Life cycle assessment of tunnel structures

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Published in:
IOP Conference Series: Earth and Environmental Science

DOI (link to publication from Publisher):
10.1088/1755-1315/1078/1/012117

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

PAPER • **OPEN ACCESS**

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To cite this article: Bernhard W. Hopf *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1078** 012117

Life cycle assessment of tunnel structures: Assessment of the New Austrian Tunnelling Method using a case study

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Abstract. One important measure to combat progressing climate change is compliance with and under no circumstances to exceed the decreasing greenhouse gas budget. Every economic sector must strive to make its ecological contribution to achieve this objective. The construction sector is largely responsible for these negative environmental burdens. Although tunnels are considered to have extensive energy and material consumptions the literature has failed to present their environmental impacts. Aimed at this knowledge gap, the objective of this study is to present the life cycle assessment (LCA) of a tunnel construction project situated in Bulgaria. The study analyzes the impacts of the New Austrian Tunnelling Method (NATM) using the case study "Modernization of Railway Section Elin Pelin-Kostenets – Lot 3". Moreover, by applying dominance and sensitivity analyses, the environmental drivers and optimization potential for reducing greenhouse gas emissions are identified. The results show that steel, shotcrete, and concrete, contribute the most to the global warming potential indicator and are responsible for 85% of this. Furthermore, the life cycle stages for the production of materials and components have a share close to 85 % of the total global warming potential. These findings may help future tunnelling construction projects to improve the environmental performance and thus to combat the alarming development of climate change.

Keywords: tunnel construction, LCA, scenario analyses, case study, GWP, New Austrian Tunnelling Method, NATM

IOP Conf. Series: Earth and Environmental Science 1078 (2022) 012117 doi:10.1088/1755-1315/1078/1/012117

1. Introduction

Human influence, increasing resource consumption and waste largely due to industrialization and growth are the factors that shape and change the global environment. This change is accompanied by a continuous rise in world average temperatures, local weather catastrophes, the formation of ozone holes, the extinction of species and forest among other serious detrimental effects. In 1947, the "Bulletin of the Atomic Scientists" introduced the fictional Doomsday Clock (also called the Atomic War Clock). The clock is a widely accepted indicator of the world's vulnerability to disasters from nuclear weapons, climate change, and disruptive technologies. In 2020, the clock was set to 100 seconds to midnight [1] with climate change and its consequences for the world as one of the major reasons. The year 2021 is defined by the "Bulletin of the Atomic Scientists" as the "point-of-no-return" if general conditions remain the same or deteriorate.

Since the beginning of the industrial revolution, anthropogenic greenhouse gas (GHG) emissions have been the main factor behind the increase in concentrations of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) in the atmosphere [2]. In the past 40 years, there has been a rapid increase in the GHG released. For this reason and as an illustration, the term "greenhouse gas budget" was introduced in the literature. The budget and its quantitative values define the maximum total emissions of GHG into our environment per scenario depending on a limitation of the increase in average global temperature (< 1.5 °C, < 2 °C, < 3 °C) and the probability (66 %, 50 %, 33 %). According to studies by the International Panel of Climate Change (IPCC), published in the "Climate Change 2021" report [2], 400 gigatons of CO_2 can still be released into the atmosphere, calculated from the beginning of 2020, not to miss the scenario of an average temperature increase of 1.5 °C.

Due to this, there is a need for action, and consequently, the European Council reached an informal agreement on 2021 in the "Green Deal" [3]. The European climate law provides for GHG neutrality, the so-called net zero target, legally binding by 2050. Measures are defined in the key areas of climate, energy, agriculture, industry, environment and oceans, transport, finance and regional development and research and innovation. The subsequent legislation and the legal framework derived from it will require a general rethinking, both in economic sectors and in the private sphere. In resource-intensive sectors, such as the construction industry, new approaches and the implementation of sustainable constructions will be needed to achieve the ambitious but necessary goals of the "Green Deal". Recording the current state and the relevant human activities that influence the climate is a primary necessity in order to implement climate efforts. The construction sector is responsible for 38 % of global GHG emissions [4]. In tunnel construction, however, scarcely any information is available on the percentage of GHG emissions emitted. A life cycle assessment (LCA) was conducted on a single-tube railway tunnel in the study of Duarte et al. The results show that the project team estimates the total CO2 quantity released during construction at 1.7 million tons. Set against this the study concludes that the project saves between 70,000 and 225,000 tons per year during operation due to reduced car and diesel train trips, essentially offsetting the project's CO2 emissions in 7 to 26 years [5]. On the other hand, however, the analysis and consideration of embodied impacts are emergent targets for reducing the GHG emissions in tunnel projects. Furthermore, the LCA study "Life cycle assessment of Norwegian road tunnel" analyses the distribution of direct and indirect shares of GHG emissions for tunnelling projects. It is shown that the construction produces 52 % of the total GHG emissions of the case study project, and 48 % are produced by operation [6]. Only a very few studies, however, have been published in the literature that addresses the environmental impacts of tunnels.

To close this gap, this study analyses and evaluates the contractor's sphere of influence in the constructing of a tunnel in a case study project. Following the design and the building contract for the specific case study project the LCA modules A1 - A5 represent the scope of influence of the employee. It is intended to show the environmental impacts of tunnels constructed using the New Austrian Tunnelling Method (NATM). Dominance and sensitivity analyses point out major contributors to GHG emissions and optimization potentials.

IOP Conf. Series: Earth and Environmental Science 1078 (2022) 012117 doi:10.1088/1755-1315/1078/1/012117

2. Materials and methods

This LCA study follows the methodology defined by ISO 14040 [7] and ISO 14044 standards [8]. The Swiss Ecoinvent database v.3.6 [9] is used for all unit processes needed to model the resource consumption and method EN 15804(2019) – EF Method – Level(s) – UpdateDM02 V1.07 is used to calculate environmental indicator values of global warming potential (GWP) within the environmental impact indicator global warming.

The functional unit as a framework for the works and resource consumption considered is defined for a 1.0 m tunnel and applicable for the full length of the tunnel. The system boundary of the study includes and is limited to resource consumption for the following construction works:

- Excavation works
- Primary liner works
- Support works
- Dewatering works
- Waterproofing works
- Reinforcing works
- Concrete works of
    - Secondary liner
    - Fill concrete
    - Sidewalk
    - Subgrade

The tunnel structure is a single-tube double-track tunnel with an approximate cross-section of 120 m^2 for the railway infrastructure with a minimum service life of 50 years. The LCA study is limited to the life cycle phases “Production” (A1-A3), "Transport” (A4) and "Construction” (A5). The tunnel excavation methods, used for the case study project, are mechanical excavation and Drill & Blast. Both are state-of-the art excavation methods used in contemporary NATM tunnelling. Construction processes define the construction of the tunnel. The main construction processes are:

- Excavation
- Support
- Waterproofing
- Secondary Liner
- Built-In Parts

System boundaries allocate in- and outputs for the evaluated processes. The construction of a tunnel project requires a great many processes, highly connected and dependent on each other, but only a few different construction materials. The LCA study focuses only on resource production and consumption within the life cycle modules A1-A5. Main resource productions are for shotcrete, concrete, steel and electricity.

Tunnel construction machines and tools are generally used during their service lifetimes at more than one construction site. Due to the absence of knowledge about the origin, age and condition of the equipment used and its stock or invest status, this study does not take into account the manufacturing of equipment, its transport to and from the site or wear and tear during execution of works. The energy (electricity, fuel, …) consumption of the equipment is considered.

The system boundary for the treatment of excavated material includes the transport from the tunnel face to the disposal site with average transport distances but excludes processing, handling at temporary or permanent disposal sites and reuse. Waste treatment processes, processes, and works for site installation and human resources are outside the system boundaries. Water consumption, reuse treatment and discharge are not considered due to the lack of precis information about ground and mountain water inflow during excavation and local requirements for wastewater treatment.

3. Case study project – Modernization of railway section Elin Pelin-Kostenets – Lot 3 (EP-KN – Lot3)

The sub-project EP-KN - Lot3 is one part of the construction project "Modernisation of the railway line Elin Pelin-Kostenets, which is part of the modernization of the railway line from Sofia via Plovdiv to Burgas, the Mediterranean Corridor. The sub-project Lot 3 is located south-east of Sofia and stretches from Ichtiman to Kostenets. The railway section starts at KM 22+554 in Elin Pelin and ends at KM 73+598 in Kostenets. The project includes tunnels, bridges, and other structures in addition to the railway line itself. The region is very rural and the development of access to site and site infrastructure is an essential requirement before construction. Figure 2 shows the location of sub-project Lot3.

Figure 1. Project map of EP-KN - Lot3 [10]

The subject of this LCA study is the evaluation of one tunnel of the sub-project EP-KN - Lot 3, Tunnel 3 (T3). T3 is excavated and built with NATM. Excavation cross-sections, rock support, primary and secondary lining of T3 are heavily dependent on the geological, hydrogeological and geotechnical conditions along the tunnel alignment. The work design includes eight different excavation/support classes and five different standard cross section classes to deal with the challenging conditions. Within these different excavation/support and secondary liner classes two decisively different cross-sections can be determined:

- Standard cross-section without closed invert
- Standard cross-section with closed invert

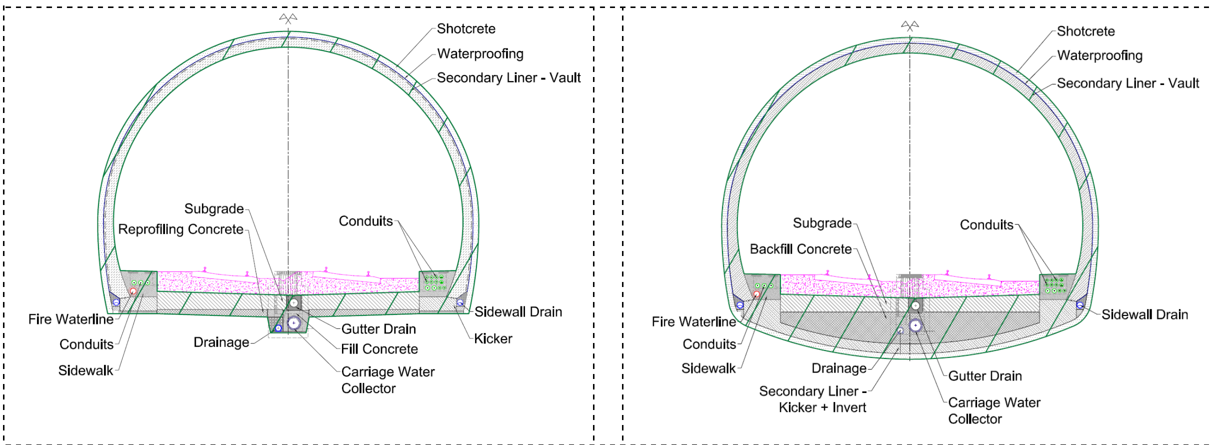

Figure 2. Standard cross-section without closed invert (Green-hatched area shows functional unit).	**Figure 3.** Standard cross-section with closed invert (Green-hatched area shows functional unit).

The data used for this study is mainly based on working design, tender estimation and working estimation. The data obtained and collected is empirical and derived from theoretical construction process planning. The working estimation is assumed to be accurate and excavation processes well modelled. The bill of quantities, one output of the working estimation, and the major database for all resource consumptions (materials, products, power, fuel, and other consumptions) do not consider any errors. No data is collected on-site because the study was completed before the start of the execution of the works. The data for the case study was collected and evaluated by one member of the researcher team and who is involved in the case study project as a member of the staff.

Table 1. Inventory data sources, allocation and assumptions

Construction Process	Ressource	Data source	Allocation and Assumption
Excavation	Electricity, diesel, explosives, drill steel	Working design, tender and working estimation	Excavation under pipe umbrella with excavator LIEBHERR R950 T for 475.5 m. Mechanical excavation with excavator LIEBHERR R950 T and drill hammer EPIROC HB 2500 DP for 370,75 m. Drill & Blast for 1288.75 m with drill jumbo SANDVIK 922i. Top heading excavation advances vary within the excavation/support classes from 1.0 to 3.0 m. Bench excavation advances vary within the excavation/support classes from 1.0 – 6.0 m. Invert excavation advances vary within the excavation/support classes from 4.0 – 5.2 m. The excavated material is transported to different deposits with dump trucks BERGMANN C828s/A and 16-32 metric ton lorry [EURO5]. The transport distance of trucks increases when the tunnelling advances. The average transport distance from face to disposal site is 3.82 km per m^3 of excavated material.
Support	Electricity, shotcrete, shotcrete accelerator, steel mesh, anchors, spiles, lattice girder, pipe umbrella, anchor mortar	Working design, tender and working estimation	Quantities of shotcrete and bolts/anchors are collected from work estimation. The material consumption of grout for bolt/anchor grouting is estimated with the size of the hole and the installed type of bolt/anchor. Holes for bolts/anchors are drilled with the same machine used for the excavation process. Wet shotcrete spraying is assumed to be done with PUTZMEISTER Wetkret5. Installation of pipe umbrella and spiles is done with a drill jumbo. The drill jumbo is the one used for the excavation process. The installation works for mesh and anchors are supported with GTA Normlifter 750D. Pipe umbrellas, spiles, bolts/anchors and lattice girders are imported with an average transport distance of 1300 km.
Water-proofing	PVC foil, geotextile	Working design, tender and working estimation	Electricity consumption for welding and associated works for waterproofing are not considered.
Secondary Liner	Electricity, concrete, steel mesh, steel rebars, repair mortar, crown gap mortar	Working design, tender and working estimation	Quantities of most materials are collected from working design drawings. The construction process secondary liner includes all concrete works for vault, invert, foundation, backfill invert, reprofiling, sidewalks and subgrade. All concrete quantities are transported from the batching plant situated on the construction site with an average transport distance of 1.35 km, including transport distances inside the

			tunnel. Energy consumption includes electricity for concrete pumps. Stell rebars and steel mesh are assumed to be produced in Europe and supplied locally.
Built-In Parts	Gutter drain, concrete pipes, PVC pipes, HDPE pipes, fire-waterline, hydrants, shafts, shaft covers, drainage gravel	Working design, tender and working estimation	Quantities of most materials are collected from working estimation. Plastic pipes are assumed to be supplied locally. Concrete pipes, shafts and shaft covers are assumed to be supplied locally. The gutter drain is assumed to be imported, transport distance is assumed with 360km.

4. Results

The case study tunnel construction, executed in NATM, is divided into the five construction processes excavation, support, waterproofing, secondary liner, and built-in parts. These processes use the ten tunnelling resources steel, shotcrete, concrete, cement/mortar, plastic, soil/backfill material, explosives, others, and energy and produce excavated material in significant quantities. Figure 5 the GWP due to resource consumptions for each defined construction process for the life cycle modules A1-A5. The construction process "support" and "secondary liner" together contribute 83.9 % to the total GWP. The construction processes "waterproofing" and "built-in parts" contribute a very small quantity, amounting to less than 5.0 % each for the total GWP of NATM tunnelling. The three main material contributors are steel, shotcrete and concrete. These materials are also the main drivers within the two major construction process shares of GWP.

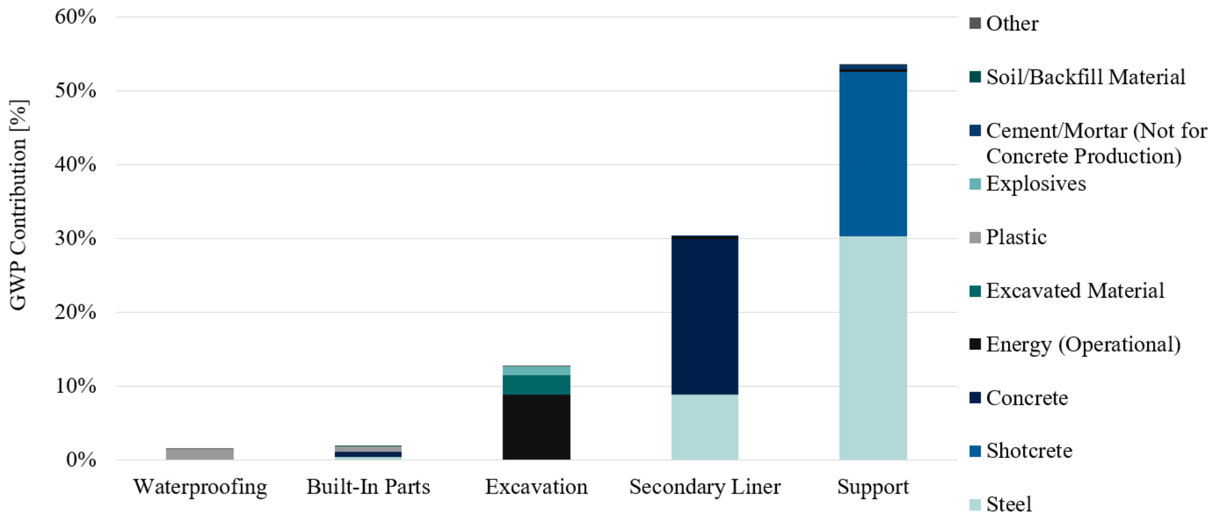

Figure 4. GWP contribution of resource consumptions per construction processes.

If all GWP contributions in Figure 6 below 5 % are neglected only three materials and the use of energy can be identified as GWP drivers. The three biggest shares combined represent 83.7 %. Steel consumption with 39.5 % of the total GWP is by far the largest driver and the others in descending order are shotcrete, concrete, energy, excavated material, plastic, explosives, cement/mortar, and soil/backfill material and others. Both shotcrete and concrete use the same raw materials and can be seen as one kind of material contributing 44.2 % to total GWP.

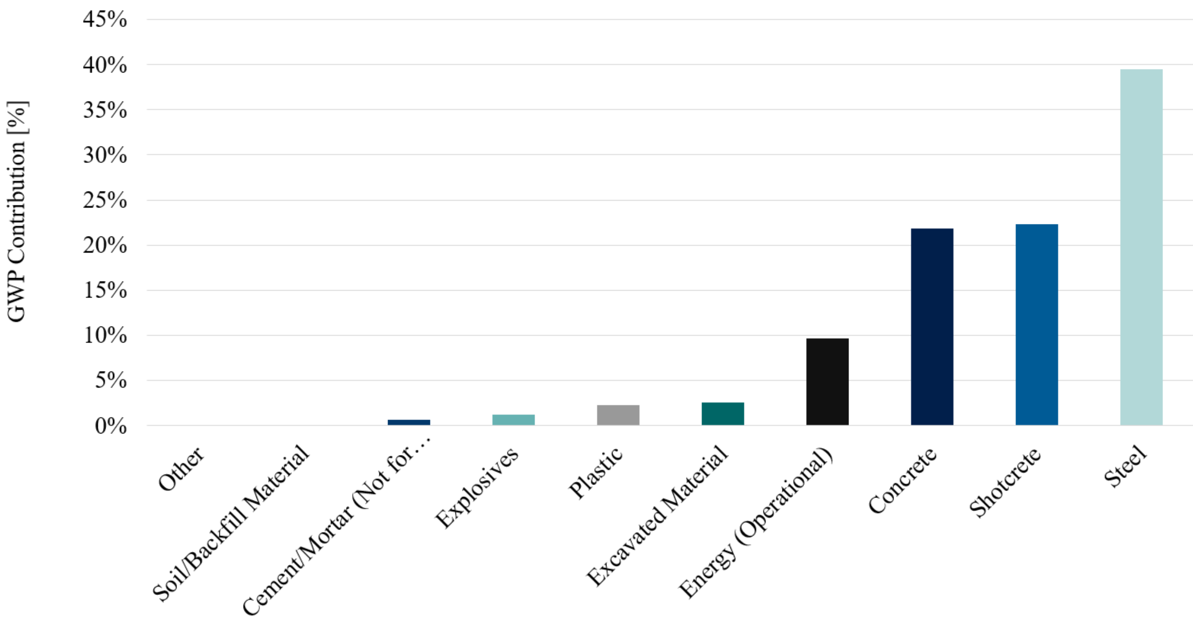

Figure 5. Resource consumptions contributing to GWP.

Figures 5 and 6 above picture the GWP for Tunnel 3 executed in NATM for the life cycle modules A1-A5. In addition to identifying material drivers, it is important to evaluate the shares of life cycle modules A1-A3, A4 and A5 within the resources. Figure 7 shows the distribution of GWP for the life cycle modules A1 - A3, A4, and A5 per resource.

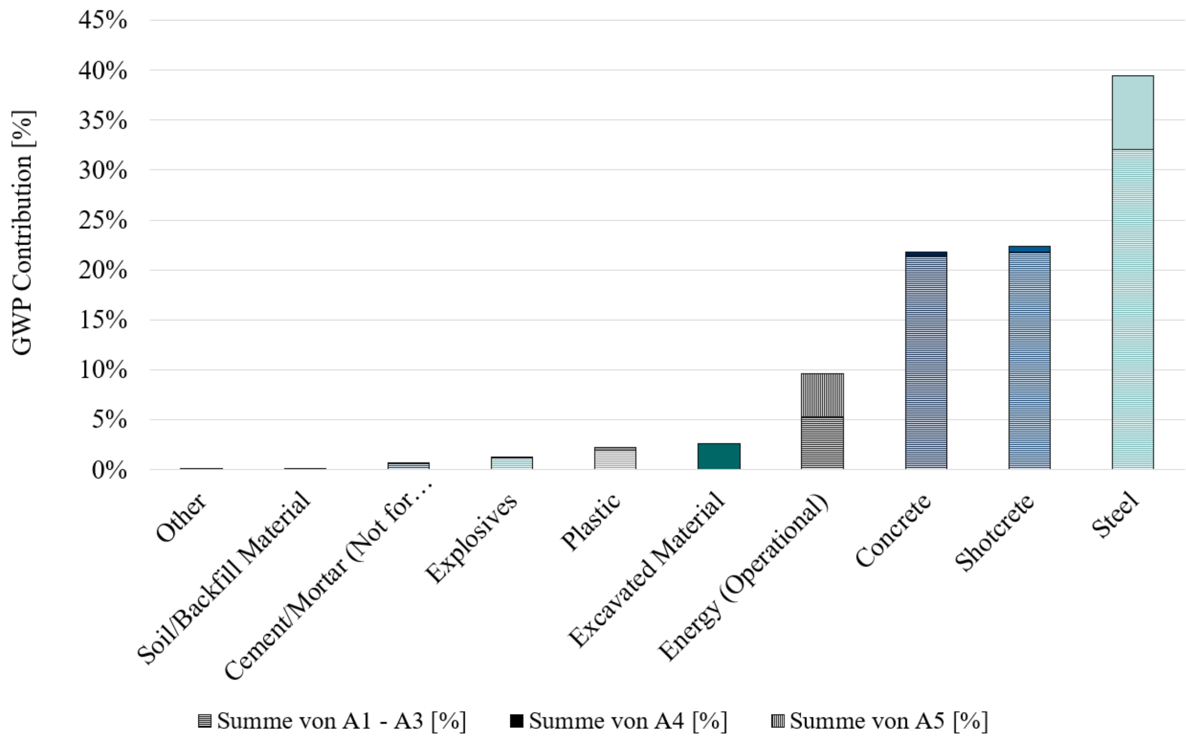

Figure 6. GWP contribution of life cycle modules A1 - A3, A4 and A5 per resource.

The environmental impact of life cycle modules A1-A3 dominates nearly all resource consumption in the GWP. Only excavated material and energy show a different trend. The system boundaries for excavated material only include the transport of excavated material, which is part of life cycle module A4. The GWP of life cycle module A5 for energy consumption is nearly as high as the one from modules A1-A3. The GWP of life cycle module A5 is formed by fuel combustion to power construction machines such as excavators, drill jumbo, dump trucks, and others, as listed in Table 1,

Module A4 includes transporting all materials and products from producers and manufacturers to the construction site. Most of the transport distances are assumed (Table 1). In Figure 7 the share of GWP due to transportation is very low for all materials except steel. Steel is assumed to be imported and nearly all kinds of supports, except for rebars and steel mesh, are transported by truck from Central Europe to the site. The GWP share of transportation for steel is thus significant, but is nevertheless still low compared to the contribution of A1-A3. The distribution of GWP shares for all life cycle modules can be seen in Table 2 and shows A1-A3 as the main driver of GWP within the modules.

Table 2. Total GWP contribution for life cycle modules

Life Cycle Module	GWP Contribution [%]
A1 - A3	84,3
A4	11,3
A5	4,4

5. Discussion

The LCA study for the given case study project reveals a very high GWP contribution for a small number of materials and a very high contribution of life cycle modules A1 – A3. Modules A1 – A3 have a total GWP share of 85 % in all the life cycle modules. What this means is that the production of construction materials has a significant GWP influence, and furthermore this is an influence with more or less no direct connection to the construction process. In this context it can be seen that any contractor has a scope of action in reducing CO_2e emissions, which is limited by the available goods on the market produced by third parties. This statement does not release any contractor from the obligation to strive for optimized solutions but it is a clear indicator of the need for novel material production processes or the use of other materials.

Steel, shotcrete and concrete consumptions contribute around 85 % to GWP. The share for life cycle modules A1-A3 contributions of these three material consumptions is around 75 %. This means three quarters of the entire GWP is related to steel, shotcrete, and concrete production. When energy consumption is also taken into account, four resource consumptions have a share of up to 80 % in the total GWP. This indicates a strong correlation between GWP and consumption of these four resources. It also shows that the major GWP portion can be evaluated solely by taking into account the main drivers, steel, shotcrete, concrete and energy. This means it would thus be possible to obtain ballpark figures in an LCA study with very little effort by considering these four consumptions. More research in this direction and more tunnelling case study assessments are necessary to support this statement and also to develop a simplified method for GWP estimation of tunnel projects.

The contribution of explosives to GWP is very small and in comparison with other case studies it is only a mere 1.22 % it would appear to be underestimated. Drill & Blast excavation represents only 60 % of the whole excavation for the case study. This means that its impact is less than in tunnel construction projects in which Drill & Blast excavation is used over the whole length. However, since the influence is very small, no detailed analysis has been carried out.

The influence of transport is higher in this LCA study when compared with the study of Schwartzentruber et al., [11]. A reasonable explanation for this may lie in the assumed transportation distances. Only very few products/materials are sourced locally for this tunnel project, with the exception of concrete. Support materials, representing the highest contribution to total GWP, are

assumed to be transported by trucks over long distances from central Europe to the construction site. Some built-in materials are assumed to be transported by truck from the Anatolia region to the construction site. These assumptions might not be valid after supply contracts are fixed and therefore overestimate the contribution of transport to GWP. However, even if the over-estimate is it is 50 % this would still only represent a decrease of 5 % in the total GWP.
Finally, it must be mentioned that LCA standards require the assessment of all environmental indicators. Due to the large data volume required, this article focuses only on the environmental indicator GWP. Furthermore, the environmental impacts of tunnel constructions and their effects, for example to the biodiversity, needs to be discussed more widely than is the case using LCA.

6. Conclusion

The objective of the study is to analyze the environmental impacts of the New Austrian Tunnelling Method using the case study "Modernization of Railway Section Elin Pelin-Kostenets – Lot 3". Moreover, the environmental drivers and optimization potentials for reducing greenhouse gas emissions have been identified by applying dominance and sensitivity analyses of the LCA study. Only a few studies research the environmental impacts of tunnel construction projects in the literature. This study, presenting an LCA of a tunnel construction project in Bulgaria shall help to close this gap.

The construction of a tunnel is a massive intervention in nature and the environment requiring a large consumption of resources. This resource consumption is the basis for the LCA, and the environmental impacts have been evaluated. The emission of greenhouse gases, CO2-equivalent, is enormous for constructing one tunnel. Furthermore, if the operation and maintenance of a tunnel are also considered in an LCA, then this would be spoken of as a multiple of the CO_2-equivalent caused solely by the structure's construction. This type of consideration can be deceptive if only emissions quantified by means of a LCA are considered. An overall environmental evaluation of such structure needs to take any advantageous or disadvantageous influence due to the construction, operation, maintenance and end of life into account. An LCA, like the one performed in this case study is not enough to judge the value of such construction projects.

Three materials consumptions, those for steel, shotcrete and concrete, are the environmental drivers of the tunnel construction project T3. These three material consumptions together share around 85 % of total GWP. Life cycle modules A1 – A3 dominate the life cycle modules and share nearly 85 % of the total GWP. As a result approximately 75 % of the GWP is contributed solely by producing the main materials steel, shotcrete and concrete.

More research on different tunnel case study projects needs to be carried out to understand more fully and to quantify what the life cycle modules A1 - A5 contribute to GWP if all life cycle modules A – C are considered in an LCA. Only if the GWP shares in the construction, operation, maintenance and the end of life for a tunnel project are known can the GWP contribution of different life cycle modules be identified and relativized as major drivers for the total life span.

The wide range of available tools but the lack of standardization and legal requirements to model and evaluate LCAs during tender phases do yet not allow competitive advantages in the tunnelling industry for competitors willing to deal with environmental topics. In order to reduce emissions and achieve the milestones defined in the Green Deal, the defining of the tunnelling industry's legal frameworks and making environmental awareness and environmental goals a major requirement in our business are now overdue.

Acknowledgement

The analysis and results described in this paper relate to ongoing research within the international project HERMES, which focuses on emission reduction potential and management strategies for urban road systems (https://jpi-urbaneurope.eu/project/hermes). The Austrian contribution is financially supported via the Austrian Research Promotion Agency (FFG) Grant #870294.

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