesel fraction is assumed. According to current regulations, the concepts with a fuel cell do not need an exhaust after-treatment system. Liquefied methane combined with a fuel cell produces only CO_2 and water. Liquefied hydrogen combined with a fuel cell produces only water. The results of the comparison of these five concepts are shown in Table 8-4. The conventional diesel & ICE combination is the lightest drive train. It is then followed by the OME & ICE combination with a weight increase of 44 % and a volume increase of 15 % (reference is the diesel & ICE drivetrain). Taking into account the total weight of 30 t for the excavator, the weight increase for all four concepts is between 2 and 6 %. The volume

increase for all four concept ranges from 0.2 m³ to 3.9 m³. The weight as well as the volume increase are within an acceptable range for an excavator[54].

Table 8-3: Weight and volume calculation of the five drive train concepts[55]

Drivetrain for an excavator of 30 t & 6,340 MJ energy output		Fuel	Tank	Primary energy converter		Exhaust aftertreatment system	Total
				parts	value		
Diesel & ICE	Weight [kg]	433	26	ICE	715	140	1,313 kg
	Volume [m³]	0.52	0.52	ICE	0.79	0.33	1.6 m³
OME & ICE	Weight [kg]	1,008	45	ICE	715	118	1,885 kg
	Volume [m³]	0.91	0.91	ICE	0.79	0.18	1.9 m³
Liquefied CH_4 & ICE	Weight [kg]	373	1,044	ICE	715	140	2,272 kg
	Volume [m³]	0.91	1.82	ICE	0.79	0.33	2.9 m³
Liquefied CH_4 & fuel cell	Weight [kg]	313	666	Fuel cell Battery Reformer	531 670 804	0	2,983 kg
				Total	2,004		
	Volume [m³]	0.58	1.04	Fuel cell Battery Reformer	0.82 0.74 2.89	0	5.5 m³
				Total	4.46		
Liquefied H_2 & fuel cell	Weight [kg]	117	827	Fuel cell & battery	1,201	0	2,145 kg
	Volume [m³]	1.65	3.31	Fuel cell & battery	1.56	0	4.9 m³

Table 8-4 also shows the CO_2e emitted when consuming a full tank of the energy carrier. If, assuming that all sources of the energy carriers for mobile machines can be produced in a sustainable way, but rather proportional to the types of fuel sources listed in Table 8-4, then liquefied methane drive trains are the most promising ones.

54 An excavator has a varying operating weigth (± 0.5-4 t) and is equipped with a counter weight (± 3-6 t), see excavator brochures. Therefore, an additional weight for an excavator of 0.6 to 1.7 t are in an acceptable range. Further, a 30 t excavator is usually used on large construction sites where an additional occupancy volume of 1.6 to 5.5 m³ does not impair the construction work.

55 Further calculation details can be found in appendix A.3

Table 8-4: Comparison of the five drive train concepts (based on Edwards et al. 2014b; Wu 2018)

Drivetrain of a 30 t excavator with 6,340 MJ energy output	Total weight & volume	Drive increase	Overall increase	CO_2e emissions		
				Fuel source	Value [kg CO_2e/tank]	Average value [kg CO_2e/tank]
Diesel & ICE (reference)	1,313 kg	1.00	30 t	fossil	1,652	1,652
	1.6 m³	1.00	0 m³			
OME & ICE	1,885 kg	1.44	1.02	natural gas	2,481	1,483
	1.9 m³	1.15	0.24 m³	biomass	485	
Liquefied CH_4 & ICE	2,272 kg	1.73	1.03	fossil	1,399	751
	2.9 m³	1.79	1.30 m³	biogas	595	
				synthetic & wind energy	259	
Liquefied CH_4 & fuel cell	2,983 kg	2.27	1.06	fossil	1,129	586
	5.5 m³	3.35	3.85 m³	biomass	441	
				synthetic & wind energy	187	
Liquefied H_2 & fuel cell	2,145 kg	1.63	1.03	EU-Mix	3,188	1,624
	4.9 m³	2.97	3.23 m³	wind energy	59	

8.3 CO_2 capture and storage systems for mobile machines

Installing a CO_2 capture and storage (CCS) system before the exhaust gas is released in the air can enable a reduction in the amount of emitted CO_2 emissions. If the CO_2 emissions are already considered as zero during combustion because the energy carrier has been produced in a sustainable way, then the CO_2 captured and stored by the CCS systems have a negative value which means more CO_2 has been removed than produced in the atmosphere.
The captured CO_2 by such CCS systems can be sold and reused for the production of e-fuels or other industrial products.
In order to predesign a possible CO_2 capture and storage system, a morphological box has been developed giving an overview of possible solutions for the functions defined in 4.3.7. Each level represents a step for the designing process and solutions are proposed on how to fulfil the function. The first step is to choose a way to adjust the temperature and pressure of the exhaust gas, so the right conditions for the CO_2 separation process is obtained. The separation process is chosen in the second step. Depending on the separation process, a regeneration of the CO_2 separating agent can be necessary. The choice of the type of regeneration process takes place in step three. The

fourth step is the storage of the separated CO_2. For this purpose, first the temperature and pressure of the CO_2 has to be adjusted so that it can be stored under the right conditions. The choice of the type of storage is the fifth step. Finally, a solution has to be chosen on how to remove the stored CO_2 from the mobile machine (step six). Figure 8.4 depicts the morphological box showing possible solutions for each design step.

		Operations	Function carriers						
CO_2-Capture		Adjustment of temperature and pressure of gas	Exhaust gas cooler	Compressor	No adjustment				
	Separation of CO_2 in the exhaust gas	Process principle	Pre-Combustion Capture	Oxy-Combustion Capture	Post-Combustion Capture				
		Chemical absorption	Amines	Absorption with amino acid salts	Sulfinol process	Alkaline solutions	Carbonates	Ionic Liquids	Chilled Ammonia-process
		Physical absorption	Selexol Process	Rectisol Process	Fluorine Process	Purisol Process			
		Gas-solid reactions	CaO	MgO	FeO				
		Adsorption	Activated carbon	Zeolites	Metal-organic frameworks	Super capacitive swing adsorption			
		Cryogen	Condensations						
		Membrane	Organic membrane	Ceramic membrane					
		Natural binding	Mineralisation	Algae	Plants				
		Hydrate-based gas separation	H_2O & Additive						
		Regeneration of the separating medium	Heating/Temperature - Swing-Adsorption (TSA)	Flash-Desorption	Vacuum-Swing-Adsorption (VSA)	Compressing/ Pressure-Swing-Adsorption (PSA)	Compressor&Heater/ Pressure-Temperature-Swing- Adsorption (PTSA)		
			Vacuum-Pressure-Swing-Adsorption (VPSA)	Vacuum-Temperature-Swing-Adsorption (VTSA)	Electric Swing Adsorption (ESA)	Stripping	Not desired/ not necessary/ not possible		
CO_2-Storage		Adjustment of temperature and pressure of CO_2 (gas, liquid, solid)	Compressor	Gas cooler	No adjustment				
		Storage of CO_2	Tank for liquid	Tank for gas	Tank for solid				
		Extraction of CO_2	Emptying with direct connection to factories for further processing	CO_2-storage tank exchange	Emptying via transport medium into intermediate storage tank				

Figure 8.4: Design method for a possible CCS system for mobile machines

Based on the morphological box, two systems for mobile machines of the type “post-combustion” have been developed. Both system concepts separate the CO_2e emissions by adsorbing CO_2. In the first system, an adsorber material is used as filter and as storage. When the filter is full of adsorbed CO_2, it is removed and replaced with a new filter. The filter has to be able to store as much CO_2 as is produced by a full consumed tank. Ideally, when a fuel tank has to be filled up at a gas station, the filter can be replaced with a new one. The saturated filter can then together with others be brought into a central regeneration centre. For such a system, a gas cooler and a compressor are needed to bring the exhaust gas to the right temperature and pressure before flowing through the filter. The temperature and pressure to set, depends of the material used. The first system is schematically represented in Figure 8.5. Overall, this system has the advantage that it can be built in existing machines with little effort. A major disadvantage is the need for an existing infrastructure and regeneration centre to get the filters regenerated.

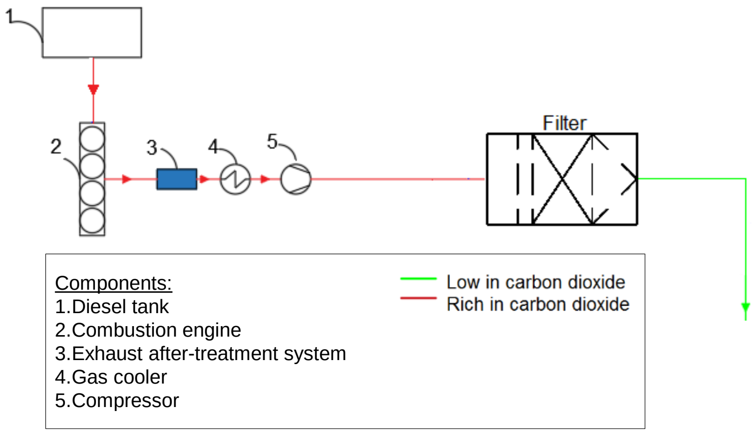


Figure 8.5: CO_2 capture and storage system 1 with an adsorber material used as a filter and as storage (based on Zeng 2018)

The second system is schematically represented in Figure 8.6. Instead of a gas cooler, the system uses a turbocharger to cool down the exhaust gas with air to the right temperature. The cooled down exhaust gas is then lead through a three way valve through the filter of an adsorber material. The CO_2 molecules are adsorbed by the filter and the exhaust gas now free of CO_2 can be released into the atmosphere. In the meantime, when one filter is in the adsorption state, the other parallel filter is in the desorption or regeneration state where CO_2 is released from the filter and lead through the three-way valve, the gas cooler and compressor into a storage tank. In the storage tank, the CO_2 is stored in liquid form at ambient temperature and 200 bar in order to need the minimum storage space.

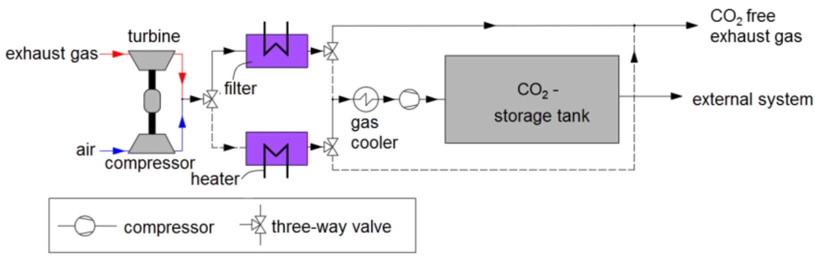


Figure 8.6: CO_2 capture and storage system 2 with an adsorber material used as a filter and a CO_2 tank as storage

Depending on the adsorber material used in the system, the adsorption and desorption conditions (temperature and pressure) will vary. For both systems, the following three materials are the best adequate: Metal-Organic Framework (MOF), zeolite material or activated carbon.

Table 8-5: Properties overview of 3 possible CO_2-adsorbent materials (Ben-Mansour et al. 2016; Zeng 2018)

Properties	MOF	Zeolite	Activated carbon
CO_2-separation rate	60-90%		
CO_2-purity	>99.9%	>90%	
CO_2-separation pressure	1-96 bar	1-2 bar	
CO_2-separation temperature	ca. 30°C		
Specific capacity [g CO_2/g adsorbent]	until 1.47	0.004 - 0.216	0.003 - 0.154
Regeneration method R_g	TSA (>100°C)	TSA (150°C-200°C)	TSA (100°C-700°C)
Energy demand for R_g [MJ/kg CO_2]	ca. 1.7	3-13.7	3-4
Comments	Special material, therefore not easily available	Sensitive to H_2S	- Reactivation process necessary - Sensitive to H_2S

MOF materials are light, crystalline, sponge-like materials used to store or filter and separate selected elements from gases while letting the other elements pass through (MOF Technologies Adsorbent Nanomaterials). Zeolite material is composed of „an aluminosilicate framework which is comprised of a tetrahedral arrangement of silicon cations (Si^{4+}) and aluminium cations (Al^{3+}) that are surrounded by four oxygen anions (O^{2-})“ (Moshoeshoe et al. 2017). Zeolite occurs in nature but can also be produced synthetically (ibid.). Activated carbon „is a porous carbon material, a char which has been subjected to a reaction with gases, sometimes with the addition of chemicals (e.g. $ZnCl_2$) before, during or after carbonisation in order to increase its adsorptive properties“ (Marsh and Rodríguez-Reinoso 2006). An overview of the CO_2 capturing properties of all three materials are shown in Table 8-5.

Table 8-6: Additional mass, volume and energy calculations for both systems[56]

CO_2 capture and storage	Components	Additional mass	Additional volume	Additional Energy
System 1	Gas cooler	Use of an already existing gas cooler in the machine		Neglected
	Compressor	4 kg	0.36 m³	124 MJ
	Filter	931 kg	2.16 m³	-
	Total	**934 kg**	**2.52 m³**	**124 MJ**
System 2 (Regeneration energy is neglected because engine heat is assumed to be used for it)	Turbocharger	Use of an already existing turbocharger for engine		Neglected
	Filter x 2	45 kg	0.02 m³	-
	Three-way valve x 3	8 kg	0.003 m³	-
	Gas cooler	Use of an already existing gas cooler in the machine		Neglected
	Compressor	34 kg	0.08 m³	449 MJ
	CO_2 liquid	When diesel mass decreases, CO_2 mass increases → neglected	1.54 m³	-
	CO_2 tank	128 kg	0.05 m³	-
	Total	**214 kg**	**1.68 m³**	**449 MJ**

In order to compare both system to each other, a CO_2-adsorbent material is chosen for both systems. The material MOF-177 is chosen for system 1 because of its high specific capacity. Zeolite 13X is chosen for system 2

[56] For more calculation details, see appendix A.4

because no reactivation process is necessary for the material contrary to activated carbon. Both system are designed for an excavator of 30t, 152 kW. The additional mass, volume and energy necessary can be seen in Table 8-6. System 1 implemented in the reference excavator will correspond to an additional mass of 3.11 %, to an additional volume of 2.52 m³ and to an additional energy consumption of 1.96 %. System 2 implemented in the reference excavator will correspond to an additional mass of 0.71 %, to an additional volume of 1.68 m³ and to an additional energy consumption of 7.07 %. In both cases, the resulting additional mass, volume and energy consumption are within an acceptable range for the excavator.

In conclusion with such CO_2 capture and storage systems implemented in mobile machines suited for conventional diesel engines drives or alternative future drives like fuel cells or use of alternative fuels, the CO_2 emissions produced by the machine can be reduced over 99 %. The liquid CO_2 stored in the machine can be sold and reused for the production of e-fuels or other industrial products. This results in new business models for construction companies. The additional workload of the system for the driver is low, as only the CO_2 storage tank has to be emptied. This can take place at the same time as filling the fuel tank without needing additional time.

8.4 Climate-friendly mobile machine

The analysis of alternative energy carriers resulted in OME and liquefied methane being the most promising alternatives for mobile machines. The combination of these fuels with a primary energy converter like an engine or a fuel cell compared to the conventional drive of an excavator resulted in a better overview of the resulting variations of weight, volume and greenhouse gas emissions. Considering all three criteria, drives with liquefied methane show the best results. By combining the drives of mobile machines with an additional system capturing and storing CO_2, greenhouse gas emissions can further be reduced, eliminated or even reduced below zero so that the mobile machine becomes a CO_2 atmosphere cleaning machine, see Table 8-7.
These are only some measure examples on how to transform the mobile machine into a greenhouse gas emissions reduced or free machine. All

possible alternatives need to be further examined concerning environmental constraints, duty cycles of the specific mobile machine, etc.

Table 8-7: Total CO_2e emissions from combining a CO_2 carbon capture and storage system with one of the five drive train concepts

Drivetrain of a 30t excavator with 6340 MJ energy output	CO_2e emissions			
	Fuel source	Value [kg CO_2e/tank]	CO_2 capture & storage system (assumption 99% of CO_2) [kg CO_2e/tank]	Total emitted CO_2e [kg CO_2e/tank]
Diesel & ICE (reference)	fossil	1,652.11	-1,354.43	**298**
OME & ICE	natural gas	2,480.95	-1,653.12	**828**
	biomass	484.63	-1,653.12	**-1,169**
Liquefied CH_4 & ICE	fossil	1,398.51	-1,033.78	**365**
	biogas	594.83	-1,033.78	**-439**
	synthetic & wind energy	259.19	-1,033.78	**-775**
Liquefied CH_4 & fuel cell	fossil	1,128.66	-852.37	**276**
	biomass	440.98	-852.37	**-411**
	synthetic & wind energy	187.38	-852.37	**-665**
Liquefied H_2 & fuel cell	EU-Mix	3,188.27	-	**3,188**
	wind energy	59.17	-	**59**

Further, other alternative solutions have to be looked into like mini mobile machines with photovoltaic drives working in swarms.

The focus in this chapter was on the reduction or elimination of CO_2 emissions which is only one ecological aspect of sustainability. According to the analysis of Chen, a mobile machine is only sustainable if the ecological, economic and social aspects are considered of the whole chain from material extraction, through machine production, transportation, construction applications to recycling of the machine. (Chen 2019a)

Therefore, further work is necessary considering all ecological, economic and social aspects in order to develop a sustainable mobile machine which “meets the needs of the present without compromising the ability of future generations to meet their own needs”[57] (Brundtland 1987).

[57] Definition of sustainable development

9 Summary

In order to slow down the wide-ranging impact of global warming, manmade greenhouse gas emissions have to be reduced. Each industry sector has to contribute to reducing their share of greenhouse gas emissions. The present work focused on developing a method for assessing the CO_2e emitted from construction equipment during various construction processes.

On these grounds, it was first essential to define greenhouse gas emissions and understand how they affect the temperature on earth. By increasing gas concentrations in the atmosphere called greenhouse gases, more long-wave radiation (heat) is reflected back to the earth's surface which leads to a global temperature rise.
For a scientifically robust CO_2e quantification method, requirements need to be specified. Therefore, first measures taken in different industries were analysed and needs were derived.

Then, through the analysis of existing CO_2e quantification methods for construction equipment and construction applications shortfalls and thus research gaps were identified for these methods.

Identified needs and research gaps permitted developing the CO_2e quantification method. First, a general common approach was defined on how to quantify CO_2e emissions and their reduction valid for the construction sector and by extension, the agriculture sector. In fact, it is not uncommon to find e.g. tractors specifically developed for the agricultural sector working at construction sites or e.g. wheel loaders developed for construction applications working in the agricultural sector. The general common approach consisted of defining six common CO_2e reduction potential pillars which cover past, present and future measures taken by the industry. The method should not only focus on machine engines but rather on machines in their various application areas. In order to quantify the CO_2e reduction reached and expected, the method permits CO_2e emissions assessment over different time periods. The CO_2e emission amount difference between each period represents an increase or a reduction of greenhouse gas emissions reached or expected to be reached.

Table 9-1: Influencing factors categorised according to the six pillars

Influencing factors categorised according to the six pillars		
Machine Efficiency	$f_{machine\ technology}$	f_{engine}
		f_{eco}
		$f_{significant\ improvement}$
	$f_{machine\ condition}$	f_{age}
		$f_{service\ regularity}$
Process Efficiency	$f_{site\ orga.}$	
	$f_{idle\ unavoidable}$	
	$f_{process\ assistant}$	
	$f_{constr.\ complexity}$	$f_{weather}$
		$f_{construction\ time}$
		$f_{site\ freedom}$
Energy Source	$f_{CO_2e/energy\ carrier}$	
Operation Efficiency	f_{driver}	$f_{physical\&mental\ state}$
		$f_{knowledge\&skills}$
		$f_{workplace\&working\ environment}$
	$f_{stop\&go}$	
Material Efficiency	$GWP_{material}$	
CO_2e Capture & Storage	f_{CCS}	

In order to quantify the CO_2e emission consequences of certain measures taken, it is essential to correctly define the system boundaries of the method. If the system is too broad, the method becomes too complex and measures taken won't be apparent in the total CO_2e emissions assessment. On the contrary, if the system is too narrow, the result does not yield the correct

effect for measures taken to reduce CO_2e emissions and can lead to false conclusions.
Therefore, in this work, it was decided to take into account the destruction of CO_2e sinks considered as preparatory work before construction takes place and the new formation of CO_2e sinks after construction. Further, the method not only focuses on machine efficiencies but considers also process efficiencies, energy sources, operation efficiencies, material efficiencies and CO_2e capture and storage technologies (the six CO_2e reduction potential pillars). For each of the six pillars corresponding factors were defined (see Table 9-1). The factors categorised according to the pillar machine efficiency for example consider not only the engine, but the whole technology system of the machine as well as the machine's condition. Therefore, the method considers the whole machine and not just components like e.g. the engine (G1).

Some scientists argue that the amount of CO_2e emissions is not informative enough to be able to deduce if the amount is within an acceptable range or simply too much (Stocker 9/19/2018). Therefore, the method gives the possibility of converting the CO_2e amount into a currency value e.g. €, so that everybody including non-scientific persons can understand the impact of emitted greenhouse gas emissions.

In order to show that the method is valid for different construction applications, first, representative construction applications for the European sector were defined for the times past, present and near future.

Afterwards, through literature and expert surveys, it was possible to verify the defined individual factors for each of the six CO_2e reduction potential pillars as well as to define their value ranges. By defining their values for the times past, present and near future, an influence analysis of these factors on an excavator took place. On the example of the excavator, it was possible to show the range of influence some factors can take on the total amount of CO_2e emitted. The weather is the factor with the greatest influence range potential. It is followed by the factor representing the workplace and working environment conditions. This factor influences the driver of the machine and can consequently affect total CO_2e emissions. The factor with the third largest potential in influencing the total greenhouse gas emissions is the energy source, e.g. using an alternative energy carrier to fossil diesel.

Applying the factor values for past, present and near future on the defined representative construction applications, enabled showing the development over time of CO_2e emissions and thereby prove that the method is valid for different time periods (G2) and for different construction applications (G5). The simulation also showed that through variation of the factors from the six pillars, the resulting CO_2e difference can be assessed with the method. Materials, construction processes, energy sources as well as operating conditions are taken into account in the method thus closing the research gaps G3, G4 and G6. In other words, by considering the six pillars, need N2 is fulfilled since the focus not only lies on the machine but rather on a holistic approach.
Another simulation on the example of a BK10 road construction showed that CO_2e sinks destruction can contribute to an important CO_2e share of the total amount of greenhouse gases emitted (13 %). However, this effect can be reduced or even eliminated with the right measures.

The CO_2e quantification method was then validated at construction sites. An excavator, single drum roller, road pavers and tandem rollers were observed at a construction site. The total amount of fuel consumed was assessed and converted into CO_2e emissions. The results were then compared with the theoretical amount of CO_2e, resulting from application of the CO_2e quantification method. According to the Pareto principle, the method should at least consider 80 % of the CO_2e emissions emitted by each sub process. The difference between the practical and theoretical approaches were all within the acceptable range below 20 %.

In summary, the developed CO_2e quantification method can be applied in different construction sectors and show the evolution of CO_2e emissions along a specific timeline. By applying the method, comparisons between different processes or CO_2e reduction measures can be made. The validation procedure of the method showed that the resulting CO_2e amount values are credible, sufficiently representative estimates, enabling making statements about which measures should be taken and about how much influence these

measures will have on the total CO_2e amount emitted during a construction process. The method therefore fulfils need N4.
Through the application of the method, different measures could be derived on how to reduce CO_2e emissions from mobile construction machines. One measure consisted of choosing an alternative energy carrier for mobile machines. Synthetic liquefied methane was determined as the most promising alternative for mobile machines. This measure closes research gap G7 by proving that the CO_2e quantification method not only quantifies CO_2 emissions but all greenhouse gas (CO_2e) emissions and thus fulfils need N1.
Another measure consisted of combining an adequate alternative energy carrier with an adequate primary energy converter. Here the most promising solution seemed to be liquefied methane combined with a fuel cell drive.
Finally, in order to reach zero CO_2e emissions, two concepts on what a carbon capture system for mobile machines could look like have been designed.
Combining all three measures in a mobile machine together, greenhouse gas emissions can be further reduced, eliminated or even reduced below zero so that the mobile machine removes CO_2 from the atmosphere. These are only some measure examples on how to transform the mobile machine into a greenhouse gas emissions reduced or free machine. All possible alternatives need to be further examined concerning environmental constraints, duty cycles of the specific mobile machine, etc.

The focus in this thesis was on the reduction or elimination of CO_2 emissions which is only one ecological aspect of sustainability. Ecological, economic and social aspects need to be considered for the whole chain from material extraction, through machine production, transportation, construction applications to recycling of the machine in order to develop a sustainable mobile machine in a sustainable construction environment.

Nevertheless, the validation of the CO_2e quantification method was only made possible through the cooperation of construction industries and construction machine producers. Additionally, a transformation of mobile machines with an alternative drive as well as/or with an alternative energy source will only be possible if cooperation between different industry sectors and government takes place (N3).

To conclude, the “*empire of climate is* [indeed] *the first empire among all*” influencing men and society (Montesquieu 1748).

Appendices

A.1 Results of the expert survey according to the Delphi method

Delphi Method

KIT Karlsruher Institut für Technologie

Preparation
- Formulation of questions
- Determination of team of experts

1st round
- Ask experts
- Collect & process answers

2nd round
- Anonymised summary provided to the experts
- Experts are encouraged to revise their earlier answers
- Collect & process answers

Consensus
- Mean or median scores of the final round determine the result

1 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)
MOBIMA

Definition of the basic machine

KIT Karlsruher Institut für Technologie

- Emission technology: **Stage 1**

	Excavator	Wheel loader	Paver	Roller
Year of construction	1999	1992	1995	1990
Size	20 t	-	1800	-
Max. engine performance	86 kW	106 kW	125 kW	91 kW
Machine characteristics	Bucket volume: 0.5m³	Bucket volume: 3.3m³	Working width: 8m	Weight: 11 t Working width: 1.9 m
Average fuel consumption (b_m)	23,8 l/h	11.4 l/h	20,4 l/h	12.7 l/h

Info.: b_m is the average fuel consumption of the machine under ideal conditions, which equals to the fuel consumption during test drives (without idle).

2 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)
MOBIMA

Elaboration of machine related efficiency

- Define the average fuel consumption at idle (b_{idle})

Definition of idle: Idle, also called "low idle" is when only the engine is switch on but no driving or other operation takes place (no air conditioning).

Excavator	Wheel loader	Paver	Roller
2.7 l/h	2.6 l/h	2.5 l/h	1.6 l/h

3 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)

M P O A

Reduction of the fuel consumption through improvement of the combustion engine (f_{engine})

- This factor equals to the reduction of the fuel consumption of the combustion engine depending on the emissions legislation stages.
- Reference is the engine with stage I; f_{engine}= 1.0
- E.g. 3% reduction of fuel consumption -> 0.97

Emission technology	Stage I	Stage II	Stage III A	Stage III B	Stage IV	Stage V
Combustion engine	1.00	1.00	1.03	1.03	1.00	0.97

4 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)

M P O A

KIT Karlsruher Institut für Technologie

Elaboration of machine related efficiency(f_{eco})

- Definition of "Ecomode": Ecomode is when the engine speed is reduced to a fix value.
- E.g. 10% reduction of fuel consumption with Ecomode → 0.9

	f_{eco}
Excavator	0.88
Wheel loader	0.90
Paver	0.85
Roller	0.87

5 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)
MOBIMA

M P O A

KIT Karlsruher Institut für Technologie

Elaboration of machine related efficiency ($f_{significant\ improvement}$)

- Describe shortly other significant technology improvements (single technologies or combination of technologies) having an influence on the fuel consumption

	Past & Present		Future
	Which technology?	Amount of Reduction of fuel consumption (%)	Prognosis of fuel reduction for the future (%)
Excavator	- Injection system in diesel engine - Engine downsizing - Improvements cooling system - Loadsensing hydraulics - Pump system - Hydraulic downsizing - Low-viscosity axle oils - Low idle - Ergonomics - Electrification	11%	15%

6 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)
MOBIMA

Elaboration of machine related efficiency ($f_{\textit{significant improvement}}$)

- Describe shortly other significant technology improvements (single technologies or combination of technologies) having an influence on the fuel consumption (the reduction percentage is referenced to the value of 1990)

	Past & Present		Future 5 years
	Which technology?	Amount of reduction of fuel consumption (%)	Prognosis of fuel reduction for the future (%)
Wheel loader	- Injection system in diesel engine - Engine downsizing - Improvements cooling system - Loadsensing hydraulics - Pump system - Hydraulic downsizing - Low-viscosity axle oils - Low idle - Ergonomics - Electrification	11%	20%

7 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)

Elaboration of machine related efficiency ($f_{\textit{significant improvement}}$)

- Describe shortly other significant technology improvements (single technologies or combination of technologies) having an influence on the fuel consumption

	Past & Present (since 1990)		Future 5 years
	Which technology?	Reduction amount of fuel consumption compared to 1990	Prognosis of fuel reduction for the future compared to 1990
Paver	– energy-optimized tamper drive – Switchable pump distribution gear – Controlled hydraulic oil temperature circuit – speed-controlled fan	12%	29%

8 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)

Elaboration of machine related efficiency ($f_{significant\ improvement}$)

- Describe shortly other significant technology improvements (single technologies or combination of technologies) having an influence on the fuel consumption

	Past & Present (since 1990)		Future 5 years
	Which technology?	Reduction amount of fuel consumption compared to 1990	Prognosis of fuel reduction for the future compared to 1990
Roller	– Injection system in diesel engine – Engine downsizing – Electronic powertrain control	28%	35%

Elaboration of machine related efficiency

- **Machine condition:** depends from “service regularity” and from “machine age”.
- **A value of 1.20 means that the fuel consumption increases by 20%**
  - Service regularity:

Service regularity	Very good, as defined by the machine producer	Exceeding by 20%	Exceeding by 50%	Exceeding by 100%
Excavator	1	1.02	1.04	1.08
Wheel loader	1	1.02	1.04	1.08
Paver	1	1.02	1.04	1.08
Roller	1	1.10	1.20	1.40

M P O A

KIT Karlsruher Institut für Technologie

Elaboration of machine related efficiency

- Machine age:
  - Statement: With correct maintenance and repair, fuel consumption of the machine will not deteriorate by more than **10%** over its lifespan.
    (source: interview with 1 project partner)
  - Hypothesis: linear performance deterioration
  - Average lifetime differs for a private owned machine & rental park machine
  - According to source Helms & Heidt, maximum lifetime is 10 000 Bh.

Average lifetime (Bh *)	Private owned machine [1]	Machine from rental park
Small machines	17,500 Bh	No info.
Big machines	25,000 Bh	17,500 Bh[2]
Mining machines	35,000 Bh	No info.

* Bh: stands for operation hour (*dt. Betriebsstunden*)
1: data from interview with 1 project partner
2: data from interviews with 2 machine rental parks

$\frac{Age\ (Bh)}{average\ lifetime\ (Bh)}$	f_age
0	1.00
0.5	1.05
1	1.10
1.5	1.15
2	1.20
2.5	1.25
3.0	1.30
3.5	1.35

Helms H, Heidt C. Erarbeitung eines Konzepts zur Minderung der Um-weltbelastung aus NRMM (non road mobile machinery) unter Berück-sichtigung aktueller Emissionsfaktoren und Emissionsverminde-rungsoptionen für den Bestand 2014(24).

11 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)
MOBIMA

M P O A

KIT Karlsruher Institut für Technologie

Elaboration of machine related efficiency

- Effects of "process assistant systems" on the driver performance

$f_{process\ assistant}$ *(driver experience)*
$=1+\sum a$ *(driver experience)*

E.g expert driver of an wheel loader with tire pressure monitoring and payload weighting system
$f_{process\ assistant}$ (expert) = 1+0.02 +0.05 = 1.07

		$f_{driver\ experience}$
Driver Experience + basic educational training	Expert 15y-25y	0.92
	Good 8y-15y	0.83
	Medium 3y-8y	0.77
	Beginner <3y	0.55

a (efficiency increase through assistant systems)		Excavator & Wheel loader					
		Tire Pressure monitoring	Bucket filling assist system	Visibility assistants (sensors, cameras, etc.)	Semi-automatic movements	Payload weighting System	Data analysis & visualisation
Driver experience	Expert 15y-25y	0.02	0.00	0.01	0.00	0.05	0.05
	Good 8y-15y	0.04	0.02	0.02	0.05	0.07	0.08
	Medium 3y-8y	0.07	0.10	0.02	0.07	0.12	0.10
	Beginner <3y	0.10	0.20	0.02	0.10	0.15	0.15

12 12/03/2019 Dipl.-Ing. Isabelle Ays
Results of the expert survey according to the Delphi method
Institute of Vehicle System Technology (FAST)
Chair of Mobile Machines (Mobima)
MOBIMA

MPOA KIT Karlsruher Institut für Technologie

Elaboration of machine related efficiency

- Effects of "process assistant systems" on the driver performance

a (efficiency increase through assistant systems)		Paver			
		Repositioning & paving function	3D positioning system	Communication system between truck & paver	**All 3 features combined together**
Driver experience	Expert 15y-25y	0.00	0.00	0.00	0.00
	Good 8y-15y	0.10	0.20	0.00	0.30
	Medium 3y-8y	0.10	0.20	0.10	0.35
	Beginner <3y	0.20	0.30	0.10	0.40

MPOA KIT Karlsruher Institut für Technologie

Elaboration of machine related efficiency

- Effects of "process assistant systems" on the driver performance

a (efficiency increase through assistant systems)		Roller (avoidance of unnecessary passages)		
		Measurement of the compaction degree	Measurement of the compaction degree + Automatic continuously variable amplitude System	Measurement of the compaction degree + Automatic continuously variable amplitude system + Track and temperature control
Driver experience	Expert 15y-25y	0.12	0.14	0.12
	Good 8y-15y	0.18	0.23	0.28
	Medium 3y-8y	0.21	0.27	0.34
	Beginner <3y	0.40	0.51	0.63

A.2 Simulation parameters of representative applications

Building construction

Flat construction

Past

Structural elements	Name	Amount		GWP		m_{CO_2e} [kg CO_2e]
Windows	Triple glazing (incl. argon filling)	101.57	m²	58.64	kg/m²	5,956
	Outer frame (PVC)	472.70	m	8.07	kg/m	3,813
	Sash frame	449.07	m	9.09	kg/m	4,082
	Profile seals (chloroprene rubber)	449.07	m	0.96	kg/m	433
	Sealing tape (butyl)	472.70	m	0.33	kg/m	154
	Window handles	95	pieces	0.84	kg/piece	80
Roof	Surface protection: gravel	15.90	t	2.96	kg/t	47
	Protective layer: PVC roofing membrane	212.00	m²	6.45	kg/m²	1,367
	Mineral wool insulation (flat roof insulation)	36.04	m³	214.30	kg/m³	7,723
	Roof sealing: bitumen membrane	212.00	m²	2.65	kg/m²	563
	Separating layer: glass fleece	212.00	m²	0.32	kg/m²	67
	Gradient screed	57.24	t	156.00	kg/t	8,929
	Reinforcing steel	2.78	t	750.00	kg/t	2,084
	Concrete	96.70	t	104.00	kg/t	10,057
Storey ceiling	Reinforcing steel	13.19	t	750.00	kg/t	9,892
	Concrete	459.10	t	104.00	kg/t	47,746
	Mineral wool insulation (flat roof insulation)	48.31	m³	138.80	kg/m³	6,706
	Screed	75.49	t	156.00	kg/t	11,776
Walls	Brick	230.56	m³	138.30	kg/m³	31,887
	Mortar	59.29	t	87.70	kg/t	5,200
	Mineral wool insulation (flat roof insulation)	83.30	m³	41.61	kg/m³	3,466
	Gypsum plaster	19.08	t	140.00	kg/t	2,671
	Mortar	27.89	t	87.70	kg/t	2,446
	Facing layer: clinker	143.04	t	234.00	kg/t	33,471
Staircase	Concrete	25.77	t	104.00	kg/t	2,680
	Reinforcing steel	0.74	t	750.00	kg/t	555
	Screed	4.81	t	156.00	kg/t	750
	Mineral wool insulation (flat roof insulation)	2.24	m³	138.80	kg/m³	311
Basement walls	Brick	107.68	m³	138.30	kg/m³	14,891
	Mortar	28.76	t	87.70	kg/t	2,522
Foundations	Concrete	287.67	t	104.00	kg/t	29,918
	Reinforcing steel	16.57	t	750.00	kg/t	12,427
	Mineral wool insulation (floor insulation)	21.20	m³	138.80	kg/m³	2,943
	Screed	15.90	t	156.00	kg/t	2,480
				Total:		**270 t CO_2e**

Sub process	Machines	Material	Amount	Energy consumption		m_{CO_2e} [kg CO_2e]
				b_l or b_m	b_{idle}	
Loading	Forklift	Brick, mortar, insulation, protective layer, roof sealing, separating layer, plaster, facing layer	798 t	11.25 kg CO_2e/h	1.43 kg CO_2e/h	7.34
Transporting				10.71 kg CO_2e/h	1.36 kg CO_2e/h	78.59
Transporting	Truck	Reinforced steel, bricks, mortar, insulation, protective layer, roof sealing, separating layer, plaster, facing layer, surface protection	814 t	58.83 l/h	-	4,953.21
Transporting	Truck mixer	Screed, concrete	1023 t	58.83 l/h	-	20,621.59
Lifting	Crane	Reinforced steel, bricks, mortar, insulation, protective layer, roof sealing, separating layer, plaster, facing layer, surface protection	740 t	7.07 kg CO_2e/h	0.90 kg CO_2e/h	59.63
Forward driving				0.58 kg CO_2e/h	0.07 kg CO_2e/h	2.85
Rotating				0.71 kg CO_2e/h	0.09 kg CO_2e/h	4.21
Mixing	Drum mixer	Mortar, plaster	98 m³	1.21 kg CO_2e/h	0.15 kg CO_2e/h	229.21
Concreting	Concrete pump	Concrete	378 m³	1.30 kg CO_2e/m³	0.17 kg CO_2e/m³	864.88
Compacting	Internal vibrator	Concrete	1,431 m²	0.27 kg CO_2e/h	0.03 kg CO_2e/h	10.36
Pumping	Double piston pump	Plaster	21 m³	4.82 kg CO_2e/h	0.61 kg CO_2e/h	87.71
Pumping	Screed pump	Screed	102 m³	7.32 l/h	0.93 l/h	510.84
					Total	27,430 kg CO_2e
						27 t CO_2e

Present

Structural elements	Name	Amount		GWP		m_{CO_2e} [kg CO_2e]
Windows	Triple glazing (incl. argon filling)	101.57	m^2	58.64	kg/m^2	5,956
	Outer frame (PVC)	472.70	m	8.07	kg/m	3,813
	Sash frame	449.07	m	9.09	kg/m	4,082
	Profile seals (chloroprene rubber)	449.07	m	0.96	kg/m	433
	Sealing tape (butyl)	472.70	m	0.33	kg/m	154
	Window handles	95.00	pieces	0.84	kg/piece	80
Roof	Surface protection: gravel	15.90	t	2.96	kg/t	47
	Protective layer: PVC roofing membrane	212.00	m^2	6.45	kg/m^2	1,367
	Mineral wool insulation (flat roof insulation)	36.04	m^3	214.30	kg/m^3	7,723
	Roof sealing: bitumen membrane	212.00	m^2	2.65	kg/m^2	563
	Separating layer: glass fleece	212.00	m^2	0.32	kg/m^2	67
	Gradient screed	57.24	t	156.00	kg/t	8,929
	Reinforcing steel	1.29	t	750.00	kg/t	966
	Concrete	95.38	t	104.40	kg/t	9,957
Storey ceiling	Reinforcing steel	5.86	t	750.00	kg/t	4,396
	Concrete	434.07	t	104,40	kg/t	45,317
	Mineral wool insulation (flat roof insulation)	48.31	m^3	138.80	kg/m^3	6,706
	Screed	75.49	t	156.00	kg/t	11,776
Walls	Reinforcing steel	4.44	t	750.00	kg/t	3,332
	Concrete	429.44	t	104.40	kg/t	44,833
	Mineral wool insulation (flat roof insulation)	83.30	m^3	41.61	kg/m^3	3,466
	Gypsum plaster	19.08	t	140.00	kg/t	2,671
	Mortar	27.89	t	87.70	kg/t	2,446
	Facing layer: clinker	143.04	t	234.00	kg/t	33,471
Staircase	Concrete	39.64	t	104.40	kg/t	4,139
	Reinforcing steel	0.35	t	750.00	kg/t	265
	Screed	4.81	t	156.00	kg/t	750
	Mineral wool insulation (flat roof insulation)	2.24	m^3	138.80	kg/m^3	311
Basement walls	Reinforcing steel	2.71	t	750.00	kg/t	2,033
	Concrete	247.09	t	104.40	kg/t	25,796
Foundations	Concrete	140.16	t	104.40	kg/t	14,633
	Reinforcing steel	1.04	t	750.00	kg/t	782
	Mineral wool insulation (floor insulation)	21.20	m^3	138.80	kg/m^3	2,943
	Screed	15.90	t	156.00	kg/t	2,480
					Total:	**257 t CO_2e**

Sub process	Machines	Material	Amount		Energy consumption				m_{CO_2e} [kg CO_2e]
					b_l or b_m		b_{idle}		
Loading	Forklift	Reinforced steel mortar, insulation, protective layer, roof sealing, separating layer, plaster, facing layer	599	t	11.25	kg CO_2e/h	1.43	kg CO_2e/h	2.00
Transporting					10.71	kg CO_2e/h	1.36	kg CO_2e/h	21.46
Transporting	Truck	Reinforced steel, bricks, mortar, insulation, protective layer, roof sealing, separating layer, plaster, facing layer, surface protection	614	t	60.38	l/h	-		3,272.55
Transporting	Truck mixer	Screed, concrete	1,539	t	60.38	l/h	-		13,663.00
Lifting	Crane	Reinforced steel, bricks, insulation, protective layer, roof sealing, separating layer, plaster, facing layer, surface protection	567	t	7.07	kg CO_2e/h	0.90	kg CO_2e/h	19.08
Forward driving					0.58	kg CO_2e/h	0.07	kg CO_2e/h	0.89
Rotating					0.71	kg CO_2e/h	0.09	kg CO_2e/h	1.31
Mixing	Drum mixer	Mortar, plaster	40	m^3	1.21	kg CO_2e/h	0.15	kg CO_2e/h	33.72
Concreting	Concrete pump	Concrete	603	m^3	1.30	kg CO_2e/m^3	0.17	kg CO_2e/m^3	751.56
Compacting	Internal vibrator	Concrete	1,431	m^2	0.27	kg CO_2e/h	0.03	kg CO_2e/h	3.77
Pumping	Double piston pump	Plaster	21	m^3	4.82	kg CO_2e/h	0.61	kg CO_2e/h	31.94
Pumping	Screed pump	Screed	102	m^3	7.32	l/h	0.93	l/h	186.02
							Total	17,987	kg CO_2e
								18	t CO_2e

Future

Structural elements	Name	Amount		GWP		m_{CO_2e} [kg CO_2e]
Windows	Triple glazing (incl. argon filling)	101.57	m²	58.64	kg/m²	5,956
	Outer frame (PVC)	472.70	m	8.07	kg/m	3,813
	Sash frame	449.07	m	9.09	kg/m	4,082
	Profile seals (chloroprene rubber)	449.07	m	0.96	kg/m	433
	Sealing tape (butyl)	472.70	m	0.33	kg/m	154
	Window handles	95.00	pieces	0.84	kg/piece	80
Roof	Surface protection: gravel	15.90	t	2.96	kg/t	47
	Protective layer: PVC roofing membrane	212.00	m²	6.45	kg/m²	1,367
	Mineral wool insulation (flat roof insulation)	36.04	m³	214.30	kg/m³	7,723
	Roof sealing: bitumen membrane	212.00	m²	2.65	kg/m²	563
	Separating layer: glass fleece	212.00	m²	0.32	kg/m²	67
	Gradient screed	57.24	t	156.00	kg/t	8,929
	Reinforcing steel	2.78	t	750.00	kg/t	2,084
	Concrete	96.70	t	104.00	kg/t	10,057
Storey ceiling	Reinforcing steel	13.19	t	750.00	kg/t	9,892
	Concrete	459.10	t	104.00	kg/t	47,746
	Mineral wool insulation (flat roof insulation)	48.31	m³	138.80	kg/m³	6,706
	Screed	75.49	t	156.00	kg/t	11,776
Walls	Sand-lime brick	230.20	m³	136.00	kg/m³	31,308
	Mortar	59.29	t	87.70	kg/t	5,200
	Mineral wool insulation (flat roof insulation)	83.30	m³	41.61	kg/m³	3,466
	Gypsum plaster	19.08	t	140.00	kg/t	2,671
	Mortar	27.89	t	87.70	kg/t	2,446
	Facing layer: clinker	143.04	t	234.00	kg/t	33,471
Staircase	Concrete	25.77	t	104.00	kg/t	2,680
	Reinforcing steel	0.74	t	750.00	kg/t	555
	Screed	4.81	t	156.00	kg/t	750
	Mineral wool insulation (flat roof insulation)	2.24	m³	138.80	kg/m³	311
Basement walls	Sand-lime brick	108.70	m³	136.00	kg/m³	14,783
	Mortar	28.76	t	87.70	kg/t	2,522
Foundations	Concrete	287.67	t	104.00	kg/t	29,918
	Reinforcing steel	16.57	t	750.00	kg/t	12,427
	Mineral wool insulation (floor insulation)	21.20	m³	138.80	kg/m³	2,943
	Screed	15.90	t	156.00	kg/t	2,480
				Total:		269 t CO_2e

Sub process	Machines	Material	Amount	Energy consumption: b_l or b_m	Energy consumption: b_{idle}	m_{CO_2e} [kg CO_2e]
Loading	Forklift	Brick, mortar, insulation, protective layer, roof sealing, separating layer, plaster, facing layer	1,002 t	11.25 kg CO_2e/h	1.43 kg CO_2e/h	2.28
Transporting				10.71 kg CO_2e/h	1.36 kg CO_2e/h	24.44
Transporting	Truck	Reinforced steel, bricks, mortar, insulation, protective layer, roof sealing, separating layer, plaster, facing layer, surface protection	1,018 t	57.28 l/h	-	3,341.39
Transporting	Truck mixer	Screed, concrete	1,023 t	57.28 l/h	-	9,525.13
Lifting	Crane	Reinforced steel, bricks, insulation, protective layer, roof sealing, separating layer, plaster, facing layer, surface protection	943 t	7.07 kg CO_2e/h	0.90 kg CO_2e/h	18.70
Forward driving				1.16 kg CO_2e/h	0.07 kg CO_2e/h	1.80
Rotating				1.41 kg CO_2e/h	0.09 kg CO_2e/h	2.66
Mixing	Drum mixer	Mortar, plaster	98 m^3	1.21 kg CO_2e/h	0.15 kg CO_2e/h	56.79
Concreting	Concrete pump	Concrete	378 m^3	1.30 kg CO_2e/m^3	0.17 kg CO_2e/m^3	349.50
Compacting	Internal vibrator	Concrete	1,431 m^2	0.27 kg CO_2e/h	0.03 kg CO_2e/h	2.57
Pumping	Double piston pump	Plaster	21 m^3	4.82 kg CO_2e/h	0.61 kg CO_2e/h	21.73
Pumping	Screed pump	Screed	102 m^3	7.32 l/h	0.93 l/h	126.56
					Total	**13,474 kg CO_2e**
						13 t CO_2e

Office building

Past

Structural elements	Name	Amount		GWP		m_{CO_2e} [kg CO_2e]
Roof	Surface protection: gravel	28.10	t	30.00	kg/t	843
	Protective layer: PVC roofing membrane	374.58	m²	5.64	kg/m²	2,113
	Mineral wool insulation (flat roof insulation)	18.73	m³	41.62	kg/m³	780
	Roof sealing: bitumen membrane	374.58	m²	2.65	kg/m²	993
	Nonius hanger	0.19	t	2,700.00	kg/t	513
	Aluminium frame profiles	0.29	t	10,930.00	kg/t	3,170
	Plaster mortar	2.90	m²	240.00	kg/m²	696
	Gradient screed	21.72	t	123.00	kg/t	2,672
	Reinforcing steel	15.83	t	750.00	kg/t	11,873
	Concrete	216.73	t	130.00	kg/t	28,175
Storey ceiling	Screed	108.62	t	123.00	kg/t	13,360
	Mineral wool insulation	93.64	m³	41.62	kg/m³	3,897
	Concrete	869.26	t	130.00	kg/t	113,004
	Reinforcing steel	55.36	t	750.00	kg/t	41,520
	Plaster mortar	14.51	t	240.00	kg/t	3,482
	Nonius hanger	1.11	t	2,700.00	kg/t	2,997
	Aluminium frame profiles	1.16	t	10,930.00	kg/t	12,679
Walls	Double layer Insulating glass	816.67	m²	37.52	kg/m²	30,641
	Aluminium frame profiles	2,008.00	m	12.44	kg/m	24,980
	Aluminium sheets	5.46	t	10,690.00	kg/t	58,367
	Mineral wool insulation	183.58	m³	41.62	kg/m³	7,640
	Plaster mortar	17.96	t	240.00	kg/t	4,310
	Concrete	472.60	t	130.00	kg/t	61,438
	Reinforcing steel	23.63	t	750.00	kg/t	17,723
	Gypsum plasterboard	1,677.60	m²	1.24	kg/m²	2,080
Staircase	Concrete	57.68	t	130.00	kg/t	7,498
	Reinforcing steel	1.97	t	750.00	kg/t	1,478
Structure	Concrete	37.27	t	130.00	kg/t	4,845
	Steel beams	181.91	t	1,040.00	kg/t	189,186
	Steel pillars	44.98	t	1,470.00	kg/t	66,121
Basement walls	Concrete	477.28	t	130.00	kg/t	62,046
	Reinforcing steel	20.84	t	750.00	kg/t	15,630
Foundation	Concrete	754.44	t	130.00	kg/t	98,077
	Reinforcing steel	39.41	t	750.00	kg/t	29.,558
					Total:	924 t CO_2e

Sub process	Machines	Material	Amount	Energy consumption		m_{CO_2e} [kg CO_2e]
				b_l or b_m	b_{idle}	
Loading	Forklift	Reinforcing steel, insulating glass, Aluminium profiles and sheets, mineral wool insulation, plaster mortar, gypsum plasterboard, nonius hanger, bitumen membrane, PVC membrane	541 t	13.05 kg CO_2e/h	1.66 kg CO_2e/h	5.77
Transporting				12.42 kg CO_2e/h	1.58 kg CO_2e/h	61.78
Transporting	Truck	Reinforcing steel, insulating glass, Aluminium profiles and sheets, mineral wool insulation, plaster mortar, gypsum plasterboard, nonius hanger, bitumen membrane, PVC membrane	541 t	58.83 l/h	-	4,863.28
Transporting	Truck mixer	Screed, concrete	2,353 m³	58,.83 l/h	-	97,284.29
Lifting	Crane	Reinforcing steel, insulating glass, Aluminium profiles and sheets, mineral wool insulation, plaster mortar, gypsum plasterboard, nonius hanger, bitumen membrane, PVC membrane, steel	541 t	17.89 kg CO_2e/h	2.27 kg CO_2e/h	73.20
Forward driving				2.24 kg CO_2e/h	0.28 kg CO_2e/h	1.67
Rotating				3.73 kg CO_2e/h	0.47 kg CO_2e/h	8.11
Concreting	Concrete pump	Concrete	2,267 m³	1.30 kg CO_2e/m³	0.17 kg CO_2e/m³	5,186.84
Compacting	Internal vibrator	Concrete	818 m²	0.70 kg CO_2e/h	0.09 kg CO_2e/h	72.38
Pumping	Vibrating beam	Concrete	360 m³	0.72 l/h	0.09 l/h	4.14
Pumping	Screed pump	Screed	87 m³	7.32 l/h	0.93 l/h	433.95
					Total	107,995 kg CO_2e
						108 t CO_2e

Present and future

Structural elements	Name	Amount		GWP		m_{CO_2e} [kg CO_2e]
Roof	Surface protection: gravel	28.09	t	33.80	kg/t	950
	Protective layer: PVC roofing membrane	749.16	m²	5.64	kg/m²	4,225
	Mineral wool insulation (flat roof insulation)	65.55	m³	214.30	kg/m³	14,047
	Roof sealing: bitumen membrane	374.58	m²	2.65	kg/m²	993
	Nonius hanger	0.19	t	2,700.00	kg/t	521
	Aluminium frame profiles	0.29	t	10,930.00	kg/t	3,173
	Gypsum plaster board	694.05	m²	1.72	kg/m²	1,194
	Gradient screed	31.51	t	160.00	kg/t	5,041
	Reinforcing steel	16.46	t	750.00	kg/t	12,344
	Concrete	225.39	t	130.30	kg/t	29,368
Storey ceiling	Mineral wool insulation	69.41	m³	41.62	kg/m³	2,889
	Gypsum fibreboard	4,164.30	m²	3.08	kg/m²	12,826
	Metal support	0.77	t	2,700.00	kg/t	2,082
	Concrete	983.33	t	130.30	kg/t	128,127
	Reinforcing steel	62.59	t	750.00	kg/t	46,941
	Gypsum plaster board	2,776.20	m²	1.72	kg/m²	4,775
	Nonius hanger	1.11	t	2,700.00	kg/t	2,998
	Aluminium frame profiles	1.16	t	10,930.00	kg/t	12,692
Walls	Double layer Insulating glass	590.63	m²	37.52	kg/m²	22,160
	Aluminium frame profiles	3,560.00	m	12.44	kg/m	44,286
	Aluminium sheets	8.46	t	10,690.00	kg/t	90,390
	Mineral wool insulation	77.38	m³	41.62	kg/m³	3,221
	Mineral wool insulation (facades)	41.76		72.57	kg/m³	3,031
	Plaster mortar	9.76	t	242.00	kg/t	2,361
	Concrete	236.51	t	130.30	kg/t	30,817
	Steel profile - floor connections & stand	3.90	t	2,371.00	kg/t	9,256
	Reinforcing steel	9.22	t	750.00	kg/t	6,913
	Gypsum plasterboard	4,294.84	m²	1.24	kg/m²	5,330
Staircase	Concrete	57.69	t	130.30	kg/t	7,517
	Reinforcing steel	2.00	t	750.00	kg/t	1,503
Structure	Concrete	69.36	t	130.30	kg/t	9,038
	Reinforcing steel	7.19	t	750.00	kg/t	5,392
Basement	Concrete	457.80	t	130,30	kg/t	59,652
	Screed	33.71	t	160,00	kg/t	5,394
	Plaster mortar	7.34	t	242,00	kg/t	1,775
	Mineral wool insulation	23.67	m³	41,61	kg/m³	985
	Mineral wool insulation (ground)	37.46	m³	138,80	kg/m³	5,199
	Reinforcing steel	17.08	t	750,00	kg/t	12,813
Foundations	Concrete	741.17	t	130,30	kg/t	96,574
	Screed	31.11	t	160,00	kg/t	4,978
	Mineral wool insulation (ground)	34.57	m³	138,80	kg/m³	4,798
	Reinforcing steel	39.40	t	750,00	kg/t	29,554
					Total:	748 t CO_2e

Sub process	Machines	Material	Amount	Energy consumption		m_{CO_2e} [kg CO_2e]	
				b_l or b_m	b_{idle}	Present	Future
Loading	Forklift	Reinforcing steel, insulating glass, Aluminium profiles and sheets, mineral wool insulation, plaster mortar, gypsum plasterboard, nonius hanger, bitumen membrane, PVC membrane	407 t	13.05 kg CO_2e/h	1.66 kg CO_2e/h	1,.58	1.08
Transporting				12.42 kg CO_2e/h	1.58 kg CO_2e/h	10.16	6.91
Transporting	Truck	Reinforcing steel, insulating glass, Aluminium profiles and sheets, mineral wool insulation, plaster mortar, gypsum plasterboard, nonius hanger, bitumen membrane, PVC membrane	407 t	Present: 60.38 l/h Future: 57.28 l/h	-	2,262.12	2,033.57
Transporting	Truck mixer	Screed, concrete	1,269 m³	Present: 60.38 l/h Future: 57.28 l/h	-	24,101,.92	25,563.69
Lifting	Crane	Reinforcing steel, insulating glass, Aluminium profiles and sheets, mineral wool insulation, plaster mortar, gypsum plasterboard, nonius hanger, bitumen membrane, PVC membrane, steel	282 t	17.89 kg CO_2e/h	2.27 kg CO_2e/h	14.31	9.74
Forward driving				2.24 kg CO_2e/h	0.28 kg CO_2e/h	0,.32	0.22
Rotating				3.73 kg CO_2e/h	0.47 kg CO_2e/h	1.54	1.05
Concreting	Concrete pump	Concrete	1,269 m³	1.30 kg CO_2e/m³	0.17 kg CO_2e/m³	1,583.06	1,173.62
Compacting	Internal vibrator	Concrete	1,316 m²	0.70 kg CO_2e/h	0.09 kg CO_2e/h	42.37	28.83
Pumping	Vibrating beam	Concrete	375 m³	0.72 l/h	0.09 l/h	1.57	1.07
Pumping	Screed pump	Screed	64 m³	7.32 l/h	0.93 l/h	116.78	79.46
					Total	**28,136 kg CO_2e** **28 t CO_2e**	**28,899 kg CO_2e** **29 t CO_2e**

Road construction

Material	Material amount [m³]		GWP			m_{CO_2e} [kg CO_2e]		
	Past	Present & Future	Past	Present	Future	Past	Present	Future
1. Antifreeze layer	3,300	2,925	12.36 kg/m³	12.36 kg/m³	1.89 kg/m³	40,783	36,149	5,527
2. Base course	1,050	1,050	133.24 kg/m³	113.67 kg/m³	94.02 kg/m³	139,899	119,358	98,725
3. Binder course	600	600	144.33 kg/m³	127.78 kg/m³	123.47 kg/m³	86,598	76,667	74,083
5. Riding course	300	300	180.27 kg/m³	119.38 kg/m³	98.74 kg/m³	54,081	35,813	29,622
					Total	321,361	267,987	207,957

Process	Sub process	Machine	Unit	$V_{material}$ Past	$V_{material}$ Present	$V_{material}$ Future	b_l or b_m [l/h]	b_{idle} [l/h]	m_{CO_2e} [kg CO_2e] Past	m_{CO_2e} [kg CO_2e] Present	m_{CO_2e} [kg CO_2e] Future
1. Antifreeze layer	1.1 Dismantling & load	Excavator	m³	3,300	2,925	2,925	23.8	2.7	4,573	1,516	1,043
	1.2. Transport & unloading	Rear-dump truck	m³	3,300	2,925	2,925	Past: 58.83 Present: 60.38 Future: 57.28	-	50,140	27,453	27,741
	1.3. Rough distribution	Crawler Dozer	m³	1,650	1,463	1,463	16.8	2.1	2,129	687	468
	1.4. Fine distribution	Grader	m²	7,500	7,500	7,500	19.88	2.5	428	156	106
	1.5. Dynamic compaction	Drum roller	m²	7,500	7,500	7,500	12.7	1.6	1,825	666	453
2. Base course	2.1. Transport & unloading	Rear-dump truck	m³	1,050	1,050	1,050	Past: 58.83 Present: 60.38 Future: 57.28	-	19,898	13,242	11,338
	2.2. Paving & precompaction	Paver	m³	1,050	1,050	1,050	20.4	2.5	515	189	129
	2.3. Compaction	Tandem roller static	m²	7,500	7,500	7,500	12.7	1.6	347	127	86
	2.4. Compaction	Tandem roller dynamic	m²	7,500	7,500	7,500	12.7	1.6	1,085	396	269
3. Binder course	3.1. Transport & unloading	Rear-dump truck	m³	600	600	600	Past: 58.83 Present: 60.38 Future: 57.28	-	13,111	8,101	7,283
	3.2 Paving & precompaction	Paver	m³	600	600	600	20.4	2.5	515	189	129
	3.3. Compaction	Tandem roller static	m²	7,500	7,500	7,500	12.7	1.6	347	127	86
	3.4. Compaction	Tandem roller dynamic	m²	7,500	7,500	7,500	12.7	1.6	868	317	216
4. Riding course	4.1. Transport & unloading	Rear-dump truck	m³	300	300	300	Past: 58.83 Present: 60.38 Future: 57.28	-	8,640	5,004	3,999
	4.2. Paving & precompaction	Paver	m³	300	300	300	20.4	2.5	515	189	129
	4.3. Compaction	Tandem roller static	m²	7,500	7,500	7,500	12.7	1.6	347	127	86
	4.4. Compaction	Tandem roller dynamic	m²	7,500	7,500	7,500	12.7	1.6	651	237	162
	4.5. Compaction	Tandem roller static	m²	7,500	7,500	7,500	12.7	1.6	347	127	86
								Total	106 t CO_2e	59 t CO_2e	54 t CO_2e

Road renewal

Material for inlay process	Material amount [m³]		GWP			m_{CO_2e} [kg CO_2e]		
	Past	Present & Future	Past	Present	Future	Past	Present	Future
1. Base course	1,050	1,050	133.24 kg/m³	113.67 kg/m³	94.02 kg/m³	139,899	119,358	98,725
2. Binder course	600	600	144.33 kg/m³	127.78 kg/m³	123.47 kg/m³	86,598	76,667	74,083
3. Riding course	300	300	180.27 kg/m³	119.38 kg/m³	98.74 kg/m³	54,081	35,813	29,622
					Total	**280,578**	**231,838**	**202,430**

Process	Sub process	Machine	Unit	$V_{material}$ Past	$V_{material}$ Present	$V_{material}$ Future	b_l or b_m [l/h]	b_{idle} [l/h]	m_{CO_2e} [kg CO_2e] Past	Present	Future
1. Removal of the existing road	1.1 Milling	Cold-milling-machine	m³	1,950	1,950	1,950	76	9,7	10.606	3.862	2.628
	1.2 Transporting	Rear-dump truck	m³	1,950	1,950	1,950	Past: 58.83 Present: 60.38 Future: 57.28	-	47.128	27.296	26.175
2. Base course	2.1. Transport & unloading	Rear-dump truck	m³	1,050	1,050	1,050	Past: 58.83 Present: 60.38 Future: 57.28	-	19,898	13,242	11,338
	2.2. Paving & precompaction	Paver	m³	1,050	1,050	1,050	20.4	2.5	515	189	129
	2.3. Compaction	Tandem roller static	m²	7,500	7,500	7,500	12.7	1.6	347	127	86
	2.4. Compaction	Tandem roller dynamic	m²	7,500	7,500	7,500	12.7	1.6	1,085	396	269
3. Binder course	3.1. Transport & unloading	Rear-dump truck	m³	600	600	600	Past: 58.83 Present: 60.38 Future: 57.28	-	13,111	8,101	7,283
	3.2 Paving & precompaction	Paver	m³	600	600	600	20.4	2.5	515	189	129
	3.3. Compaction	Tandem roller static	m²	7,500	7,500	7,500	12.7	1.6	347	127	86
	3.4. Compaction	Tandem roller dynamic	m²	7,500	7,500	7,500	12.7	1.6	868	317	216
4. Riding course	4.1. Transport & unloading	Rear-dump truck	m³	300	300	300	Past: 58.83 Present: 60.38 Future: 57.28	-	8,640	5,004	3,999
	4.2. Paving & precompaction	Paver	m³	300	300	300	20.4	2.5	515	189	129
	4.3. Compaction	Tandem roller static	m²	7,500	7,500	7,500	12.7	1.6	347	127	86
	4.4. Compaction	Tandem roller dynamic	m²	7,500	7,500	7,500	12.7	1.6	651	237	162
	4.5. Compaction	Tandem roller static	m²	7,500	7,500	7,500	12.7	1.6	347	127	86
								Total	105 t CO_2e	60 t CO_2e	53 t CO_2e

Earthmoving work

Pit construction for a flat

Process	Sub process	Machine	Unit	$V_{material}$ Past	$V_{material}$ Present	$V_{material}$ Future	b_l or b_m [l/h]	b_{idle} [l/h]	m_{CO_2e} [kg CO_2e] Past	Present	Future
1. Construction of the excavation pit	1.1 Earth removal	Crawler dozer	m³	136	136	136	13.58	1.7	189	69	47
	1.2 Loading onto the truck	Excavator	m³	136	136	136	23.8	2.7	156	59	40
	1.3 Transporting the earth away	Rear-dump truck	m³	136	136	136	Past: 58.83 Present: 60.38 Future: 57.28	-	1.715	1.060	1.071
	1.4 Digging and loading the earth onto the truck	Excavator	m³	940	940	940	23.8	2.7	1.108	414	285
	1.5 Transporting the earth away	Rear-dump truck	m³	940	940	940	Past: 58.83 Present: 60.38 Future: 57.28	-	16.378	9.486	9.096
2. Compaction	2. Compacting	Vibratory plate compactor	m²	252	252	252	1.6	0.2	82	30	20
3. Backfilling after cellar construction	3.1 Backfilling	Wheel loader	m³	441	441	441	11.4	2.6	644	199	125
	3.2 Compacting	Vibratory plate compactor	m²	203	203	203	1.6	0.2	66	24	16
								Total	20 t CO_2e	11 t CO_2e	11 t CO_2e

Pit construction for an office building

Process	Sub process	Machine	Unit	$V_{material}$ Past	$V_{material}$ Present	$V_{material}$ Future	b_l or b_m [l/h]	b_{idle} [l/h]	m_{CO_2e} [kg CO_2e] Past	Present	Future
1. Construction of the excavation pit	1.1 Earth removal	Crawler dozer	m³	246	246	246	13.58	1.7	439	160	109
	1.2 Loading onto the truck	Excavator	m³	246	246	246	23.8	2.7	283	106	73
	1.3 Transporting the earth away	Rear-dump truck	m³	246	246	246	Past: 58.83 Present: 60.38 Future: 57.28	-	3,102	1,916	1,936
	1.4 Digging and loading the earth onto the truck	Excavator	m³	2309	2309	2309	23.8	2.7	2,722	1,018	701
	1.5 Transporting the earth away	Rear-dump truck	m³	2309	2309	2309	Past: 58.83 Present: 60.38 Future: 57.28	-	40,248	23,312	22,354
2. Compaction	2. Compacting	Vibratory plate compactor	m²	431	431	431	1.6	0.2	140	51	35
3. Backfilling after cellar construction	3.1 Backfilling	Wheel loader	m³	1039	1039	1039	11.4	2.6	1,516	469	295
	3.2 Compacting	Vibratory plate compactor	m²	391	391	391	1.6	0.2	127	46	31
								Total	49 t CO_2e	27 t CO_2e	26 t CO_2e

Dam construction for a BK10 road

Material for dam	Material amount [kg]		GWP			m_{CO_2e} [kg CO_2e]		
	Past	Present & Future	Past	Present	Future	Past	Present	Future
Lime	264,898	269,995	1.38 kg/t	1.19 kg/t	1.01 kg/t	366	321	273
Sand	10,335	10,542	6.90 kg/t	5.80 kg/t	5.05 kg/t	71	61	53
Clay	7,071	7,221	8.71 kg/t	7.40 kg/t	6.37 kg/t	62	53	46
					Total	**498**	**436**	**372**

Process	Sub process	Machine	Unit	$V_{material}$ Past	$V_{material}$ Present	$V_{material}$ Future	b_l or b_m [l/h]	b_{idle} [l/h]	m_{CO_2e} [kg CO_2e] Past	Present	Future
1. Topsoil removal	1.1 Removal of the topsoil to the pit	Crawler dozer	m³	4,675	4,765	4,765	21.70	2.76	9,790	3,634	2,472
2. Preparation of the ground	2.1 Compaction	Rubber wheeled roller	m³	15,582	15,882	15,882	12.70	1.60	3,558	1,323	901
3. Improvement of the subsoil	3.1 Transportation of lime	Binding agent spreader	m³	318	318	318	Past: 38.69 Present: 39.70 Future: 37.67	-	3,413	2,337	2,032
	3.2 Lime pre-scattering	Binding agent spreader	m²	15,882	15,882	15,882	33.88	4.30	1,197	436	297
	3.3 Mixing lime into the soil	Stabilizer	m²	15,882	15,882	15,882	66.28	8.42	7,667	2,792	1,900
	3.4 Compaction of the soil-lime mixture	Sheepfoot roller	m²	15,882	15,882	15,882	12.70	1.60	2,536	925	630
	3.5 Levelling of the soil-lime mixture	Grader	m²	15,882	15,882	15,882	20.30	2.58	131	48	32
	3.6 Fine compaction of the soil	Rubber wheeled roller	m²	15,882	15,882	15,882	12.70	1.60	3,627	1,323	901
4. Dam filling	4.1 Transporting the coarse sand	Rear-dump truck	m³	3,796	3,871	3,871	Past: 58.83 Present: 60.38 Future: 57.28	-	38,916	27,209	23,691
	4.2 Distribution	Crawler dozer	m³	3,796	3,871	3,871	21.70	2.76	4,984	1,851	1,259
	4.3 Compaction	Roller	m²	14,582	14,882	14,882	12.70	1.60	2,699	1,005	684
	4.4 Compaction of the dam shoulder	Vibratory plate compactor	m²	1,118	1,118	1,118	1.60	0.20	363	132	90
	4.5 Transporting the clay	Rear-dump truck	m³	3,536	3,611	3,611	Past: 58.83 Present: 60.38 Future: 57.28	-	36,250	25,381	22,099
	4.6 Distribution	Crawler dozer	m³	3,536	3,611	3,611	21.70	2.76	5,962	2,217	1,508
	4.7 Compaction	Roller	m²	13,582	13,882	13,882	12.70	1.60	3,102	1,157	788
	4.8 Compaction of the dam shoulder	Vibratory plate compactor	m²	1,118	1,118	1,118	4.20	0.53	220	80	54
	4.9 Transporting the fine sand	Rear-dump truck	m³	3,316	3,383	3,383	Past: 58.83 Present: 60.38 Future: 57.28	-	33,996	23,784	20,709
	4.10 Distribution	Crawler dozer	m³	3,316	3,383	3,383	21.70	2.76	4,354	1,618	1,101
	4.11 Compaction	Roller	m²	12,582	12,882	12,882	12.70	1.60	2,329	870	592
	4.12 Compaction of the dam shoulder	Vibratory plate compactor	m²	1,118	1,118	1,118	1.60	0.20	363	132	90
								Total	165t CO_2e	98t CO_2e	82 t CO_2e

Slot construction for a BK10 road

Material for dam	Material amount [kg]		GWP			m_{CO_2e} [kg CO_2e]		
	Past	Present & Future	Past	Present	Future	Past	Present	Future
Lime	96,900	102,000	1.38 kg/t	1.19 kg/t	1.01 kg/t	133.72	121.38	103.02
Sand	450	450	6.90 kg/t	5.80 kg/t	5.05 kg/t	3.11	2.61	2.27
Clay	2,917	2,917	8.71 kg/t	7.40 kg/t	6.37 kg/t	25.41	21.59	18.58
Reinforced concrete pipe	506,000	506,000	209.17 kg/t	177.79 kg/t	152.9 kg/t	105,840.02	89,961.74	77,367.40
					Total	**106 t CO_2e**	**901 t CO_2e**	**775 t CO_2e**

Process	Sub process	Machine	Unit	$V_{material}$ Past	$V_{material}$ Present	$V_{material}$ Future	b_l or b_m [l/h]	b_{idle} [l/h]	m_{CO_2e} [kg CO_2e] Past	Present	Future
1. Topsoil removal	1.1 Removal of the topsoil to the pit	Crawler dozer	m³	4,650	4,800	4,800	21.70	2.76	9,739	3,661	2,491
2. Construction of the slot	2.1 Excavation and loading onto the truck	Excavator	m³	13,450	13,952	13,952	23.80	2.70	15,853	6,152	4,233
	2.2 Transporting the earth	Rear-dump truck	m³	13,450	13,952	13,952	Past: 58.83 Present: 60.38 Future: 57.28	-	168,084	133,102	106,359
3. Preparation of the ground	3.1 Compaction	Rubber wheeled roller	m³	9,500	10,000	10,000	12.70	1.60	1,759	675	460
4. Improvement of the subsoil	4.1 Transportation of lime	Binding agent spreader	m³	114	120	120	Past: 38.69 Present: 39.70 Future: 37.67	-	1,225	883	768
	4.2 Lime pre-scattering	Binding agent spreader	m²	9,500	10,000	10,000	33.88	4.30	716	274	187
	4.3 Mixing lime into the soil	Stabilizer	m²	9,500	10,000	10,000	66.28	8.42	4,586	1,758	1,196
	4.4 Compaction of the soil-lime mixture	Sheepfoot roller	m²	9,500	10,000	10,000	12.70	1.60	1,517	583	397
	4.5 Levelling of the soil-lime mixture	Grader	m²	9,500	10,000	10,000	18.62	2.36	72	28	19
	4.6 Fine compaction of the soil	Roller	m²	9,500	10,000	10,000	12.70	1.60	1,759	675	460
5. Slot filling	5.1 Excavation and loading of the earth onto the truck	Excavator	m³	2,125	2,125	2,125	23.80	2.70	2,505	937	645
	5.2 Transporting earth	Rear-dump truck	m³	2,125	2,125	2,125	Past: 58.83 Present: 60.38 Future: 57.28	-	37,035	21,451	17,141
	5.3 Compacting	Trench roller	m²	2,000	2,000	2,000	4.20	0.53	393	143	97
	5.4 Transporting coarse sand	Rear-dump truck	m³	300	300	300	Past: 58.83 Present: 60.38 Future: 57.28		3,076	2,109	1,836
	5.5 Filling the lower bedding layer	Crawler dozer	m³	300	300	300	17.45	2.22	538	196	133
	5.6 Compacting	Vibratory plate compactor	m²	2,000	2,000	2,000	1.60	0.20	650	237	161
	5.7 Transporting the reinforced concrete pipes	Truck	m³	594	594	594	Past: 58.83 Present: 60.38 Future: 57.28	-	4,721	3,237	2,819
	5.8 Installing the reinforced concrete pipes	Excavator	pieces	666	666	666	23.80	2.70	18,679	6,988	4,809
	5.9 Transporting clay	Rear-dump truck	m³	1,459	1,459	1,459	Past: 58.83 Present: 60.38 Future: 57.28	-	17,036	11,680	10,170
	5.10 Filling	Crawler dozer	m³	1,459	1,459	1,459	17.45	2.22	2,568	935	636
	5.11 Compacting	Trench roller	m²	2,000	2,000	2,000	4.20	0.53	393	143	97
6. Embankment	6.1 Compacting embankment	Trench roller	m²	3,354	3,354	3,354	4.20	0.53	659	240	163
								Total	294 t CO_2e	196 t CO_2e	155 t CO_2e

Material extraction

Machines	Number of machines	$t_{working}$/day [h/day]	b_l or b_m [l/h]	b_{idle} [l/h]	m_{CO_2e} [kg CO_2e] Past	Present	Future
Excavator	0.3	4	26.5	3.4	148	81	60
Rotatory drilling rigs	0.8	2	42.1	5.3	353	192	143
Explosives	-	-	-	-	24	24	24
Excavator	0.7	7	51.7	6.6	1.417	772	573
Wheel loader	0.4	7	28.9	3.7	452	246	183
Dump truck	1.5	7	21.6	2.7	1.271	693	514
Crusher	0.8	6	28.9	3.7	775	422	313
Screen	0.8	6	10.8	1.4	291	158	117
Wheel loader	1.0	5	20.4	2.6	572	312	231
Crawler dozer, motor grader	0.3	2	27.7	3.5	93	51	38
		Total per day			5,395	2,951	2,194
		Total per year (220 days/year)			1,186,802	649,301	482,734
		m_{CO_2e}/ t granulate [kg CO_2e/ t granulate]			10.79	5.90	4.39

Volume to blast [m³]	Quantity of ANFO explosives [kg]	CO_2e-factor for ANFO explosives [kg CO_2e/ t ANFO explosives]	m_{CO_2e} [kg CO_2e]
73,333	20,533	258	5,290

A. 3 Weight and volume calculation details of the five drive train concepts

For the calculations, an excavator of 30 t with an engine power of 152 kW and a fuel tank of 520 l diesel, corresponding to 6,340 MJ is taken as reference.

Fuel

The volume of fuel (V_{fuel}) is calculated for each concept with following formula:

$$V_{fuel} = \frac{m_{fuel}}{\rho_{fuel}} \quad (1)$$

Where m_{fuel} stands for the fuel mass and ρ_{fuel} for the fuel density. The following table shows the density value and the lower heating values used for the calculations.

Table A.3-1: Fuel density and lower heating value

Fuel	Fuel density ρ_{fuel} [kg/m³]	Lower heating value $H_{u,fuel}$ [MJ/kg]
Diesel	832	43.1
OME	1106	18.5
Liquefied methane	410	50
Liquefied H_2	71	120

The fuel mass for concepts working with an ICE is calculated with following equation *(2)*.

$$m_{fuel} = \frac{E}{H_{u,fuel} \times \eta_{ICE}} \quad (2)$$

Where E equals the energy output of 6,340 MJ, η_{ICE} the ICE engine efficiency of 0.34 and $H_{u,fuel}$ the lower heating value of the fuel.

The fuel mass for the concept working with a fuel cell and hydrogen H_2 (m_{H_2}) is calculated with following equation *(3)*.

$$m_{H_2} = \frac{E}{H_{u,H_2} \times \eta_{E-Motor} \times \eta_{Fuel\ cell}} \tag{3}$$

Where E equals the energy output of 6,340 MJ, $\eta_{E-Motor}$ the electric engine efficiency of 0.9 and H_{u,H_2} the lower heating value of hydrogen.

The fuel mass for the concept "Liquefied CH_4 & fuel cell" is calculated based on the stoichiometric ratio of reactions *(4)*.

$$\begin{array}{c} CH_4 + H_2O \rightarrow CO + 3H_2 \\ CO + H_2O \rightarrow CO_2 + H_2 \\ \hline CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \end{array} \tag{4}$$

This leads to the following stoichiometric ratio:

$$n_{CH_4} = \frac{1}{4} \times n_{H_2} \tag{5}$$

Where n_x stands for the mol of molecule x. Further, by inserting the mathematical relation *(6)* in *(5)*, equation *(7)* is obtained.

$$n_x = \frac{m_x}{M_x} \tag{6}$$

$$m_{CH_4} = \frac{1}{4} \times \frac{m_{H_2}}{M_{H_2}} \times M_{CH_4} \tag{7}$$

Where m_x stands for the mass and M_x for the molar mass of molecule x.
The mass of hydrogen m_{H_2} is calculated with equation *(8)*.

$$m_{H_2} = \frac{E}{\eta_{fuel\ cell} \times \eta_{Reformer} \times \eta_{E-motor} \times H_{u,H_2}} \tag{8}$$

Where $\eta_{fuel\ cell}$ is the fuel cell efficiency with 0.5, $\eta_{Reformer}$ the reformer efficiency with 0.75, $\eta_{E-motor}$ the electric engine efficiency with 0.9 and H_{u,H_2} the lower heating value of hydrogen.

Tank

The diesel and OME tank volume corresponds to the fuel volume. The volume of the hydrogen tank is considered to be twice as large as the volume of the fuel it contains. According to Weberbeck, the volume of the liquefied methane tank is twice as large as that of a diesel tank with the same energy output (Weberbeck 2016).

The mass of the tank of fuel x is calculated by multiplying the tank density $\rho_{tank,x}$ by the tank volume $V_{fuel,x}$, see equation *(9)*.

$$m_{tank,x} = \rho_{tank,x} \times V_{fuel,x} \qquad (9)$$

The tank densities used are listed in Table A.3-2 and are calculated on the basis of tank data available on the market.

Table A.3-2: Tank densities

Fuel	Tank density ρ_{tank} [kg/m³]
Diesel	49
OME	49
Liquefied methane	1148
Liquefied H_2	500

Drive

According to CAT, the diesel engine of a 30 t excavator has a weight of approximately 715 kg and a volume of 0.79 m³ (CAT 2011). The weight and volume of the fuel cell, battery and reformer are approximate values calculated on the basis of existing products on the market.

Exhaust aftertreatment system

The weight and volume of the exhaust aftertreatment system are approximate values calculated on the basis of existing products on the market.

A. 4 Calculation details of two CCS systems

For both systems, the weight and volume of the components are approximate values calculated on basis of existing products on the market.

System 1

According to Göttlicher, the specific compaction work amounts at 35 bar approximately to 0.091 kWh per kg CO_2 (f_x) (Göttlicher 1999).
An excavator with a diesel fuel tank of 520 l (V_{Diesel}) will produce 1,368 kg CO_2/Tank ($m_{CO_2/tank}$), see calculation in *(1)*.

$$m_{CO_2/tank} = V_{Diesel} \times f_{CO_2,TTW} = 520\ l \times 2.63\ kg\ CO_2/l = 1{,}368\ kg\ CO_2 \quad (1)$$

Where $f_{CO_2,TTW}$ stands for the converting factor of diesel into CO_2 during combustion (tank-to-wheel).
The compressor will have an energy demand of 124 kWh for 1,368 kg CO_2e, see equation *(2)*.

$$E_{Compressor} = m_{CO_2/tank} \times f_x = 1{,}368\ kg\ CO_2 \times 0.091 \frac{\text{kWh}}{kg\ CO_2} = 124\ MJ \quad (2)$$

System 2

The energy demand for the compressor of system 2 is calculated as for the compressor of system 1 using equation *(2)*. The only difference is the CO_2 mass $m_{CO_2/tank}$, which is composed of the mass of CO_2 produced by the combustion of the fuel ($m_{CO_2,fuel}$)and the mass of CO_2 in the air absorbed to cool the exhaust gas ($m_{CO_2,absorbed\ air}$), see equation *(3)*.

$$m_{CO_2/tank} = m_{CO_2,fuel} + m_{CO_2,absorbed\ air} \quad (3)$$

Where $m_{CO_2e,fuel}$ is equals to the value calculated in *(1)* and $m_{CO_2e,absorbed\ air}$ is calculated with equation *(7)*.
In order to calculate $m_{CO_2e,absorbed\ air}$ with equation *(7)*, the following calculations must be performed beforehand:

a) Calculation of the mas of the exhaust gas

b) Calculation of the amount of heat needed to uniformly lower the temperature of the exhaust gas ($\Delta Q_{exhaust\ gas}$)

c) Calculation of the air mass required for the cooling process (m_{air})

The mass of the exhaust gas $m_{exhaust\ gas}$ is calculated according to equation *(4)*.

$$m_{exhaust\ gas} = m_{diesel} + m_{air\ for\ fuel\ combustion} = V_{diesel} \times \varrho_{diesel} + V_{diesel} \times \varrho_{diesel} \times f_{air/diesel} = 520\ l \times 0.832\ \frac{kg\ diesel}{l} \times \left(1 + 14.5\ \frac{kg\ air}{kg\ diesel}\right) = 6{,}706\ kg \tag{4}$$

Where $f_{air/diesel}$ stands for the factor of how much air is needed in the ICE to burn diesel.

The heat energy $\Delta Q_{exhaust\ gas}$ to cool down the exhaust gas from 300°C to 30°C is calculated with equation *(5)*.

$$\Delta Q_{exhaust\ gas} = (m_{exhaust\ gas} = \left(303\ K \times 1{,}042 \frac{J}{kg\ K} - 573\ K \times 1{,}108 \frac{J}{kg\ K}\right) \times 6{,}706 = 2{,}143\ MJ \tag{5}$$

Where $c_{p,exhaust\ gas}$ stands for the specific heat capacity at different temperatures, T_2 for the target temperature to cool down, T_1 for the original temperature of the exhaust gas before flowing the turbine, see Figure 8.6.

The heat energy necessary to cool down the exhaust gas will be provided with the absorbed air. Therefore $\Delta Q_{exhaust\ gas}$ equals ΔQ_{air}, which leads to equation *(6)*.

$$m_{air} = = \frac{2{,}143\ MJ}{\left(303\ K \times 1{,}007 \frac{J}{kg\ K} - 573\ K \times 1{,}108 \frac{J}{kg\ K}\right)} = 6{,}491\ kg \tag{6}$$

The air contains 0.058 % of CO_2 which means that according to equation *(7)*, 3.76 kg CO_2 are contained in 6,491 kg air

$$m_{CO_2,absorbed\ air} = f_{CO_2/air} \times m_{air} = 0.058\ \% \times 6{,}491\ kg = 3.76\ kg \qquad (7)$$

According to equation *(3)* the total mass of CO_2 ($m_{CO_2/tank}$) equals 1,372 kg. The demand of energy for the compressor in system 2 equals consequently 449 MJ.

Curriculum vitae

Isabelle AYS
1989-12-07
French-German

WORK EXPERIENCE

Since 2014
Karlsruhe
GERMANY

RESEARCH ASSOCIATE IN MOBILE MACHINES -
Karlsruhe Institute of Technology (KIT)
Institute mobile machines (MOBIMA)

Research
Since 2014: European project with the Committee for European Construction Equipment (CECE) in cooperation with the European Agricultural Machinery (CEMA) on how to quantify CO_2e emissions for typical mobile machine application processes in quarry, earthmoving, road construction and building construction.

Since 2014: Research project on Liquefied Natural Gas for mobile machines (LNG) as an alternative energy source

Teaching
Since 2014: Lecturer for *Exercises of Modelling and Simulation* (Master class in German and English – approx. 700 students)

Since 2014: Lecturer for *Exercises of Projection and Development of Oil-hydraulic Drive Systems* (Master class in German – approx. 35 students)

Since 2014: Supervision and tutoring of student research projects (bachelor/ master / diploma theses)

Others
02/2017: Main organiser for the conference *6th symposium hybrid and energy efficient drives for mobile machines* (150 participants)

09/2016: Main organiser for the conference *9th mobile hydraulic colloquium* (100 participants)

INTERNSHIPS

06/2011- 10/2011 Tyumen *RUSSIA*	**FACTORY PLANNING AT MOSTOSTROY 11** Specialised in bridge construction 15-weeks internship within the mechanical engineering studies Activity: Modernisation of a plant producing prefabricated concrete components
06/2011 Paris Noisy-le-Sec *FRANCE*	**MARKETING & SALE AT PTC - FAYAT GROUP** Specialised in production of vibrodrivers 2-weeks internship within the mechanical engineering studies Activity: Sale of spare parts and writing job reports
02/2010 Ipswich *UK*	**NEW HAMMER RAIL DEVELOPMENT AT BSP** Specialised in production of hydraulic hammers 4-weeks internship within the mechanical engineering studies Activity: Dimensioning the rail of the new hammer product group
08/2007- 09/2007 Biberach *GERMANY*	**TECHNICAL WORKER AT LIEBHERR-WERK BIBERACH** Specialised in production of construction and industry cranes 6-weeks internship within the mechanical engineering studies Activity: Technical work in the machine tool centre and in the welding department

EDUCATION

2014 – exp. 2020 *FR / GER / IT*	**MASTER OF BUSINESS ADMINISTRATION - MBA** Collège des Ingénieurs (CDI), Paris, Munich, Torino
2007-2013 Karlsruhe Metz Paris *GER / FR*	**FRENCH-GERMAN DIPLOMA IN MECHANICAL ENGINEERING** Karlsruhe Institute for Technology (KIT), Karlsruhe (1.2 – Top 6 %) 2013: Diploma Thesis at Dr. Ing. h. c. F. Porsche AG in the drive train predevelopment department, Weissach (Germany)

	<u>Topic:</u> Building of a model-in-the-loop environment for the development of innovative engine control functions 2012: Second part of the main diploma at the KIT 2011: Intermediary Diploma Thesis (Studienarbeit) in the Grande Ecole Arts et Métiers ParisTech in Paris (ENSAM-Paris, France) <u>Topic:</u> Optimisation of manufacturing process by rapid prototyping in the art foundry 2009-2011: Grande Ecole Arts et Métiers ParisTech (ENSAM) in Metz (France): Mechanical Engineering studies as part of the French-German double diploma course between the KIT and ENSAM–Metz 2007-2009: Intermediate Diploma (Vordiplom) at the KIT
2002-2007 Freiburg im Breisgau *GERMANY*	**FRENCH-GERMAN ABITUR / BACCALAURÉAT** High School Graduation Deutsch-französisches Gymnasium/ Lycée Franco-Allemand Section: Mathematics-Physics

LANGUAGES

German, French, Spanish: mother tongue
English: business fluent
Russian: Good knowledge in spoken and written

OTHERS

2019	**1. Prize** for outstanding research, awarded by the VDBUM – German association for the Construction Industry, Environment technologies and Machine technologies
2015-2017	Baden-Wuertemberg didactic certificate of higher education (Baden-Württemberg Zertifikat für Hochschuldidaktik)
2017	**2. Prize** for outstanding research, awarded by the VDBUM
2009-2012	Mobility allowance from the DFH (Deutsch-Französische Hochschule)

ENGAGEMENT

Since 2016	Mentoring, coaching and tutoring a refugee from Afghanistan
2015	2. Chairman of the scientific association WVMA e.V.

List of all scientific publications

Analysis and Preliminary Design of Oxymethylene ether (OME) Driven Mobile Machines
Wu, Y.; Ays, I.; Geimer, M.
2019. Karlsruher Institute of Technology, Karlsruhe.
doi:10.5445/IR/1000097941

Methane-Fuel cell-CCS-Drive: the emission-free working machine
Ays, I.; Geimer, M.
2019. Hybride und energieeffiziente Antriebe für mobile Arbeitsmaschinen : 7. Fachtagung, 20. February 2019, Karlsruhe, 143–163, KIT Scientific Publishing, Karlsruhe. doi:10.5445/IR/1000091557

Flüssiges Methan als alternativer Energieträger für Landmaschinen
Engelmann, D.; Ays, I.; Geimer, M.
2018. 76. Internationale Tagung LAND.TECHNIK (2018), Leinfelden-Echterdingen, 20.–21. November 2018

Flüssigerdgas (LNG) als alternativer Energieträger für Landmaschinen- Geschlossener CO_2 Kreislauf mit synthetischem Methan
Ays, I.; Engelmann, D.; Geimer, M.
2018. Land. Technik - Agricultural Engineering - Das Forum für agrartechnische Innovationen, Leinfelden-Echterdingen, 20. - 21. November 2018, 119–128, VDI Verlag, Düsseldorf

Maschinenkonzepte für Mobile Arbeitsmaschinen mit Methanantrieb
Ays, I. A.; Weberbeck, L.; Engelmann, D.; Geimer, M.
2018. Mobile Maschinen, 2018 (5), 36–41

Einflüsse der Betriebseffizienz auf die CO_2e-Emissionen und die entstehenden Änderungen mit automatisierten Arbeitsmaschinen
Ays, I.; Becker, S.; Geimer, M.
2018. Mobile Maschinen, (4), 24–29

CO_2e Quantifizierung von mobilen Arbeitsmaschineneinsätzen im Erdbau, Steinbruch, Straßen- und Hochbau
Ays, I.; Geimer, M.
2017. Hybride und energieeffiziente Antriebe für mobile Arbeitsmaschinen : 6. Fachtagung, 15. February 2017, Karlsruhe, 145–161, KIT Scientific Publishing, Karlsruhe

Flüssiges Methan als alternativer Energieträger für mobile Arbeitsmaschinen
Ays, I.; Engelmann, D.; Geimer, M.
2017. Hybride und energieeffiziente Antriebe für mobile Arbeitsmaschinen : 6. Fachtagung, 15. February 2017, Karlsruhe, 125–143, KIT Scientific Publishing, Karlsruhe

Liquefied Natural Gas in Mobile Machines
Weberbeck, L.; Engelmann, D.; Ays, I.; Geimer, M.
2016. ATZoffhighway worldwide, 9 (4), 38–45. doi:10.1007/s41321-016-0532-8

Verflüssigtes Erdgas in mobilen Arbeitsmaschinen
Weberbeck, L.; Engelmann, D.; Ays, I.; Geimer, M.
2016. ATZ offhighway, 9 (4), 40–46. doi:10.1007/s35746-016-0033-9

Sustainable energy storages for mobile machines
Geimer, M.; Ays, I.
2015. Symposium on Efficiency of mobile machines and their processes in Brunswick 10/11. March 2015

CO_2 Quantification for Typical Mobile Machine Application Processes in Road Building, Earthmoving
Ays, I.; Geimer, M.
2015. Symposium on Efficiency of mobile machines and their processes in Brunswick 10/11. March 2015

Nachhaltige Energiekonzepte für mobile Arbeitsmaschinen - in welche Richtung gehen sie?
Geimer, M.; Ays, I.
2014. Mobile Maschinen, (6), 18–25

List of references

Abele, G. (1986): Technology transfer opportunities for the construction engineering community. Effect of cold weather on productivity. Edited by U.S. Army Cold Regions Research and Engineering Laboratory. U.S.

ACEA (2019): What is WLTP and how does it work? Edited by European Automobile Manufacturers' Association (ACEA). Available online at https://wltpfacts.eu/link-between-co2-emissions-fuel-consumption/, checked on 5/20/2019.

Adolph, L. et al. (2016): Ratgeber zur Gefährdungsbeurteilung - Handbuch für Arbeitsschutzfachleute: Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA). Available online at https://www.baua.de/DE/Angebote/Publikationen/Fachbuecher/Gefaehrdungsbeurteilung.pdf?__blob=publicationFile&v=12, checked on 2/22/2019.

AECC (2019): Real-driving emissions. Edited by Association for Emissions Control by Catalyst (AECC). Available online at https://www.aecc.eu/key-topics/real-driving-emissions/, checked on 5/20/2019.

Ahn, C. et al. (2009): Sustainability analysis of earthmoving operations. In A. Dunkin (Ed.): Proceedings of the 2009 Winter Simulation Conference. Austin, Texas, 13-16. December 2009: IEEE Service Center, pp. 2605–2611.

Ahn, C. et al. (2010): Enhanced estimation of air emissions from construction operations based on descrete-event simulation. In W. Tizani (Ed.): Proceedings of 13th International Conference on Computing in Civil and Building Engineering (ICCBE 2010) and the 17th International EG-ICE Workshop on Intelligent Computing in Engineering (ICE10), 30. June - 2. July 2010. Nottingham: The University of Nottingham.

Ahn, C. R.; Lee, S. (2013): Importance of operational efficiency to achieve energy efficiency and exhaust emission reduction of construction operations. In Journal of construction engineering and management

139 (4), pp. 404–413. DOI: 10.1061/(ASCE)CO.1943-7862.0000609.

Al-Abbasi, M. D. (2014): Impact of weather conditions on construction labor productivity in state of qatar. Supervisor: Senouci, A. Report. College of Engineering, Qatar University, Qatar.

Anon. (2017): Notwendiger Ölwechsel: Warum auch das Getriebe an und an neuen Schmierstoff benötigt. Published under the pseudonym Julian. Edited by Moto Integrator powered by Intercars. Available online at https://www.motointegrator.de/blog/notwendiger-oewechsel-getriebeoel/, checked on 12/23/2018.

Arocho, I. et al. (2016): Time and cost characterisation of emissions from non-road diesel equipment for infrastructure projects. In International Journal of Sustainable Engineering 11 (2), pp. 1–12. DOI: 10.1080/19397038.2016.1218569.

asPECT. Asphalt Pavement Embodied Carbon Tool (2014): TRL The Future of Transport. Available online at http://www.sustainabilityofhighways.org.uk/Index.aspx, checked on 10/3/2018.

Ays, I. et al. (2018a): Maschinenkonzepte für Mobile Arbeitsmaschinen mit Methanantrieb. In Mobile Maschinen (5), pp. 36–41.

Ays, I.; Becker, S.; Geimer, M. (2018b): Einflüsse der Betriebseffizienz auf die CO2e-Emissionen und die entstehende Änderungen mit automatisierten Arbeitsmaschinen. In Mobile Maschinen (4), pp. 24–29.

Ays, I.; Engelmann, D.; Geimer, M. (2017): Flüssiges Methan als alternativer Energieträger für mobile Arbeitsmaschinen. In M. Geimer, P.-M. Synek (Eds.): 6. Fachtagung - Hybride und energieeffiziente Antriebe für mobile Arbeitsmaschinen. Karlsruhe, 15. February 2017. Karlsruhe: KIT Scientific Publishing (50), pp. 125–143.

Ays, I.; Geimer, M. (2019): Methane-Fuel cell-CCS-Drive: the emission-free working machine. In M. Geimer, P.-M. Synek (Eds.): 7. Fachtagung - Hybride und energieeffiziente Antriebe für mobile Arbeitsmaschinen. Karlsruhe, 20. February 2019. Karlsruhe: KIT Scientific Publishing (67), pp. 143–163.

Bajjou, M. S.; Chafi, A.; En-Nadi, A. (2017): A comparative study between lean construction and the traditional production system. In JERA 29, pp. 118–132. DOI: 10.4028/www.scientific.net/JERA.29.118.

Barandica, J. M. et al. (2013): Applying life cycle thinking to reduce greenhouse gas emissions from road projects. In Journal of Cleaner Production 57, pp. 79–91. DOI: 10.1016/j.jclepro.2013.05.036.

Barandica, J. M. et al. (2014): Estimation of CO2 emissions in the life cycle of roads through the disruption and restoration of environmental systems. In Ecological Engineering 71, pp. 154–164. DOI: 10.1016/j.ecoleng.2014.07.009.

Barati, K.; Shen, X. (2016): Operational level emissions modelling of on-road construction equipment through field data analysis. In Automation in Construction 72, pp. 338–346. DOI: 10.1016/j.autcon.2016.08.010.

Barati, K.; Shen, X. (2017): Optimal driving pattern of on-road construction equipment for emissions reduction. In Procedia Engineering 180, pp. 1221–1228. DOI: 10.1016/j.proeng.2017.04.283.

BDI (2004): Freiwillige Vereinbarung und Selbstverpflichtungen. Edited by Bundesverband der Deutschen Industrie e.V. Berlin.

Behched, B.; Delikostov, T.; Enchev, E. (2011): Research the influence of technical condition of the intake air filter on fuel consumption. In : Scientific proceedings XIX international scientific-technical conference "trans & MOTAUTO ’11", XIX. Varna, Bulgaria, 29. June - 1. July 2011 (123), pp. 43–44. Available online at https://trans-motau-to.com/sbornik/2011/1/14.RESEARCH%20THE%20INFLUENCE%20OF%20TECHNICAL%20CONDITION%20OF%20THE%20INTAKE%20AIR%20FILTER%20ON%20FUEL%20CONSUMPTION.pdf, checked on 12/23/2018.

Ben-Mansour, R. et al. (2016): Carbon capture by physical adsorption: Materials, experimental investigations and numerical modeling and simulations – A review. In Applied Energy 161, pp. 225–255. DOI: 10.1016/j.apenergy.2015.10.011.

Bomag GmbH, F. G. (Ed.) (2009): Grundlagen der Asphaltverdichtung. Verdichtungsverfahren, Verdichtungsgeräten, Walztechnik. Boppard. Available online at https://www.bomag.com/de/media/pdf/PRD109016_0109_Walzfibel.pdf, checked on 2/27/2019.

Bomag GmbH, F. G. (Ed.) (2015): Technical Data. Asphalt Manager 2, BW 154 AP-4V AM, BW 174 AP-4F AM. Hellerwald. Available online at https://www.bomag.com/dam/BOMAG/Other/Data_Sheets/Datasheet_BW154AP-4iAM_BW174AP-4FAM_PRE870548010_SA03.pdf, checked on 2/27/2019.

Bös, M. (2015): Untersuchung und Optimierung der Fahrkomfort- und Fahrdynamikeigenschaften von Radladern unter Berücksichtigung der prozessspezifischen Randbedingungen. Dissertation. Institute Mobile Machines. Karlsruhe Institute of Technology (KIT), Karlsruhe.

Böser, C.; Brütting, M.; Ellegast, R. (2011): Einsatz von VR zur Sichtfeldgestaltung von Baumaschinenführer. Themenblock „Konzeptive Ergonomie“. In R. P. Ellegast (Ed.): 4. Fachgespräch Ergonomie 2010. Sankt Augustin, 10-11 November 2010. Sankt Augustin, Berlin: IFA; DGUV (IFA-Report, 2011,6), pp. 19–24.

Brickenkamp, R.; Schmidt-Atzert, L.; Liepmann, D. (2010): d2-R. Test d2 - Revision. Aufmerksamkeits- und Konzentrationstest. Göttingen: Hogrefe Verlag GmbH&Co. KG.

Brixel, R. (2018): Validierung des Einflusses eines Baumaschinenführers auf die CO2e-Quantifizierungsmethode. Supervisors: Geimer, M.; Ays, I. Bachelor thesis. Institute Mobile Machines. Karlsruhe Institute of Technology (KIT), Karlsruhe.

Brundtland, G. H. (1987): Report of the World Commission on Environment and Development: Our Common Future. Available online at https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf, checked on 5/12/2019.

Bubb, H. et al. (2015): Automobilergonomie. Wiesbaden: Springer Fachmedien Wiesbaden.

Bullinger, H.-J. (1994): Ergonomie. Produkt- und Arbeitsplatzgestaltung. Wiesbaden: Vieweg+Teubner Verlag (Technologiemanagement - Wettbewerbsfähige Technologieentwicklung und Arbeitsgestaltung).

Cao, T. et al. (2016): Evaluations of in-use emission factors from off-road construction equipment. In Atmospheric Environment 147, pp. 234–245. DOI: 10.1016/j.atmosenv.2016.09.042.

CARB (2006): Overview: OFFROAD Model. Appendix A. Edited by California Air Resources Board. Boston. Available online at https://www.arb.ca.gov/msei/offroad/pubs/offroad_overview.pdf, checked on 9/2/2019.

CARB (2009): Appendix - D: OSM and summary of off-road emissions inventory update. Edited by California Air Resources Board. Available online at https://www.arb.ca.gov/regact/2010/offroadlsi10/offroadappd.pdf, checked on 8/29/2018.

Castellania, B. et al. (2012): Capture of carbon dioxide using gas hydrate technology. In : Proceedings of ECOS 2012. The 25th international conference of efficiency, cost, optimization, simulation and environmental impact of energy systems. Perugia, 26-29. June 2012. Perugia, Italy.

CAT (1999): Fluid Contamination - the silent thief. Caterpillar Inc.

CAT (2011): C7.1 ACERT Industrial Engine. Tier 4 Interim/ Stage IIIB. Edited by Caterpillar Inc.

CECE (2016): Constructing the Europe of tomorrow. Edited by Committee for European Construction Equipment (CECE). Brussels.

CEMA; CECE (Eds.) (2011): CECE and CEMA Optimising our industry 2 reduce emissions. Available online at http://cema-agri.org/sites/default/files/publications/CECE-CEMA-CO2-SuccessStories.pdf, checked on 10/6/2018.

Chen, N. (2019a): Entwicklung einer Nachhaltigkeit-Bewertungsmethode für mobile Arbeitsmaschinen. Supervisors: Geimer, M.; Ays, I. Master thesis. Institute Mobile Machines. Karlsruhe Institute of Technology (KIT), Karlsruhe.

Chen, X. et al. (2018): A novel biomass lubricant filter and its effect on gasoline engine emissions and fuel economy. In Journal of the Energy Institute, pp. 1–9. Available online at https://www.sciencedirect.com/science/article/pii/S1743967117303392, checked on 12/23/2018.

Chen, X. (2019b): Quantification of the loss of CO2e sinks due to vegetation clearance and soil movement before construction work & quantification of the effects of restoration after construction work. Supervisors: Geimer, M.; Ays, I. Master thesis. Institute Mobile Machines. Karlsruhe Institute of Technology (KIT), Karlsruhe.

CNH Industrial: Intelligentes Design verbunden mit Brachialer Kraft. Ein patentiertes neues Zahnsystem mit einer Befestigunstechnik, die keinen Hammer erfordert. SMARTFIT Bucket Tooths System. Edited by Case construction.

Cummins MPG Guide (Ed.) (2012): Secrets of better fuel economy. The physics of MPG. Available online at https://www.idleair.com/wp-content/uploads/2011/02/2012-04-26-Cummins-Secrets-of-Fuel-Economy-Idling-pgs-29-and-32.pdf, checked on 11/25/2018.

Dai, J. et al. (2009): Latent Structures of the factors affecting construction labor productivity. In Journal of construction engineering and management 135 (5), pp. 397–406. DOI: 10.1061/(ASCE)0733-9364(2009)135:5(397).

Demaison, C. et al. (2017): Les conditions de logement en France. Edited by Institut national de la statistique et des études économiques (INSEE). Paris. Available online at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwi6u5SDrcneAhUHTsAKHTOjAl8QFjAAegQI-ABAC&url=https%3A%2F%2Fwww.insee.fr%2Ffr%2Fstatistiques%2Ffichier%2F2586377%2FLOGFRA17.pdf&usg=AOvVaw2Rp5LeRfPvsKk8GuxkoIR3, checked on 11/10/2018.

Department for Transport (Ed.) (2014): Transport Statistics Great Britain 2014. National Statistics. Available online at https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/389592/tsgb-2014.pdf, checked on 11/17/2018.

Destatis (2015): Bautätigkeit und Wohnungen. Bautätigkeiten. 2014. Edited by Statistisches Bundesamt. Wiesbaden.

Destatis (2018a): Bauen und Wohnen. Baugenehmigungen / Baufertigstellungen u.a. nach der Gebäudeart - Lange Reihen z.T. ab 1960 - 2017. 2017. Edited by Statistisches Bundesamt. Available online at https://www.destatis.de/DE/Publikationen/Thematisch/Bauen/BautaetigkeitWohnungs-bau/BaugenehmigungenGebaeudeartPDF_5311102.pdf?__blob=publicationFile, checked on 11/10/2018.

Destatis (2018b): Bauen und Wohnen. Baugenehmigungen von Wohn- und Nichtwohngebäuden nach überwiegend verwendetem Baustoff - Lange Reihen ab 1980 - 2017. 2017. Edited by Statistisches Bundesamt. Available online at https://www.destatis.de/DE/Publikationen/Thematisch/Bauen/BautaetigkeitWohnungs-bau/BaugenehmigungenBaustoffPDF_5311107.pdf?__blob=publicationFile, checked on 11/10/2018.

Directive 2002/44/EC (2002): Directive 2002/44/EC of the European Parliament and of the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (sixteenth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). Available online at https://eur-lex.europa.eu/resource.html?uri=cellar:546a09c0-3ad1-4c07-bcd5-9c3dae6b1668.0004.02/DOC_1&format=PDF, checked on 1/24/2019.

Directive 2003/10/EC (2003): Directive 2003/10/EC of the European Parliament and of the Council of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise) (Seventeenth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC). Available online at https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32003L0010&from=DE, checked on 1/22/2019.

Dore, C. et al. (2016): EMEP/EEA air pollutant emission inventory guidebook 2016. Technical guidance to prepare national emission inventories. Luxembourg: Publications Office of the European Union (EEA report, 21/2016).

Drobek, J. (2003): Die Auswirkung von ungünstigen Witterungseinflüssen auf den arbeitenden Menschen in Hinblick auf Gesundheit und Produktivität. Hamburg: Diplomica GmbH (Technik).

Ecoinvent. Version 3.4 (2007): institutes of the ETH Domain; the Swiss Federal Offices. Available online at https://www.ecoinvent.org/about/about.html, checked on 9/2/2019.

Edwards, R. et al. (2014a): Well-To-Tank Appendix 1 - Version4a. Conversion factors and fuel properties. Well-to-wheels analysis of future automative fuels and powertrains in the European contextT. Edited by Institute for Energy and Transport, Joint research Centre, European Comission. Italy.

Edwards, R. et al. (2014b): WELL-TO-TANK Appendix 4 - Version 4a: Description, results and input data per pathway. Well-to-wheels analysis of future Automotive fuels and powertrains in the European context. Edited by Institute for Energy and transport, Joint Research Centre. Ispra, Italy.

EEA (2016): Trends and projections in Europe 2016 - Tracking progress towards Europe's climate and energy targets. Edited by European Environment Agency. Denmark. Available online at https://www.eea.europa.eu/themes/climate/trends-and-projections-in-europe, checked on 2/14/2018.

Egbu, C.; Sihabuddin, S. S.; Ariaratnam, S. T. (2009): Methodology for estimating emissions in underground utility construction operations. In Journal of Engineering, Design and Technology 7 (1), pp. 37–64. DOI: 10.1108/17260530910947259.

Ehrhard, T.; Widmann, A. (2017): Abgasgesetzgebung Diesel- und Gasmotoren. Motoren und Systeme. Edited by Mechanical Engineering Industry Association (VDMA). Frankfurt. Available online at mus.vdma.org/emission, checked on 3/27/2018.

Eisele, J.; Staniek, B. (Eds.) (2005): BürobauAtlas. Grundlagen, Planung, Technologie, Arbeitsplatzqualitäten. München: Callwey.

Engelmann, D.; Ays, I.; Geimer, M. (2018): Flüssiges Methan als alternativer Energieträger für Landmaschinen. 76. Internationale Tagung LAND.TECHNIK (2018). VDI Wissensforum GmbH. Leinfelden-Echterdingen, 11/20/2018.

EPA (1991): Nonroad engine and vehicle emission study. Report. Edited by United States Environmental Protection Agency (EPA). National Vehicle and Fuel Emissions Laboratory Office of Transportation and Air Quality. U.S. Available online at https://nepis.epa.gov/Exe/ZyPDF.cgi/P100AI9E.PDF?Dockey=P100AI9E.PDF, checked on 8/12/2018.

EPA (1997): Evaluation of power systems research (PSR) Nonroad population database. Pechan Report No. 97.09.003/1807. Edited by United States Environmental Protection Agency (EPA). Available online at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.360.4253&rep=rep1&type=pdf, checked on 9/2/2019.

EPA (2002): Exhaust and crankcase emission factors for nonroad engine modeling compression-ignition. Edited by United States Environmental Protection Agency (EPA). Available online at https://nepis.epa.gov/Exe/ZyPDF.cgi/P10005BI.PDF?Dockey=P10005BI.PDF, checked on 8/12/2018.

EPA (2006): Compilation of state, county, and local anti-idling regulations. Edited by United States Environmental Protection Agency (EPA). Available online at https://www.epa.gov/sites/production/files/documents/CompilationofStateIdlingRegulations.pdf, checked on 9/2/2019.

EPA (2009): Potential for reducing greenhouse gas emissions in the construction sector. Edited by United States Environmental Protection Agency (EPA). U.S. Available online at https://archive.epa.gov/sectors/web/pdf/construction-sector-report.pdf, checked on 9/2/2019.

EPA (2010a): Exhaust Emission Factors for Nonroad Engine Modeling -- Spark-Ignition. Report No. NR-010F. Edited by United States Environmental Protection Agency (EPA). Ann Arbor, U.S., checked on 8/1/2018.

EPA (2010b): Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling, Report No. NR-005d (EPA420-R-10-016) (July 2010). NR-005d. Edited by United States Environmental Protection Agency (EPA). Available online at https://nepis.epa.gov/Exe/ZyPDF.cgi/P10081RV.PDF?Dockey=P10081RV.PDF, checked on 8/12/2018.

EPA (2010c): Nonroad engine population estimates. NR-006e. Edited by United States Environmental Protection Agency (EPA). Available online at https://nepis.epa.gov/Exe/ZyNET.exe/P10081T6.TXT?ZyActionD=ZyDocument&Client=EPA&Index=2006+Thru+2010&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C06thru10%5CTxt%5C00000019%5CP10081T6.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL, checked on 9/2/2019.

Ernst, C.-S. (2014): CO2-Emissionsreduktion bei PKW und leichten Nutzfahrzeuge nach 2020. Edited by RWTH Aachen University. Institut für Kraftfahrzeuge Strategie und Beratung. Aachen.

Euromot, CECE, CEMA (Ed.) (2008): European Inventory Calculations for Agricultural (Ag) and Construction Equipment (CE) Applications of Diesel-Powered Non-Road Mobile Machinery (NRMM). Available online at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwjUkejVxLLkAhVQZlAKHVSdCHQQFjAAegQIAR-AB&url=http%3A%2F%2Fec.europa.eu%2FDocsRoom%2Fdocuments%2F1632%2Fattachments%2F1%2Ftranslations%2Fen%2Frenditions%2Fnative&usg=AOvVaw1h5rbMeK-v-4S1gAVgyNBo, checked on 9/2/2019.

Europäische Parlament und Rat der Europäischen Union (2003): Förderung der Verwendung von Biokraftstoffen oder anderen erneuerbaren

Kraftstoffen im Verkehrssektor. Richtlinie 2003/30/EG. Available online at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:123:0042:0046:DE:PDF, checked on 9/2/2019.

Europäische Parlament und Rat der Europäischen Union (2009): Förderung der Nutzung von Energie aus erneuerbaren Quellen und zur Änderung und anschließenden Aufhebung der Richtlinie 2001/77/EG und 2003/30/Eg. Richtlinie 2009/28/EG. Available online at https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32009L0028&from=EN, checked on 9/2/2019.

European Commission (Ed.) (2013): Questions & Answers on EU ratification of the second commitment period of the Kyoto Protocol. Available online at http://europa.eu/rapid/press-release_MEMO-13-956_en.htm, checked on 5/19/2019.

European Commission (Ed.) (2016): EU science hub: The European Commission's science and knowledge service - Well-to-Wheels Analyses. Available online at https://ec.europa.eu/jrc/en/jec/activities/wtw, checked on 8/23/2018.

European Commission (Ed.) (2017a): 2030 climate & energy framework. Available online at https://ec.europa.eu/clima/policies/strategies/2030, checked on 5/19/2019.

European Commission (Ed.) (2017b): Reducing CO2 emissions from heavy-duty vehicles. Available online at https://ec.europa.eu/clima/policies/transport/vehicles/heavy_de, checked on 2/14/2019.

European Commission (Ed.) (2019): Simulation tool for heavy duty vehicles (HDVs). Available online at https://ec.europa.eu/clima/policies/transport/vehicles/vecto_en, checked on 1/20/2020.

Eurostat (2003): The Lucas survey. European statisticians monitor territory. Luxembourg: Publications Office (Working papers & studies. Agriculture and fisheries).

Eurostat (2013): Civil engineering statistics. NACE. Edited by European Statistical Office - statistics explained. Available online at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Civil_engineering_statistics_-_NACE_Rev._2#Country_analysis, checked on 11/17/2018.

Eurostat (2017a): Climate change- driving forces. Edited by Eurostat Statistics Explained. Available online at http://ec.europa.eu/eurostat/statistics-explained/index.php/Climate_change_-_driving_forces, checked on 9/2/2019.

Eurostat (2017b): Europe 2020 indicators - climate change and energy. Edited by Eurostat Statistics Explained. Available online at http://ec.europa.eu/eurostat/statistics-explained/index.php/Europe_2020_indicators_-_climate_change_and_energy, checked on 9/2/2019.

Eurostat (2018): Building permits - quarterly data. Edited by European Statistical Office. Available online at http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do, checked on 11/8/2018.

Fan, H. (2017): A critical review and analysis of construction equipment emission factors. In Procedia Engineering (196), pp. 351–358. DOI: 10.1016/j.proeng.2017.07.210.

Feng, Y.; Zhong, Y. (2015): Case study on CO2 emission by construction of structural elements of a residential project in Singapore. In L. Shen (Ed.): Proceedings of the 19th international symposium on advancement of construction management and real estate. CRIOCM2014. Chongqing, China, 7-9. November 2014. Berlin: Springer (Business/Economics), pp. 303–312.

Fernández-Sánchez, G. et al. (2015): Opportunities for GHG emissions reduction in road projects: a comparative evaluation of emissions scenarios using CO2NSTRUCT. In Journal of Cleaner Production 104, pp. 156–167. DOI: 10.1016/j.jclepro.2015.05.032.

Fischedick, M.; Görner, K.; Thomeczek, M. (Eds.) (2015): CO2: Abtrennung, Speicherung, Nutzung. Ganzheitliche Bewertung im Bereich von Energiewirtschaft und Industrie. Berlin: Springer Vieweg.

Fischer, M.; Fontana, M.; Krämer, K. (2010): Wirtschaftliche Optimierung im vorbeugenden Brandschutz. In Die Volkswirtschaft - Das Magazin für Wirtschaftspolitik (6), pp. 60–63. Available online at https://dievolkswirtschaft.ch/content/uploads/2010/06/fischer.pdf, checked on 11/11/2018.

FNTP (2014): Activités en 2013. Edited by Fédération Nationale des Travaux publics. Paris. Available online at http://www.fntp.fr/upload/docs/application/pdf/2014-11/z_card_2014.pdf, checked on 10/20/2015.

Frank, B. et al. (2012a): On increasing fuel efficiency by operator assistance systems in a wheel Loader. In : Proceedings of 2012 International Conference on Advanced Vehicle Technologies and Integration. International Conference on Advanced Vehicle Technologies and Integration (VTI 2012). Changchun, China, 2012. Beijing: China Machine Press.

Frank, B.; Skogh, L.; Alaküla, M. (2012b): On wheel loader fuel efficiency difference due to operator behaviour distribution. In K. Berns et al. (Eds.): Commercial Vehicle Technology 2012. Proceedings of the 2nd Commercial Vehicle Technology Symposium (CVT 2012). Kaiserslautern, 13-15. March 2012. 2nd ed. Aachen: Shaker (Berichte aus der Fahrzeugtechnik). Available online at https://www.iea.lth.se/publications/Papers/Frank_2012.pdf, checked on 7/11/2018.

Fraunhofer IWM (Ed.) (2018): Wasserstoffversprödung metallischer Werkstoffe - Fraunhofer IWM. Available online at https://www.iwm.fraunhofer.de/de/geschaeftsfelder/werkstoffbewertung-lebensdauerkonzepte/mikrostruktur-eigenspannungen/wasserstoffversproedung-metallischer-werkstoffe.html, updated on 9/10/2018, checked on 9/11/2018.

Gehbauer, F.; Gentes, S. (2011): Lecture documents “Baubetriebsplanung und Grundlagen der Verfahrenstechnik im Hoch-, Tief-und Erdbau". Edited by Karlsruhe Institute of Technology (KIT). Institute for Technology and Management in Construction (TMB). Karlsruhe.

Geimer, M. (2014): Grundlagen mobiler Arbeitsmaschinen. With assistance of C. Pohlandt. Karlsruhe, Baden: KIT Scientific Publishing (22).

Geimer, M. (2018/2019): Fluidtechnik. Lecture document. Edited by Karlsruhe Institute of Technology (KIT). Institute Mobile Machines (MOBIMA). Karlsruhe.

Geimer, M.; Ays, I. (2014): Nachhaltige Energiekonzepte für mobile Arbeitsmaschinen – in welche Richtung gehen sie? In Mobile Maschinen (6/2014), pp. 18–25.

Gemis. Version 2018 (1989): Internationales Institut für Nachhaltigkeitsanalysen und -strategien (IINAS). Available online at http://iinas.org/gemis-de.html, checked on 10/3/2018.

Golombek, N.; Klovert, H. (2019): Dürfen Schüler schwänzen, wenn sie demonstrieren wollen? Edited by Spiegel online. Available online at https://www.spiegel.de/lebenundlernen/schule/fridays-for-future-duerfen-schueler-gegen-klimawandel-protestieren-a-1257881.html, checked on 9/3/2019.

Goris, A.; Schneider, K.-J. (Eds.) (2010): Bautabellen für Ingenieure. Mit Berechnungshinweisen und Beispielen. 19th ed. Neuwied, Köln: Werner; Wolters Kluwer.

Göttlicher, G. (1999): Energetik der Kohlendioxidruckhaltung in Kraftwerken. In Fortschritt-Berichte VDI. Reihe 6, Energietechnik 421.

Gralla, M. (2011): Baubetriebslehre, Bauprozessmanagement. Köln: Werner.

GreenDOT. Greenhouse Gas Calculator for State Departments of Transportation. Version version 1.5 beta (2010): NCHRP Project 25-25/Task 58 and ICF International.

Greenhouse Gas Protocol (Ed.) (2016): Global Warming Potentials Values. Available online at https://www.ghgprotocol.org/sites/default/files/ghgp/Global-Warming-Potential-Values%20%28Feb%2016%202016%29_1.pdf, checked on 2/14/2019.

Grüneberg, E.; Ziche, D.; Wellbrock, N. (2014): Organic carbon stocks and sequestration rates of forest soils in Germany. In Global change biology 20 (8), pp. 2644–2662. DOI: 10.1111/gcb.12558.

Hajji, A. (2015): The use of construction equipment productivity rate model for estimating fuel use and carbon dioxide (CO2) emissions. Case study: bulldozer, excavator and dump truck. In International Journal of Sustainable Engineering 8 (2), pp. 111–121. DOI: 10.1080/19397038.2014.962645.

Hajji, A. M.; Lewis, M. P. (2013a): Development of productivity-based estimating tool for fuel use and emissions from earthwork construction activities. In Journal of Construction Engineering and Project Management 3 (2), pp. 58–65. DOI: 10.6106/JCEPM.2013.3.2.058.

Hajji, A. M.; Lewis, P. (2013b): Development of productivity-based estimating tool for energy and air emissions from earthwork construction activities. In Smart and Sustainable Built Environment 2 (1), pp. 84–100. DOI: 10.1108/20466091311325863.

Hanke, S. (2014): Nachweisführung. Freiwillige Selbstverpflichtung der Landtechnik zur CO2 Reduktion. Nachweisführungsworkshop. Institute for Mobile Machinery and Utility Vehicles (IMN) from the Technical University of Brunswick. Karlsruhe Institute of Technology (KIT). Karlsruhe, 2014.

Hass, J.; Popescu, C. (2011): Economy-wide material flows: European countries required more materials between 2000 and 2007. 9/2011. Edited by Eurostat statistics in focus. Environment and energy. Available online at https://ec.europa.eu/eurostat/documents/3433488/5578544/KS-SF-11-009-EN.PDF/ad6cc3eb-c3af-49ea-9b88-e2fce770e4ac, checked on 3/9/2019.

Heidari, B.; Marr, L. C. (2015): Real-time emissions from construction equipment compared with model predictions. In Journal of the Air & Waste Management Association (1995) 65 (2), pp. 115–125. DOI: 10.1080/10962247.2014.978485.

Heine, T. (2018): Lecture documents: "Fahrzeugergonomie". Edited by Karlsruhe Institute of Technology (KIT). Institute for Human and Industrial Engineering (ifab). Karlsruhe.

Helms, H.; Heidt, C. (2014): Erarbeitung eines Konzepts zur Minderung der Umweltbelastung aus NRMM (non road mobile machinery) unter Berücksichtigung aktueller Emissionsfaktoren und Emissionsverminderungsoptionen für den Bestand (24). Available online at https://www.umweltbundesamt.de/publikationen/erarbeitung-eines-konzepts-zur-minderung-der, checked on 2/13/2018.

Hilgers, M. (2016): Kraftstoffverbrauch und Verbrauchsoptimierung. Wiesbaden: Springer Fachmedien (Nutzfahrzeugtechnik lernen).

Hlawitschka, E. (1980): Energetische Aspekte des Betriebes von Hydraulikanlagen. In Agrartechnik 20 (10), pp. 458–460. Available online at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwjt8OjFs7XfAhXEYlAKHSjHD7UQFjAAegQIBxAC&url=http%3A%2F%2F440ejournals.uni-hohen-heim.de%2Findex.php%2Fagrartechnik%2Farticle%2Fdownload%2F5973%2F5679&usg=AOvVaw2NnrdGFZhhHS2KrzzBTwz_, checked on 12/23/2018.

Hoffmann, M. et al. (2011): Zahlentafeln für den Baubetrieb. 8th ed. Wiesbaden: Vieweg Teubner Verlag (Praxis).

Holt, G. D.; Edwards, D. (2015): Analysis of interrelationships among excavator productivity modifying factors. In International Journal of Productivity and Performance Management 64 (6), pp. 853–869. DOI: 10.1108/IJPPM-02-2014-0026.

Hoske, P. et al. (2010): Prognose und Bewertung der Sicht für mobile Arbeitsmaschinen (Teil 1). In Bauportal (9), pp. 530–536.

Howdy Honda (Ed.) (2016): How do warm temperatures affect a vehicle's MPG? Available online at http://www.howdyhonda.com/blog/how-do-warm-temperatures-affect-a-vehicles-mpg/, checked on 12/4/2018.

Ibbs, W.; Vaughan, C. (2015): Change and the loss of productivity in construction: A field guide. University of California, Berkley. U.S. Available online at http://ibbsconsulting.com/uploads/Changes_Field_Guide_Feb_2015.pdf, checked on 12/5/2018.

ifo (Ed.) (2012): Summary Report. Outlook for the World's Key Construction Markets. 74th Euroconstruct Conference. Munich, 11-12 December 2012: Leibniz Institute for Economic Research (ifo) at the University of Munich.

Intergraph Corporation (Ed.) (2012): Factors Affecting Construction Labor Productivity. Managing Efficiency in Work Planning. Available online at https://www.intergraph.com/assets/global/documents/SPC_LaborFactors_WhitePaper.pdf, checked on 9/3/2019.

Iseley, T.; Gokhale, S. (2002): 3. Equipment Productivity. In T. Burke, W. F. Chen, J. Y. R. Liew (Eds.): The Civil Engineering Handbook. 2nd ed. Baton Rouge: CRC Press (New Directions in Civil Engineering), 3-1–3-24. Available online at http://freeit.free.fr/The%20Civil%20Engineering%20Handbook,2003/0958%20ch03.pdf, checked on 1/12/2019.

ISO 5006:2017 (E) (2017): Earth-moving machinery - Operator's field of view - Test method and performance criteria. Switzerland: ISO copyright office, 2017. Available online at https://www.sis.se/api/document/preview/921770/, checked on 1/18/2019.

Ivers-Tiffée, E. (2017/2018): Lecture documents: "Batterien und Brennstoffzellen". Edited by Karlsruhe Institute of Technology (KIT). Institut für Angewandte Materialien Werkstoffe der Elektrotechnik (IAM-WET). Karlsruhe.

Jäger, W.; Stieglitz, R. (2017/2018): Energy Storages & Grid Integration. Lecture documents. Edited by Karlsruhe Institute of Technology (KIT). Institute of Fusion and Reactor Technology (IFRT). Karlsruhe.

Jassim, H.; Lu, W.; Olofsson, T. (2016): A Practical Method for Assessing the Energy Consumption and CO2 Emissions of Mass Haulers. In Energies 9 (10), p. 802. DOI: 10.3390/en9100802.

Ji, Y.; Wang, Y.; Li, X. (2015): Research on the measurement on carbon emissions for industrialized buildings. In L. Shen (Ed.): Proceedings of the 19th international symposium on advancement of construction management and real estate. CRIOCM2014. Chongqing, China, 7-9. November 2014. Berlin: Springer (Business/Economics), pp. 407–417.

Jonker, R. (2017): Alternative CO2-Absorber auf der Basis ausgewählter Amidine. Dissertation. Chair of Technical Chemistry II. University of Duisburg-Essen, Duisburg. Available online at https://duepublico2.unidue.de/servlets/MCRFileNodeServlet/duepublico_derivate_00045464/DissJonker.pdf, checked on 2/9/2019.

Kauffeld, S. (2014): Arbeits-, Organisations- und Personalpsychologie für Bachelor. Mit 44 Abbildungen und 36 Tabellen. 2nd ed. Berlin: Springer (Springer-Lehrbuch).

Kazaz, A.; Manisali, E.; Ulubeyli, S. (2008): Effect of basic motivational factors on construction workforce productivity in turkey. In Journal of Civil Engineering and Management 14 (2), pp. 95–106. DOI: 10.3846/1392-3730.2008.14.4.

Kim, B.-s.; Jang, W.-S.; Lee, D.-E. (2015): Analysis of the CO2 emission characteristics of earthwork equipment. In KSCE Journal of Civil Engineering 19 (1), pp. 1–9. DOI: 10.1007/s12205-014-0679-8.

Kirchner, R. (2013): Einführung von Antidumping-Zöllen für Biokraftstoff-Importe in die EU. Edited by BiomassMuse. Available online at http://www.biomasse-nutzung.de/antidumping-zolle-europa-biokraftstoffe-importe/, checked on 9/3/2019.

Knirsch, J. (2002): Büroräume Bürohäuser. Gelingt der Wandel zum Lebensraum Büro? 2nd ed. Leinfelden-Echterdingen: Koch.

Knörr, W. et al. (2010): Ermittlung der Unsicherheiten der mit den Modellen TREMOD und TREMOD-MM berechneten Luftschadstoffemissionen des landgebundenen Verkehrs in Deutschland. Edited by Umweltbundesamt. ifeu -Institut für Energie- und Umweltforschung; INFRAS. Dessau-Roßlau. Available online at https://www.umweltbundesamt.de/sites/default/files/medien/461/publikationen/3937.pdf, checked on 9/3/2019.

Knörr, W. et al. (2016): Aktualisierung „Daten- und Rechenmodell: Energieverbrauch und Schadstoffemissionen des motorisierten Verkehrs in Deutschland 1960-2035“ (TREMOD) für die Emissionsberichterstattung 2016 (Berichtsperiode 1990-2014). Anhang. Endbericht. Edited by Ifeu-Institut für Energie-und Umweltforschung Heidelberg GmbH. Available online at https://www.ifeu.de/wp-content/uploads/Endbericht_TREMOD_2016_160701.pdf, checked on 9/3/2019.

Komatsu (Ed.) (2014): Kmax-Zahnsystem. Ground Engaging Tools (G.E.T.). Vilvoorde (Belgium) (FGSS000201).

Koskela, L. et al. (2002): 14. The foundations of lean construction. In G. d. Valence, R. Best (Eds.): Design and Construction. Building in Value. 1st ed.: Elsevier professional, pp. 211–226.

Krantz, J. et al. (2017): Analysis of alternative road construction staging approaches to reduce carbon dioxide emissions. In Journal of Cleaner Production 143, pp. 980–988. DOI: 10.1016/j.jclepro.2016.12.023.

Kunze, G. (2010): Ergonomie und Wohlfühlfaktor im Arbeitsprozess. In Bauportal (9), p. 510.

Kunze, G. et al. (2012a): Methode zur dynamischen Sichtfelderfassung und -bewertung für mobile Arbeitsmaschinen unter Einbeziehung der Prozessund Nutzercharakteristik. Abschlussbericht zum DFG-Projekt "DYNASICHT". Edited by Dresden University of Technology. Dresden.

Kunze, G.; Göhring, H.; Jacob, K. (2012b): Baumaschinen. Erdbau- und Tagebaumaschinen ; mit 147 Tabellen. 2nd ed. Wiesbaden: Vieweg + Teubner (Aus dem Programm Maschinenelemente und Konstruktion).

LärmVibrationsArbSchV (2007): Bundesministerium der Justiz und für Verbraucherschutz: Verordnung zum Schutz der Beschäftigten vor Gefährdungen durch Lärm und Vibrationen (Lärm- und Vibrations-Arbeitsschutzverordnung - LärmVibrationsArbSchV). LärmVibrationsArbSchV, pp. 1–10. Available online at https://www.gesetze-im-internet.de/l_rmvibrationsarbschv/L%C3%A4rmVibrationsArbSchV.pdf, checked on 1/24/2019.

Leisering, H. (2013): Wie wird man Baumaschinenführer? Die ZUMBau-Qualifikation. In Bauportal (11), pp. 34–36. Available online at http://www.zumbau.org/dateien/bauportal-11-13-interview-horst-leisering-wie-wird-man-baumaschinenfhrer.pdf, checked on 2/2/2019.

Lewis, M. P. (2009): Estimating fuel use and emission rates of nonroad diesel construction equipment performing representative duty cycles. Dissertation. North Carolina State University, Raleigh, North Carolina.

Available online at https://repository.lib.ncsu.edu/bitstream/handle/1840.16/5008/etd.pdf?sequence=1, checked on 2/14/2018.

Lewis, P. et al. (2012a): Effects of engine idling on national ambient air quality standards criteria pollutant emissions from nonroad diesel construction equipment. In Transportation Research Record: Journal of the Transportation Research Board (2270), pp. 67–75. DOI: 10.3141/2270-09.

Lewis, P.; Fitriani, H.; Arocho, I. (2015): Engine variable impact analysis of fuel use and emissions for heavy-duty diesel maintenance equipment. In Transportation Research Record: Journal of the Transportation Research Board 2482, pp. 8–15. DOI: 10.3141/2482-02.

Lewis, P.; Leming, M.; Rasdorf, W. (2012b): Impact of engine idling on fuel use and CO2 emissions of nonroad diesel construction Equipment. In Journal of Management in Engineering 28 (1), pp. 31–38. DOI: 10.1061/(ASCE)ME.1943-5479.0000068.

Li, H.-x.; Lei, Z. (2010): Implementation of Discrete-Event Simulation (DES) in Estimating & Analyzing CO2 Emission during Earthwork of Building Construction Engineering. In : IEEE International Conference on Industrial Engineering and Engineering Management; IE&EM. Xiamen, China, 29 -31. October 2010: IEEE, pp. 87–89. Available online at https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5646619, checked on 8/1/2018.

Li, X.; Zhu, Y.; Zhang, Z. (2010): An LCA-based environmental impact assessment model for construction processes. In Building and Environment 45 (3), pp. 766–775. DOI: 10.1016/j.buildenv.2009.08.010.

Liebchen, J. H.; Viering, M. G.; Zanner, C. (2007): Baumanagement und Bauökonomie. Wiesbaden: Teubner.

Liebherr (Ed.) (2012): Granulate production in Europe. Colmar, France.

Lindgren, M. (2007): A methodology for estimating annual fuel consumption and emissions from non-road mobile machinery. -Annual emissions from the non-road mobile machinery sector in Sweden for year 2006. Edited by Department of Biometry and Engineering (SLU). Uppsala. Available online at https://pub.epsilon.slu.se/3791/1/lindgren_m_091217.pdf, checked on 9/3/2019.

Liu, C.; Landskron, K. (2017): Design, construction, and testing of a supercapacitive swing adsorption module for CO2 separation. In Chemical communications (Cambridge, England) 53 (26), pp. 3661–3664. DOI: 10.1039/c7cc01055a.

Locatelli, G. et al. (2013): Improving projects performance with lean construction: State of the art, applicability and impacts. 5th ed. Edited by Organization, Technology & Management in Construction: An International Journal (OTMCJ). Croatia (2).

Lukavich, P. J. (1974): Quick change cutting edge. Applied by Caterpillar Inc. on 12/3/1974. Patent no. US3851413A.

Lüttig (2007): Die (neue) Rohstoffschlange. In World of Mining 59 (1). Available online at https://www.ra-anders.de/pdf/id/1307.pdf, checked on 9/3/2019.

Macron, E. (2017): One Planet Summit. The One Planet Summit: A platform of commitments to meet the challenge of climate change. Available online at https://www.oneplanetsummit.fr/en/events-16, checked on 9/3/2019.

Marsh, H.; Rodríguez-Reinoso, F. (2006): Activated carbon. 1st ed. Amsterdam: Elsevier.

Masala, A. et al. (2017): CO2 Capture in Dry and Wet Conditions in UTSA-16 Metal-Organic Framework. In ACS applied materials & interfaces 9 (1), pp. 455–463. DOI: 10.1021/acsami.6b13216.

Maus, W.; Jacob, E. (2014): Synthetische Kraftstoffe – OME1: Ein potenziell nachhaltig hergestellter Dieselkraftstoff Synthetic Fuels – OME1: A Potentially Sustainable Diesel Fuel. Available online at https://www.emitec.com/fileadmin/user_upload/Bibliothek/Vortraege/140217_Maus_Jacob_LVK_Wien_englisch.pdf, checked on 12/21/2018.

Mell, W.-D. (2005): Studie: Langzeitmessung Herz-Kreislaufbelastung. Fahrtensegeln und Alltagsaktivitäten. Seniorensegeln. Edited by Institut für Boots-Tourismus (IBoaT). Bonn, Germany (IBoaT-Report, 3.1).

Melzig-Thiel, R.; Kinne, J.; Schatte, M. (2001): Technik 23 "Schwingungsbelastung in der Bauwirtschaft". Beurteilung und Schutzmaßnahmen. Edited by Bundesanstalt für Arbeitsschutz und Arbeitsmedizin. Dresden, Germany.

Menzel, J.; Finger, W.; Rickes, K. (2015): Öffentliches Baurecht für Architekten und Bauingenieure. 1st ed. Stuttgart: Boorberg.

Merkel, T.; Schmauder, M. (2012): Ergonomisch und normgerecht konstruieren. [Handlungsleitfaden zur Anwendung von Richtlinien und Normen in der ergonomischen Produktgestaltung]. 1st ed. Berlin, Wien, Zürich: Beuth (Praxis : Maschinenbau).

Millstein, D. E.; Harley, R. A. (2009): Revised estimates of construction activity and emissions: Effects on ozone and elemental carbon concentrations in southern California. In Atmospheric Environment 43 (40), pp. 6328–6335. DOI: 10.1016/j.atmosenv.2009.09.028.

MOF Technologies Adsorbent Nanomaterials (Ed.): Technology - MOF technologies. Available online at http://www.moftechnologies.com/technology/, checked on 4/25/2019.

Montesquieu, C. L. d. S. d. (1748): De l'esprit des Loix. ou du rapport que les loix doivent avoir avec la constitutution de chaque gouvernement, les moeurs, le climat, la religion, le commerce &c. à quoi l'auteur a ajouté des recherches sur les loix romaines touchant les successions, sur les lois françoises, & sur les loix féodales. Geneve: Barrillot & fils.

Moshoeshoe, M.; Nadiye-Tabbiruka, M. S.; Obuseng, V. (2017): A review of the chemistry, structure, properties and applications of Zeolites. In American Journal of Materials Science (5), pp. 196–221. DOI: 10.5923/j.materials.20170705.12.

Murtonen, T.; Kytö, M. (2004): The effect of lubrication oil on the fuel consumption of heavy-duty diesel engine. Edited by VTT Technical Research Centre of Finland. Finland (31HDEVOITELU / C3SU00545). Available online at https://www.motiva.fi/files/1051/HD-energia_VoiteluVolvo2003.pdf, checked on 12/23/2018.

Naoum, S. G. (2016): Factors influencing labor productivity on construction sites. In International Journal of Productivity and Performance Management 65 (3), pp. 401–421. DOI: 10.1108/IJPPM-03-2015-0045.

Needelman, W. M.; Madhavan, P. V. (1988): Review of ubricant contamination and diesel engine wear. In : SAE Technical Paper Series. SAE International Truck and Bus Meeting and Exposition. Indianapolis, 7-10. November 1988. Warrendale, PA, United States: SAE International (SAE Technical Paper Series). Available online at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.404.7165&rep=rep1&type=pdf, checked on 12/24/2018.

Nessau, B. (1977): Zur Diagnose von Kraftstoffeinspritzanlagen. In Agrartechnik 27 (1), pp. 6–9. Available online at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwj5_9y6prXfAhVGzqQKHSRbCMoQFjAAegQIBBAC&url=http%3A%2F%2F440ejournals.uni-hohen-heim.de%2Findex.php%2Fagrartechnik%2Farticle%2Fdownload%2F5311%2F5019&usg=AOvVaw3N8PtaNlsD324_aze4ecAQ, checked on 12/23/2018.

Notter, B.; Schmied, M. (2015): Energieverbrauch und Schadstoffemissionen des Non-road-Sektors. Studie für die Jahre 1980–2050. Edited by Bundesamt für Umwelt. Bern (Umwelt-Wissen, 1519). Available online at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=2ahUKEwiYzr3AjbzdAhUDyqQKHb3xAGkQFjABegQIC-RAC&url=https%3A%2F%2Fwww.bafu.admin.ch%2Fdam%2Fbafu%2Fde%2Fdokumente%2Fluft%2Ffachinfo-daten%2Fanleitung_zur_online-non-road-datenbank.pdf.download.pdf%2Fanleitung_zur_online-non-road-datenbank.pdf&usg=AOvVaw2m4ykcg2zx4yUkQzh-orEu, checked on 9/15/2018.

OECD (Ed.) (2018): Effective carbon rates 2018. Pricing carbon emissions through taxes and emissions trading. 1st ed. Paris: Organisation for Economic Co-operation and Development OECD Publishing. Available online at http://www.oecd.org/tax/tax-policy/effective-carbon-rates-2018-summary.pdf, checked on 10/16/2018.

Ok, S. C.; Sinha, S. K. (2006): Construction equipment productivity estimation using artificial neural network model. In Construction Management and Economics 24 (10), pp. 1029–1044. DOI: 10.1080/01446190600851033.

Ökobaudat. Version 2017-I (2013): German Federal Ministry of the Interior, for Building and Home Affairs. Available online at https://www.oekobaudat.de/, checked on 9/3/2019.

PaLATE. Version 2.0 (2003). Berkeley: Consortium on Green Design and Manufacturing, University of California.

Park, H.-S. (2006): Conceptual framework of construction productivity estimation. In KSCE Journal of Civil Engineering 10 (5), pp. 311–317. DOI: 10.1007/BF02830084.

Patzold, V.; Gruhn, G.; Drebenstedt, C. (2008): Der Nassabbau. Erkundung, Gewinnung, Aufbereitung, Bewertung. Berlin, Heidelberg: Springer.

PCC. Version 2.0 (2009): BAM CO2-Desk. Available online at https://www.bamco2desk.nl/project-carbon-calculator, checked on 10/3/2018.

Pfab, H. (2017): Lecture documents: "Konstruktion und Entwicklung von Erdbewegungsmaschinen am Beispiel des Radladers". Edited by Karlsruhe Institute of Technology (KIT), Liebherr. Institute Mobile Machines (MOBIMA). Karlsruhe.

Pfluger, B. et al. (2017): Modul 10.a: Reduktion der Treibhausgasemissionen Deutschlands um 95 % bis 2050 Grundsätzliche Überlegungen zu Optionen und Hemmnissen. Langfristszenarien für die Transformation des Energiesystems in Deutschland. Edited by Bundesministerium für Wirtschaft und Energie. Fraunhofer Institut für System- und Innovationsforschung (Fraunhofer ISI); Institut für Energie- und Umweltforschung Heidelberg (IFEU); TU Wien; TEP Energy; M-Five GmbH; Consentec GmbH. Berlin.

ProBas. Version ProBas ReLaunch (2015): German Federal Environment Agency. Available online at http://www.probas.umweltbundesamt.de/php/index.php, checked on 10/3/2018.

PTBLE (2016): Ekotech-Projekt. Effiziente Kraftstoffnutzung der Agrartechnik. Edited by Projektträger Bundesanstalt für Landwirtschaft und Ernährung (PTBLE). Available online at https://www.ekotech-projekt.eu/, checked on 1/17/2020.

Rachel Muncrief and Ben Sharpe (2015): Overview of the heavy-duty vehicle market and CO2 emissions in the European Union. Edited by ICCT - The international council on clean transportation. Available online at https://theicct.org/sites/default/files/publications/ICCT_EU-HDV_mkt-analysis_201512.pdf, checked on 9/3/2019.

Rahmstorf, S.; Schellnhuber, H.-J. (2007): Der Klimawandel. Diagnose, Prognose, Therapie. 6th ed. München: Verlag C. H. Beck (Beck'sche Reihe C.-H.-Beck-Wissen, 2366).

Randalls, S. (2010): History of the 2°C climate target. In Wiley Interdisciplinary Reviews: Climate Change 1 (4), pp. 598–605. DOI: 10.1002/wcc.62.

Rashid, H. A. (2014): Microclimatic factors effect on productivity of construction industry. In OJCE Open Journal of Civil Engineering 04 (02), pp. 173–180. DOI: 10.4236/ojce.2014.42015.

Rashidi, A.; Nejad, H. R.; Maghiar, M. (2014): Productivity estimation of bulldozers using generalized linear mixed models. In KSCE Journal of Civil Engineering 18 (6), pp. 1580–1589. DOI: 10.1007/s12205-014-0354-0.

Rheinisch-Westfällisches Institut für Wirtschaftsforschung (Ed.) (2008): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft - Monitoringbericht 2005-2007. Essen. Available online at http://www.rwi-essen.de/media/content/pages/publikationen/rwi-projektberichte/PB_CO2-Monitoring-2005-2007.pdf, checked on 9/3/2019.

Rheinisch-Westfällisches Institut für Wirtschaftsforschung (Ed.) (2013): Die Klimavorsorgeverpflichtung der deutschen Wirtschaft - Monitoringbericht 2011 und 2012. Essen. Available online at http://www.rwi-essen.de/media/content/pages/publikationen/rwi-projektberichte/RWI_PB_Monitoringbericht-2011-und-2012.pdf, checked on 9/3/2019.

Sandanayake, M.; Zhang, G.; Setunge, S. (2016): Environmental emissions at foundation construction stage of buildings – Two case studies. In Building and Environment 95, pp. 189–198. DOI: 10.1016/j.buildenv.2015.09.002.

Schlick, C.; Bruder, R.; Luczak, H. (2018): Arbeitswissenschaft. 4th ed. Berlin: Springer Vieweg, checked on 12/5/2018.

Schmauder, M. (2005): Arbeitswissenschaft. Fernstudium. Edited by Dresden University of Technology. Institute for Ergonomics. Dresden. Available online at https://tu-dresden.de/ing/maschinenwesen/itla/aiw/ressourcen/dateien/studium/lehrfachbeschreibungen/fernstudium.pdf?lang=de, checked on 9/3/2019.

Schmid, R. R. (1961): Untersuchungen über den Zusammenhang zwischen Arbeitszeit, Leistung und Ermüdung. Grandjean, E.; Daenzer, W. F. Dissertation. Eidgenössischen Technischen Hochschule in Zürich, Zürich, Switzerland. Available online at https://doi.org/10.3929/ethz-a-000107868, checked on 12/5/2018.

Senouci, A.; Abbasi, M. A.; Eldin, N. N. (2018): Impact of weather conditions on construction labour productivity in Qatar. In MEJM Middle East Journal of Management 5 (1), p. 34. DOI: 10.1504/MEJM.2018.088734.

Shao, Z. (2016): Non-road emission inventory model methodology. Edited by The International Council on Clean Transportation (icct) (Working Paper, 2016-4). Available online at https://www.theicct.org/sites/default/files/publications/ICCT_nonroad-model-method_20160224.pdf, checked on 9/1/2018.

Singh, A. et al. (2011): Review of life-cycle assessment applications in building construction. In Journal of Architectural Engineering 17 (1), pp. 15–23. DOI: 10.1061/(ASCE)AE.1943-5568.0000026.

Smith, S. (1999): Earthmoving productivity estimation using linear regression techniques. In Journal of construction engineering and management, pp. 133–141.

Solomon, S. et al. (2007): Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change 2007. Edited by Cambridge University Press. New York, U.S.

Stan, C. (2015): Alternative Antriebe für Automobile. Hybridsysteme, Brennstoffzellen, alternative Energieträger. 4.th ed. Berlin, Heidelberg: Springer Vieweg.

Statista (Ed.) (2015): Straßen in Deutschland. Available online at http://de.statista.com/themen/1199/strassen-in-deutschland/, checked on 10/20/2015.

Stec, M. (2016): Emerging Technologies. Volvo Operator Tool. Xploration Forum 2016: Innovation conference. Volvo Construction Equipment. Eskilstuna, Sweden, 9/7/2016.

Stocker, T. (2018): Climate Change: What if Paris fails ? KIT Climate Lecture. Karlsruhe Institute of Technology (KIT). Karlsruhe, 9/19/2018.

Sturm, C. (2015): Bewertung der Energieeffizienz von Antriebssystemen mobiler Arbeitsmaschinen am Beispiel Bagger. Dissertation. Karlsruhe Institute of Technology (KIT), Karlsruhe.

SUVA (2018): Schallpegeltabelle im Baugewerbe. Typische Lärmbelastungen für Berufe und Funktionen. Gesundheitschutz am Arbeitsplatz, Bereich Physik. Edited by Swiss accident insurance (SUVA). Lucerne, Switzerland (86208-2018). Available online at https://www.suva.ch/material/Dokumentationen/schallpegeltabelle-baugewerbe, checked on 1/23/2019.

Swiss Federal Office for the Environment (Ed.) (2016): Non-road-Datenbank. Available online at https://www.bafu.admin.ch/bafu/de/home/themen/luft/zustand/non-road-datenbank.html, updated on 11/10/2016, checked on 9/15/2018.

Takahashi, Y. et al. (2006): Development of bucket scooping mechanism for analysis of reaction force against rock piles. In : 23rd International Symposium on Automation and Robotics in Construction. ISARC 2006. Tokyo, Japan, 3-5. October 2006. Tokyo: Japan Robot Association, pp. 476–481. Available online at https://www.iaarc.org/publications/fulltext/isarc2006-00031_200606060835.pdf, checked on 12/26/2018.

Thagard, P. (2018): What are moods? Good and bad moods are dispositions to have emotions using the same mechanisms. Edited by Psychology Today. New York, U.S. Available online at https://www.psychologytoday.com/intl/blog/hot-thought/201805/what-are-moods, checked on 1/26/2019.

Tissot, B. P.; Welte, D. H. (2013): Petroleum Formation and Occurrence. 2nd ed. Berlin, Heidelberg: Springer Berlin / Heidelberg.

Todsen, U. (2012): Verbrennungsmotoren. München: Hanser Carl.

Trani, M. L. et al. (2016): Predicting fuel energy consumption during earth-works. In Journal of Cleaner Production 112, pp. 3798–3809. DOI: 10.1016/j.jclepro.2015.08.027.

Tschöke, H.; Mollenhauer, K.; Maier, R. (Eds.) (2018): Handbuch Dieselmotoren. 4th ed. Wiesbaden: Springer Vieweg (Springer Reference Technik).

Umweltbundesamt (Ed.) (2018): Emissionsdaten. Available online at https://www.umweltbundesamt.de/themen/verkehr-laerm/emissionsdaten#textpart-1, checked on 9/7/2018.

UNFCCC (1992): United Nations Framework Convention on Climate Change. Edited by United Nations.

UNFCCC (2014): Kyoto Protocol. Edited by United Nation Framework Convention Climate Change (UNFCCC). Available online at http://unfccc.int/kyoto_protocol/items/2830.php, updated on 9/3/2019.

UNFCCC (2017): The Paris Agreement. Edited by United Nation Framework Convention Climate Change (UNFCCC). Available online at https://unfccc.int/process/the-paris-agreement/what-is-the-paris-agreement, checked on 5/26/2019.

UNFCCC (2019): What is the United Nations Framework Convention on Climate Change? Edited by United Nation Framework Convention Climate Change (UNFCCC). Available online at https://unfccc.int/process/the-convention/what-is-the-united-nations-framework-convention-on-climate-change, checked on 5/26/2019.

van Gurp, C.; Larsen, M. R. A. (2014): CEREAL - Carbon road map: ERA-NET-European Research Area Net.

Vandenbroucke, D.; Van Hyfte, A.; Francx, L. (2010): Study in view of the revision of directive 97/68/EC on non-road mobile machinery (NRMM) (An emissions inventory and impact assessment). Final

Report. Module 1 - An Emissions Inventory. Edited by ARCADIS Belgium nv, Risk & Policy Analysts Limited, checked on 2/13/2018.

VDI 2057 (2017): Human exposure to mechanical vibrations. Whole-body vibration. VDI-Richtlinien. Edited by Verein Deutscher Ingenieure (VDI 2057).

VDMA (Ed.) (2017): Abgasgesetzgebung Diesel- und Gasmotoren. Motoren und Systeme. Frankfurt. Available online at http://mus.vdma.org/documents/266753/15962998/VDMA+Emissionsbrosch%C3%BCre+Deutsch.pdf/31da9c95-bbe7-45f1-9c8c-9000810a87c5, checked on 10/6/2018.

Velske, S.; Eymann, P.; Mentlein, H. (2013): Strassenbau, Strassenbautechnik. 7th ed. Köln: Werner (Werner-Ingenieur-Texte WIT).

Vögele (Ed.): Vögele Einbaufibel. Available online at http://media.voegele.info/media/03_voegele/kundenservice/einbaufibel/Einbaufibel_DE_Leseprobe.pdf, checked on 2/27/2019.

Vogt, J. (2010): Simulation baulogistischer Prozesse – Berücksichtigung räumlicher Aspekte, Teil 1. In H.-J. Bargstädt (Ed.): Modellierung von Prozessen zur Fertigung von Unikaten. Forschungsworkshop zur Simulation von Bauprozessen. Beiträge vom Forschungsworkshop zur Simulation von Bauprozessen. Weimar, 25. March 2010. Chair of Construction Management and Construction Methods. 19th ed. Weimar: Bauhaus University Weimar, pp. 35–39.

Voigt, S.; Mieth, S.; Kunze, G. (2012): Bedienereinfluss auf Leistungszyklen mobiler Arbeitsmaschinen. Enwicklung einer Bemessungsgrundlage. In Wissensportal baumaschine.de (1), pp. 1–9. Available online at https://www.baumaschine.de/vibrosim/publikationen/2012_mieth_voigt.pdf, checked on 2/2/2019.

Volvo CE (2010): Förslag till standard ISO 11152. 2010-03-25. Edited by Volvo Construction Equipment AB. Hauler & Loader Division. Eskilstuna, Sweden.

Volvo CE (2015): Volvo Construction Equipment: Corporate presentation 2015. Edited by Volvo Construction Equipment.

von Schlippenbach, U. (2001): Selbstverpflichtung als Instrument regionaler Energie- und Klimapolitik. Eine Analyse am Beispiel des Berliner

KlimaSchutzPartner. Küchler, J. Diplomarbeit. Institute for Management in Environmental Planning. Technical University of Berlin, Berlin.

Waard, D. d. (1996): The measurement of drivers' mental workload. Dissertation. The Traffic Research Centre VSC. University of Groningen, Netherlands.

Waris, M. et al. (2014): Criteria for the selection of sustainable onsite construction equipment. In International Journal of Sustainable Built Environment 3 (1), pp. 96–110. DOI: 10.1016/j.ijsbe.2014.06.002.

Weberbeck, L. (2016): Analyse und Vorauslegung einer mit verflüssigtem Erdgas angetriebenen mobilen Arbeitsmaschine. Supervisors: Geimer, M.; Ays, I.; Engelmann, D. Master thesis. Institute Mobile Machines. Karlsruhe Institute of Technology (KIT), Karlsruhe.

Weberbeck, L. et al. (2016): Liquefied natural gas in mobile machines. In ATZoffhighway worldwide 9 (4), pp. 38–45. DOI: 10.1007/s41321-016-0532-8.

Wenzel, H. G.; Piekarski, C. (1980): Klima und Arbeit. Munich, Germany: Bayerischen Staatsministerium für Arbeit und Sozialordnung.

WetterKontor GmbH (Ed.) (2019): Skala für Windstärken. Available online at https://www.wetterkontor.de/de/bft_tabelle.html, checked on 12/7/2019.

Will, D.; Gebhardt, N. (Eds.) (2011): Hydraulik. Grundlagen, Komponenten, Schaltungen. 5th ed. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg.

Winther, M. et al. (2017): EMEP/EEA air polluatnt emission inventory guidebook 2016. Non-road mobile sources and machinery. Edited by Long-range Transboundary Air Pollution, European Environment Agency. Available online at https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=2ahUKEwju-sTdspfdAhXCjqQKHY_DAREQFjAAegQIABAC&url=https%3A%2F%2Fwww.eea.europa.eu%2Fds_resolveuid%2F6H3DTV1K4Z&usg=AOvVaw385C075AMfRW0J5uGt3bXK, checked on 9/1/2018.

Winther, M.; Nielsen, O.-K. (2006): Fuel use and emissions from non-road machinery in Denmark from 1985–2004 – and projections from 2005-2030. Edited by Danish Ministry of the Environment - Environmental Protection Agency. National Environmental Research Institute. Denmark (Environmental Project, 1092 2006). Available online at https://inis.iaea.org/collection/NCLCollectionStore/_Public/37/098/37098389.pdf, checked on 9/2/2018.

Wittig, P.; Nöllenheidt, C.; Brenscheidt, S. (2013): Grundauswertung der BIBB/BAuA-Erwerbstätigenbefragung 2012. Mit den Schwerpunkten Arbeitsbedingungen, Arbeitsbelastungen und gesundheitliche Beschwerden. Edited by Bundesanstalt für Arbeitsschutz und Arbeitsmedizin. Dortmund, Berlin, Dresden. Available online at https://www.baua.de/DE/Angebote/Publikationen/Berichte/Gd73.pdf?__blob=publicationFile, checked on 1/23/2019.

Wu, Y. (2018): Analyse uns Vorauslegung einer mit OME angetriebenen mobilen Arbeitsmaschinen. Supervisors: Geimer, M.; Ays, I. Master thesis. Institute Mobile Machines. Karlsruhe Institute of Technology (KIT), Karlsruhe.

Wu, Y.; Ays, I.; Geimer, M. (2019): Analysis and Preliminary Design of Oxymethylene ether (OME) Driven Mobile Machines. Edited by Karlsruhe Institute of Technology (KIT). Karlsruhe.

Yan, H. et al. (2010): Greenhouse gas emissions in building construction: A case study of One Peking in Hong Kong. In Building and Environment 45 (4), pp. 949–955. DOI: 10.1016/j.buildenv.2009.09.014.

Yi, W.; Chan, A. P. C. (2017): Effects of heat stress on construction labor productivity in Hong Kong: A case study of rebar workers. In International journal of environmental research and public health 14 (9). DOI: 10.3390/ijerph14091055.

Zarghampoor, M. H. et al. (2017): Modeling of CO2 adsorption on activated carbon and 13X zeolite via vacuum swing adsorption. In Department of Chemical Engineering, Curtin University, Malaysia and Institution of Chemical Engineers (IChemE), Malaysia (Eds.): 29th Symposium of Malaysian Chemical Engineers (SOMChE), vol. 206. Engineering Solutions for Sustainable Development. Miri, Sarawak, Malaysia, 1-3. December 2016 (206), pp. 1–10.

Zeng, W. (2018): Entwicklung von CO2 Abscheidesystemen für eine mobile Arbeitsmaschine mit dem ,,Pre- und Post-Combustion“ Verfahren. Supervisors: Geimer, M.; Ays, I. Master thesis. Institute Mobile Machines. Karlsruhe Institute of Technology (KIT), Karlsruhe.

Zhang, H. (2015): Simulation-based estimation of fuel consumption and emissions of asphalt paving operations. In Journal of Computing in Civil Engineering 29 (2), pp. 1–13. DOI: 10.1061/(ASCE)CP.1943-5487.0000326.

Zieschang, H.; Müller-Gethmann, H. (2004): Ergonomische Anforderungen an Multifunktionsstellteile bei Erdbaumaschinen. Edited by Hauptverband der gewerblichen Berufsgenossenschaften (HVBG), Berufsgenossenschaftliches Institut Arbeit und Gesundheit - BGAG. Dresden.

Zou, H. (2018): Validierung des Einflusses „Maschineneffizienz“ auf die gesamten CO2e Emissionen von Bauanwendungen am Beispiel eines Radladers mit LVG. Supervisors: Geimer, M.; Ays, I. Master thesis. Institute Mobile Machines. Karlsruhe Institute of Technology (KIT), Karlsruhe.

Zülch, G. (2012): Arbeitswissenschaft. Lecture notes. Edited by Institute for Human and Industrial Engineering. Karlsruhe Institute of Technology (KIT). Karlsruhe.

Zülch, G.; Kiparski, R. v.; Brinkmeier, B. (1999): Messen, Beurteilen und Gestalten von Arbeitsbedingungen. Handbuch für die betriebliche Praxis zur Umsetzung ergonomischer Erkenntnisse. 2nd ed. Heidelberg: Haefner (Schriftenreihe Ergo-Med, 4).