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Evaluating environmental impacts of road routing alternatives using Building Information Modeling

Scientific work to obtain the degree

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Abstract

In terms of climate change and the scarcity of resources, it is necessary for the Architecture, Engineering and Construction (AEC) sector to sufficiently evaluate and justify the decision-making for new construction projects. In addition to building construction, this is also of utmost importance for infrastructure projects. The greatest potential to reduce the environmental impact of infrastructure projects occurs in early design stages. At this stage, the decision of the routing with the associated engineering structures such as tunnels and bridges is determined. However, information to assess environmental impacts is difficult to obtain and time consuming to collect at that early design stage.

In this context, a methodology is presented for infrastructure projects, which intends to support the decision-making process of different road routing alternatives. In particular, this involves a Life Cycle Assessment (LCA) based on Building Information Modeling (BIM). Therefore, the BIM models are linked with predefined LCA profiles for the road superstructure, with its earthworks as well as with engineering structures such as tunnels and bridges. The bill of quantities is automatically derived from the BIM model for reducing the manual workload and to automate the subsequent integration and calculation process of the life cycle assessment.

With the help of a prototypical implementation and a subsequent case study, the embodied emissions of the individual variants are calculated in a first step. The second step consists of calculating the traffic-related emissions. For a holistic decision-making process, the resulting global warming potential of the different variants is compared and the individual factors are evaluated in relation to each other.

Zusammenfassung

In Hinblick auf den Klimawandel und die Ressourcenknappheit, gilt es auch für den Bausektor die derzeitige Entscheidungsfindung für neue Baumaßnahmen ausreichend abzuwägen und zu begründen. Dies ist neben dem Hochbau auch für Infrastrukturprojekte von herausragender Bedeutung. Der größte Einfluss, um die Umweltauswirkungen von Infrastrukturprojekten zu reduzieren, ist in der frühen Planungsphase vorhanden. Dort wird die Entscheidung der Linienführung mit den zugehörigen Ingenieurbauwerken wie Tunneln und Brücken getroffen. Allerdings sind die Informationen zur Beurteilung der Umweltauswirkungen schwierig zu erhalten und zeitaufwendig zusammenzustellen.

In dem Zusammenhang wird für Infrastrukturmaßnahmen eine Vorgehensweise vorgestellt, welche den Bewertungsprozess von unterschiedlichen Trassierungsvarianten von Straßen unterstützen soll. Dabei handelt es sich um eine Ökobilanzierung, welche mithilfe von Building Information Modeling (BIM) durchgeführt wird. Die BIM Modelle werden dazu mit vordefinierten Datensätze für den Straßenoberbau und dessen Damm und Einschnitt, sowie für Ingenieurbauwerke wie Tunnel und Brücken verknüpft. Die Mengenermittlung findet auf Basis des BIM Modells statt, um den manuellen Arbeitsaufwand zu reduzieren und den darauffolgenden Integrations- und Berechnungsprozess der Ökobilanzierung zu automatisieren.

Mithilfe einer prototypischen Implementierung und einer darauffolgenden Fallstudie werden in einem ersten Schritt die grauen Emissionen der einzelnen Varianten berechnet. In einem zweiten Schritt folgt die Berechnung der verkehrsbedingten Emissionen. Für eine holistische Entscheidungsfindung wird das resultierende Treibhauspotential der einzelnen Varianten gegenübergestellt und die einzelnen Faktoren untereinander abgewogen.

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Acronyms

AADT	Annual Average Daily Traffic
AEC	Architecture, Engineering and Construction
AP	Acidification Potential
API	Application Programming Interface
BASt	Bundesanstalt für Straßenwesen
BBSR	Bundesinstitut für Bau-, Stadt- und Raumforschung
BIM	Building Information Modeling
BMI	Bundesministerium des Innern, für Bau und Heimat
BoQ	Bill of Quantities
CAD	Computer Aided Design
CBA	Cost-Benefit Analysis
DTM	Figital Terrain Modell
EAs	Environmental Assessments
EIA	Environmental Impact Assessments
EoL	End of Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
FGSV	Forschungsgesellschaft für Straßen- und Verkehrswesen
GHG	Greenhouse Gas
GUID	Global Unique Identifier
GWP	Global Warming Potential
HBEFA	Handbook Emission Factors for Road Transport
IFC	Industry Foundation Classes
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LICCER	Life Cycle Considerations in EIA of Road Infrastructure
LoD	Level of Detail
LOD	Level of Development
LOG	Level of Geometry
LOI	Level of Information
ODP	Ozone Depletion Potential
PENRT	Primary Energy Non-Renewable Total
PERT	Primary Energy Renewable Total
PET	Primary Energy Total
PLCA	Parametric Life Cycle Assessment
POCP	Photochemical Ozone Creation Potential
PVIs	Points of Vertical Intersection

S-LCA	Social Life Cycle Assessment
SEA	Strategic Environmental Assessment
TBM	Tunnel Boring Machine
VPL	Visual Programming Language
WDP	Water Depriviation Potential
ÖKOBAUDAT	Ökobilanz-Datenbank für Baustoffe

Chapter 1

Introduction

1.1 Motivation and aim of the work

The German government's goal of achieving climate neutrality by 2045 holds a great challenge for our society. The Architecture, Engineering and Construction (AEC) sector can be assigned a great deal of responsibility as they account for 40 % of the total energy use, 32 % of CO_2 emissions, and 25 % of the generated waste in Europe annually. (VAN ELDIK et al., 2020).

An important success factor, for achieving the climate goals of the Paris agreement, is the continuous reduction of CO_2 emissions in this sector. While the focus has been mainly on reducing emissions from buildings in recent years, a new trend in research is to consider embodied and traffic emissions of infrastructure projects. (LILJENSTRÖM, 2021 and SAUER, 2016)

Traffic emissions are the emissions emitted by vehicles during their operation. Globally, these are responsible for 24% of energy-related Greenhouse Gas (GHG) emissions (International Energy Agency, 2018).
Embodied emissions are connected with the life cycle of an infrastructure project and include the construction, operation, maintenance and demolition of the engineering constructions such as roads, bridges and tunnels. According to SAUER (2016), the construction of a tunnel in mountainous regions might reduce the CO_2 emissions as a smaller longitudinal gradient is achieved. The emissions from the reduced traffic will compensate the higher emissions during the construction phase after several years.

In order to elaborate these correlations and use them for the decision-making process, Life Cycle Assessment (LCA) can be carried out. LCA is a standardised approach to calculate the environmental performance of products and processes and "can be used to identify the highest points of concentration of emissions and analyse which actions can be taken to achieve their reduction more efficiently" (de OLIVEIRA et al., 2021). It can be used to calculate the embodied as well as traffic emissions over the whole life cycle of the infrastructure project, helps identifying the major emission polluter and provides a basis for emission reduction measures (LILJENSTRÖM, 2021).
The greatest opportunity to reduce the environmental impacts of a road design, is located in the early design stage where the choice of the road corridor and the construction type is made (LILJENSTRÖM et al., 2021). However, the required information for conducting a LCA, such as the quantity of construction material, is hardly available and time consuming to collect in an early planning stage. The relevant information becomes available in later

design stages where less opportunities exist to reduce the environmental impacts. This is referred to as the paradox of eco-design (LILJENSTRÖM et al., 2021).

A possibility to solve this problem is the use of Building Information Modeling (BIM) as the time-consuming aspects of data collection and design evaluation can be reduced. The BIM methodology shifts the design efforts into earlier design stages as the semantic 3D models are developed and their relevant information is collected. This digital model enables the possibility to conduct computational analyses in early planning stages. Therefore, the evaluation of different design possibilities can be conducted earlier where changes have greater effectiveness and possible conflicts can be resolved in time which improves the design quality. (BORRMANN et al., 2018)

Analyses show that sustainable buildings are economically viable. The conviction that sustainable buildings are more expensive than conventional buildings should be countered by life cycle considerations. (BUILDINGSMART DEUTSCHLAND, 2022)

The aim of this thesis is therefore to provide a basis for the decision-making of road routing alternatives by combining Building Information Modelling and Life Cycle Assessment.

1.2 Research objectives

For reasoning about the environmental impact of different infrastructure routing alternatives, the required information and its availability need to be evaluated in first step. After the relevant information sets are defined, the integration of the BIM data with the environmental data has to be elaborated in a second step. The goal is to develop a methodology to automatise the the integration and calculation process of the BIM-based life cycle assessment. By using the methodology, conclusions can be drawn in a third step about the distribution of embodied and traffic emissions of a routing variant. The research questions are defined as follows:

1. Which geometrical and semantic information sets are relevant and available in the early planning phase for reasoning on the environmental impact of different road routing alternatives?
2. How can those be integrated with the BIM methodology for automatising the environmental evaluation process in form of a life cycle assessment and support the design decision-making process?
3. How does the construction of engineering structures, such as bridges and tunnels, influence the embodied and traffic emissions of different routing alternatives over the whole life cycle?

1.3 Outline

In chapter 2, the necessary background knowledge is provided and the current state of research in the field of BIM-based LCA in the infrastructure sector is elaborated.

In a first step, the individual sub-areas of infrastructure planning, sustainability with LCA and BIM are examined in more detail. The second step results in the consideration of the combination of the individual sub-areas as shown in fig. 1.1. This includes LCA in infrastructure projects and the integration of BIM and LCA. In the third step, the state of research in the integration of BIM and LCA in the infrastructure sector is presented.

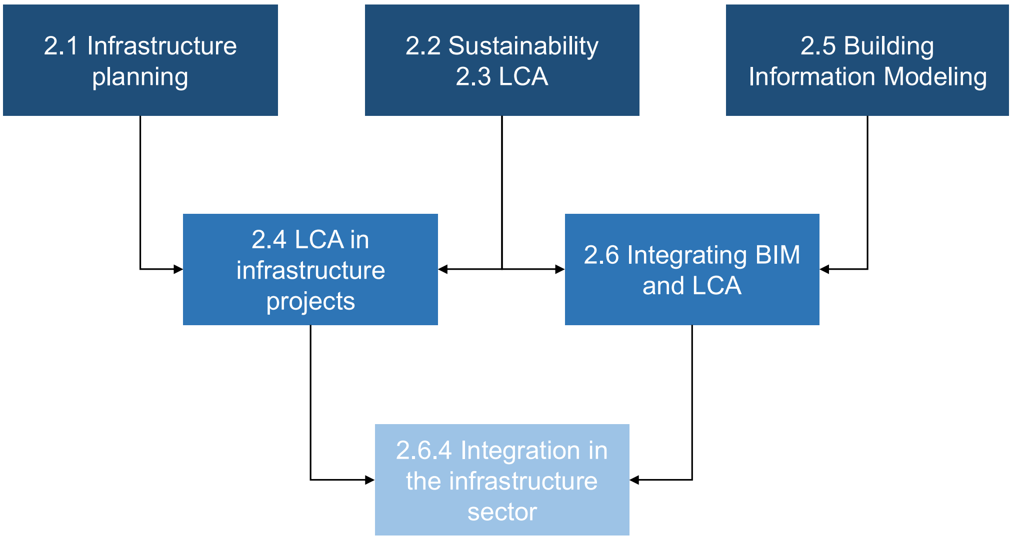


Figure 1.1: Structure of the literature review

The thesis is divided in the following into three main parts according to the research questions. Based on the first research question, a methodology for environmental design decision making is proposed.
To illustrate the integration process of the BIM with LCA data and to demonstrate the proposed methodology, chapter 4 includes a prototypical implementation.
In order to verify this, a case study is carried out in chapter 5, for which the results can be used to draw conclusions for the third research question.
Finally, chapters 6 and 7 provide an evaluation of the proposed methodology with a conclusion and outlook.

Chapter 2

State of the Art

2.1 Infrastructure planning in early design stages

Infrastructure planning includes the design of transport routing alignments (road and rail) and their required building constructions like bridges and tunnels. Due to the long planning and construction periods of infrastructure projects, its planning has a long-term character. Time periods of 10 to 20 years from the start of planning to implementation are common. (GERTZ, 2021)

The main stages of road infrastructure planning, according to MILIUTENKO et al. (2014), were analysed in Sweden, Norway, Denmark and the Netherlands and can be distinguished in three main stages:

1. Choice of transport modality at the national level
2. Choice of road corridor and construction type of a specific project
3. Choice of specific construction design

At first, the need for a new infrastructure on a public level is discussed and whether alternative infrastructure measures can be implemented. If the need is confirmed the mode of transport is selected (e.g. road or train).

Secondly, the corridor is analysed, which includes the location and routing of the road or rail alignment. Third, the construction design is developed, which contains the need of infrastructure elements like bridges or tunnels, depending on the route of the infrastructure project.

2.1.1 Planning process in Germany

In Germany, transport planning is structured as a multi-stage process, which starts with the determination of basic principles including a problem analysis and leads to the investigation of different kinds of possible measurements. The planning process is described by the Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV) (FGSV, 2018, FGSV, 2012). In addition, a large number of transport-specific regulations exist.

Even though, the planning process is described as linear, it is difficult to realise in practice since iterations of different steps happen due to the consideration of many different interests. (GERTZ, 2021)

Main stages in the planning procedure

Similar to the stages elaborated by MILIUTENKO et al. (2014), the stages in Germany are divided as shown in table 2.1.

Table 2.1: Stages of the planning procedure in Germany according to ISO 14040 (2006)

1. Demand planning on national and regional level
2. Preliminary planning Investigation of different road corridors and construction types
3. Draft design planning Choice of specific construction designs
4. Approval planning
5. Implementation planning

Impulse for the planning process

Reasons for new planning processes are indications of deficiencies, a specific need for action or the development of an area in federal or state programmes.
If the need is confirmed, the transport project is either included in the demand plan on a federal level or in the expansion plan on a national level. On a communal level, there is no legal obligation to develop a transport development plan (German: Verkehrsentwicklungsplan). However, many funding programmes require one and the majority of municipalities are providing such plans. (UMWELT BUNDESAMT, 2022)

Initial planning

Different route variants are developed and their traffic, economic, spatial and environmental aspects are examined. Within the scope of the route variant planning process, different alignments with the associated elevation profiles and cross-sections are planned and investigated. Therewith, a choice for the best alignment option and its use of infrastructure elements such as bridges and tunnels can be made. An exemplary illustration of different route alternatives is depicted in fig. 2.1. In addition to the new construction variants, expansion variants and the zero variant should also be evaluated. The latter can be seen as the inventory variant. (WIEDEMANN, 2019)

Within the framework of the regional planning procedure (German: Raumordnungsverfahren), it is examined whether the transport planning is compatible with the objectives of regional and federal state planning. Such objectives are water conservation, protection of species and biotopes and the promotion of structurally weak regions. The different variants are prepared as planning documents on the scale of 1:50.000 and 1:25.000 and are made available to public interest groups. These groups include, for example, nature conservation authorities and municipalities.

In order to compare the different alternatives, the individual effects are evaluated by means of a point system. The objectives named in the planning process are specified by means of indicators in order to assess the alternatives individually. (GERTZ, 2021)

The final line of the infrastructure project is subsequently determined by the Federal Ministry of Transport and Digital Infrastructure (BMVI) for federal roads. (WIEDEMANN, 2019)

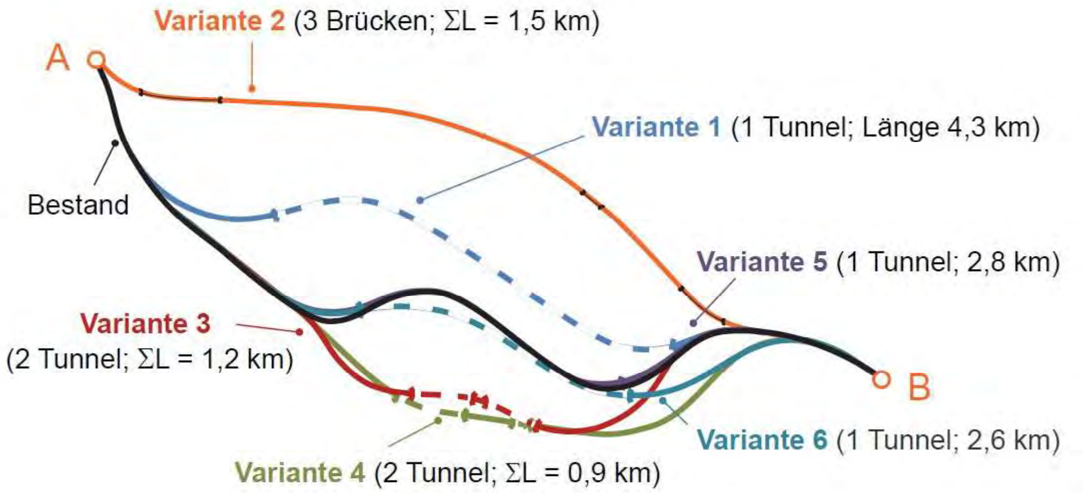


Figure 2.1: Example of different route alternatives (SAUER, 2016)

Draft design and approval planning

Once the line has been defined, a draft design (German: Vorentwurf) of the specific construction design is constructed and afterwards approved by the planning determination procedure (German: Planfeststellungsverfahren). The construction design (German: Bauentwurf) conclusively forms the basis for the execution. (WIEDEMANN, 2019)

2.1.2 Environmental contributions in the staged planning process

With its noise pollution, air emissions, high energy and resource consumption, the transport sector has a considerable impact on our environment. Therefore, in addition to the traffic assessment, an environmental assessment must be carried out in the planning process within the framework of the line determination as well as the regional planning procedures. Based on FGSV (2001), low-conflict areas are identified for the routing of the infrastructure project. Within the framework of an environmental impact study, the effects on the environment are recorded, described and evaluated for each variant. In accordance with the Habitats Directive or the European Birds Directive, their compatibility with the conservation objectives of the existing sites must be evaluated. (Richter, 2016)

In order to ensure that the environmental contributions are considered, the European Union requires to perform Environmental Assessments (EAs). The Environmental Impact Assessments (EIA) directive is one of the oldest environmental regulations in the EU and was initialised in 1986. Its aim was the reduction of environmental impacts of construction projects and contribution to a sustainable development (European Commission, 2021). It is distinguished between a Strategic Environmental Assessment (SEA) for public plans and policies as well as in an EIA for public and private projects.
In the assessment, the environmental impacts are evaluated and compared to the zero alternative. According to the European Commission the "environmental impact assessment must identify, describe and assess the direct and indirect effects of a project on a number of environmental factors (population and human health, biodiversity, land, soil, water, air, climate, landscape, material assets and cultural heritage), as well as the interaction between these various elements" (European Commission, 2021).
However, according to Miliutenko et al. (2014), life cycle energy use or Greenhouse Gas (GHG) emissions are not included in an EIA. Furthermore, EAs do not have a clear definition of how climate change should be included and mostly focus on possible measures. It can be distinguished in two different types of measures of climate change:

- Mitigation measures: Strategies for reducing GHG emissions
- Adaption measures: Road infrastructure is adjusted to the consequences of climate change

2.2 Sustainability in infrastructure projects

Sustainability is based on the three dimensions ecology, economy and socio-culture as depicted in fig. 2.2. "This concept simultaneously addresses ecological, economic and socio-cultural requirements as equally important aspects and includes future generations in the analysis. Furthermore, the concept also underlines the responsibility of the individual and, in particular, the function of the public sector as a role model." (BMI, 2019)

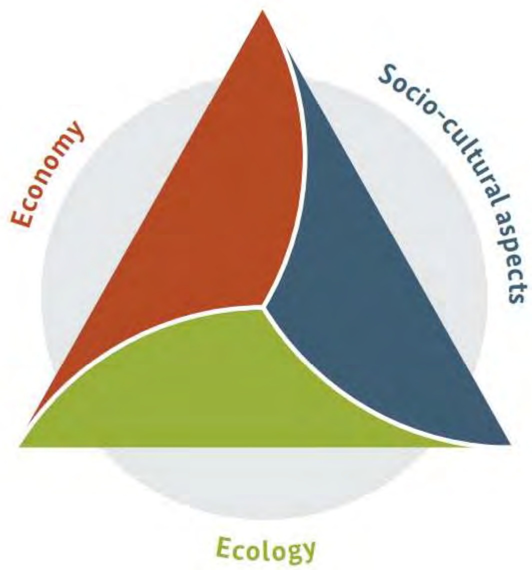


Figure 2.2: Dimensions of Sustainability (BMI, 2019)

For infrastructure buildings, such as bridges, roads and tunnels, the main criteria for the decision process used to be the production price (ZINKE et al., 2021). Currently, criteria that correspond to sustainability aspects are increasingly taken into account.

The building sector already has internationally accepted certification systems (e.g. German: Bewertungssystem für nachhaltiges Bauen (BNB) und Gütesiegel der deutschen Gesellschaft für nachhaltiges Bauen (DGNB) (DGNB, 2018)).
However, the approaches used in building construction cannot be transferred as (ZINKE et al., 2021):

- label certification are not appropriate in infrastructure projects, as they are public projects. An evaluation after construction completion therefore does not contribute to communication with the users.
- for infrastructure projects the integration into a public-law regulated planning process is required.

In the field of infrastructure construction, research on sustainability analyses began increasingly in 2010. There is now a consensus that sustainability aspects should be integrated into the planning process as early as possible in order to be able to exert the greatest influence. (ZINKE et al., 2021)

2.2.1 Rating systems in Germany

In Germany, there is currently no established system for the holistic sustainability assessment of infrastructures (ZINKE et al., 2021).However, the German Federal Highway Research Institute (German: Bundesanstalt für Straßenwesen (BASt)) has commissioned several research projects for the evaluation of infrastructure constructions in recent years.

Hauptkriteriengruppe	Kriteriengruppe	Nr.	Titel	Gewichtung Einzelkriterium Gesamtbewertung	Punktekriterium IST	Punktekriterium SOLL	Bedeutungsfaktor	Erfüllungsgrad	Gewichtung Gruppe	Gesamterfüllungsgrad
Ökologische Qualität	Wirkung auf die globale Umwelt	1.1	Treibhauspotenzial (GWP)	4,500 %		10	3	0,0 %	22,5 %	0,0 %
		1.2	Ozonschichtzerstörungspotenzial (ODP)	1,500 %		10	1			
		1.3	Ozonbildungspotenzial (POCP)	1,500 %		10	1			
		1.4	Versauerungspotenzial (AP)	1,500 %		10	1			
		1.5	Überdüngungspotenzial (EP)	1,500 %		10	1			
		1.6	Risiken für die lokale Umwelt	1,500 %		10	1			
		1.7	Sonstige Wirkungen auf die globale Umwelt							
		1.8	Umweltwirkungen infolge von baubedingter Verkehrsbeeinträchtigung	4,500 %		10	3			
	Resourceninanspruchnahme und Abfallaufkommen	1.9	Primärenergiebedarf nicht erneuerbar (PEne)	4,500 %		10	3			
		1.10	Primärenergiebedarf erneuerbar (PEe)	1,500 %		10	1			
		1.11	Wasserbedarf und Abwasseraufkommen							
		1.12	Flächeninanspruchnahme							
		1.13	Abfall							
Ökonomische Qualität	Lebens zykluskosten	2.1	Direkte bauwerksbezogene Kosten im Lebensyklus	13,500 %		10	3	0 %	22,5 %	
	Weiterentwicklung	2.2	Externe Kosten infolge von baubedingter Verkehrsbeeinträchtigung	9,000 %		10	2			
Soziokulturelle und funktionale Qualität	Gesundheit, Behaglichkeit und Nutzerzufriedenheit	3.1	Lärmschutz	5,625 %		10	2	0 %	22,5 %	
		3.2	Komfort	5,625 %		10	2			
	Funktionalität	3.3	Umnutzungsfähigkeit	5,625 %		10	2			
		3.4	Betriebsoptimierung	5,625 %		10	2			
		3.5	Sicherheit gegenüber Störfallrisiken (Security)							
		3.6	Verkehrssicherheit (Safety)							
Technische Qualität	Qualität der technischen Ausführung	4.1	Elektrische und mechanische Einrichtungen	3,000 %		10	1	0,0 %	22,5 %	
		4.2	Konstruktive Qualität	9,000 %		10	3			
		4.3	Wartungs- und Instandhaltungsfreundlichkeit	6,000 %		10	2			
		4.4	Verstärkung und Erweiterbarkeit	1,500 %		10	0,5			
		4.5	Rückbaubarkeit, Recyclingfreundlichkeit, Demontagefreundlichkeit	3,000 %		10	1			
Prozessqualität	Qualität der Bauausführung	5.1	Qualifikation des Planungsteams und Qualität der Planung	3,750 %		10	3	0,0 %	10,0 %	
		5.2	Nachweis der Nachhaltigkeitsaspekte in der Ausschreibung	2,500 %		10	2			
		5.3	Baustelle/Bauprozess							
		5.4	Qualität der ausführenden Firmen/ Präqualifikation							
		5.5	Qualitätssicherung der Bauausführung	3,750 %		10	3			

Figure 2.3: Proposal for an indicator system for the assessment of bridges (SCHMELLEKAMP, 2016)

For example, within the scope of the research project „Einheitliche Bewertungskriterien für Elemente der Straßenverkehrsinfrastruktur im Hinblick auf Nachhaltigkeit – Straße und Tunnel" (BAST, 2011), criteria profiles for the elements of roads and tunnels were transferred in order to evaluate sustainability within the design and approval phase (FISCHER et al., 2016).

In the research project "Pilotstudie zum Bewertungsverfahren Nachhaligkeit von Straßenbrücken", the environmental component was determined by a LCA with the impact indicators Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP), Acidification Potential (AP), Eutrophication Potential (EP). However, this study is only related to the bridge structure and not to the entire route. Within the framework of a sustainability certification system for roads, the three dimensions of sustainability are for example evaluated with the help of a point system as shown in fig. 2.3.

2.2.2 European rating system

LCE4ROADS is a new sustainability certification system for roads with the goal of developing a "EU-harmonized sustainability certification system for cost-effective, safer and greener road infrastructures" (FLORES et al., 2016). It considers all sustainability pillars in order to evaluate the whole road life span, which includes planning, construction, operation, maintenance and end of life. At three different stages the certification can be awarded:

- during planning and design stage
- after construction: for validating the planning data
- during the operation phase: to check real performance

Moreover, there are two different levels of achievement. A light (basic) one, where a minimum of the requirements are met, and a complete (optimum) one, which covers the whole range of requirements.

Table 2.2: Sustainability dimensions in LCE4ROADS according to FLORES et al. (2016)

Environmental	**Economic**	**Social**
Following EN 15804	Based on the ISO 15686-5	Directive 2008/96EC
Material to be used, environmental impact associated to the infrastructure	Including agency cost (initial cost, maintenance cost and salvage value)	Criteria for comfort, safety and noise

2.2.3 Conclusion of considering environmental impacts

Currently, the environmental impacts are mostly considered within the framework of a rating system in the context of a sustainability assessment. The ecological aspects of sustainability are determined with the help of a LCA. Depending on a point system, a degree of fulfilment is determined to evaluate the different sustainability aspects.

Sustainability tools are mostly developed for end-product evaluation. The design phase must be completed to a certain extent in order to be able to carry out a sustainability assessment. However, decisions that have the highest impact on the environmental effects need to be made during the design phase.

According to van Eldik et al. (2020), a simplified LCA is required for addressing this issue. LCA only represents the ecological dimension of sustainability. More details are therefore given in the following section.

2.3 Life Cycle Assessment - LCA

A methodology mentioned by the EUROPEAN COMMISSION (2013) that can determine the environmental aspects of sustainability is called Life Cycle Assessment (LCA). Therewith, GHG emissions or life cycle energy use can be for example calculated over the whole life cycle of a product. It can be seen as an analytic tool to obtain comparable data which can be used for a decision-making process.
Indicators such as GHG emissions can be calculated and solutions can be found on how to reduce them. Based on this combined approach, mitigation measures can be implemented.
To calculate indicators as GHG emissions and finding solutions for a reduction can be assigned to mitigation measures.

With the increased awareness of protecting our environment and the scarcity of resources, the method of LCA was being established in the 1990's within the development of the standards of the International Organization for Standardization (ISO) (ISO 14040, 2006 and ISO 14044, 2006).

> *"LCA considers the entire life cycle of a product, from raw material extraction and acquisition, through energy and material production and manufacturing, to use and end of life treatment and final disposal. Through such a systematic overview and perspective, the shifting of a potential environmental burden between life cycle stages or individual processes can be identified and possibly avoided."* (ISO 14040, 2006)

2.3.1 Phases of a LCA

The implementation of a LCA is structured in four phases as depicted in table 2.3.

A LCA is useful for identifying opportunities for improving the environmental impacts of a product throughout the entire life cycle and for giving evidences to decision makers in industry or government. It refers to the environmental aspects and impacts, whereas the economic and social aspects are not considered in the scope of a LCA. The economical and social aspects are covered in Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA).

1. Goal and scope

The first phase of a LCA defines the goal, functional unit, system boundaries and the level of details of the following phases. The approach of a LCA is relative as it is structured around a **functional unit** which defines what is being studied and serves as a basis for comparability. The following analysis is related to the functional unit with all its inputs and outputs.
The system boundaries should define which life cycle stages, unit processes and flows

Table 2.3: Four phases of a LCA according to ISO 14040 (2006)

1. Goal and scope definition phase Defining system boundaries and the level of detail
2. Life Cycle Inventory analysis phase (LCI) Inventory of input / output data and collection of data
3. Life Cycle Impact assessment phase (LCIA) Analysis of inventory for environmental impacts
4. Interpretation phase Summary and discussion as a basis for conclusion, recommendations and decision-making

are taken into account. However, the initially defined system boundaries can be redefined during the working process due to the iterative character of the assessment. The life cycle stages (fig. 2.4) are defined in DIN EN 15978 (2021) and can be categorised in four main modules: product stage (A1-A3), construction process (A4-A5), use stage (B1-B8), end of life stage (C1-C4) as well as benefits and loads beyond the system boundary (D1-D2).

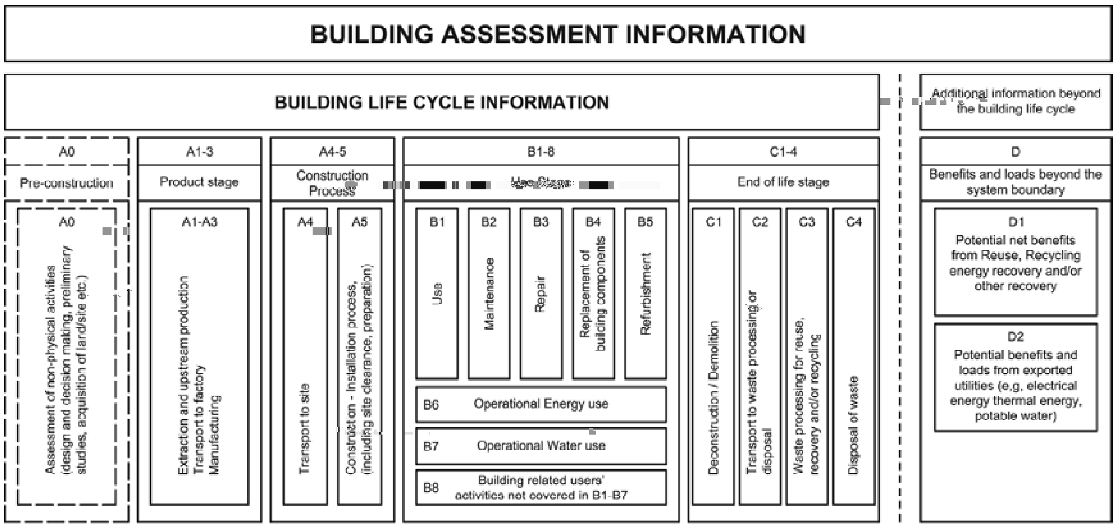


Figure 2.4: Life cycle stages (DIN EN 15978, 2021)

Depending on which stages are considered, the observation period can be for example denoted as cradle to gate, cradle to grave or cradle to cradle. In a cradle to gate approach only the manufacturing phases A1-A3 are considered, while in a cradle to gate approach the life cycle of a product according to system boundaries A1-C4 are depicted. In a cradle to cradle consideration the focus is on recycling and consistency. (DIN EN 15804, 2022)

2. Life Cycle Inventory (LCI) analysis phase

During the LCI, data concerning the input and output is collected and calculated. Data collection includes for example the energy and material inputs on the one side, and emissions to air, water or land on the other side.
The type of data can be product-specific data, generic data or estimates. Specific data includes calculated primary data as Environmental Product Declaration (EPD), while generic data contains averaged values e.g. data on background processes. EPDs represent verifiable environmental information over the life cycle of a product. They represent data packages according to the different life cycle stages and can also be subdivided into different observation periods. They are presented in a way that aggregation of the data is possible in order to provide complete information for buildings or other constructions. (DIN EN 15804, 2022)
After the collection process, the data needs to be calculated in means of the validation and relating the data to unit processes and to the functional unit.

3. Life Cycle Impact Assessment (LCIA) phase

The third phase is based on the LCI and analyses the environmental impacts of the previously derived quantities by connecting them to the LCA databases. Therewith, the significance of environmental impacts is assessed. Mandatory elements of the third phase are:

- "the selection of impact categories, category indicators and characterisation models;
- assignment of LCI results to the selected impact categories (classification);
- calculation of category indicator results (characterisation)." (ISO 14044, 2006)

Optional elements are the normalisation, grouping, weighting or the data quality analysis whose use depends on the goal and scope.

Depending on the impact categories different indicators can be selected. A selection of the most common indicators for environmental impacts are listed in table 2.4.

The LCIA phase considers and investigates only the environmental impacts that are defined in the goal and scope. Therefore, not all environmental aspects have to be considered during a LCIA which represents limitations of this approach. Due to the iterative character of this assessment, the goal and scope can be reviewed after the LCIA phase and checked whether the objective of the study has been met or not. If this is not the case, the goal and scope can be modified. (ISO 14040, 2006)

Table 2.4: Indicators depending on impact category according to DIN EN 15978, 2021

Impact category	Indicator for environmental impacts	Indicator unit
Climate change	Global Warming Potential (GWP)	kg CO_2 eq.
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC 11 eq.
Acidification	Acidification Potential (AP)	mol H+ eq.
Eutrophication	Eutrophication Potential (EP)	kg PO_4 eq.
Photochemical ozone formation	Photochemical Ozone Creation Potential (POCP)	kg NMV OC eq.
Water use	Water Depriviation Potential (WDP)	m^3 world eq.
Resource use	Primary Energy Total (PET) Primary Energy Renewable Total (PERT) Primary Energy Non-Renewable Total (PENRT)	MJ MJ MJ

4. Interpretation phase

The last phase of a LCA is based on the results of the previous phases and identifies their most significant issues. It should be kept in mind that the results are all related to the relative approach. They "indicate potential environmental effects, and that they do not predict actual impacts on category endpoints, the exceeding of thresholds or safety margins or risks" (ISO 14040, 2006).
A following evaluation should consider completeness, sensitivity and consistency checks. In the end, conclusions and recommendations with limitations should be made.

2.3.2 Available databases

For performing a LCA, a database is required that provides the environmental indicators. With the German database Ökobilanz-Datenbank für Baustoffe (ÖKOBAUDAT), a very comprehensive and high-quality database is available, provided by the German Bundesministerium des Innern, für Bau und Heimat (BMI) and Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR).
It is an online database with tested data quality and uniform data formats. Moreover, it is free of charge and the data transfer to other tools is possible. The database provides the environmental indicators depending on the life cycle stage (building materials, construction, transport, energy and disposal processes) for conducting a LCA. The mapped data is bound to strict quality characteristics and can be assigned to three different categories. Category A represents data from EPD, while category B is critically reviewed data from LCA data and category C represents generic data (Brockmann et al., 2019). An overview of the data providers can be found in fig. 2.5.

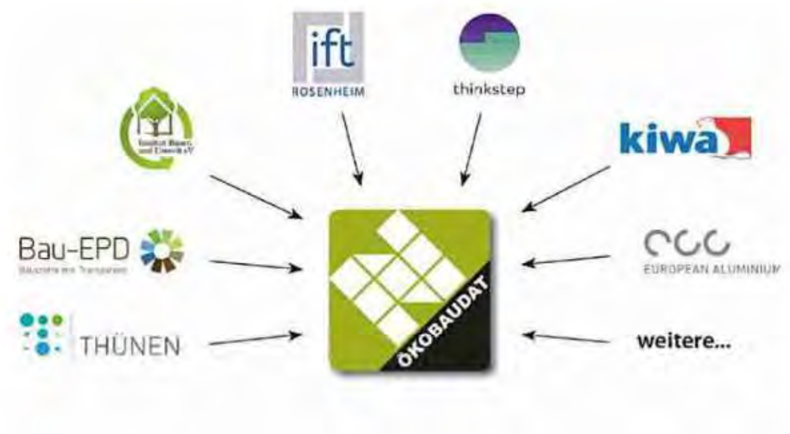


Figure 2.5: Data providers of the ÖKOBAUDAT (Brockmann et al., 2019)

There are different types of environmental labels to evaluate the environmental performance of a product. The Environmental Label Type I is based on third parties organisation criteria and identifies products that showed a reduced environmental impact throughout their whole life cycle. Type II is a self-declared environmental label, that is often connected to a single attribute. An Environmental Product Declaration (EPD) belongs to Type III and is a registered trademark. (ISO 14040, 2006)

Next to theÖKOBAUDAT, the swiss database ecoinvent should be mentioned as it is one of the world's leading life cycle assessment databases. Around 18.000 life cycle inventories of different sectors such as building constructions, transports and other industrial sectors are available. It can be used in the form of an online version as well or is available for software download. However, the access is not for free but commercial or educational licences can be aquried. With a free guest licence basic information about its datasets can be accessible. (ecoinvent, 2022)

2.4 LCA in infrastructure projects in an early design stage

In infrastructure projects, a LCA is rarely performed in an early design stage. According to a study for life cycle consideration of road infrastructure (MILIUTENKO et al., 2014), Norway is one of the only countries that has a formalised way to carry out a LCA during the choice of road corridor.

As mentioned in section 2.1, the European Union has a requirement for performing an EIA to ensure that all environmental aspects are considered before making final decisions. However, GHG emissions and energy use are not included in this process.
Norway can be seen as a role model in this area, as it already developed a model called EFFEKT to estimate the life cycle energy use and GHG emissions in road projects as part of the Cost-Benefit Analysis (CBA) in a feasibility study. (H. BRATTEBØ et al., 2013)

2.4.1 Possible integration in the planning process

The question arises, on how to integrate the methodology of LCA in the infrastructure planning process. MILIUTENKO et al. (2014) therefore suggest three different options as shown in fig. 2.6.

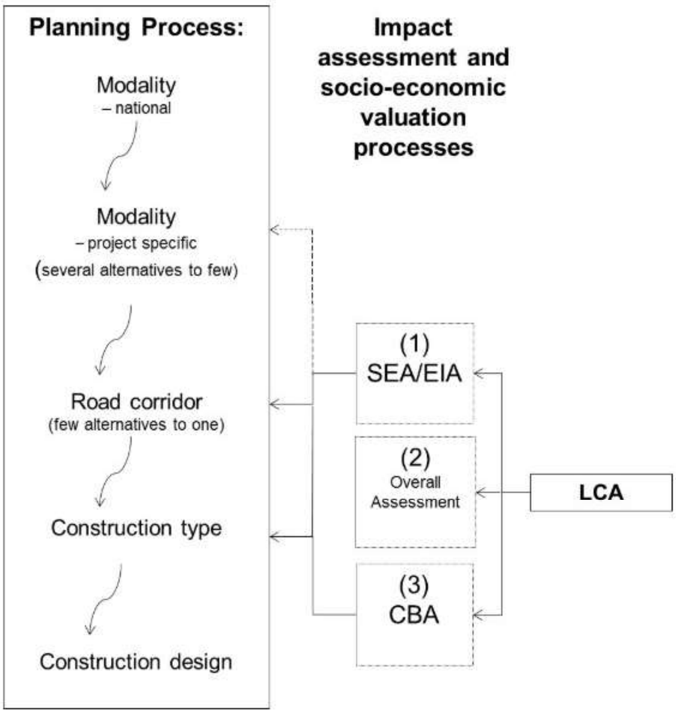


Figure 2.6: Possible integration of LCA in early planning stages (MILIUTENKO et al., 2014)

The first option suggests to implement the LCA as a standardised model in the framework of an EIA or SEA. This option enables the possibility to use the assessment as a decision support for the choice of road corridor to reduce the GHG emissions and energy use. The second option considers the LCA separately to the EIA giving it a higher weight by standing alone. The third and last option represents the way of how it is done in Norway, where the assessment is included in the CBA. However, each country should decide which option suits the best for itself. More research might be required to evaluate this matter. (MILIUTENKO et al., 2014)

2.4.2 Important parameters to consider in an early planning stage

For conducting a LCA in an early planning stage as the choice of road corridor, a simplified LCA is required with usable software. (VAN ELDIK et al., 2020)
An European research project about **Life Cycle Considerations in EIA of Road Infrastructure (LICCER)** addressed this issue. They developed a tool to calculate GHG emissions and life cycle energy, the results of which can be used in an early design stage. It is a research project of a cross-border funded joint research programme including Germany, Ireland, Netherlands, Sweden, Norway, Denmark and the United Kingdom. It was initiated by ERA-NET ROAD II – Coordination and Implementation of Road Research in Europe.
The LICCER LCA-tool is based on Mircosoft Excel to calculate the annual energy use and related annual GHG emissions (CO_2-equivalents) over the life cycle. However, it is still necessary to enter the data manually from the road model to the LCA model which is time consuming and error-prone. The reason for developing the LICCER tool is the consideration of emissions "as a consequence of production and construction of road elements (e.g. roads, bridges and tunnels), the operation of the road (e.g. for lighting and maintenance) and the end-of-life processing after a road becomes obsolete." (H. BRATTEBØ et al., 2013)

With performing a sensitivity analysis, critical parameters were evaluated according to LILJENSTRÖM et al. (2021). The resulting infrastructure GHG emissions and energy use, calculated with the tool, were sensitive to:

- the amount of asphalt required during the lifetime of the road which makes the assumption of the resurfacing period an important variable
- changes in parameters that affect the impacts of earthworks (specific GHG emissions of diesel) and pavement (energy use per unit of bitumen input)

In general, the most important parameters to be considered at an early planning stage were elaborated by H. BRATTEBØ et al. (2013). Table 2.5 provides an overview with regard to different life cycle stages and their important parameters. An important point is the consideration of traffic as well as infrastructure impacts. When comparing the results, the road corridors should be differentiated in terms of traffic or in terms of infrastructure and possible improvements should be identified for both of them. (LILJENSTRÖM et al., 2021)

Table 2.5: Project parameters of importance according to H. BRATTEBØ et al. (2013)

Life cycle stage	Important parameters
Construction	- Length, width and depth of road layers - Earthworks by indicating diesel usage or soil volumes - Most transport of materials used in larger quantities, such as concrete and soil or come from long distance as steel - Material consumption for tunnels and bridges - Diesel fuel consumption by machinery
Use stage	- All service life of road infrastructure variables - Share length of road lighting, especially in tunnels where lighting occurs 24 hours a day
Traffic	- All fuel consumption from traffic variables

2.4.3 Applicability of the results

For a tool in an early planning stage, a simplified LCA is required where the use of default data can reduce the complexity and workload. However, the variation of default data is high as it has been collected from different sources which can influence the results.

Typical default data according to H. BRATTEBØ et al. (2013) are listed in the following:

- the assumed diesel use for soil excavation
- the assumed default quantity of explosives for rock blasting
- the amount of diesel consumption of traffic which depends on local conditions such as road incline and speed limit

Therefore, default data should be used with caution as it can vary between different road corridors and therewith may influence the ranking. If default data is common for all road corridors, the ranking between different road corridors may not necessarily change. To solve the former, experts suggest to reduce the amount of input data for reducing the complexity. However, this can lead to the problem that the model becomes considerably simplified to distinguish between different corridors at all. (H. BRATTEBØ et al., 2013)

A suggestion by LILJENSTRÖM et al. (2021) is the use of default data that is nation specific and preferably approved by the national road authority. If possible, the model or tool should include national default data for construction measures such as different types of roads, bridges, and tunnels.

Deviations in conducting a LCA can also emerge due to the use of different tools based on different databases. DOS SANTOS et al. (2017) therefore compare different life cycle assessment tools for road pavement infrastructure and outline their potential differences. Examined tools are "PaLATE V2.2, VTTI/UC asphalt pavement LCA model, GaBi, DuboCalc, and ECORCE-M" (DOS SANTOS et al., 2017). All of these were applied to a spanish pavement reconstruction project. Life cycle stages which were included are the construction and maintenance stage.
The results show that it is crucial to develop a "(1) a standardized framework for performing a road pavement LCA that can be adapted to various tools and (2) local databases of materials and processes that follow national and international standards" (DOS SANTOS et al., 2017).
Moreover, the results also show that the calculated values differ greatly due to different databases. For example the GaBi tool achieves higher impact category stores on a material level than the other tools. This may be traced back to different system boundaries or that the materials have different sources or processes in different countries.
The LCIA comparison shows that the demolition of old pavement is the lowest contributor to the impact category, while the pavement structure construction is considered as the main contributor. The case study shows that the impacts of the most common materials are less sensitive when comparing different LCA tools, while less common materials have greater deviations and which might not even be included in the databases. The value of the final results is therefore mostly dependent on the quality of the databases and the uncertainty should be considered with the help of a sensitivity analysis. (DOS SANTOS et al., 2017)

2.4.4 Dominance of traffic related impacts

Road projects are unique which makes the results of different LCA difficult to compare. However, H. BRATTEBØ et al. (2013) have indicated important indicators such as:

- the dominance of traffic related impacts
- the relative importance of material production and construction compared to maintenance and end-of-life
- the importance of earthworks in case of difficult construction conditions

In a dissertation on the sustainable assessment of tunnel structures, SAUER (2016) also emphasises the major influence of traffic emissions.
The evaluation of different routing options takes into account all elements of the transport infrastructure as roads, bridges and tunnels. However, traffic emissions in particular have a major impact when comparing different alignment options. Traffic emissions are the effects caused by flowing and disturbed traffic. In particular, the use of lower longitudinal gradients and the resulting lower CO_2 emissions of motor vehicles and trucks improve the ecological impact.

However, the most ecological alignment variant is mainly realisable through the use of engineering structures. As a result, a construction project that is initially more costly due to the construction of tunnels appears at first to be environmentally more harmful due to high CO_2 emissions during the construction phase. A case study of SAUER (2016) has shown that the traffic emissions may exceed the embodied emissions within a period of 10 years. However, this is not transferable to other construction projects, as the geographical conditions are always different.

The opposite is shown in another study according to DITTMER et al. (2020) in which the carbon footprint of Berlin underground and tramway plans is evaluated.
The CO_2 emissions of the construction of an underground line in tunnel position are compared with the CO_2 emissions saved by car and bus journeys. The production of cement and steel, which are needed for the construction of the tunnel, are the biggest CO_2 emitters. Compensation of the CO_2 emissions would on average occur after 139 years, whereas the construction of a tramway can already be compensated after 10 years. The conversion to electric mobility of cars and buses has not yet been taken into account and would worsen the results. Therefore, the authors recommend the rehabilitation of existing tunnels and the expansion of the tram network before the construction of new metro lines.

Another study, by MILACHOWSKI et al. (2010), is presenting the balancing of a 1km long motorway section in different design variants. As a data source, the Swiss database ecoinvent was used and the data was evaluated by the life cycle assessment software SimaPro. The authors conclude that a fuel-saving design of the road superstructure is more important than a design variant with a lower environmental impact during production and maintenance. Road surface properties such as surface texture, unevenness and stiffness can influence the fuel consumption for determining traffic emissions in a range of 5 to 20%. High temperatures lead to an increased deformation of asphalt pavements which causes higher fuel consumption. In this case, harder pavement surfaces may result in fuel savings of 7 to 15%.

2.5 Building Information Modeling in the infrastructure sector

2.5.1 BIM methodology

With Building Information Modeling (BIM) complex information and relationships regarding the construction project are stored and depicted. Various definitions of BIM already exist, but it is important to understand that it is not only the representation of a 3D model, instead it also stands for an information management method. The German Federal Ministry of Transport and Digital Infrastructure, defines BIM as the following:

> “Building Information Modelling means a collaborative work method that creates and uses digital models of an asset as a basis for the consistent generation and management of information and data relevant to the asset’s life cycle as well as for the sharing or passing on of such information and data between the participants for further processing by way of transparent communication.” (BMVI, 2015)

BIM application methods

As it is seen as an information management method and not as a single software product, the data exchange scenario between different software products becomes very important. Therefore, it can be distinguished in different application methods as depicted in fig. 2.7.

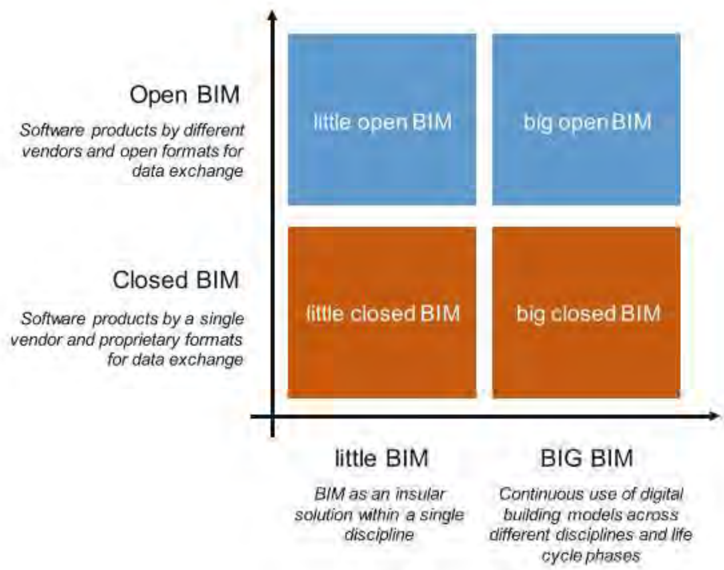


Figure 2.7: Matrix of BIM application methods (Borrmann et al., 2018)

The terms "open" and "closed BIM" distinguish between the use of software by a single or multiple vendors with open data formats and a high interoperability. Another distinction is seen in the use of BIM as an insular solution which is described as "little BIM" or the continuous use of the digital model over the life cycle as "big BIM". (BORRMANN et al., 2018)

BIM dimensions

Next to the geometric representation of the construction, semantic data, such as, the material, technical properties or construction methods are captured in the BIM model. Additionally, other dimensions like time (4D) or costs (5D) can be included with the BIM methodology. The consideration of BIM in combination with sustainability is described as the sixth dimension. In addition to energy analyses and sustainability certifications, the sixth dimension can also include LCA. (FHWA, 2020)

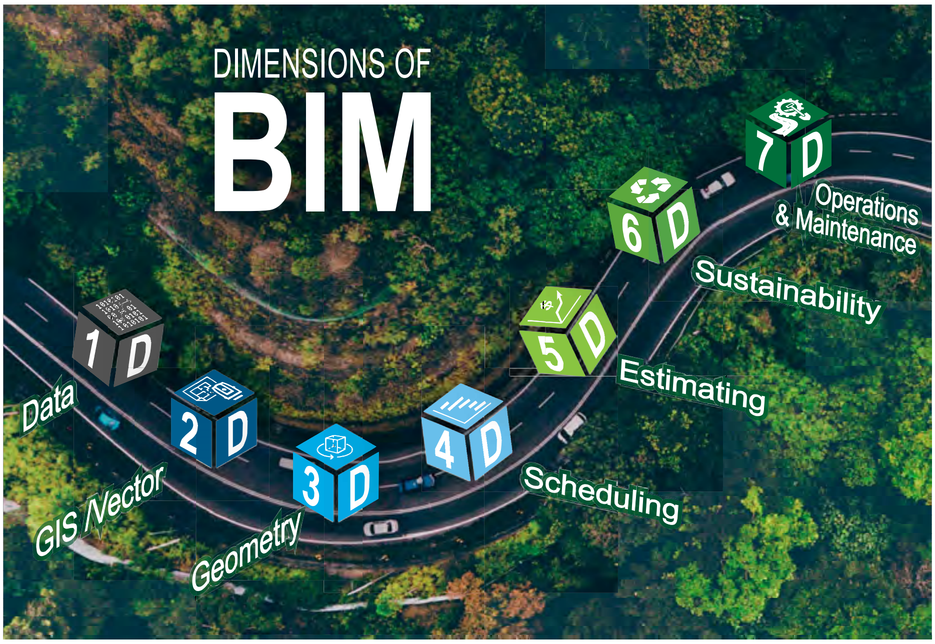


Figure 2.8: Dimensions of BIM for infrastructure (FHWA, 2020)

The geometric and semantic representation of a BIM model can be implemented and presented in different levels of development which is elucidated in the following.

Level of Development

For realising the potential of BIM, an agreement on the information that is modelled and exchanged over the whole life cycle of a project is required. In contrast to the conventional 2D planning process, the BIM model does not have any scale as it is always 1:1. The Level of Development (LOD) therefore represents an analogy to the drawing scale, which defines what level of maturity of a particular design stage must be represented. Its requirements should be defined by the client at the beginning of a project as they are typically a part of the Employer's Information Requirements (EIR). (BORRMANN et al., 2018)

The LOD is composed of the Level of Geometry (LOG) and the Level of Information (LOI) and is often represented in the following equation:

$$LOD = LOG + LOI \tag{2.1}$$

The geometric detailing is thereby depicted in the LOG, whereas the LOI is representing the alphanumeric information.
Next to the term of LOD another term is used interchangeably in literature which is the Level of Detail (LoD). However, this leads to confusion as the two definitions represent different concepts. In contrast to LoD, the LOD includes the model elements reliability, whereas the LoD is only describing the amount of detailing. (ABUALDENIEN & BORRMANN, 2022)

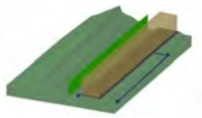
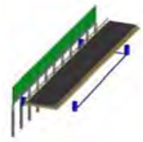
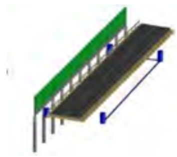
LOD	Modell description	Illustration
100	Preliminary design stage model: Rough construction parameters, such as area, length, width, height, location and position	
200	Draft design models for approval planning: Essential model elements with correct geometric and alphanumeric data	
300	Execution models: Model elements with great geometric and alphanumeric information depth, examplarily used for quantity takeoff for tendering purposes	
350	Supplementary detailed drawings such as slope protection or railings	
400	Construction and assembly models: Model with additional alphanumeric information such as manufacturing and installation details	
500	As-built-Models: Model with alphanumeric information for operation and maintenance	

Figure 2.9: Definition of LODs according to BIM4INFRA (2019)

The definition of LOD includes a scale of detailing from 100 to 500. However, several definitions of it exist nationally and internationally. ABUALDENIEN and BORRMANN (2022) therefore urge for unifying the different concepts internationally as their deviations cause misunderstandings.

The German Ministry of Transport funded the project BIM4INFRA2020 to develop guidelines and recommendations for the mandatory use of BIM in infrastructure projects. In this framework, specifications for the LOD were developed for infrastructure projects and matched to national design phases according to the German HOAI (German: Honorarordnung für Ingenieure und Architekten). A corresponding overview is presented in fig. 2.9.

2.5.2 Modelling of infrastructure projects

An infrastructure model is mainly built out of two components which are the Figital Terrain Modell (DTM) and the routing model.
The planning process starts on the basis of the DTM, which reflects the topographic surface of the terrain. The DTM was created on the basis of recorded survey points and is usually made available through a geographic information system database (GIS database). (OBERGRIESSER, 2017)
An exemplary representation of a DTM in the form of a grid model is depicted in fig. 2.10. Grid surfaces are thereby formed out of points that lie on a regular grid.

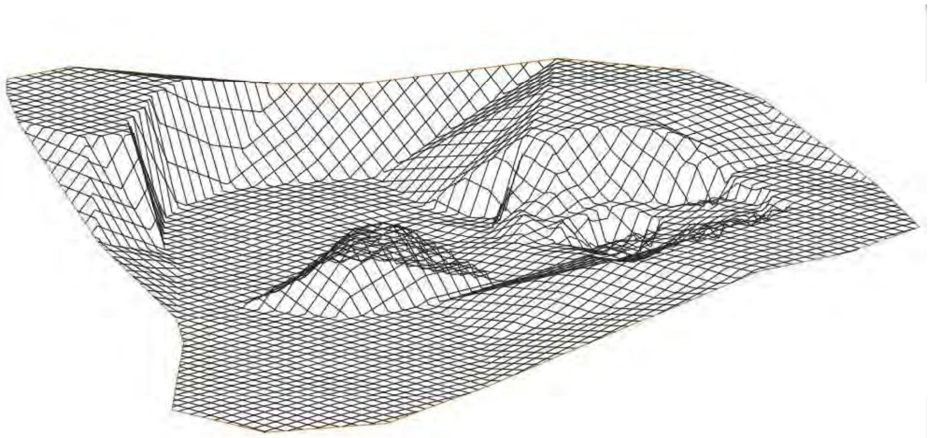


Figure 2.10: Exemplary DTM in form of a grid model (OBERGRIESSER, 2017)

In the next step, the routing model is created depending on the terrain model. For this purpose, Computer Aided Design (CAD) software products offer a drawing-oriented view, which has already been established in the planning process for many years and is further on regarded as relevant. Even though it is now possible to plan geometric representation of parametric curves with the help of splines, the adaptation of the routing to the terrain model would be difficult to achieve.

The three different drawing-oriented views are based on the following components:

1. site plan: horizontal view of the road alignment

2. elevation view: vertical view of the road profile

3. cross-section

The site plan (fig. 2.11) shows the road corridor and its alignment projected into the xy plane. The alignment describes the horizontal course of a traffic route between two points. In particular, the road axis with the kilometre marking and the alignment elements as bridges and other engineering structures (e.g. noise barriers, retaining walls) are depicted.

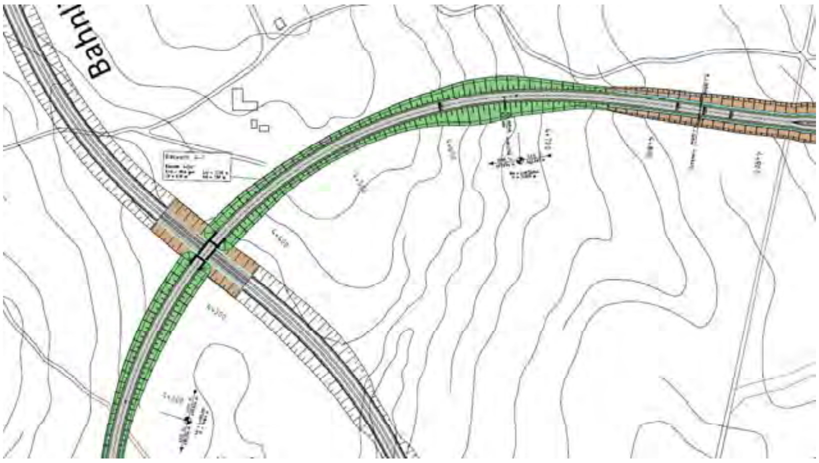


Figure 2.11: Site plan

The elevation plan (fig. 2.12) shows the gradient using a specific s-z coordinate system where s specifies the station and z the elevation at the corresponding s. Depending on the planning phase, the scale and the representation of the building structures varies.

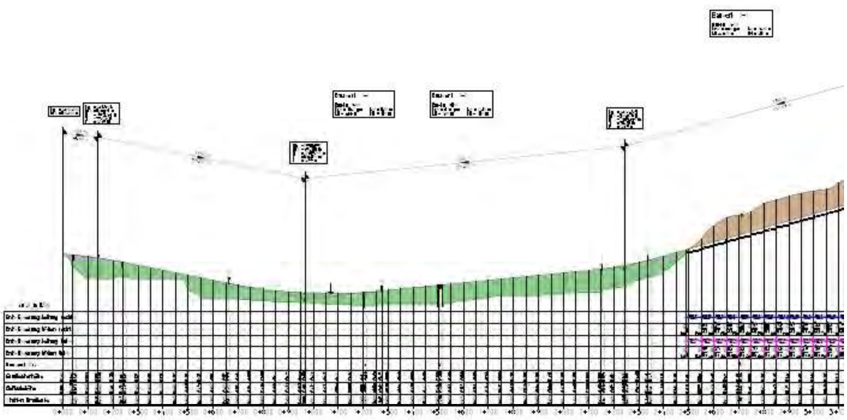


Figure 2.12: Elevation plan

Next to the profile of the routing, the profile of the terrain model is pictured as well in an elevation plan. Therewith, the vertical alignment can be adjusted to the course of the terrain. If the vertical alignment of the routing is underneath the terrain, soil has to be executed for creating a cut (brown area). On the contrary, if the gradient of the road runs above the ground, soil is required to create a dam for the road (green area).

With the cross-section view (fig. 2.13), the different layers of the road construction are modelled with its respective thickness, width and cross slope. (WIEDEMANN, 2019)

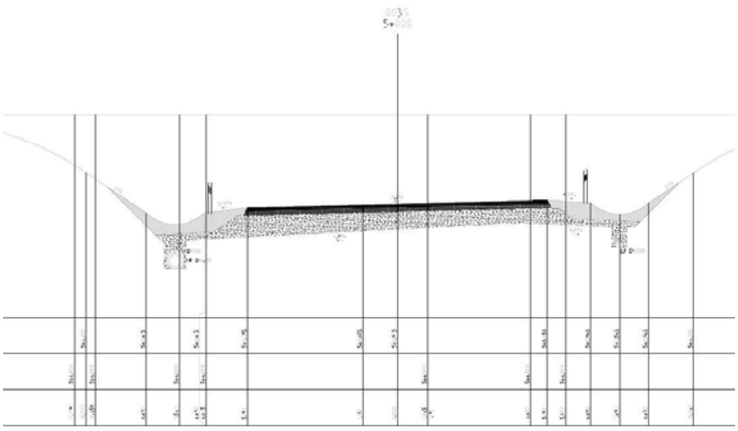


Figure 2.13: Cross-section view

The design is continuously adapted in three different planning views in order to achieve an optimum. The BIM models are then created out of the different drawing views with its parameters as length, heigth and width of the objects which is referred to as implicit geometry modelling. (OBERGRIESSER, 2017)

The result is a complete 3D route construction ground model including the dam bodies (brown body) and cut areas (white areas) as depicted in fig. 2.14.

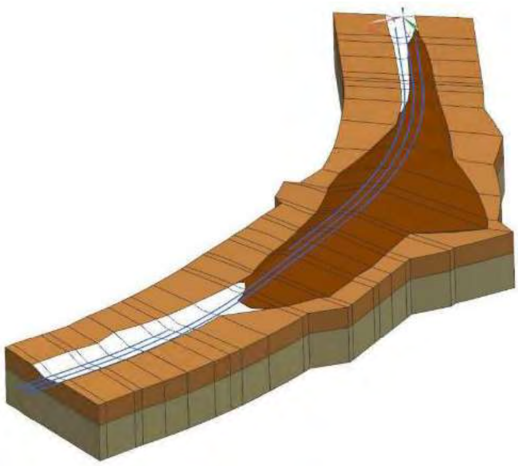


Figure 2.14: 3D route construction model (OBERGRIESSER, 2017)

2.5.3 Industry Foundation Classes (IFC)

A common detailed description of semantic information is required for vendor neutral data exchange of BIM models. A hierarchy for the classification of building components, their relationship between each other and their relevant properties therefore needs to be defined. The term interoperability becomes relevant here, as it aims for loss-free data exchange between software products by different vendors and lays the foundation for big open BIM. Especially in the construction sector, the term interoperability is difficult to realise, as compared to other industries, the planning, construction or maintenance phase is occupied by many different companies which use different kinds of programs. The process can be seen as highly fragmented, which makes it challenging to define one uniform standard. However, it is relevant to avoid becoming dependent on one software producer for both public and private clients to avoid vendor lock-in and to ensure that data is still accessible even if the company may not exist anymore. (BORRMANN et al., 2018)

The task of developing a uniform standard was realised and is still optimised and extended by buildingSMART international (bSI) with the Industry Foundation Classes (IFC), which is an ISO standard 16739 (JAUD et al., 2021). The international non-profit organisation developed in 2005 out of the International Alliance for Interoperability (IAI) which consisted of a group of engineering offices, construction firms and software manufacturers due to several research projects. "The resulting object-oriented data model named Industry Foundation Classes (IFC) provides very rich data structures covering almost all aspects of built facilities. In 2013, the data format was adopted as an ISO standard (ISO 2013)" (BORRMANN et al., 2018).

IFC-INFRA

In Germany, all federal construction projects are to be implemented with BIM since 2020. With the introduction of the BIM master plan of the Federal Ministry of Transport and Digital Infrastructure (BMVI) in 2021, projects in infrastructure construction require model-based information exchange and subsequent processing. (BMVI, 2015)
The version of IFC 4.0 only focuses on building construction, but currently BIM applications are mainly required in the infrastructure sector. Therefore, several international projects have been conducted to extend the IFC standard with infrastructure elements as road, rail, bridges and tunnels. The extensions will enable the exchange of BIM models from road and rail construction with semantic and geometric properties. (IFCINFRA, 2022)

2.6 Integrating BIM and LCA

With the mandatory application of the BIM methodology in infrastructure projects (BMVI, 2015), the possibility arises to integrate LCA into early design stages. In this way, the main causes of environmental impacts can be identified in an early planning stage, where the greatest potential for reducing environmental impacts occurs (SAUER, 2016, H. BRATTEBØ et al., 2013).
By integrating BIM and LCA, the manual effort of data collection, for example the quantity determination of the materials, can be conducted more efficient and thus reduced in time. The interpretation of the environmental assessment results can already be carried out by a designer which provides the potential of iterative and different variant analyses.

A question arising in this matter, is how to link the semantic data from the BIM model and the environmental information needed for conducting an environmental assessment. Mainly publications in the field of building construction exist in the integration of BIM and LCA. Due to the increasingly need to design building projects more sustainable, a lot of research has been conducted in the past years. Different approaches are presented in the following.

2.6.1 Integration types

An established classification of different integration types was developed by WASTIELS and DECUYPERE (2019). According to them, the integration can be carried out in five different types as depicted in fig. 2.15.

For the first type, which is also seen as the most common one, the integration is conducted through the Bill of Quantities (BoQ) from the BIM model and is further used in LCA software.
The second type consists of an import of an Industry Foundation Classes (IFC) file into the LCA software. The data of the IFC file should therefore include the geometric parameters (surfaces and volumes) for calculating the material quantities as well as the Global Unique Identifier (GUID) and the material name. The components will then be linked to predefined LCA profiles. The results will be depicted in the LCA software.
Type three uses the BIM viewer as an intermediate step to connect the LCA profiles to the geometric data. The connected data is then used in a LCA software for conducting the analysis and then for picturing the results.
The fourth approach provides the most benefit to the design process as specific LCA plugins are used to perform LCA in the BIM environment. With the help of the plugins the LCA profiles are connected to the BIM objects. The following calculation and picturing of the results is all done by the LCA plugins which makes the other LCA software redundant. The results from the LCA calculation can be visualized in the BIM model which helps optimizing the design more easily.
In the fifth strategy, the environmental data is integrated in the BIM models directly to the BIM objects. Compared to the fourth strategy the LCA data no longer needs to be

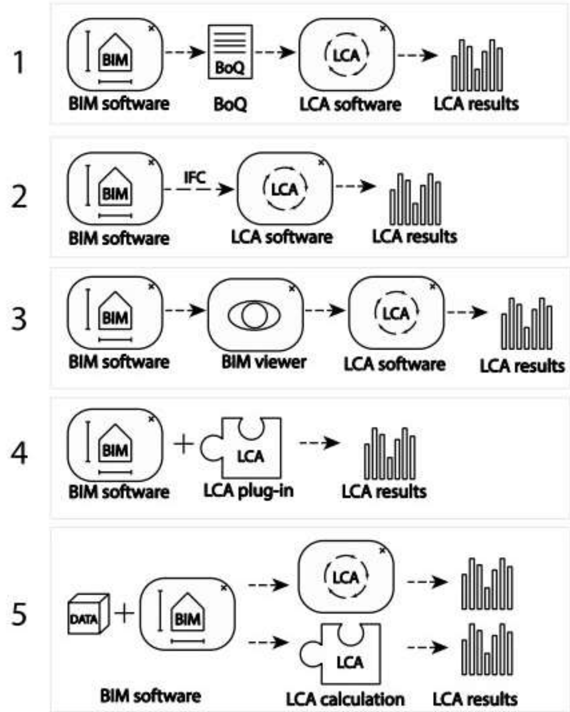


Figure 2.15: Integration types according to WASTIELS and DECUYPERE (2019) pictured in POTRČ OBRECHT et al. (2020)

connected in later stages. The calculation of the LCA can then be conducted either via a plugin or a by a dedicated software with importing the data of the BIM model with an IFC file. A substantial advantage of the LCA enriched BIM objects is that all data is centralised in the model and the design process can be conducted with current environmental impacts. A disadvantage, however, is that the change of the materials also lead to a change of the connected LCA data which is more time consuming than changing the LCA data in the LCA software (WASTIELS & DECUYPERE, 2019).

2.6.2 Automating the process of integration

The goal of the integration process is to reduce the manual inputs and simplify the LCA process for enabling a designer to interpret the results without much previous knowledge in that area. Therewith, a higher validity of the results and a lower uncertainty should be achieved. The previous described integration types can be assigned to different degrees of automatising. POTRČ OBRECHT et al. (2020) divide them in the following categories:

- Manual: Data is transferred by manual copying from one file and inserting it to another
- Semi-automated: Data is changed automatically; for some exports and imports the interaction of a user is still required
- Automated: Data exchange is considered as fully automatic

Similar to that, SAFARI and AZARIJAFARI (2021) divide the types in conventional, static and dynamic which corresponds to the previous described classification. The two main approaches, according to K. FORTH et al. (2021), are currently applied in:

- Bill of quantity for integration approach
- enrich BIM objects for IFC data exchange with property sets

The integration approach through the BoQ can happen as a semi-automated approach by integrating the information in the BIM model or by improving the link between LCA tools and BIM model. The integration can be done by either adding additional parameters into the BIM model or by using tools that enable the insertion of information as Dynamo (POTRČ OBRECHT et al., 2020).

2.6.3 Visual Programming Language for the integration process

Visual Programming Language (VPL) is a tool which is increasingly used in the AEC sector. Instead of programming in written syntax, it allows programming by means of graphical connection of elements representing an algorithm or procedure.

> "A visual language is defined as a formal language with visual syntax and semantics. It describes a system of signs and rules on the syntactic and semantic level with the help of visual elements, which are more readily understandable for non-professional programmers." (BORRMANN et al., 2018)

According to RITTER et al. (2015), VPL can be used as an application for geometric modelling, knowledge-based design, design decision support or code checking. For example, HÄUSSLER et al. (2020) integrated BIM, BPMN and DMN with the help of VPL for code compliance checking.

In order to carry out a BIM-based LCA, VPL can be used to extract the required information from the BIM model. The BIM model is used for storing the geometric information while the additional environmental information are included via parametric tools (CAVALLIERE et al., 2020).
"Parametric approaches such as these based in Rhino/Grasshopper and Dynamo are considered of high potential for performing LCA" (CAVALLIERE et al., 2020). FORTH (2017) for example used this approach and developed a tool in Autodesk Dynamo to automatise the BIM-based LCA for buildings. The Parametric Life Cycle Assessment (PLCA) was firstly introduced by HOLLBERG (2016) in 2016. In addition to time savings, the method also provides a good basis for the optimisation process as the visualisation of the results in the BIM model is possible. Parametric based LCA tools mostly refer to early design stages as it is difficult to use for detailed modelling.

2.6.4 Integration in the infrastructure sector

In infrastructure projects, a BIM-based LCA has rarely been implemented so far. Limitations exist due to the following aspects according to VAN ELDIK et al. (2020):

- Different kind of software used for LCA calculations and the design
- Lack of explicit data structure for environmental and BIM-based data which limits interoperability

The goal of the integration process, according to VAN ELDIK et al. (2020), is seen by systemically integrating data from various sources and by enabling a bidirectional data exchange.
In previous studies, different approaches with different system boundaries of the conducted LCAs were found. Differences exist in the functional unit, the consideration of different life cycle stages, different environmental indicators and in the integration process of BIM and LCA. In table 2.6, an overview of thesedifferent aspects is provided. Thereby (1) is representative for SLOBODCHIKOV et al. (2019), (2) for VAN ELDIK et al. (2020) and (3) for MAIBAUM and BLOCK (2022).

Table 2.6: Overview of previous BIM-based LCAs of infrastructure projects with corresponding functional unit, life cycle stages and environmental indicators

	(1)	**(2)**	**(3)**
Functional Unit	Road alignment	Bridge	Road alignment
Life cycle stages	Cradle to gate	Cradle to grave	All stages except use stage
Environmental indicators	GWP and CED	Several environmental indicators such as GWP and ODP	PET, GWP and waste

In all three research cases, Autodesk Civil 3D or Revit was used to build the 3D model. SLOBODCHIKOV et al. (2019) conducted the integration process with a C# code implemented in Revit to carry out the calculations in form of an add-on application. Data concerning the inventory analysis and emission data were imported from a Microsoft Excel file. Dynamic link library files enabled the import of external coding into Civil 3D. In comparison to that, MAIBAUM and BLOCK (2022) and VAN ELDIK et al. (2020) both used Dynamo to develop the tool as a plug-in for Revit or Autodesk. However, the exact implementation of the tools was implemented differently in both cases. In the end, the results of the LCA were integrated into the BIM model for visualisation of the results and for possible export with the neutral data exchange format IFC.

Chapter 3

Methodology for environmental design decision making

As the literature review has shown, the highest potential for reducing the environmental impacts of an infrastructure project occurs in early design stages during the choice of road corridor. However, specific information is required for performing a holistic LCA which is usually not available during that early stage or is very time consuming to collect.
With the help of the BIM methodology, it is possible to roughly determine the environmental impact for different variants and parameters. This approach reduces the complexity and the required time and provides a meaningful reference point for the decision-making process.
BIM-based LCAs for infrastructure projects have been carried out for different goals and scopes. A BIM-based life cycle assessment for the choice of road corridor with regard to embodied and traffic emissions has not been carried out so far.
Thus, the challenge is to define and gather all relevant information for performing a simplified BIM-based LCA for an early planning stage that can be useful in the decision making process.
The developed methodology therefore consists of the integration of predefined LCA profiles and parametric BIM models to reduce the collection of data from various sources and enable the identification of main environmental indicators over the whole life cycle of the construction.

In a first step, this chapter presents the goal and scope of the LCA that can be conducted with the methodology. The second part presents the developed methodology. In order to be able to apply the methodology, the first research question, is addressed in section 3.3:

Which geometrical and semantic information sets are relevant and available in the early planning phase for reasoning about the environmental impact of different road routing alternatives?

3.1 Goal and scope of the LCA

The goal of the following considerations is to compare different routing alternatives regarding their environmental impact with the help of a LCA. Similar to the first phase of a LCA the definition of the goal, functional unit, and its system boundaries need to be defined at the beginning. The functional unit of the conducted LCA is set as:

- **GWP [kg CO_2 equivalents] over the life cycle of 100 years of different infrastructure routing alternatives enabling traffic between the same start and end point.**

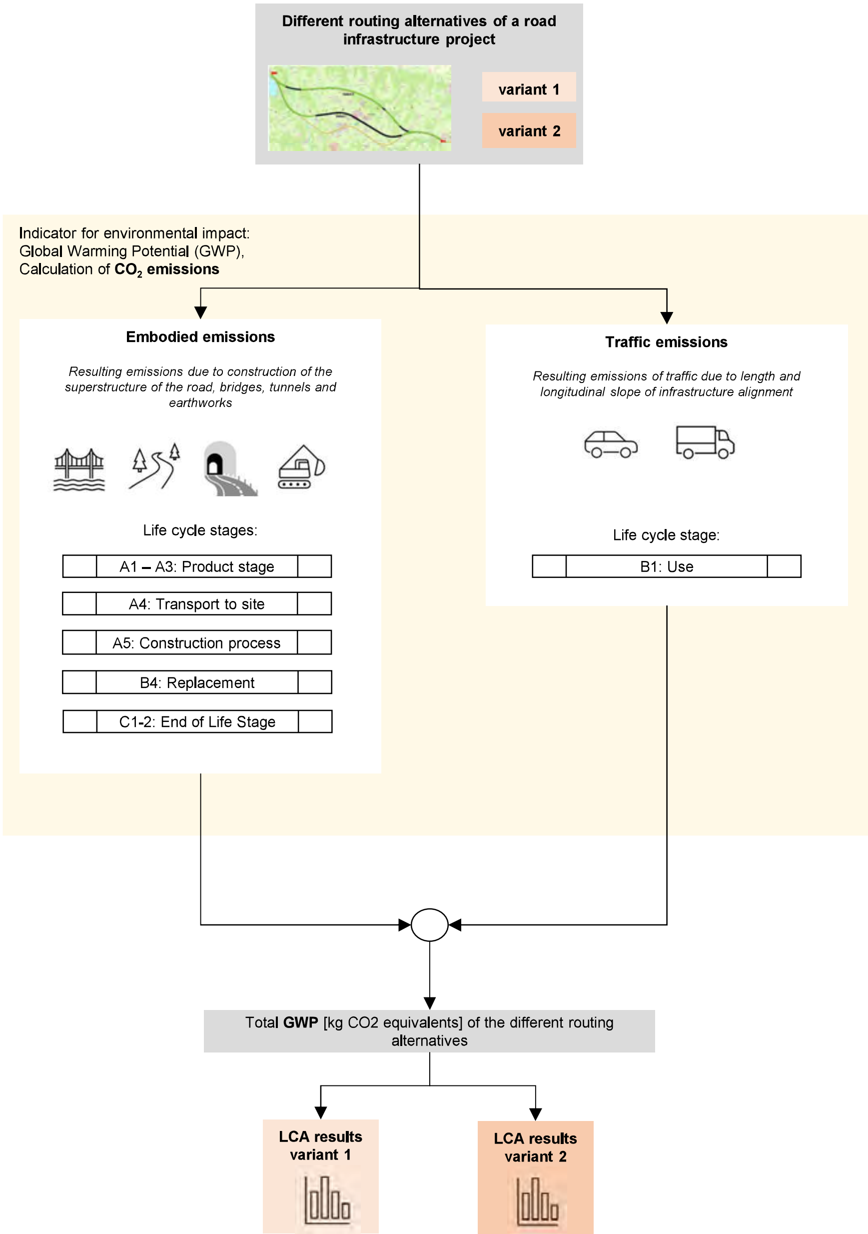


Figure 3.1: Goal and scope of the LCA

Since engineering structures are designed for 100 years (EN 1990, 2010), a corresponding observation period is assumed here.
The system boundaries of the LCA are pictured in fig. 3.1.

The scope only includes the consideration of road infrastructure projects. Rail infrastructure projects are not considered as the decision of the transport mode is conducted before the choice of the corridor. However, structural assets of rail infrastructure like bridges and tunnels are agnostic to the actual traffic type. Differences exist in the determination of embodied emissions for the superstructure and that the alignment and the required cross section must follow other rules and regulations.

As depicted in fig. 3.1, the LCA is conducted separately for each routing alternative of a road infrastructure project. The indicator of the environmental impact is the GWP and is separately calculated for embodied and traffic emissions.
Embodied emissions are resulting due to the construction of bridges, tunnels, earthworks and the superstructure of the road. Considering the infrastructure project over its entire life cycle, CO_2 emissions of the product stage, transport to site, construction process, replacement of components and end of life stage need to be summed up.
The traffic emissions result due to fuel consumption of cars and trucks. The resulting emissions are attributed to the operation phase of the infrastructure asset.
The final LCA result is the total GWP of each routing alternative created over the defined observation period.

3.2 Proposed workflow

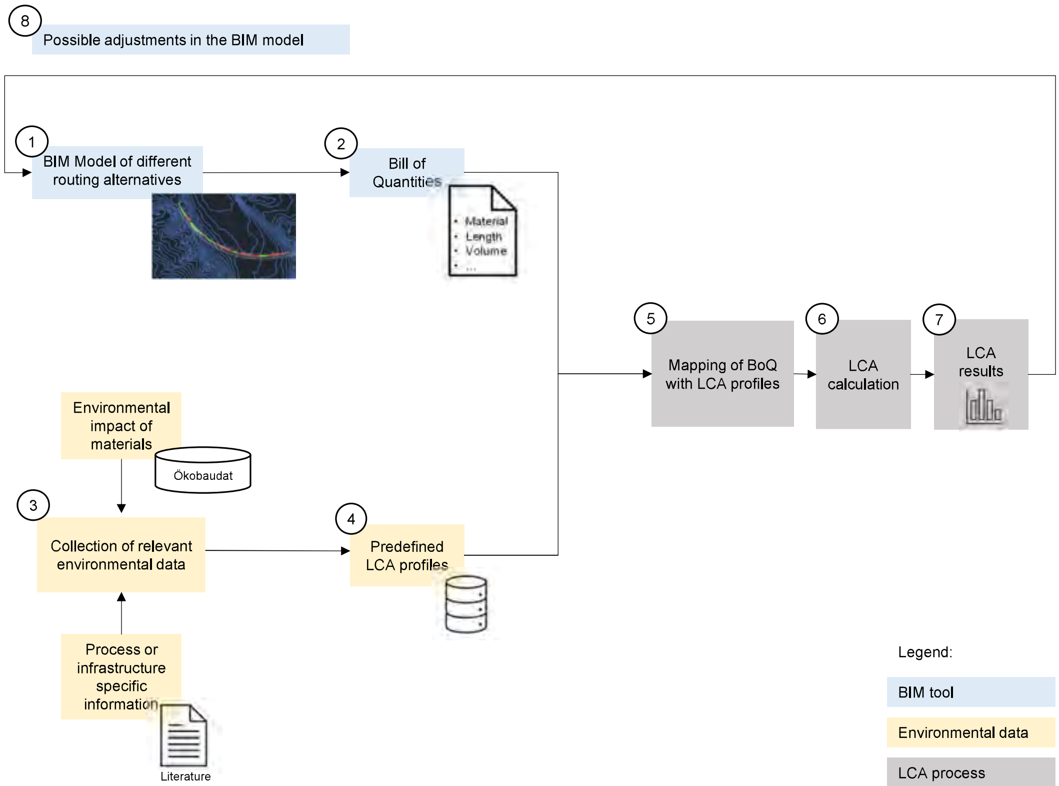


Figure 3.2: Overview of the proposed methodology including model preparation, calculation, result assembly and impact evaluation

In order to carry out a BIM-based LCA in an early planning stage, the parametric BIM models on the one side and the predefined LCA profiles on the other side are required. In the first step, the BIM models of the different routing alternatives are modelled. When creating the routing alternatives, the focus is not on a geometrically exact representation. Rather, the focus is on a simple geometric representation for the early planning phase where detailed information about the construction is not available yet. This should allow a fast modelling to roughly determine the environmental impact and to derive its main indicators.
In a second step, the relevant geometric and semantic information need to be collected, meaning the BoQ needs to be extracted. This includes, for example, the type of material and its volume. The manual, time-consuming process of calculating the bill of quantities can thus be reduced in time and increased in quality simultaneously.
The third step involves the data collection process of environmental data. First of all, a distinction is made between two different sources. The first and main source is the Ökobaudat. All relevant indicators for environmental impact, in this case GWP, for the materials and construction processes are collected from there. Unfortunately, the Ökobaudat does not represent all of the necessary data. Therefore, missing information, such as transport distances and environmental coefficients for fuel consumption, must be gathered from other sources.
In a fourth step, all relevant data is tabulated in order to use them for the following calculations. The values must be tabulated in order to be able to link them individually with the associated BIM elements.
In the fifth step, the extracted BIM data is linked with the predefined LCA profiles in order to calculate the environmental impact (step 6). The subsequent calculation of the LCA (step 6) results in the GWP for each routing alternative (step 7). The results can be subsequently visualised in the model, offering a better understanding and also giving the designer the opportunity to optimise the routing alternative and iterate through the steps 1, 2 and 5 to 8 until a sufficient design option is reached.

3.3 Required data for BIM-based LCA

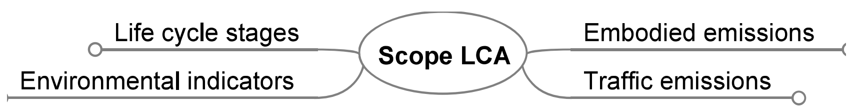


Figure 3.3: Main areas for the scope of the BIM-based LCA for infrastructure assets

For conducting a BIM-based LCA for the presented scope, the required data can be divided in four main areas as depicted in fig. 3.3. It is distinguished in the areas of different life cycle stages, environmental indicators and the consideration of traffic and embodied

emissions.
On the one side, it needs to be delimited which life cycle stages and environmental indicators are considered during the LCA of the different routing options in order to achieve comparability. On the other side, as elaborated in section 2.4, the results of the LCA should be divided in traffic and embodied emissions. As studies have shown, the traffic related impact in comparison to the embodied emissions can determine whether a routing option is ecologically sustainable over the whole life cycle or not. In the following the different areas are described in more detail.

3.3.1 Life cycle stages

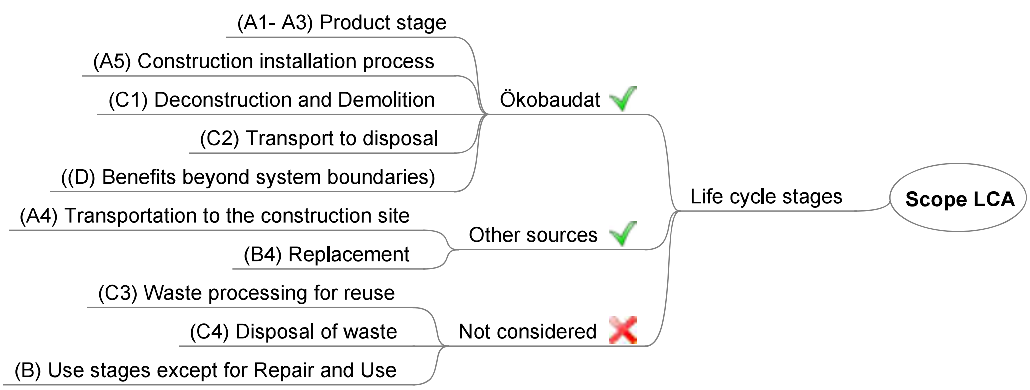


Figure 3.4: Considered life cycle stages

The life cycle stages according to DIN EN 15978 (2021) consist of the four main modules product stage (A1-A3), construction process (A4-A5), use stage (B1-B5) and end of life stage (C1-C4).
The ÖKOBAUDAT provides environmental data depending on the different life cycle stages. For most of the materials used for the superstructure of a road, the product stage (A1-A3), the construction installation process (A5), the deconstruction/ demolition (C1), the transport to disposal (C2) and additional information beyond the building life cycle (D) are covered. The transportation of the material to the construction site (A4) or any other data concerning the use stage (B1-5) are not represented. The replacement during the use stage can be calculated with information of the product stage, construction process and the service life of the road components.
The ÖKOBAUDAT was created for building data which is the reason why infrastructure data is rarely represented. Which life cylce stages are taken into account for the following assessment is shown in fig. 3.4.

3.3.2 Environmental indicators

Several different indicators for environmental impacts exists where GWP is one of the most common ones. The determination of the different indicators is very complex and for

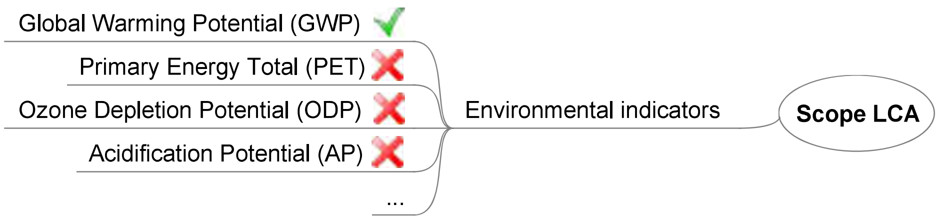


Figure 3.5: Considered environmental indicator

most of the infrastructure materials and construction processes not all of them are defined or available.
In this case, environmental indicators for tunnels and bridges and the traffic emissions are only available for the GWP. The ÖKOBAUDAT is not the limiting factor.. Even though it should be kept in mind that a holistic LCA would need to consider other indicators as well, and if the data availability for infrastructure projects will be improved in the future, the methodology can correspondingly be expanded.

3.3.3 Embodied emissions

Embodied emissions emerge due to the construction of the superstructure of a road and its related earthworks for creating an embankment or cut as well as the construction of engineering constructions like tunnels and bridges. The resulting emissions depend on various parameters of the infrastructure element as shown in fig. 3.6.

Starting with the **superstructure** of a road, at first, it needs to be distinguished between the used material. Either asphalt or concrete can be used to build a road, with asphalt being the most common one. The amount of each material or layer of the road structure can be determined by the structure of the cross section. In Germany different standardised cross sections exist for different road types such as highway or rural road.
The resulting emissions can then be calculated with information regarding the material, volumes and its environmental indicator.
There have already been studies which investigated in depth the influence of the superstructure of a road. MILACHOWSKI et al. (2011) compared the environmental impact of an asphalt and a concrete superstructure. The results show that concrete has higher CO_2 emissions in the production phase but lower emissions in the maintenance phase due to its high durability compared to asphalt. To compare both of the different superstructures, the whole life cycle must be considered as the service life and the durability of the materials have a high impact on the overall emissions. "Motorway pavement maintenance for the

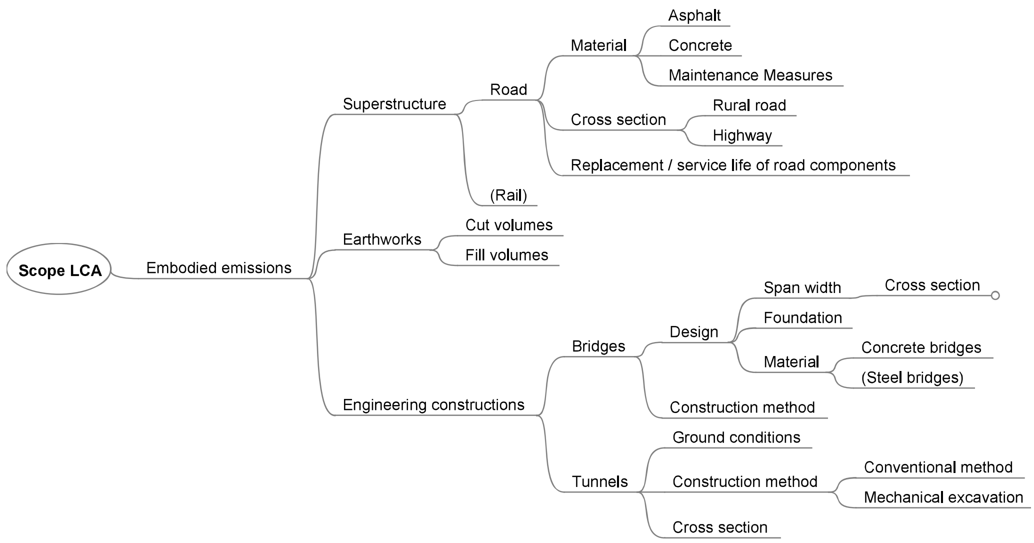


Figure 3.6: Factors influencing the embodied emissions

concrete construction methods over a service period of 30 years leads, compared with asphalt pavement, to significantly lower potential environmental impacts in all categories. Hence, investment in durable motorway construction is rewarded in the service phase." (MILACHOWSKI et al., 2011)
Since the decision whether to build the road out of asphalt or concrete is made after the routing phase, the LCA is carried out with an exemplary structure for each type of construction.

The construction of the cut or embankment requires **earthworks** by machinery which also causes CO_2 emissions. Its amount is the volume that needs to be excavated (cut volume) or new soil that needs to be transported to the construction site (fill volume). The total mass balance is also an important reference point for the environmental impact. It shows whether soil has to be additionally transported to and from the construction site or whether the cut and fill volume balance each other out well. In planning terms, the aim is to achieve a good balance between the two volumes and to minimise the transportation of soil in general.

At last, **engineering constructions** such as bridges and tunnels are one of the biggest polluters of CO_2 emissions. Next to the building process with the requirement of different construction machines, the enormous amount of concrete and cement required per meter

are responsible for major emissions. (SAUER, 2016)
The amount of released emissions through the building and use of **bridges** is depending on the design and construction method. The design is decisively determined by the required span width on which the superstructure form and the construction process are based as well. The bridge can either be build out of reinforced concrete or out of steel. In the following only concrete bridges are taken into account.
As part of the Integbridge research project, a BIM-based LCA has already been developed for steel bridges at the detailed planning stage. In addition to the ecological aspects, the other two dimensions of sustainability are also taken into account. (ZINKE et al., 2022)
When constructing a **tunnel** the greatest uncertainty exists in the forthcoming ground conditions on which the construction method as well as the structure and lining are both depending. If groundwater is present, the tunnel must be excavated mechanically with the help of a shield Tunnel Boring Machine (TBM). Otherwise, the tunnel can be built conventionally, for example by blasting. However, the construction method also depends on the stability of the ground, which makes the decision-making process an engineering task. With the help of preliminary observations the soil layers which need to be passed through can be determined in advance. In some areas, already existing soil surveys can be used at an early stage of planning. In this case, depending on the soil layer, the excavation method can be chosen which determines the cross-section of the tunnel.

3.3.4 Traffic emissions

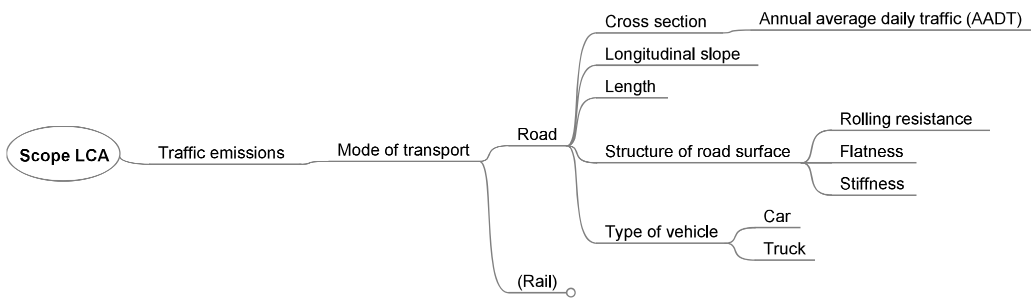


Figure 3.7: Factors influencing traffic related emissions

Traffic related emissions occur due to vehicles fuel consumption during the use phase (B1). The amount of the emissions depends on the type of cross section which determines the Annual Average Daily Traffic (AADT), the length of the route and the type of vehicle. The latter is distinguished in car or truck, and both of them are powered with diesel or petrol. The consideration of electric cars is not part of this framework. DITTMER et al. (2020) point out that the average systemic CO_2 emissions of battery vehicles are equal to those of petrol or diesel cars (157g CO_2/km and 150g CO_2/km). However, this would form another

research question on what approaches the emissions and the share of electric cars are given for the future.
Another aspect that FISCHER et al. (2012) consider, is the dependency of emission factors of cars or trucks to the longitudinal gradient of the road. SAUER (2016) points out the emissions per km must be differentiated for the boundary conditions of vehicle type, reference year, traffic situation and associated speed as well as the longitudinal gradient.

According to MILACHOWSKI et al. (2011), the largest potential for reducing the environmental impact is in lowering fuel consumption since its impact occurs due to the combustion of fossil fuel.

> "In the past, numerous investigations concentrated on the effect of road surfaces (rolling resistance, flatness, stiffness) on fuel consumption. Road surface properties such as texture, unevenness (macro and mega texture) and pavement stiffness can reduce fuel consumption by 5 to 20 %. Optimisation potential is therefore available in pavement construction as well in car and tyre manufacture." (MILACHOWSKI et al., 2011)

3.4 Data from BIM model

"A major challenge is determining the relevant inputs that have to be placed in the BIM model. Generally, the BIM model should provide data regarding the quality and quantity of materials but additional information is needed to conduct a LCA analysis" (POTRČ OBRECHT et al., 2020).
For the calculation of the LCA, the information listed in table 3.1 needs to be extracted from the BIM model.

Table 3.1: Required information to extract from the BIM model

	Required information from BIM model
Embodied emissions	- Element and its materials / layers - Quantities and volumes of element (functional unit according to its LCA profile) - Kind of road structure element (road, bridge, tunnel) - Cut and fill volumes of road corridor
Traffic emissions	- Length - Longitudinal slope - Type of cross section

It is distinguished between information needed to calculate the embodied and traffic emissions. For the embodied emissions, the BoQ is needed which includes mostly the

geometric information as volumes and quantities of the construction project.
The traffic emissions are depending on the length and the longitudinal slope of the alignment. The AADT which is used for calculating the annual CO_2 emissions of the traffic is depending on the type of cross section.

3.5 LCA profiles for the early planning stage

According to POTRČ OBRECHT et al. (2020), the environmental information that needs to be integrated with the BIM tool is influenced by the LCA methodology. With the proposed methodology the information listed in table 3.2 needs to be collected and mapped with the BIM data.

Table 3.2: Required data for calculating the environmental impact

	Required data
Embodied emissions	- Indicators for environmental impact of materials or construction process - Transport distances - GWP for transporting goods - Information concerning the construction process of bridges and tunnels - Service life of road infrastructure components
Traffic emissions	- AADT depending on type of cross section - GWP of cars and trucks depending on longitudinal slope

In general, for calculating the embodied emissions the indicators for the environmental impact (GWP) of materials or construction processes are required. As the Ökobaudat is not providing any data concerning the transport to site, the transport distances of the materials need to be known for calculating the emissions released due to the transport process with the environmental indicator for transporting goods. The emissions caused by the construction process of tunnels and bridges are difficult to determine which is why simplified assumptions based on previous studies have to be used. At last, the service life of the road infrastructure components is a parameter that influences the emissions released during maintenance.
Depending on the cross-section used in the BIM model, the corresponding AADT can be matched which is required for calculating the CO_2 emissions of the vehicles. The corresponding environmental indicator for the fuel consumption of the vehicles can then

be selected depending on the longitudinal slope and the type of vehicle.
What kind of data these are in detail for roads, bridges and tunnels is explained below.

3.5.1 Roads

The superstructure of a road can be constructed either in asphalt or in concrete. An asphalt road is build out of a frost blanket, an asphalt base layer, an asphalt binder layer and on top of an asphalt surface layer. A road out of concrete also has a frost blanket as a bottom layer and then consists of a hydraulic bound layer and a concrete surface layer. An exemplary structure is shown in fig. 3.8 for the two different superstructure types. The depth of each layer is depending on the load and amount of the cars and trucks.

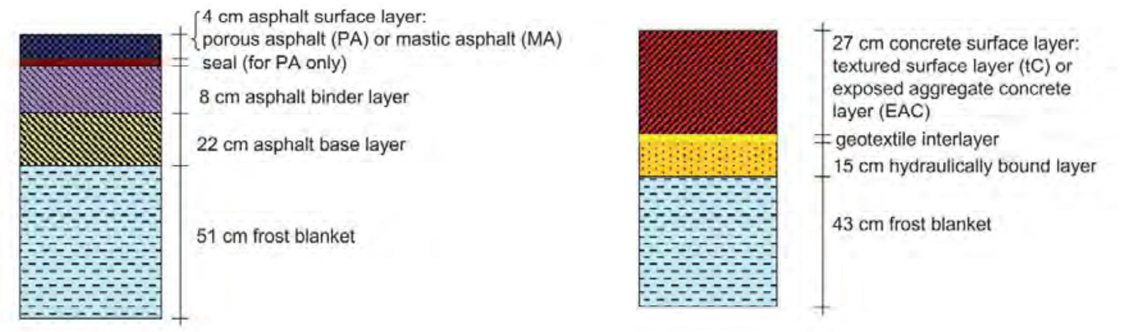


Figure 3.8: Schematic structure of an asphalt (left) and concrete (right) motorway (MILACHOWSKI et al., 2011)

For calculating the environmental impact of the superstructure, the environmental indicator GWP needs to be collected from the Ökobaudat for each layer. They are seperately listed for the different life cycle stages.

In addition to the emissions caused by the construction of the road superstructure, emissions are also caused by the construction of the embankment and the cut for the road corridor. Emission factors for excavating the soil for cut volumes and compaction of layers for material under embankments are required. In addition, the cumulative net quantity must be calculated depending on the cut and fill volumes. This ultimately indicates whether additional soil is required on the construction site and has to be transported there or whether there is excess soil on the construction site and has to be transported away.

3.5.2 Tunnels

In order to roughly estimate the GWP for the early planning phase of a tunnel, estimations developed by SAUER (2016) can be used. These results in length factors (per tunnel metre) depend on the selected standard cross-section and the type of excavation. Julia Sauer developed these using different tunnel construction projects and finally validated them by calculating the actual emissions of the different materials and construction processes.

In a first step, a distinction is made between mechanised and conventional tunnelling. The type of tunnelling depends on the soil conditions and the groundwater. If there is water, a shield TBM must be used for excavating the tunnel mechanically. The cross-section for the TBM tunneling is circular, whereby the diameter depends on the road cross-section.

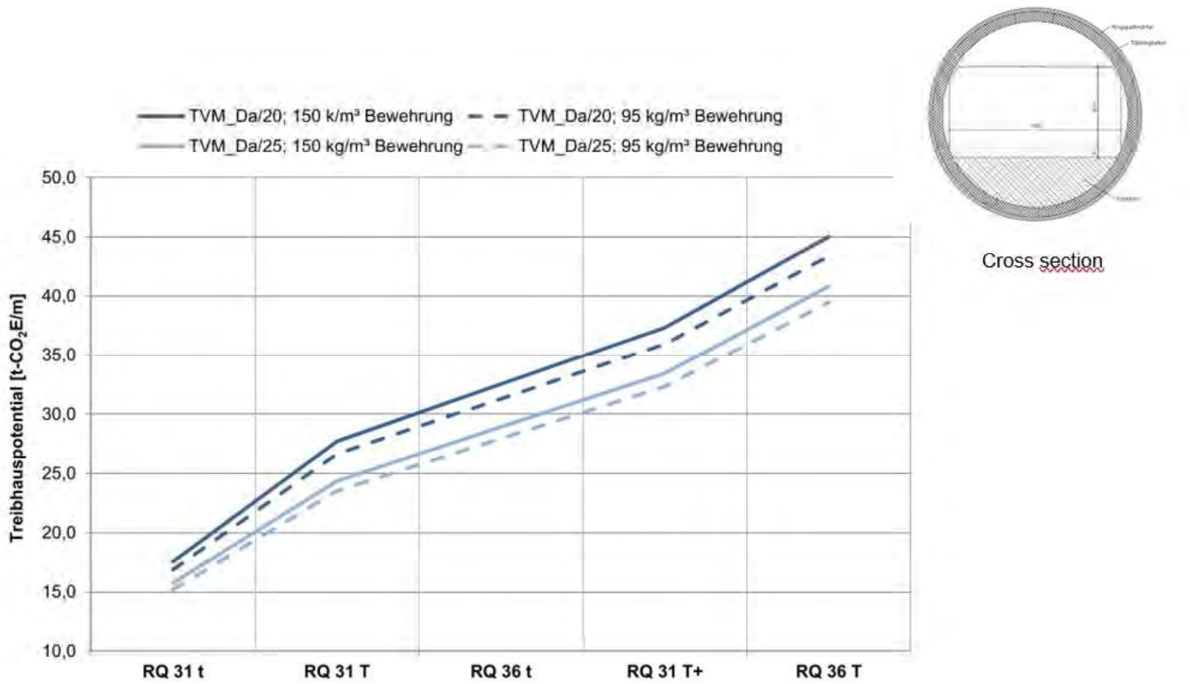


Figure 3.9: Length factor for GWP for circular cross sections with mechanical excavation according to SAUER (2016)

The GWP per metre of tunnel length (t CO_2e/m) is exemplary shown in fig. 3.9 for mechanised tunnelling in dependency of the cross-section (RQ31t, RQ31T, RQ36t, RQ31T+, RQ36T). Additionally, the four different graphs represent two different thicknesses of the lining as well as a high and a low degree of reinforcement.

For conventional tunnelling (shotcrete construction), no groundwater may be present, or the groundwater must be maintained or lowered during the construction period. The excavation cross-section is not as easy to determine as the cross-section can be adapted to the geological conditions through excavation by blasting. The tunnel lining is constructed in two linings and consists of an outer shotcrete lining and an inner concrete lining. A waterproofing membrane made of PVC-P is located between the two linings. The length factors in this case are designed according to different inner shell thicknesses (35, 40 and 60cm). A further distinction is made in each diagram between different shotcrete thicknesses (0, 15, 30, 40cm) and between different cross-section profiles. An example of the length factor is shown in fig. 3.10, which is similar to fig. 3.9, except that different types of cross-sections are considered.

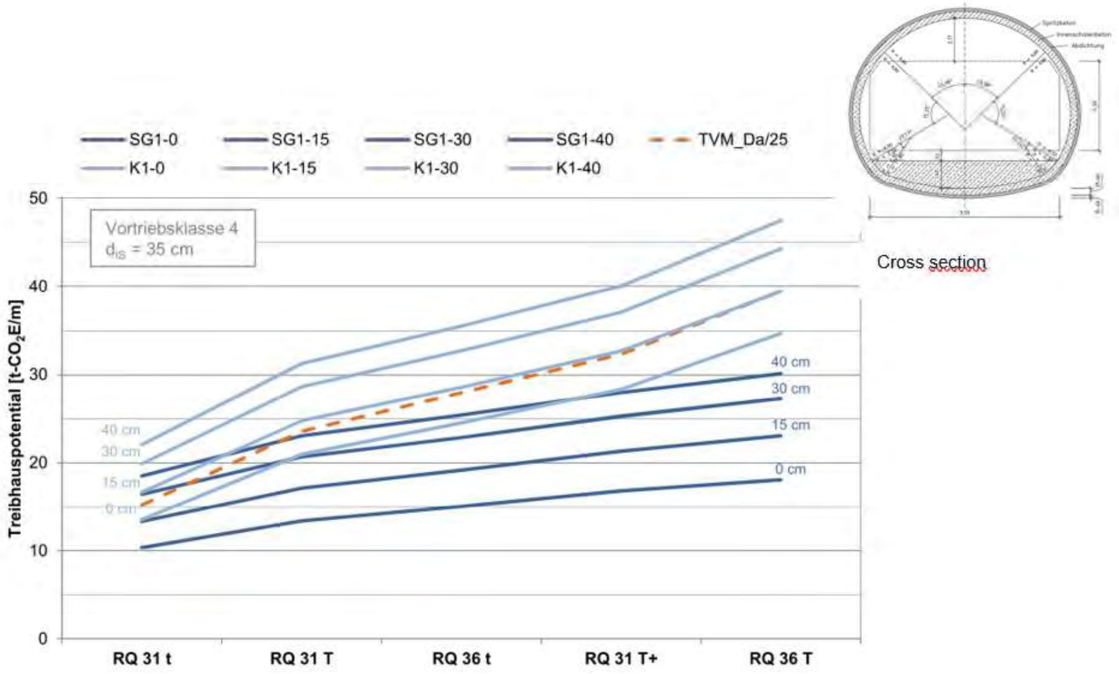


Figure 3.10: Length factor for GWP for conventional excavation according to SAUER (2016)

Length factors for the annual greenhouse potential (t-Co2E/year) were also determined for the use phase. For the GWP in the this phase, a distinction is made between operation and maintenance. The emissions in the operational phase result from the electricity consumption for lighting and operating technology. Cleaning services, maintenance and servicing of the tunnel structure lead to emissions during maintenance. SAUER (2016) has determined the associated GWP [t Co_2e/year] for the two factors depending on the length of the tunnel. In the following these factors are

3.5.3 Bridges

One of the first german life cycle assessments for bridges was carried out by LÜNSER (1999), who drew up an environmental, holistic assessment of the Schornbachtal Bridge. Based on this, SAUER (2016) roughly calculated a GWP of 1000kg-CO_2E/m² bridge area, which can be used for an initial assessment of bridge structures.
As part of another research project, BAST (2011) carried out a pilot study to assess the life cycle sustainability of road bridges. In this study, a LCA was carried out for five different bridge structures. Their environmental impact is within a range of 9,5 to 13,3 kg CO_2/m²/a. With a service life for 100 years of an engineering structure, this results in 950 to 1330 kg CO_2/m², which roughly confirms the assumption of SAUER (2016). The calculations are based on a factor of 1.14 to account for transport emissions, the manufacturing process and components not yet taken into account.

Uniform sustainability criteria for infrastructure projects were determined by MIELECKE et al. (2016). During the choice of road corridor, the bridge design is not available yet to

Table 3.3: Assumed distribution of the GWP depending on different life cycle stages of a bridge

Life cycle stage	Percentage share
Production	65%
Maintenance	20%
End of life	15%
Sum	100%

determine the concrete or steel masses. Therefore, a reference value of 1370 kg CO_2/m^2 is assumed in the following, which corresponds to the current average value. (MIELECKE et al., 2016) To address the level of uncertainty, the reference value is filled as an upper limit and the assumption of SAUER (2016) as a lower limit.

For considering the resulting GWP in dependence of different life cycle stages, a percentage share was determined. This includes the life cycle stages production, maintenance and End of Life (EoL). For this purpose, the results of a pilot study on the assessment procedure of the sustainability of road bridges (BAST, 2011) were evaluated and the percentage of the three life cycle stages was calculated. The resulting distribution is shown in table 3.3.

3.5.4 Traffic

Emissions resulting from traffic should also be taken into account in the decision-making process for the choice of road corridor. For the estimation of GWP, a reference is made to a report by FISCHER et al. (2012) on the holistic assessment of sustainability and energy efficiency in the planning and construction of infrastructure projects.

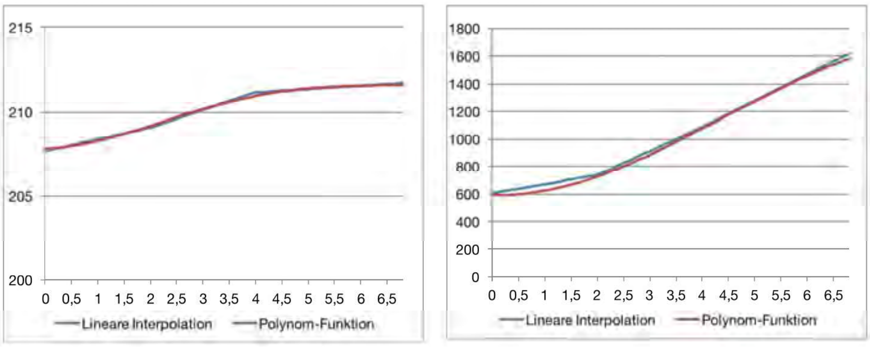


Figure 3.11: Emission factors for cars (left) and trucks (right) as a function of the longitudinal slope (FISCHER et al., 2012)

Their emission factors have been derived from the Handbook Emission Factors for Road Transport (HBEFA). The unit of the emission factors are provided per km for the boundary conditions vehicle type, reference year, traffic situation, associated speed and the longitudinal gradient.

For the emissions factors taken from HBEFA, a curve was interpolated by FISCHER et al. (2012) for the longitudinal gradients 0, ±2, ±4 and ±6 %. The curve is shown in the fig. 3.11 for the two different vehicle types car or truck. On the x-axis the longitudinal slope [%] is given with the corresponding GWP on the y-axis [g CO_2e/km]. The values were characterised for a traffic situation on the motorway at a speed of 130 km/h. The change of the GWP as a function of the longitudinal gradient is only slightly for cars, whereas for trucks there is a clear increase in emissions with an increasing longitudinal gradient. The parameters were also related to the axis of the road and thus take into account both directional lanes. Therefore, the values apply to both a positive and a negative gradient. The traffic intensity and distribution has to be evaluated on a project-specific basis and can be entered into the LCA profile. This allows different traffic scenarios to be filled in and the respective effects to be investigated.

Chapter 4

Prototypical implementation

To demonstrate the proposed methodology, a prototypical implementation has been made using well-established software tools.
As described in the previous chapter, the parametric BIM models on the one side and the predefined LCA profiles on the other side are required for the beginning. The integration process of these two components is demonstrated so that the second research question can be illuminated in more detail. The integration process of the BIM data with the LCA profiles is therefore addressed to automatise the LCA calculation.

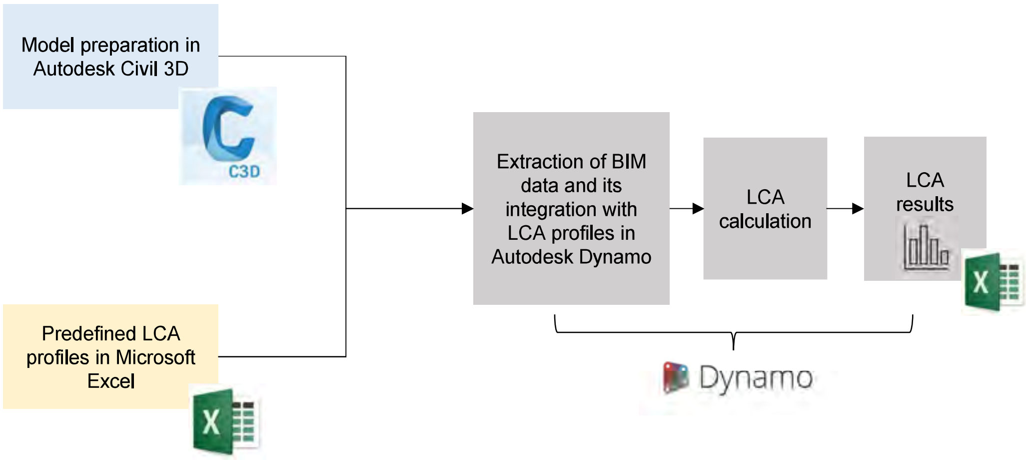


Figure 4.1: Used software for the prototypical implementation

An overview of the software architecture is depicted in fig. 4.1. The model preparation takes place in Autodesk Civil 3D (version 2022), where the BoQ and all other relevant information can be extracted using the visual programming application Dynamo for Civil 3D. In addition, the predefined LCA profiles prepared in Excel are imported into Dynamo and linked with the data from the BIM model. The subsequent calculation of the LCA is directly performed in Dynamo and its results are exported to Excel.
It is not possible to use existing LCA tools for the calculation process as not all of the

necessary data is available there. Data concerning environmental indicators for tunnel or bridge construction are for example missing. Therefore, as suggested by VAN ELDIK et al. (2020) and MAIBAUM and BLOCK (2022), VPL is used for the integration and calculation process. In case of new aspects to consider in the future, the visual programming tools moreover offer a high adaptability.

4.1 Predefined LCA profiles

The LCA profiles include environmental indicators for the following construction types and traffic modes:

- Material-based alternative for the superstructure of a road (asphalt or concrete)
- Bridges
- Tunnels
- Cut and Fill volumes of the road corridor
- Traffic related emissions of vehicles depending on longitudinal slope

In Microsoft Excel the corresponding data is structured in different worksheets where the consideration period needs to be defined at the beginning.
In the individual LCA profile sheets the described data from section 3.5 is stored. The profiles in the form of an Excel list are attached in the digital appendix A.

4.2 Used Software

4.2.1 Autodesk Civil 3D

Civil 3D is a design and documentation software from Autodesk and is used for planning, designing, and delivering transportation as well as land development and water projects. It supports BIM throughout the entire life cycle of the civil infrastructure project and is used for better design decisions compared to sketch-based design.
With its 3D model-based design environment, various representations like layout views, cross-sections and gradient plots can be automatically derived based on the model and its data can be maintained consistently and used for streamline analysis and optimisation. (AUTODESK, 2022b)

For the prototypical implementation Civil 3D is used to create the road corridor of different routing alternatives. For this purpose, various features of the software, such as

- terrain modelling (digital topography models for the design of transport systems),
- design of 3D profile bodies (dynamic and data-rich profile body models for roads),

- materials and quantities (using information on materials as well as cross sections or longitudinal sections to create quantity reports),
- and the plug-in Dynamo for information extraction and calculation

are used. (AUTODESK, 2022e)

4.2.2 Dynamo

Autodesk Dynamo is a visual programming application that can either operate as standalone "Sandbox" or as a plug-in to other design softwares as Civil 3D (AUTODESK, 2022a).

It provides easy accessibility for non-programmers and advanced users due to its visual aspect as it enables users to build up a Dynamo script upon visual syntax and semantics corresponding to a VPL. The components in form of nodes are representing an encapsulated piece of logic with specific input and output types. Therewith, the data processing pipeline and data flow of the program are defined through a graphical user interface. The sequence of the nodes compose an algorithm that can be used for applications as the processing of data and generating geometry. After execution, the results can be visualised in Civil 3D. Next to the ability of visually script algorithms, textual programming can be embedded in the flow of information. (AUTODESK, 2022f)

Dynamo was introduced to extend BIM with data and an environment of a graphical algorithm editor. It interacts directly with the Application Programming Interface (API) of Civil 3D or Revit and uses external libraries. Its source code is open source and enables the extension of functionalities. (AUTODESK, 2022f)

The user interface of Dynamo is organised in the main regions as numerated in fig. 4.2:

1. Library: contains individual components (nodes) that can be added to the canvas to define visual programs
2. Canvas: basic workspace for developing visual programs and preview of resulting geometry
3. Execution Bar

A distinction is made in the level of granularity which describes how encapsulated the individual functions are. With a fine granularity each function is graphically represented which offers a high adaptability of individual sub-steps and good traceability. In comparison, a low granularity offers a better overview as several functions are combined and the number of elements on the canvas is reduced. (BORRMANN et al., 2018)

Dynamo also offers nodes for the interaction with Civil 3D and add-on libraries from the AEC community. For instance, the Civil3DToolkit is used as an add-on library for the implementation. As depicted in fig. 4.2 on the right, the library for Civil 3D is hierarchically structured in sub-categories whether the nodes create data (+), execute an action (!) or

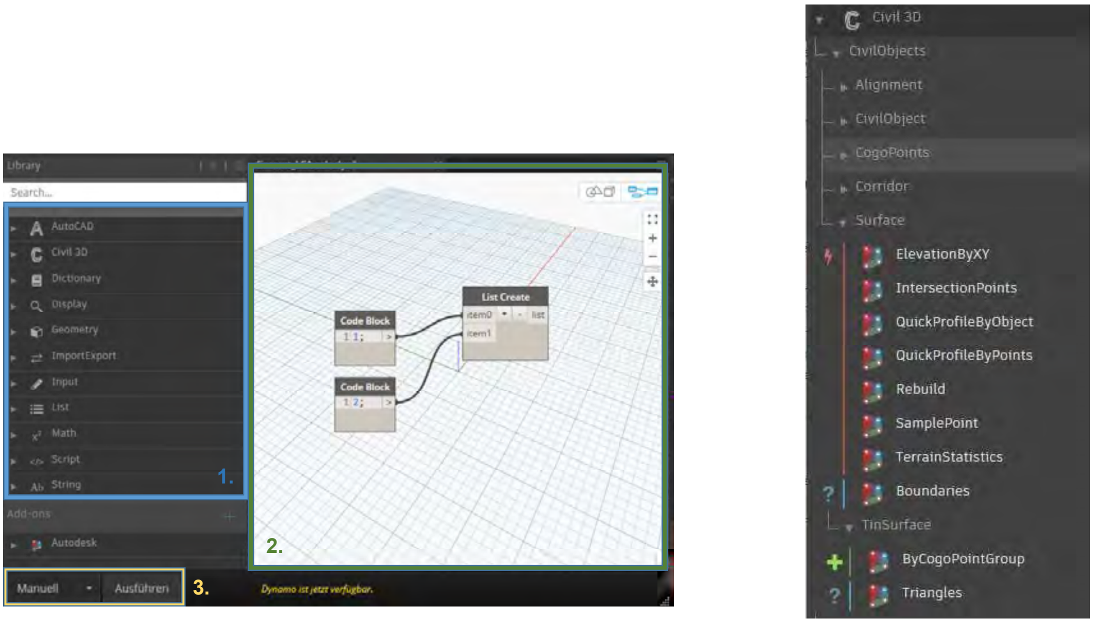


Figure 4.2: User Interface (left) and libraries (right) in Dynamo

query data (?). Possible nodes for the interaction with Civil 3D and its surfaces are shown on the right side of fig. 4.2.

4.3 Modelling procedure in Civil 3D

In order to extract the relevant geometric and semantic information from the BIM model, the different routing alternatives have to be modelled initially.

With Civil 3D configurable 3D models of road corridors can be created as exemplarily depicted in fig. 4.3. A corridor object is build out of various Civil 3D objects and data as the alignment and the profile. On the horizontal alignment, 2D sections (assemblies) are placed in a regular distance. The vertical baselines, as profiles, then define the surface elevations along the horizontal baseline. (AUTODESK, 2022c)

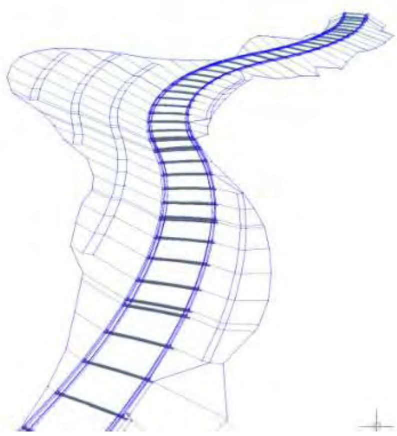


Figure 4.3: Exemplary 3D representation of a corridor (AUTODESK, 2022c)

The corridor is managing the data and can apply different assemblies to different ranges of stations. Therewith, different infrastructure elements as tunnels and bridges can be modelled along the alignment.
Subassemblies are substructures of an assembly and define the geometrical aspects of the corridor section represented as different layers out of which the roadway is built up. A subassembly is built out of points, links and shapes which are associated with codes. Points define the basic geometric structure and are connected among each other with links to form a planar surface. The shapes then define a closed region out of links, representing for example a pavement layer of the road corridor. (AUTODESK, 2022d)

After the corridor is created, the extraction of data is possible. This includes surfaces, alignments, profiles and volumes for the quantity take-off. The following steps have to be conducted in order to create the different routing alternatives:

1. Build Figital Terrain Modell (DTM) from point file
2. Alignment of the road
3. Profile of the road
4. Assembly of the road, bridge or tunnel
5. Build corridor out of belonging alignment, profile, assembly and surface
6. Create sample lines (German: Querprofillinien)
7. Extract solids from corridor
8. Create datum and top surface of the corridor for calculating cut and fill volumes

4.4 Data extraction with Dynamo

4.4.1 Cut and fill volumes

In order to determine the cut and fill volumes due to road construction, quantity lists can be exported in tabular form in Civil 3D. Using the cross-section drawings, the total volume is summed up based on the distance and the cross-sectional area.
Another, more precise option is to create a solid using Dynamo between the terrain surface and the datum surface of the corridor. The datum surface of the corridor is the lowest surface of the corridor and has to be created in Civil 3D beforehand. In Dynamo, the solids are then created by the node "TinSurfaceExtensions.CreateSolidsAtSurface" and are depicted in Civil 3D. Two solids are created for determining their volume which represents the cut and fill quantities of earthworks. Furthermore, the created objects can be coloured differently in Civil 3D with the help of Dynamo. In this implementation, fill volumes are coloured green and cut volumes are coloured red.

In order to query the volume of the two bodies, a property set must be added to the object with Dynamo. As depicted in fig. 4.4, a property set definition name has to be first created to add information about the profile type of the 3D object. In the next step, the volume can be queried over the name "Volume" of the property set. In the output of the Dynamo box, the first value belongs to the fill and the second one to the cut volume.
Alternatively, it is also possible to create the geometry in Dynamo and query the volume of the solid. However, the geometry mapping in Dynamo, for surfaces in kilometre ranges, is time-consuming and is therefore not recommended for routing alternatives.

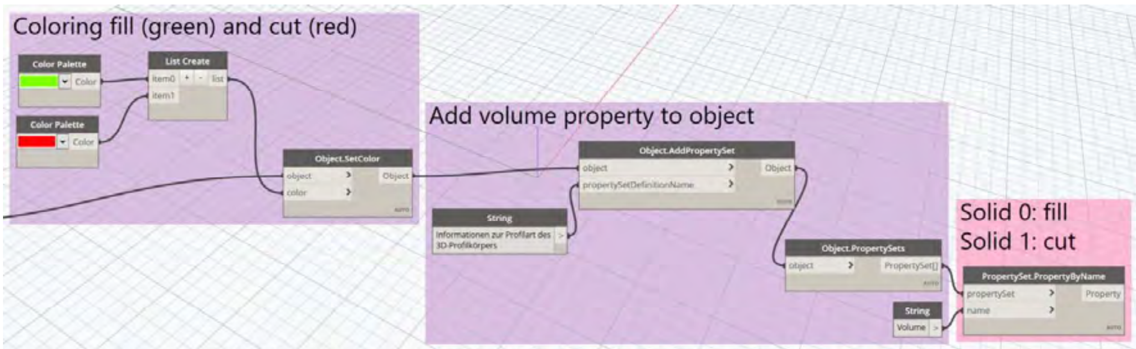


Figure 4.4: Colouring of cut and fill solids and its volume extraction in Dynamo

Due to the large horizontal longitudinal extent of infrastructure projects (several km), large terrain DTMs have to be stored, which can lead to large amounts of data for a fine-meshed network in earch direction. A DTM5 for example, with a mesh width of 5 to 5m, might overtax the computing capacities. It is therefore necessary to consider which resolution of a DTM is appropriate and required for an early design stage.

In order to shorten the calculation time in Dynamo, the DTM can be adapted as closely as possible to the corridor alignment. Moreover, if the difference in size between the DTM and the corridor surface is more than hundreds of meters, the creation of the solids in Dynamo is not working. This is another reason to reduce the DTM in its spatial expansion.

4.4.2 Material volumes of the superstructure of a road

Based on the created corridor, its solids of the different pavement layers can be extracted for determining the required material volume.

Using Dynamo, the different solids of the pavement layers can be reached via the codes of the subassembly which are defined in the corridor properties. The different solids are defined object-based to each corridor. For this reason, the first step in Dynamo is to select the required corridor. The second step is to define the belonging baseline, region name and code names of the corridor to extract the required solids.

In the German version of Civil 3D the first upper layer is referenced to as "1. Deckschicht", the second as "2. Zwischenschicht", the third as "3. Tragschicht" and the lowest layer as "4. Frostschutzschicht". As the subassemblies are built up on the left and right side of the centre line of the assembly, two individual solids are created for each side. When the

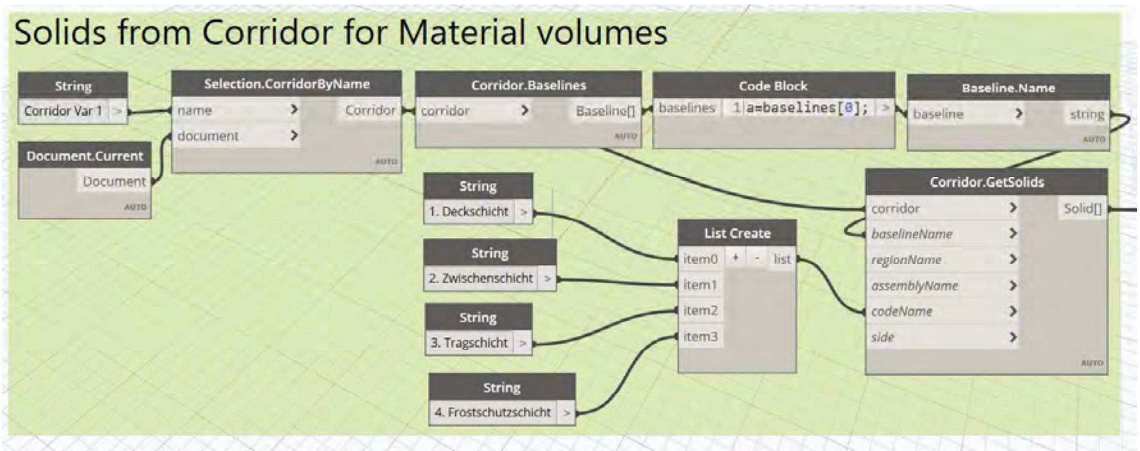


Figure 4.5: Road layers solids extraction in Dynamo

solids of a road with four layers are extracted which are modelled on the left and right side of the centre line, eight solids will be created. As a result of the node "Corridor.GetSolids", the solids are put in sub lists depending on the road layer they belong to. The volumes of the individual solids can then be queried via the property set and summed up according to the individual layers.

4.4.3 Bridge areas

To determine the GHG emissions from bridge structures, the following information must be extracted from the BIM model:

1. Regions of the corridor where bridges occur.
2. Area of each bridge which is defined over the length depending on the start and end station of each construction and the width of the assembly of the bridge.

The first step is to determine whether bridges are present and, if so, in which regions they occur. For this purpose, the different baseline regions of the corridor have to be considered. When creating the different areas, they were named according to the engineering structure tunnel, bridge or road.

As shown in fig. 4.6, the corridor needs to be defined at first. Secondly, the belonging baseline and finally its regions can be displayed in the form of a list.
With the help of an integrated Python code block, the next step is to query whether "Bridge" is present in the names of the regions and if this is the case, the respective regions are saved in a new list.
The length of the individual bridge structures can then be determined by the start and end points of the respective regions.

For the second step, determining the area of the bridges, the width of the bridge structure is required next to the length. For this purpose, the subassemblies of the corridor must

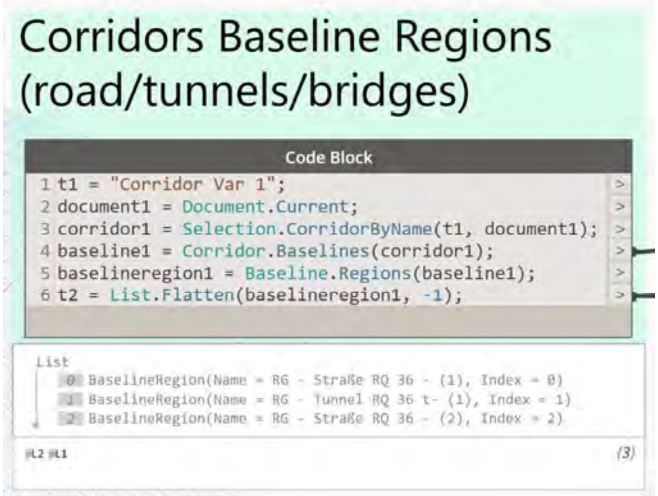


Figure 4.6: Extraction of the corridors different baseline regions in Dynamo

be accessed in which the width is stored as a parameter. If the width of the cross-section changes in the model, the updated width is automatically accessed.

Algorithm 4.1: Code in Dynamo for determining the bridge length and area

```
#Input
regions = IN[0]
width = IN[1]


length_bridges=[]
area_bridge=[]

#Determination of bridge length and calculation of its area
for elem in range(0,len(regions)):
    start = regions[elem].StartStation
    end = regions[elem].EndStation
    length = end - start
    length_bridges.append(length)

    area= width[elem]*length_bridges[elem]
    area_bridge.append(area)

OUT = area_bridge
```

The Algorithm 4.1 within a Python block is used to determine the area of the respective bridges. The results in form of a list, including the different areas, can be used in the next step to calculate the resulting GHG emissions.

4.4.4 Tunnel lengths

The required information of the BIM model for tunnel structures is similar to bridge structures. The only difference is that only the length is required as the emissions are determined depending on the tunnel length according to the length factors of SAUER (2016). The required data is therefore:

1. Regions of the corridor where tunnels occur.
2. Length of the different tunnels depending on the stationing of the individual regions.

The determination of the individual regions is carried out according to bridge structures as described in fig. 4.6 with another Python code block.
The length of the tunnels is then queried again via the start and end stations and stored in a list to determine the emissions.

4.4.5 Longitudinal gradients of different road sections

The traffic emissions, according to FISCHER et al. (2012), are determined as a function of the length and the respective longitudinal gradient. Both of these information must therefore be extracted from the respective corridor of the BIM model.

From the profile of the corridor, the individual stations can be queried where the longitudinal inclination changes. The elevation and grades along a profile are edited or defined by inserting Points of Vertical Intersection (PVIs).

As shown in fig. 4.7, all of the PVIs of the profile can be retrieved with "ProfilExtensions.PVIs". The respective stationing, elevation, "GradeIn" and "GradeOut" are displayed in a list. For further processing, the stationing for determining the length of each section and its associated "GradeOut", which is the longitudinal slope, are relevant.

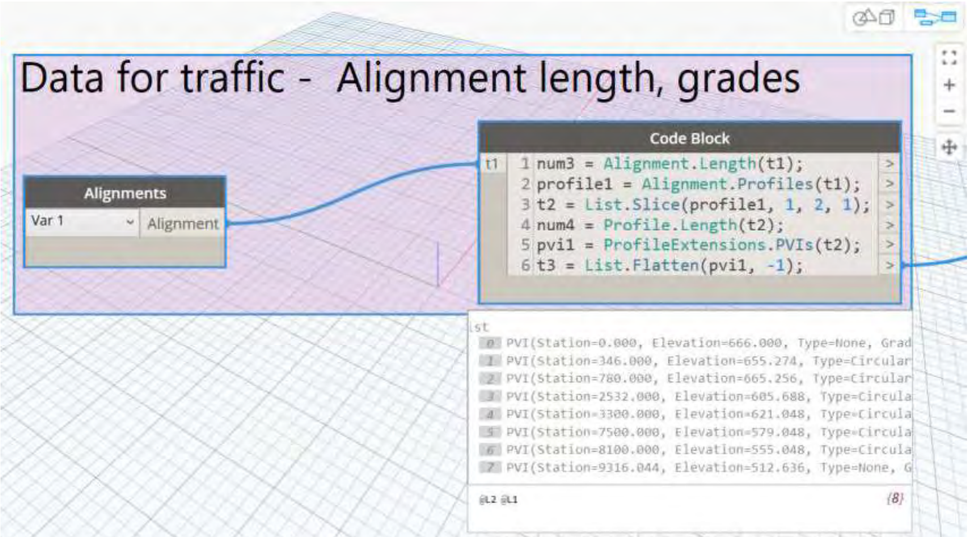


Figure 4.7: Retrieving the PVIs of the profile in Dynamo

In the next step, a distinction is made between the ranges <1%, 1-3%, 3-5% and >5% depending on the longitudinal gradient. Depending on which range is assigned to the respective longitudinal slope, a different factor is needed to determine the GHG emissions in each section of the corridor.

Algorithm 4.2: Code in Dynamo for processing the BIM data with environmental data

```
#Input
geom = IN[0]
GWP_traffic = IN[1]

stations=[]
gradeout=[]

#1. Filter stations and gradeout from list geom
for elem in range (0, len(geom)):
    stations.append(geom[elem].Station)
    gradeout.append(abs(geom[elem].GradeOut))

#2. Calculate length between stations
station_length=[]
for elem in range(0,len(stations)-1):
    length = stations[elem+1]-stations[elem]
    station_length.append(length)

#3. Assign slope to respective ranges of GHG emissions
cars_ghg=[]
trucks_ghg=[]
slope=[]
slope.append("Longitudinal slope")
for elem in range(0,len(gradeout)-1):
    if gradeout[elem] <0.01:
        cars_ghg.append(GWP_traffic[1][1])
        trucks_ghg.append(GWP_traffic[6][1])
        slope.append(" < 1 % ")
    elif gradeout[elem] >0.01 and gradeout[elem] <0.03:
        cars_ghg.append(GWP_traffic[2][1])
        trucks_ghg.append(GWP_traffic[7][1])
        slope.append(" 1 - 3 % ")
    elif gradeout[elem] >0.03 and gradeout[elem] <0.05:
        cars_ghg.append(GWP_traffic[3][1])
        trucks_ghg.append(GWP_traffic[8][1])
        slope.append(" 3 - 5 % ")
    elif gradeout[elem] >0.05:
        cars_ghg.append(GWP_traffic[4][1])
        trucks_ghg.append(GWP_traffic[9][1])
        slope.append(" > 5 % ")
    else:
        cars_ghg.append("Error")
        trucks_ghg.append("Error")

#4. Multiply GHG factor with length
cars=[]
cars.append("Cars")
trucks=[]
```

```
trucks.append("Trucks")
for elem in range(0,len(station_length)):
    cars_result= station_length[elem]/1000*cars_ghg[elem]
    trucks_result=station_length[elem]/1000*trucks_ghg[elem]
    cars.append(cars_result)
    trucks.append(trucks_result)
```

4.5 Calculation of GWP

After all the necessary data is collected accordingly to the LCI of a LCA, the next step is the LCIA. This step analyses the environmental impact of the collected quantities by connecting them with the predefined LCA profiles. Only the environmental impacts defined in the scope are considered in the following which is the GWP.

The calculation of the GWP, using the Dynamo tool, is based on various sources depending on the input of the LCA profiles. The results are related to the functional unit, which is the GWP over the life cycle of 100 years of a routing alternative. The different equations are explained in more detail in the following and are split up for embodied and traffic emissions.

4.5.1 Calculation of embodied emissions

The sum of embodied emissions consist of the emissions during construction, replacement and disposal of the individual construction materials. The embodied emissions are resulting from the GWP of the road superstructure and its earthworks, and of tunnels and bridges. In this context, the emissions result over the different life cycle stages and are the sum of the production, replacement and end of life stage:

$$GWP = GWP_{\text{production}} + GWP_{\text{maintenance}} + GWP_{\text{EoL}} \tag{4.1}$$

Superstructure

For the road superstructure, the calculation of the GWP for the different life cycle stages is composed as follows.

The calculation for the product stage (A1-A3), construction installation process (A5) and the EoL scenario (C1-4) is based on the same equation. It consists of multiplying the volume of the material by its bulk density and the environmental indicator:

$$GWP = V * \rho * I_{\text{GWP}} \tag{4.2}$$

With:

GWP Resulting GWP of the material [kg CO_2e]

V Volume of the material [m³]

ρ Bulk density of the material [kg/m³]

I_{GWP} Environmental indicator of GWP [kg CO_2e/kg]

The emissions released during transportation of the construction material (A4) is calculated from the environmental indicator for transportation multiplied by the weight to be transported and the distance. The weight of the individual construction materials is determined by the volume and the bulk density:

$$GWP = V * \rho * I_{\text{GWP-tr}} * d \tag{4.3}$$

With:

GWP Resulting GWP of the material [kg CO_2E]

V Volume of the material [m³]

ρ Bulk density of the material [kg/m³]

$I_{\text{GWP-tr}}$ Environmental indicator of GWP for transportation [kg CO_2e/1000kg/km]

d Distance of transportation [km]

The scenario for replacement (B4) is calculated using the replacement frequency, which is determined as follows (DGNB, 2018):

$$\eta_{\text{repl}} = Roundup(t_c/(t_l) - 1 \tag{4.4}$$

With:

t_c Consideration period [a]

t_l Lifespan of material or product [a]

The resulting emissions are then the sum of emissions during production and end of life scenario of the road layer multiplied with its replacement frequency:

$$GWP = (GWP_p + GWP_{\text{eol}}) * \eta_{\text{repl}} \tag{4.5}$$

With:

GWP Resulting GWP for replacement of material [kg CO_2E]

GWP_p Sum of the GWP during production

GWP_{eol} Sum of the GWP during end of life

η_{repl} Replacement cycle of material

GWP of bridges

As described in chapter 3, the calculation of CO_2 emissions for bridges is carried out with factors for the area of the bridge (SAUER, 2016). These are subdivided into production, maintenance and end of life. The total emissions during the production of a bridge structure are thus calculated as:

$$GWP_{\text{bridge}} = (factor_{\text{p}} + factor_{\text{m}} + factor_{\text{eol}}) * A_{\text{bridge}} \tag{4.6}$$

with:

GWP_{bridge} Resulting GWP of bridge [t CO_2E]

$factor_p$ Area factor for GWP during production [t CO_2e/m²]

$factor_m$ Area factor for GWP during maintenance [t CO_2e/m²]

$factor_{eol}$ Area factor for GWP during end of life [t CO_2e/m²]

A_{bridge} Bridge area [m²]

GWP of tunnels

The construction of a tunnel causes CO_2 emissions during construction and operation. With the length factors from SAUER (2016), the emissions for construction can be calculated separately for mechanical or conventional tunnel excavation. The emissions caused by the different excavation types can be used as a basis for the following decision process as the construction method of tunnels is decided after the decision of the road corridor (FISCHER et al., 2016).

The emissions during operation are determined using the respective equations for the power requirements due to interior route lighting and operating technology and the maintenance work.

$$GWP_{\text{tunnel}} = (factor_{\text{e}} + factor_{\text{m}}) * l_{\text{tunnel}} \tag{4.7}$$

with:

GWP_{tunnel} Resulting GWP of tunnel [t CO_2e]

$factor_e$ Length factor for GWP during tunnel excavation [t CO_2e/m]

$factor_o$ Length factor for GWP during operation [t CO_2e/m]

l_{tunnel} Tunnel length [m]

4.5.2 Calculation of traffic emissions

Depending on the longitudinal gradient of the route, a different factor is assigned to the individual route sections to calculate the GWP by cars and trucks according to SAUER (2016) and FISCHER et al. (2012)). The calculation is therefore carried out as follows:

$$GWP_{\text{traffic}} = \sum factor_{\text{slope}} * length_{\text{slope}} \tag{4.8}$$

with:

GWP$_{\text{traffic}}$ Resulting GWP of traffic emissions [kg CO_2e]

factor$_{\text{slope}}$ Factor for GWP for both cars and trucks depending on longitudinal slope [kg CO_2e/km]

length$_{\text{slope}}$ Respective length [km]

The exact implementation in the Python code block is depicted in Algorithm 4.2.

4.6 Result output

The results are exported from Dynamo in form of lists and imported to Excel. The individual partial results of the embodied (superstructure, bridge, tunnel) and traffic emissions are listed in separate worksheets. For the evaluation, the results are joined in Excel and illustrated in diagrams as will be shown in chapter 6.

Chapter 5

Case study and validation

In order to validate the presented methodology and its implementation, a case study is carried out. The case study evaluates different routing alternatives located at the Irschenberg in Bavaria and its results can be partially compared and validated with those of SAUER (2016).

Within the framework of a master's thesis (BRACHER, 2010), several different routing variants of the A8 in the area of Irschenberg were developed. The new variants should lead to a more optimal routing thus cope better with the considerable amount of traffic and reduce the number of accidents that occur.

Due to the difficult topography, there is a different need of engineering structures such as bridges and tunnels. In order to demonstrate the balancing of the GHG emissions for tunnels, bridges and roads, variant 1 and 2 are modelled, which are both adjusted to the same starting and end point as depicted in fig. 5.1.

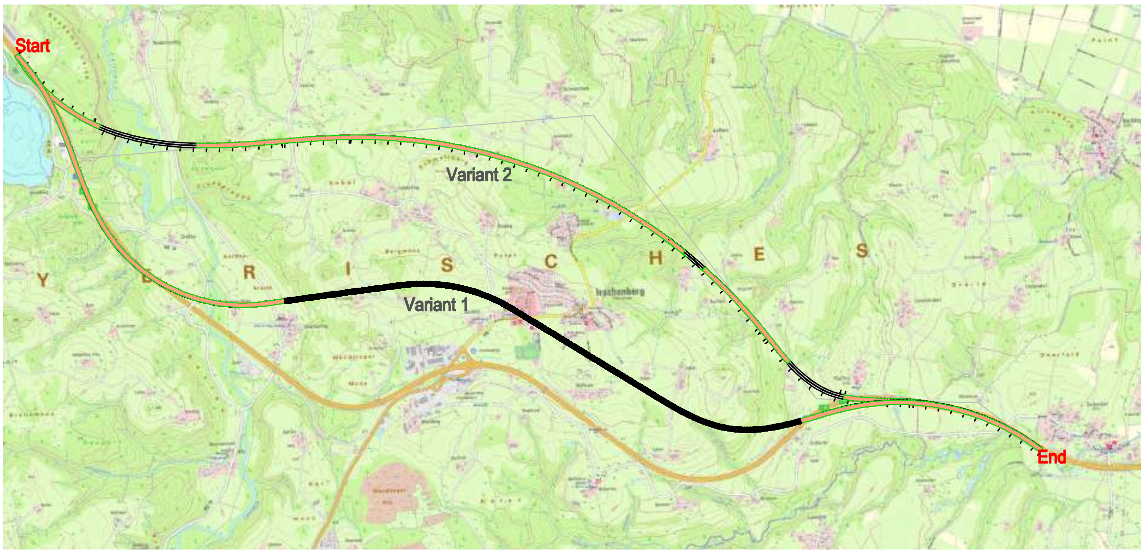


Figure 5.1: Route alternatives of the case study

5.1 Description of examined variants

5.1.1 Variant 1

The alignment of the first variant mainly consists of a 4.3 km long tunnel that passes under the Irschenberg with a longitudinal gradient of 1 %. The route begins shortly after the car park at Seehamer See on the existing road and enters the tunnel after a left-hand bend.

After the tunnel, the route rejoins the existing motorway in a right-hand bend. (BRACHER, 2010)

5.1.2 Variant 2

Variant 2 consists of three bridges with a total length of 1.5 km, more precise dimensions can be found in table 5.1. The rest of the route is a road section. The route also begins with a left-hand bend and then crosses the Leitzachtal with a 760 m long bridge. By building the long bridge, the interference with the FFH conservation area can be minimalised. Before the motorway returns to its original position, two more smaller bridges have to be passed. (BRACHER, 2010)

Table 5.1: Length and area of bridges required in variant 2

	Length [m]	Area [m²]
Bridge 1	760	22800
Bridge 2	210	6300
Bridge 3	510	15300

5.2 Technical planning principles

The existing route is the motorway A8. The route variants are to be carried out according to the planning principles of the guidelines for the construction of motorways FGSV (2008). According to SAUER (2016), the cross-sections for the roads, bridges and tunnels are modelled as follows.

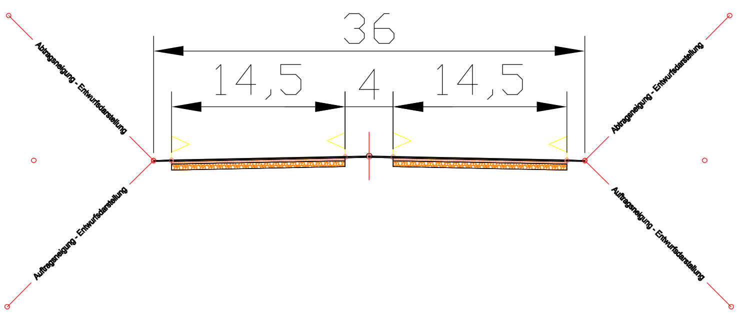


Figure 5.2: Cross section RQ36 with its dimensions [m] according to (FGSV, 2008)

5.2.1 Road planning principles

The road is analysed for two different types of superstructure which are either build out of asphalt or concrete. The road structure of the respective layers of the two different superstructure types are assumed according to the dimensions in table 5.2.

Table 5.2: Dimensions of asphalt and concrete superstructure according to SAUER (2016)

Asphalt superstructure	Concrete superstructure
4 cm asphalt surface layer	27 cm concrete surface layer
8 cm asphalt binder layer	geotextile interlayer
22 cm asphalt base layer	15 cm hydraulically bound layer
51 cm frost blanket	43 cm frost blanket

The standard cross-section for the road was set as an RQ36 based on the AADT. As depicted in fig. 5.2, the cross-section consists of 2 separate directional carriageways, each 14.5 m wide and 4 m apart resulting in a total width of 36 m.

5.2.2 Tunnel planning principles

As the tunnel is located deep down in the mountains, it has to be constructed in a closed construction method. The geology in the area of the tunnel is mainly characterised by gravel, sandy to silty. The rock water thus has the opportunity to drain away and no groundwater is present which enables conventional tunnel excavation. Thereby, the rock is excavated by blasting, secured with shotcrete in a first step and lined with a permanent concrete inner shell after excavation. (SAUER, 2016)

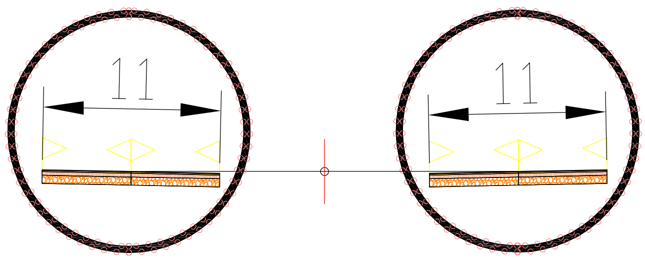


Figure 5.3: Cross section RQ36 t for tunnels with its dimensions [m] according to (FGSV, 2008)

The cross-section chosen for the tunnel is a circular cross-section with an open invert, as there is no groundwater. The inner lining is 40 cm and the shotcrete lining 30 cm thick. The tunnel will consist of two tubes, meaning that both directional carriageways will have their own tunnel tube. A RQ36 t is assumed as the standard cross-section with a respective lane width of 11 m, as shown in fig. 5.3.

5.2.3 Bridge planning principles

A RQ36 B is used for the standard cross-section on a bridge structure as depicted in fig. 5.4. The lane directions have a width of 14.5 m with a distance of 4 m from each other.

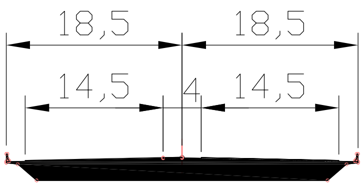


Figure 5.4: Cross section RQ36 B for bridges with its dimensions [m] according to (FGSV, 2008)

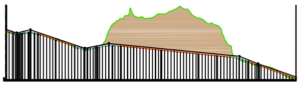
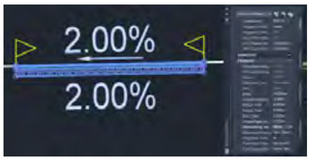
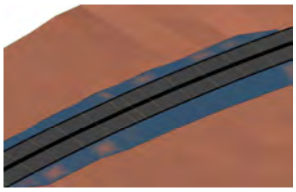
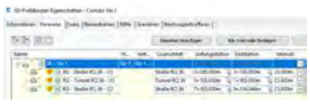
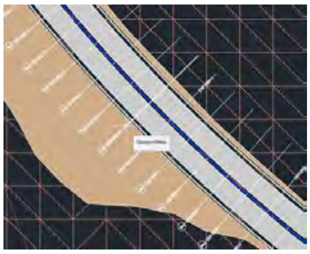
5.3 Modelling procedure in Civil 3D

The two variants are modelled in Civil3D according to section 4.3.
Table 5.3 shows the most important steps which are required for creating the model where all relevant data is available.
Step 1 includes the building of the DTM from a point file. The DTM used for the surveyed area was provided by the Bavarian Survey Administration. It is a DTM 25, which means that the survey points are located in a grid of 25 m.

This is an ASCII text file in which the points are subdivided line by line into easting (German: Rechtswert), northing (German: Hochwert) and height coordinates. The georeferencing is done in the position via the UTM32 coordinate system and in the height via the German main height network (German: Deutsche Haupthöhennetz DHHN2016) (Bayerische Vermessungsverwaltung, 2022).

In order to model the routing in the site plan, a map of the investigated area is projected onto the DTM in step 2. Step 3 to 5 include the modelling of the alignment, profile and assemblies out of which the corridor can be built in step 6. In step 7, the corridor is divided into different sections depending on whether tunnels or bridges are required or if the cross section is changing.

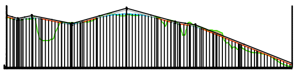
Table 5.3: Step-by-step modelling of variant 1

Description	Illustration
1. Build DTM from point file	
2. Project image onto DTM	
3. Alignment of the routing alternative	
4. Profile of the road	
5. Assembly of the road, bridge or tunnel (Geometry parametrically adjustable)	
6. Build corridor out of belonging profile, assembly and DTM	
7. Divide corridor into different sections (Road, bridges, tunnels)	
8. Create sample lines	
9. Generate datum surface from corridor	
10. Export corridor to solids	

In step 8, the sample lines of the corridor are created at a distance of 20 m and a width of 100 m. The sample lines can take data sources into account such as the surface of the DTM and surfaces of the corridor as its datum surface. The sample lines can then be used to determine quantities such as earthworks. For this purpose, an existing and a reference surface must be defined. The respective cut and fill quantities can be calculated and the output can be performed in tabular form.
For an alternative determination of the cut and fill volumes, the datum surface of the corridor is created in step 10, which is then required for further processing in Dynamo.

In a final step, the solids must be extracted from the corridor, resulting in solids of the individual road layers. The volumes of the solids can then be retrieved.

Table 5.4: Different steps for modelling of variant 2

Description	**Illustration**
3. Alignment of the routing alternative	
4. Profile of the road	
9. Generate datum surface from corridor	

In order to not show all the steps again for variant 2, only the deviant alignment, profile and datum surface are depicted in table 5.4.

5.4 Validation of the implemented calculation steps

5.4.1 Cut and fill volumes

The determination of the cut and fill volumes in Dynamo with the creation of solids is compared to the tabular determination in Civil3D for validation.

Variant 1		cumulative cut volume	cumulative fill volume	cumulative net quantity
		m³	m³	m³
	Solids (dynamo)	598111	331392	266719
	Table (Civil3D)	561312	321819	239492
	Deviation	6,2%	2,9%	10,2%

Variant 2		cumulative cut volume	cumulative fill volume	cumulative net quantity
		m³	m³	m³
	Solids (dynamo)	1217290,5	1128678,45	88612
	Table (Civil3D)	1163408	1078425	84983
	Deviation	4,4%	4,5%	4%

Figure 5.5: Comparison of the results of cut and fill volumes

As shown in fig. 5.5, a positive cumulative net quantity for variant 1 results from the difference between cumulative cut and fill volume. This means that more soil has to be excavated and thus transported away from the construction site. In case of a negative cumulative net quantity, soil would be required and had to be transported to the construction site.

Variant 1 and variant 2 show a good correspondence between the two different calculation methods. Slight deviations occur because the tabular method in Civil 3D generates a volume at a distance of 20 m from the sample lines. Larger deviations appear due to the fact that the width of the sample lines is taken into account in the tabular determination in Civil3D which is 50 m per side. However, if a wider dam or cut is built, the remaining volume is cut off and not taken into account.
The volume determination in Dynamo can thus be considered more accurate as it represents the exact volume of the created solid.

5.4.2 GWP of superstructure

The calculation of the GHG emissions of the superstructure are verified with the results from eLCA which is an online LCA tool for buildings. Its calculations are based on datasets from the ÖKOBAUDAT.

A1-A3	GWP [kg CO_2e/m²]				
Tool	Total	Tragdeckschicht	Asphaltbinder	Asphalttragschicht	Schotter
eLCA	61,1	7,6	6,2	36,8	10,5
Dynamo tool	60,7	7,5	6,2	36,6	10,4
Deviation	1%	1%	1%	1%	1%

A4 transport	GWP [kg CO_2e/t]				
Tool	Total	Tragdeckschicht	Asphaltbinder	Asphalttragschicht	Schotter
eLCA	14,8	9,6	1,9	1,9	1,3
Dynamo tool	14,8	9,7	1,9	1,9	1,3
Deviation	0%	-1%	0%	0%	0%

	volume [m³]	bulk density [kg/m³]
Tragdeckschicht	9612	2400
Asphaltbinder	19224	1000
Asphalttragschicht	52866	2350
Frostschutzschicht	122557	1400

Figure 5.6: Validation of calculating emissions from asphalt superstructure

As the software is designed for building construction, only life cycle phases A1-A3, B6, C3 and C4 can be selected as a basis for calculation. However, for materials used in the construction of asphalt roads, only data for the modules A1-5 and C1, C2 are provided. The validation is therefore only representative carried out for the product stage (modules A1-A3) and the transport to construction site (module A4). Moreover, the CO_2 emissions of an asphalt superstructure of variant 1 are used for validation.

In order to compare the results of module A1-A3, the results from the Dynamo tool must be referred to square metre as its results are related to the whole asphalt superstructure of variant 1. Therefore, the results from the Dynamo tool are divided by the length of variant 1 (9300 m) and the average width of the superstructure (26 m).

The results from eLCA for the transport stage are calculated per ton of the material. Thus the results from the Dynamo tool are divided by the total volume, multiplied with 1000 and finally divided by the bulk density.

In total, the comparison of the results of eLCA and the Dynamo tool indicate a good correspondence as depicted in fig. 5.6. As eLCA is a German tool the name of the asphalt layer is represented with the correspondent German name. The maximum deviation for both of the life cycle stages is 1%, whereby the calculation in the Dynamo tool can be verified.

5.4.3 Calculation process of GWP due to tunnels and bridges

In order to verify the GWP of bridges and tunnels calculated with the Dynamo tool, comparisons with results from SAUER (2016) are performed in the following.

As part of the Irschenberg case study, SAUER (2016) calculated the CO_2 emissions of the tunnel construction which is required for variant 1. The tunnel is excavated in conventional construction method and the emissions during the use stage are summed up for 10 years. Their results are presented in fig. 5.7.

	GHG Emissions [t CO_2e]		
Variant 1	Sauer	Dynamo tool	Deviation
Conventional tunnel excavation	149275	149275	0%
Sum: Use Stage over 10 years	27313,2	26158,89	-4%

Figure 5.7: Validation of calculating emissions due to tunnel construction

The emissions due to construction of the tunnel corresponds well as the same length factor is stored in Dynamo. In the use phase occur slight deviations of 4%. This can be attributed to the fact that the length factors are stored as equations in Dynamo. The individual factors can also be read off the diagramm manually, which can result in small differences.

				GHG Emissions [t CO_2e]		
Variant 2	Length [m]	Width [m]	Area [m²]	1000 kg CO_2e/m²	Dynamo tool (lower value)	Deviations
Bridge 1	760	37	28120	28120	28120	0%
Bridge 2	210	37	7770	7770	7770	0%
Bridge 3	510	37	18870	18870	18870	0%

Figure 5.8: Validation of calculating emissions due to bridge construction

For bridge structures, the lower limit value according to LÜNSER (1999) was set to 1000 kg CO_2e/m². For validation, the bridge area was determined by the length of the respective bridge and its width. Variant 2 of the case study was used for validation, which includes three bridge structures with the dimensions shown in fig. 5.8. Overall, a good agreement of the results was determined.

5.4.4 Calculation of traffic emissions

To verify the calculation of traffic emissions, the results of variant 1 were compared with those of SAUER (2016). For this purpose, the results from the Dynamo tool, which are exported in sum per day for cars or trucks, must be converted to CO_2 emissions per 10 years.
In total, as fig. 5.9 shows, this results in emissions of around 818.500 t CO_2e/10a. A deviation of 5% is acceptable, as small deviations or rounding inaccuracies in the length may occur due to the modelling process.

Variant 1	Dynamo Tool				
	Sum/day	CO_2 emissions /year	CO_2 emissions/10 years		
	[kg CO_2e/day]	[t CO_2e/a]	[t CO_2e/10a]		
Car	135240,6	49362,8	493628,4	Sauer	
Trucks	88999,9	32485,0	324849,7	[t CO_2e/10a]	Deviation
Sum			818478,1	777815	5%

Figure 5.9: Validation of calculating traffic emissions

Chapter 6

LCA results of the case study

Within the framework of the case study, two different routing alternatives were investigated each with a material-based alternative of the superstructure (asphalt or concrete). Variant 1 mainly consists of a tunnel, whereas variant 2 includes the construction of three bridges. Its LCA results are discussed in the following with regard to the third research question to evaluate the embodied and traffic emissions as a basis for decision making.

The Dynamo tool exports the LCA results in an Excel file for each respective routing alternative. The results of the GWP-related emissions are provided in individual worksheets for the different infrastructure elements and the traffic emissions. The worksheet "evaluation" collects the resulting embodied and traffic emissions and displays the exact distribution in form of various diagrams as shown in fig. 6.1.

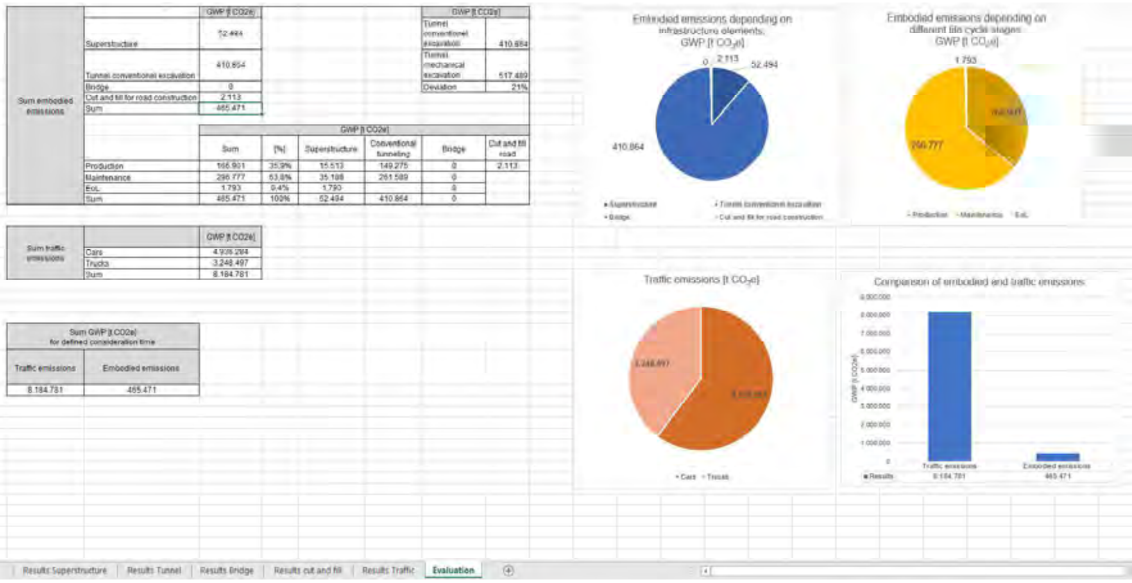


Figure 6.1: Exemplary overview of the result output in Excel

6.1 LCA results variant 1

6.1.1 Embodied emissions

The embodied GWP-related emissions of variant 1 are attributed to road construction, tunnel construction and earthworks.

Figure 6.2 displays the embodied emission depending on different infrastructure elements on the left and on different life cycle stages on the right. The construction of the tunnel

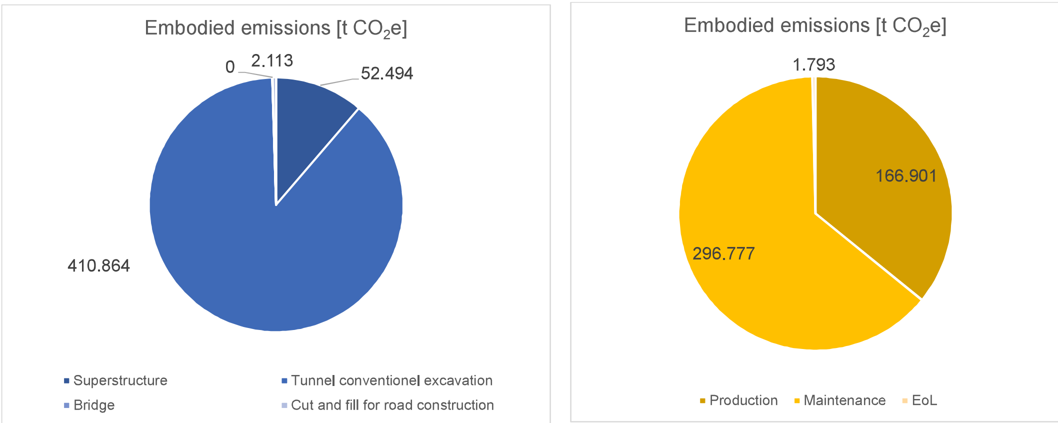


Figure 6.2: Embodied emissions of variant 1 depending on different infrastructure elements (left) and different life cycle stages (right)

causes most of the emissions of approximately 410.864 t CO_2e followed by the construction of the road superstructure amounting to approximately 52.494 t CO_2e.
Considering the embodied emissions depending on different life cycle stages (production, maintenance and end of life), the largest emissions occur during the maintenance stage (64 %), followed by the production stage (36 %) and the fewest emissions are attributed to the EoL scenario (0.5 %). Due to the long consideration period of 100 years and the large energy demand of a tunnel during the maintenance phase, most of the GWP is generated during that life cycle stage.
However, the ÖKOBAUDAT only provides data related to C1 and C2 for an asphalt superstructure. For a holistic assessment, C3 and C4 would also have to be included and should be added in the future when the data is available.
In addition, another open question is how to evaluate the EoL scenario of a tunnel. The length factors developed by SAUER (2016) are not considering that stage. The question to what extent a tunnel is rebuilt or repaired after 100 years is therefore still open to discussion.

Emissions due to earthworks (cut and fill) of the road corridor appear to be very small in relation to the other factors. This is caused by the fact that the maintenance phase of the other engineering constructions causes proportionally higher emission due to the long consideration period of 100 years. However, when compared to the production emissions of the road superstructure, the emissions due to earthworks correspond to around 14 % and should therefore not be neglected.

For tunnel construction, two different length factors depending on the excavation method are stored in the LCA profiles. Comparing these two, it becomes evident that mechanical tunnel excavation causes about 20 % more emissions than conventional tunnel excavation (see fig. 6.3). The high degree of automation in the mechanical excavation, due to the use of a TBM, is therefore also responsible for higher emissions. In some cases both types of tunnel excavation might be feasible which directly depends on the ground conditions.

Sum embodied emissions	GWP [t CO2e]
Superstructure	52.494
Tunnel conventionel excavation	410.864
Bridge	0
Cut and fill for road construction	2.113
Sum	465.471

	GWP [t CO2e]
Tunnel conventionel excavation	410.864
Tunnel mechanical excavation	517.489
Deviation	21%

	GWP [t CO2e]					
	Sum	[%]	Superstructure	Conventional tunneling	Bridge	Cut and fill road
Production	166.901	35,9%	15.513	149.275	0	2.113
Maintenance	296.777	63,8%	35.188	261.589	0	
EoL	1.793	0,4%	1.793		0	
Sum	465.471	100%	52.494	410.864	0	

Figure 6.3: Overview of resulting embodied emissions for variant 1

Concluding, this could be a criterion in the following decision process to excavate the tunnel using for example the more environmentally friendly construction method.

6.1.2 Material-based alternative

Another design aspect is the construction of variant 1 with an asphalt or concrete superstructure. As shown in fig. 6.4, an asphalt superstructure exhibits higher emissions during maintenance, whereas concrete superstructures are responsible for higher emissions during production. The durability of concrete is higher than the one of asphalt which leads to less maintenance measures and fewer emissions during maintenance. Ultimately, the overall differences between an asphalt or a concrete superstructure are about 5 % over a time period of 100 years.

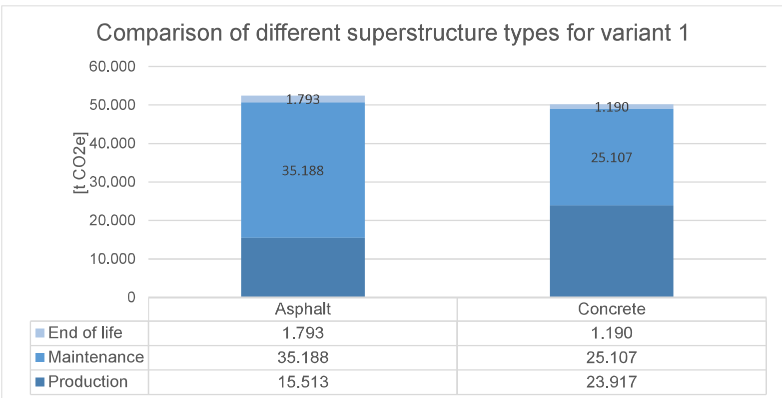


Figure 6.4: Comparison of different superstructure types, such as asphalt and concrete, for variant 1

However, the LCA data quality in the ÖKOBAUDAT for concrete road layers is incomplete compared to asphalt road layers. Therefore, it was necessary to compile different materials for individual layers. Since these were not available for all life cycle stages, a comparison at this point is not completely representative. Next to the modules C3 and C4, data for the construction installation process (module A5) of a concrete superstructure are missing. The aim is rather to demonstrate the methodology based on a BIM-integration. Once meaningful data is available, the different superstructure variants can be evaluated more validly.

6.1.3 Ratio of embodied and traffic emissions

A comparison over 100 years indicates that traffic emissions are clearly higher than embodied emissions. The percentage of embodied emissions is about 5 % despite the high emissions caused by the construction of the tunnel.
However, the traffic scenario is unpredictable for the next 100 years, since the development towards e-cars, the change in individual traffic or the development of new technologies form open questions.
Nevertheless, the BIM model offers the possibility to quickly simulate different traffic scenarios. Even if traffic emissions are reduced by 50 % in the future, the embodied emissions would still amount to 11 % of the overall traffic emissions.

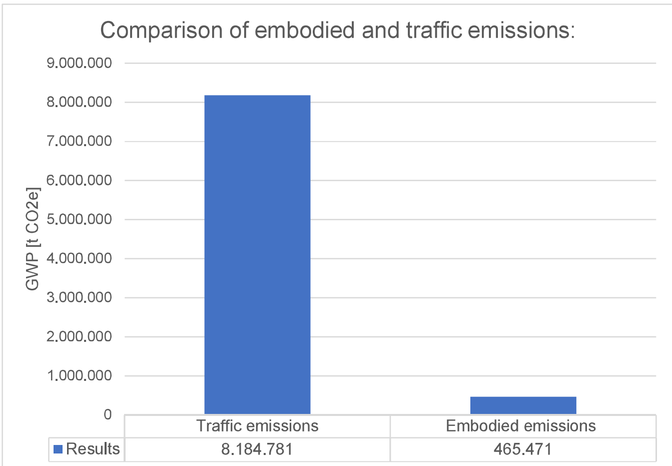


Figure 6.5: Comparison of embodied and traffic emissions for variant 1

6.2 LCA results variant 2

6.2.1 Embodied emissions

The embodied emissions of variant 2 result from the construction of bridges, the superstructure of the road and its earthworks.

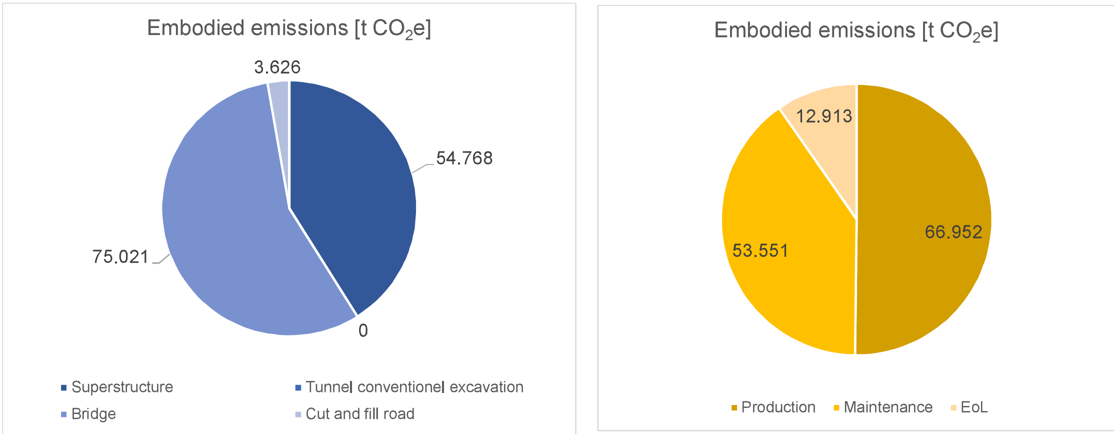


Figure 6.6: Embodied emissions of variant 2 depending on different infrastructure elements (left) and different life cycle stages (right)

The largest GWP occurs similar to variant 1 from engineering constructions which are in this case bridges. In contrast to variant 1, the majority of emissions do not occur during the maintenance phase (40 %) but during the production phase (50 %). This is explained by the fact that bridges have lower emissions during maintenance than tunnels. For example, bridges have no demand for electricity of interior lighting or ventilation as a tunnel has. However, the influences of the different EoL scenario can be discussed when more information for the respective emissions of a tunnel are available.

6.2.2 Ratio of embodied and traffic emissions

When comparing embodied and traffic emissions, a significant difference can be observed similar to variant 1. The results are shown in fig. 6.7 for a consideration period of 100 years. In this case, the embodied emissions correspond to 2% of the overall traffic emissions. In detail, the traffic emissions correspond to 7.744.015 t CO_2e whereas the embodied emissions are only responsible for 133.416 t CO_2e.

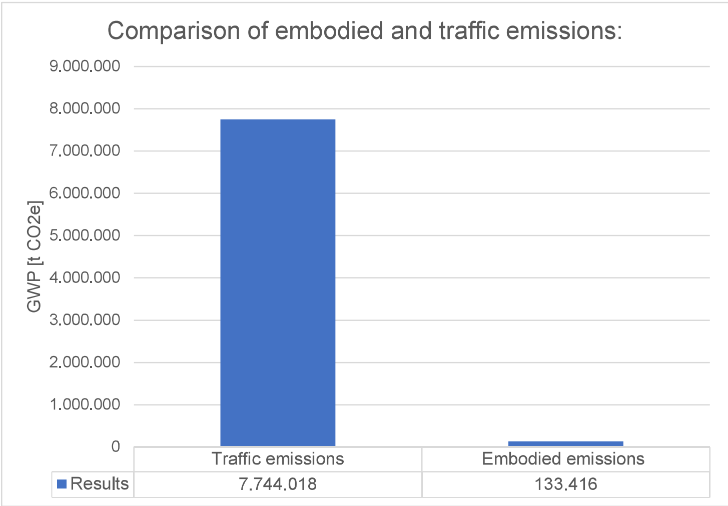


Figure 6.7: Comparison of embodied and traffic emissions for variant 2

6.3 Evaluation of the different routing alternatives

As the results of the individual variants have shown, the traffic share dominates the resulting emissions. Now the question arises how the GWP behaves in comparison to the baseline variant.
As no information on embodied emissions were available for the existing variant, they are excluded in the following. However, since only the maintenance measures for the road would be required, it can be assumed that the resulting emissions would be insignificant. In order to assess the traffic emissions of the baseline variant, the results obtained by SAUER (2016) are applied.

		Total embodied emissions over 100 years	Traffic emissions over 100 years	Sum
		GWP [t CO2e / 100a]	GWP [t CO2e / 100a]	GWP [t CO2e / 100a]
Asphalt	Variant 1	465.471	8.184.781	8.650.252
	Variant 2	133.416	7.744.018	7.877.434
	Baseline variant	-	9.300.200	9.300.200
Concrete	Variant 1	463.193	8.184.781	8.647.974
	Variant 2	125.408	7.744.018	7.869.426
	Baseline variant	-	9.300.200	9.300.200

Figure 6.8: Comparison of the GWP of the different routing alterantives and the baseline variant within a consideration period of 100 years

Figure 6.8 shows that the traffic emissions of the baseline variant are higher than those of the other two variants. The embodied emissions are, however, significantly higher, especially in variant 1 due to the tunnel construction. The question arises, after how many years the embodied emissions are compensated by the relatively lower traffic emissions. To assess this, the respective cumulative emissions of the variants are shown in fig. 6.9 in a time range of 100 years. The different time intervals of 20, 40, 60 and 80 years could be calculated automatically with the help of the Dynamo tool. Since the resulting GWP of an asphalt and concrete superstructure is similiar, only the asphalt pavement is representatively evaluated in the results.

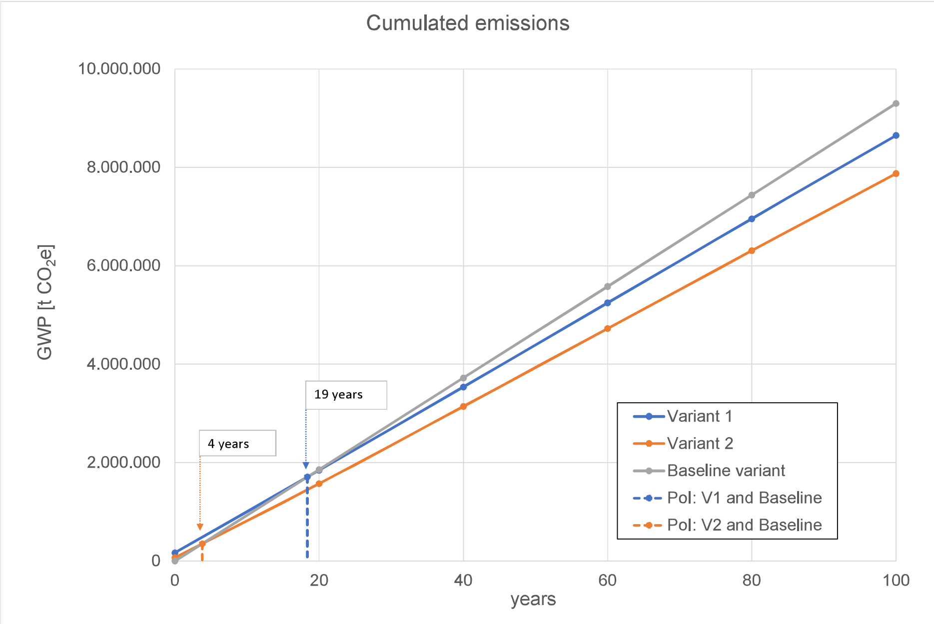


Figure 6.9: Cumulated emissions over a time period of 100 years for the different variants compared to the baseline variant

The embodied and traffic emissions were summed up for each variant. As the construction of the tunnel results in more embodied emissions in variant 1 than in variant 2, the largest GWP can be attributed to this variant after the construction is completet (year 0). The baseline variant starts with the lowest GWP because no construction measures were applied. Since the baseline variant yields the highest traffic emissions, this approach displays the steepest slope. As a result of the construction of variant 2 and the reduced traffic emissions, the point of intersection (PoI) with the baseline variant is already reached after 4 years. For variant 1, the intersection with the baseline variant occurs after approximately 19 years. With regard to the GWP, the construction of Variant 1 or 2 is an improvement over the baseline variant. When comparing variant 1 and 2, variant 2 performs better, as both embodied and traffic emissions are lower.

In the decision-making process the obtained results should be taken into account next to other economic, social and ecological aspects. The results of the case study however show that with the presented methodology sufficient conclusions can be gained to compare different routing alternatives in terms of the GWP.

Chapter 7

Conclusion

The aim of the thesis was to perform a BIM-based life cycle assessment of different road routing alternatives. Thereby, the routing alternatives were considered in the early design stage during the choice of road corridor. As the case study has demonstrated, the resulting GWP of the routing alternatives could be calculated with the Dynamo tool based on the BIM model and the LCA profiles.
The evaluated results confirm the statement of the literature review that the traffic emissions are responsible for the largest share of the GWP (SAUER, 2016 and MILACHOWSKI et al., 2010). The high emissions caused by the construction of the tunnel were exceeded over the entire life cycle by the traffic emissions.
Overall, the LCA results show that it is useful to raise awareness in the construction industry that fuel-efficient construction of infrastructure projects, such as a low longitudinal slope, can significantly reduce the GWP. A comparison of embodied and traffic emissions in the context of the choice of road corridors should therefore be considered as reasonable and important.

7.1 Feasibility of a BIM-based LCA in an early design stage

In the early design stage information regarding the rough construction parameters of different infrastructure elements such as area, length, width, height and location is available and represented in the BIM modell. Since the designs for engineering structures such as bridges and tunnels have not been made at that early stage, it is reasonable to apply length factors depending on the required cross-section or area factors for determining the GWP of engineering structures. The material components of the superstructure of the road are also not determined at that planning stage. For different superstructure variants, individual assemblies can be quickly modelled in the BIM software and their layer thicknesses and widths can be varied parametrically. Therewith, different LCA profiles can be easily linked with the corresponding volumes of the BIM model in order to investigate different materials of the superstructure such as asphalt or concrete.

As demonstrated in chapter 4, all relevant information can be extracted from the BIM model using Dynamo. This concerns the volume of the individual road layers, the cut and fill volumes, the area of the bridge structures and tunnel lengths. Next to the geometric information, semantic information like the cross-section type can be obtained.
All relevant BIM data is therefore available for conducting a LCA. The limiting factor in the presented methodology are the environmental indicators for infrastructure materials and construction processes. While comprehensive indicators are already available in the

ÖKOBAUDAT for building construction, this is unfortunately not the case for infrastructure components. Indicators for the different layers of a concrete superstructure are for example not complete or missing as explained in chapter 5.

Since the focus of the work was on the integration of the BIM data with the environmental data in the early design stage and not on the elaboration of complete LCA profiles, factors or environmental indicators from the literature were used for validation.
For the future, however, an enrichment of uniform and officially valid life cycle databases for infrastructure projects should be aimed for. In addition to material-specific emission factors, information regarding the lifespan of the materials and transport distances are required. Since the highest emissions in road construction occur during the maintenance phase, the applied maintenance cycles and lifespans are of great consequence.
As Zinke et al. (2022) remarks, it would be desirable for information gained in the operational phase to reflow into the planning phase. The resulting data cycle would lead to an improvement in data quality in the early planning phase.

7.2 Degree of automation and integration process

The presented implementation can be assigned to a semi-automatic working process as the interaction of a user is still required in some stages. This includes, for example, the adaptation of the LCA profiles for different boundary conditions such as the traffic scenario. In addition, before running the Dynamo tool, the examined road corridor has to be selected, and depending on the superstructure variant, the stored LCA profile has to be defined. After that, the respective imports and exports are conducted automatically.
An advantage of the semi-automatic working process and the use of the VPL is that it is possible to trace the individual steps and make adjustments. This ensures traceability and the verification of individual sub-steps but also a quick adaptability for possible extensions of the methodological scope.
The presented prototypical implementation can be considered as a closed BIM approach. For realising an open BIM approach, the development of a LCA software would be required into which the data from the BIM model could be imported for example as an IFC file. Even if an open BIM approach is desirable, the IFC export might be a source of error in regard to geometry and material designation, which affects the quality of the LCA (Forth, 2017).

As this is an early planning stage, the complexity of the used materials is quite low. A greater variance can be observed in the environmental data. Therefore, it is important to create the linked environmental data easily accessible. This means that the data can be quickly supplemented or changed in the event of better availability through the expansion of the ÖKOBAUDAT.

Chapter 8

Outlook

Up to now, evaluation systems for the sustainability of infrastructure projects have not been officially introduced. (ZINKE et al., 2021). In order to raise awareness of this issue and to expand the technical knowledge in this area, precise guidelines are required. The integration of the LCA into the planning process still needs to be addressed as well in more detail at a national level in order to find a common solution.
Another open research question exists in the dynamic aspect of the LCA profiles. Change occurs due to different traffic scenarios, the development of fuel efficiency and the share of electric, hydrogen or petrol-powered cars . Data in the ÖKOBAUDAT also varies over time, as different energy sources and mixes are stored.

In addition, the presented methodology offers possibilities for expansion, as limitations were initially made in order to limit the scope of the present work.
At the sustainability level, only the environmental aspects have been evaluated. However, the economical and social dimensions could be extended for a BIM-based decision-making process. With regard to the economic aspects, this could concern life cycle costing (LCC).
Another limitation is the type of traffic mode as only roads have been considered so far. An extension for railway systems would therefore be feasible.
The scope of the performed LCA only considers the GWP as an environmental indicator. If the availability of other indicators gets better in the future, the scope can be accordingly expanded.
In addition, the BIM model could also be used to model different ground layers of the terrain. This would be useful for assessing the required excavation processes for the the road or tunnel construction.

Another possibility is the use of the Dynamo tool as a basis for various parameter studies. For example, the length of infrastructure buildings, such as tunnels and bridges, could be varied to determine the impact of the resulting emissions. Different limit value considerations for environmental indicators could be conducted for evaluating the sensitivity of the results. As presented in the case study, different factors such as the embodied and traffic emission should be included in the decision-making process. In this context different time-dependant scenarios could be investigated with the requirement of a comprehensive visualisation method for better decision-making. All in all, this could provide important conclusions for the early design stage with its high level of uncertainty.

Appendix A

Digital Appendix

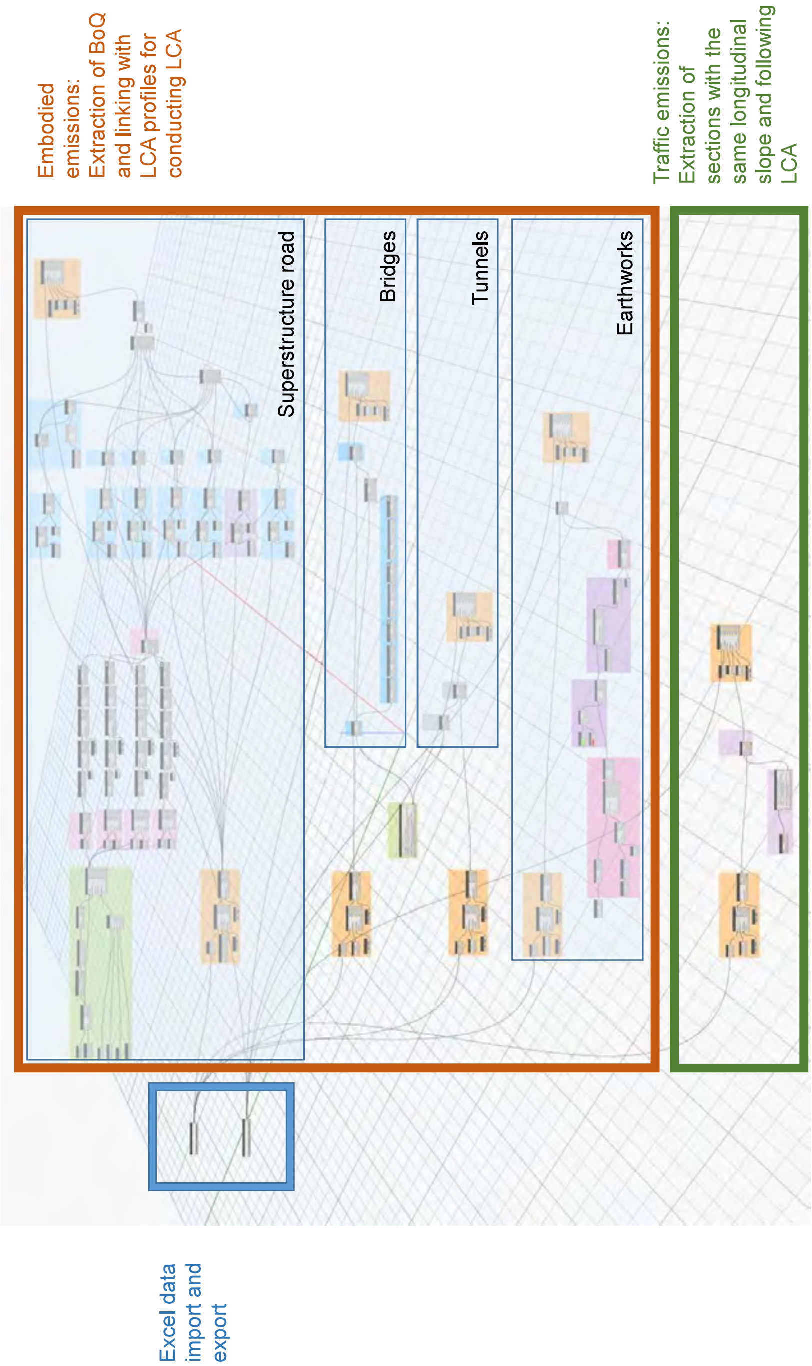
Digitally, the following content is provided:

- Documents used for validation of the Dynamo tool
  - Cut and fill volumes calculated with Civil 3D
  - eLCA results for an asphalt and concrete superstructure
- LCA profiles
- LCA results from the case study
- Civil 3D and Dynamo
  - Civil 3D models of the routing alternatives for an asphalt and a concrete superstructure
  - Dynamo script
  - DTM 25 of corresponding area

Appendix B

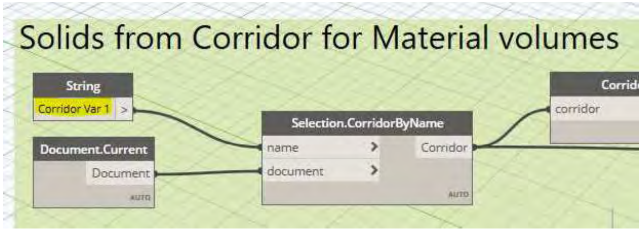
Dynamo tool

B.1 Overview of the Dynamo script

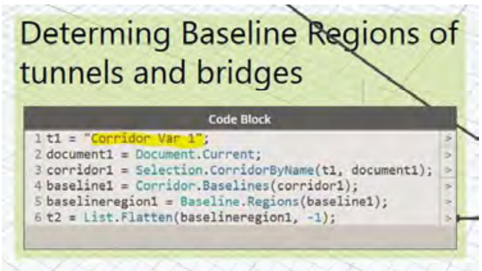


B.2 Manual adjustments

<table>
<tr>
<td>Selection of the considered variant</td>
<td>
1. For the superstructure:



2. For tunnels and bridges:

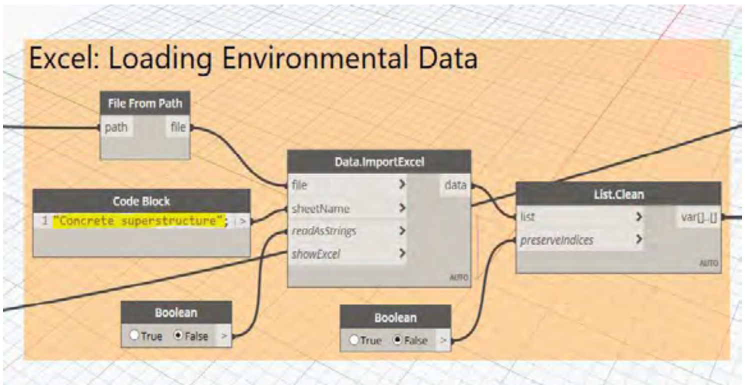
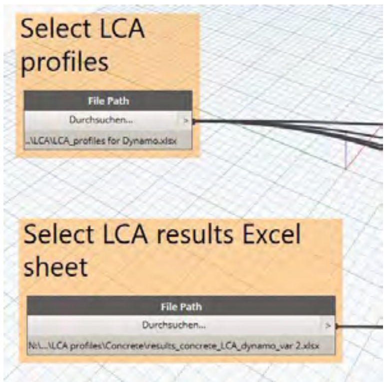


3. For earthworks:

4. For traffic:

</td>
</tr>
</table>

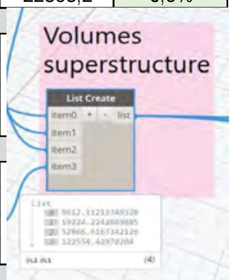
<table>
<tr>
<td>Indication of the used material of the road superstructure:

„Asphalt superstructure“
or
„Road superstructure“</td>
<td>
</td>
</tr>
<tr>
<td>Selection of LCA profiles for data import of environmental indicators and selection of LCA results Excel sheet</td>
<td>
</td>
</tr>
</table>

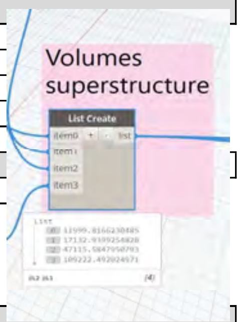
B.3 Validation of Dynamo tool

B.3.1 Volumes of asphalt superstructure

Validiation Var 1 Volume Superstructure Asphalt		Length [m]	Depth [m]	Width [m]	Approximate result	Result Dynamo	Deviation
Road RQ 36 left							
	1. Deckschicht	3100	0,04	14,5	1798	1792,8	0,3%
	2. Zwischenschicht	3100	0,08	14,5	3596	3585,6	0,3%
	3. Tragschicht	3100	0,22	14,5	9889	9860,4	0,3%
	4. Frostschutzschicht	3100	0,51	14,5	22924,5	22858,2	0,3%
Tunnel RQ36 left							
	1. Deckschicht	4265	0,04	11	1876,6		
	2. Zwischenschicht	4265	0,08	11	3753,2		
	3. Tragschicht	4265	0,22	11	10321,3		
	4. Frostschutzschicht	4265	0,51	11	23926,65		
Road RQ 36 left							
	1. Deckschicht	1951	0,04	14,5	1131,58		
	2. Zwischenschicht	1951	0,08	14,5	2263,16		
	3. Tragschicht	1951	0,22	14,5	6223,69		
	4. Frostschutzschicht	1951	0,51	14,5	14427,645		
Total							
	1. Deckschicht		0,04		9612,36	9612,1	0,0%
	2. Zwischenschicht		0,08		19224,72	19224,2	0,0%
	3. Tragschicht		0,22		52867,98	52866,6	0,0%
	4. Frostschutzschicht		0,51		122557,59	122554,4	0,0%



Validation Var 2 Volume Superstructure Asphalt		Length [m]	Depth [m]	Width [m]	Approximate result	Result Dynamo	Deviation
Road RQ 36 left							
	1. Deckschicht	7420	0,04	14,5	4303,6		
	2. Zwischenschicht	7420	0,08	14,5	8607,2		
	3. Tragschicht	7420	0,22	14,5	23669,8		
	4. Frostschutzschicht	7420	0,51	14,5	54870,9		
Bridge RQ 36 links							
	1. Deckschicht	1480	0,08	14,5	1716,8		
Total							
	1. Deckschicht		0,04		12040,8	11999	0,3%
	2. Zwischenschicht		0,08		17214,4	17132	0,5%
	3. Tragschicht		0,22		47339,6	47115,6	0,5%
	4. Frostschutzschicht		0,51		109741,8	109222,5	0,5%



B.3.2 Volumes of concrete superstructure

Validiation Variant 1 Volume Superstructure Concrete		Length [m]	Depth [m]	Width [m]	Approximate result	Result Dynamo	Deviation
Road RQ 36 left							
	1. Deckschicht	3100	0,27	14,5	12136,5		
	2. Zwischenschicht	3100	0,001	14,5	44,95		
	3. Tragschicht	3100	0,15	14,5	6742,5		
	4. Frostschutzschicht	3100	0,43	14,5	19328,5		
Tunnel RQ36 links							
	1. Deckschicht	4265	0,27	11	12667,05		
	2. Zwischenschicht	4265	0,001	11	46,915		
	3. Tragschicht	4265	0,15	11	7037,25		
	4. Frostschutzschicht	4265	0,43	11	20173,45		
Road RQ 36 left							
	1. Deckschicht	1951	0,27	14,5	7638,165		
	2. Zwischenschicht	1951	0,001	14,5	28,2895		
	3. Tragschicht	1951	0,15	14,5	4243,425		
	4. Frostschutzschicht	1951	0,43	14,5	12164,485		
Total							
	1. Deckschicht		0,27		64883,43	64881	0,0%
	2. Zwischenschicht		0,001		240,309	240	0,1%
	3. Tragschicht		0,15		36046,35	36045	0,0%
	4. Frostschutzschicht		0,43		103332,87	103330	0,0%

Validation Variant 2 Volume Superstructure Asphalt		Length [m]	Depth [m]	Width [m]	Approximate result	Result Dynamo	Deviation
Road RQ 36 left							
	1. Deckschicht	7420	0,27	14,5	29049,3		
	2. Zwischenschicht	7420	0,001	14,5	107,59		
	3. Tragschicht	7420	0,15	14,5	16138,5		
	4. Frostschutzschicht	7420	0,43	14,5	46263,7		
Bridge RQ36 left							
	1. Deckschicht	1480	0,08	14,5	1716,8		
Total							
	1. Deckschicht		0,04		61532,2	61257	0,4%
	2. Zwischenschicht		0,08		215,18	214	0,5%
	3. Tragschicht		0,22		32277	32124	0,5%
	4. Frostschutzschicht		0,51		92527,4	92089	0,5%

Appendix C

LCA

C.1 LCA results for different consideration periods

C.1.1 Asphalt superstructure

	Embodied emissions after construction	Traffic emissions 0 years	Sum	Embodied emissions over 20 years	Traffic emissions over 20 years	Sum
	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]
Variant 1	166.901	0	166.901,00	208.177	1.636.956	1.845.133,00
Variant 2	66.952	0	66.952,00	24.212	1.548.804	1.573.016,00
Baseline variant		0	0,00		1.860.040	1.860.040,00

	Embodied emissions over 40 years	Traffic emissions over 40 years	Sum	Embodied emissions over 60 years	Traffic emissions over 60 years	Sum
	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]
Variant 1	264.965	3.273.912	3.538.877,00	336.824	4.910.868	5.247.692
Variant 2	44.797	3.097.607	3.142.404,00	78.814	4.646.411	4.725.225
Baseline variant		3.720.080	3.720.080,00		5.580.120	5.580.120

	Embodied emissions over 80 years	Traffic emissions over 80 years	Sum	Embodied emissions over 100 years	Traffic emissions over 100 years	Sum
	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]
Variant 1	408.683	6.547.825	6.956.508	465.471	8.184.781	8.650.252
Variant 2	112.830	6.195.214	6.308.044	133.416	7.744.018	7.877.434
Baseline variant		7.440.160	7.440.160	-	9.300.200	9.300.200

C.1.2 Concrete superstructure

	Embodied emissions after construction	Traffic emissions 0 years	Sum
	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]
Variant 1	175.306	0	175.306,00
Variant 2	74.684	0	74.684,00
Baseline variant		0	0,00

	Embodied emissions over 20 years	Traffic emissions over 20 years	Sum
	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]
Variant 1	209.398	1.636.956	1.846.354
Variant 2	24.005	1.548.804	1.572.809
Baseline variant		1.860.040	1.860.040

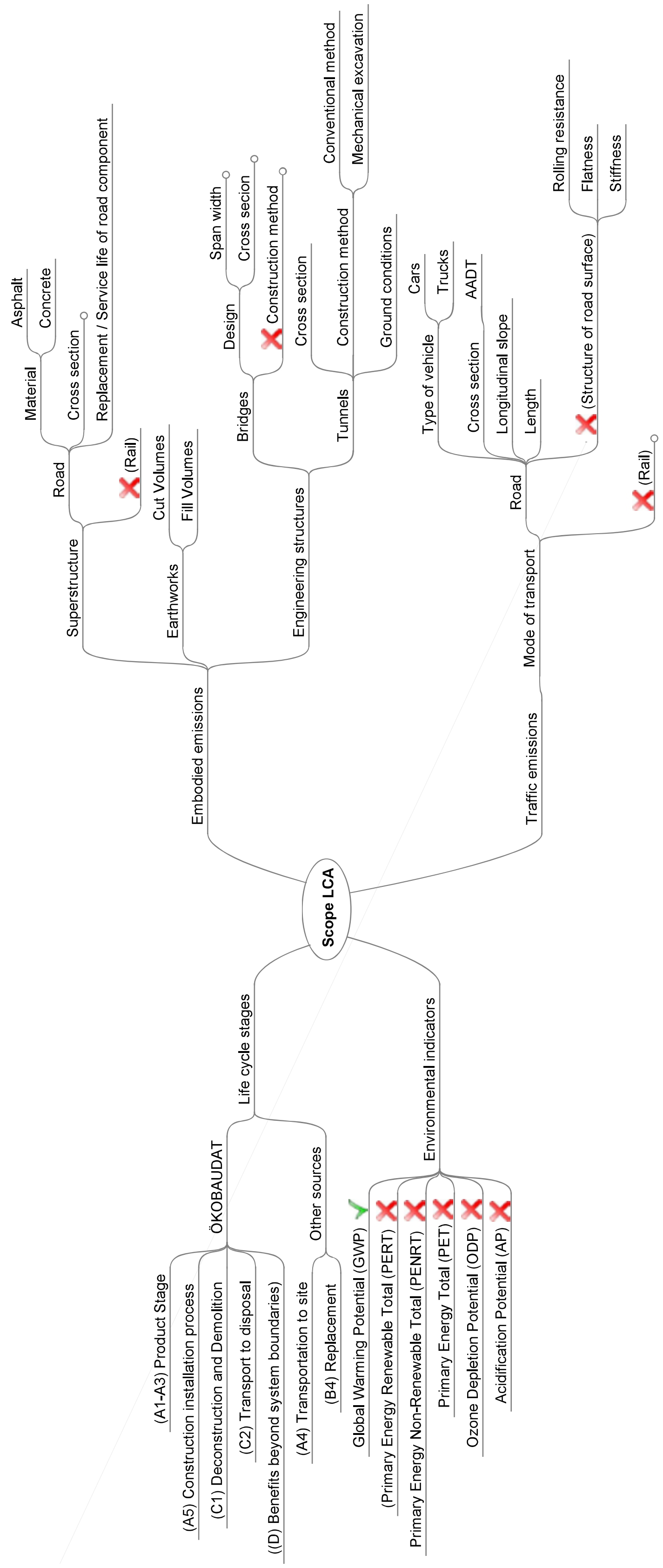
	Embodied emissions over 40 years	Traffic emissions over 40 years	Sum
	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]
Variant 1	267.406	3.273.912	3.541.318,00
Variant 2	44.382	3.097.607	3.141.989,00
Baseline variant		3.720.080	3.720.080,00

	Embodied emissions over 60 years	Traffic emissions over 60 years	Sum
	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]
Variant 1	333.450	4.910.868	5.244.318
Variant 2	72.020	4.646.411	4.718.431
Baseline variant		5.580.120	5.580.120

	Embodied emissions over 80 years	Traffic emissions over 80 years	Sum
	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]
Variant 1	399.493	6.547.825	6.947.318
Variant 2	99.658	6.195.214	6.294.872
Baseline variant		7.440.160	7.440.160

	Embodied emissions over 100 years	Traffic emissions over 100 years	Sum
	GWP [t CO_2e]	GWP [t CO_2e]	GWP [t CO_2e]
Variant 1	457.502	8.184.781	8.642.283
Variant 2	120.035	7.744.018	7.864.053
Baseline variant	-	9.300.200	9.300.200

C.2 Scope Overview



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Declaration

I hereby affirm that I have independently written the thesis submitted by me and have not used any sources or aids other than those indicated.

Location, Date, Signature