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A Systematic Methodology for CO_2 Accounting and Sustainability Assessment in Mechanized Tunnel Construction

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Tunnel projects are key to modern transport infrastructure, with growing focus on ecological sustainability. Considering global climate goals and stricter regulations, systematic CO_2 emission recording and optimization are vital. This paper presents a methodology for assessing sustainability in tunnel construction, especially mechanized tunneling with tunnel boring machines (TBMs). It combines Life Cycle Assessment and the Greenhouse Gas Protocol, tailored to tunneling projects. The approach captures emissions from material production (particularly concrete and steel), TBM operation, ventilation systems, and transport processes. Validated by expert surveys and literature, the methodology addresses gaps in tunnel-related carbon accounting. An example project with a twin-bore tunnel of 3 km per bore shows material production causes over 90% of emissions, while transport and machine operation contribute about 8%. This highlights optimization potential at the planning stage using low-CO_2 cements and steels and efficient segmental lining designs. The methodology aids planners, builders, and public clients in ecological assessment and can be adapted to project needs. It supports early-phase emission reduction decisions and may be transferred to other infrastructure projects, guiding sustainable development despite challenges like data complexity and the need for standardized emission values.

Keywords: *Sustainability in tunnel construction, mechanized tunneling, life cycle assessment, CO_2 accounting, infrastructure projects, climate policy instruments*

Introduction

Climate change is among the most pressing issues of our era (Sauer 2016, Elbers 2022, Galluccio 2022, Handler 2024). In this context, there are global efforts to intensify climate protection and reduce emissions of carbon dioxide, which is the most important greenhouse gas and has a major impact on our climate (Edenhofer et al. 2019, Galluccio 2022). CO_2 accounting is a critical instrument for evaluating the ecological sustainability of tunnel construction projects, as it methodically documents emission sources such as building materials, construction processes, and energy consumption (Lorse 2021, Wühle 2022). It provides the foundation for strategies aimed at reducing emissions and is a critical element of a comprehensive sustainability management approach (Elbers 2022, Emig 2024).

The energy-intensive production of steel and concrete has been identified as a significant contributor to the carbon footprint due to its high energy intensity

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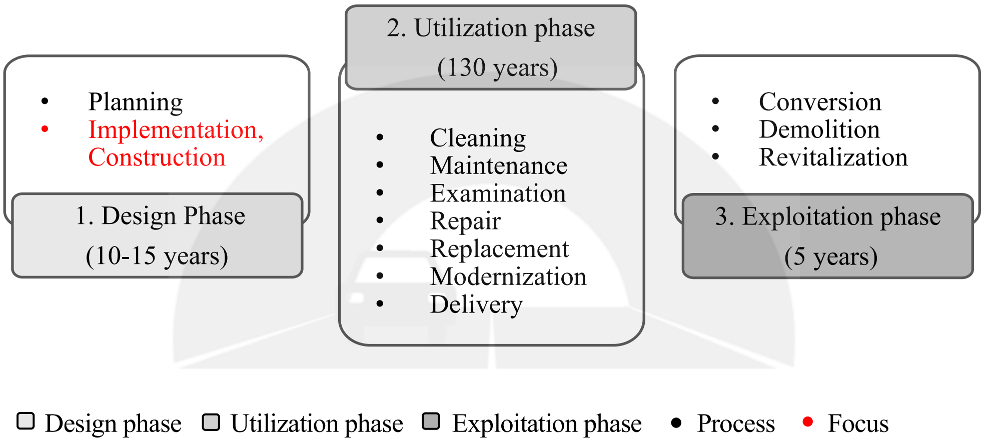
(Blöcker 2022, Druffel et al. 2022, Karlsson 2024). However, significant emissions also occur in other stages project phases, including energy consumption during the construction process, the transportation of materials, and end-of-life waste disposal (Bischofberger 2024, Menge 2023).

Accordingly, the entire life cycle of a construction project exerts a substantial influence on its carbon footprint. As illustrated in Figure 1, the life cycle of a tunnel construction project encompasses various phases, each of which is associated with distinct processes and environmental impacts.5 From the design and planning phase through construction, operation, and eventual decommissioning, each stage contributes differently to the overall environmental burden.

Figure 1. *Phases and Processes in the Life Cycle of a Tunnel Structure*



Source: Own illustration

A comprehensive analysis of these phases and the corresponding CO_2 accounting approaches is therefore essential to identify key emission sources and to develop effective mitigation strategies across the entire life cycle. The following section reviews the current state of research and existing approaches to CO_2 accounting in tunnel construction to establish a solid foundation for the development of such a methodology.

Literature Review

In the course of this research, a systematic literature review was conducted following the methodological framework proposed by Jesson et al. in 2011. The aim was to identify relevant publications addressing CO_2 accounting in mechanized tunnelling. The analysis revealed a lack of standardized guidelines and consistent methodological specifications in this field. Initially, the research questions were defined to establish the scope of the review. The formulation of relevant keywords in both English and German was conducted, employing Boolean operators to ensure the precision of the search. The search for relevant literature was conducted using general academic search engines (Google Scholar, EBSCO Discovery Service) in addition to specialized databases such as SpringerLink, ScienceDirect, Scopus, and the VDI Knowledge Portal. A dual approach of forward and backward citation tracking was adopted to ensure comprehensive coverage.

The identified publications were then evaluated based on three criteria: relevance, scientific quality, and methodological rigor. The final step entailed synthesizing the selected sources to create a comprehensive map of the current state of research in this field. This map was then used to identify existing gaps and assess the relevance of the sources to the research objectives posed in this paper. The following Table 1 presents a selection of selected publications on this subject and evaluates their relevance to the key topics.

Table 1. *Comparative Analysis and Evaluation of Select Publications*

Selected publications on the topic (study, book, specialized article, general publication)	**Authors**	**Year**	**Key topics**			
			Sustainability in tunnelling	Legal framework	CO_2 accounting approaches	Example of CO_2 accounting
The lifecycle cost concept for implementation of economic sustainability in tunnel construction	Engelhardt, S. Schwarz, J. Thewes, M.	2014	◕	○	◑	○
Ecological considerations regarding the sustainability of tunnel structures in transport infrastructure	Sauer, J.	2016	◑	◔	◕	●
CO_2 reduction in tunnelling from the point of view of construction design and implementation	Friess, J. Golser, J. Luniaczek, T.	2022	●	○	○	○
Application of the BIM Method in Sustainable Construction Status Quo of Potential Applications in Practice	Bartels, N. Höper, J. Theißen, S. Wimmer, R.	2022	◕	●	◑	○
Evaluating Carbon Emissions during Slurry Shield Tunneling for Sustainable Management Utilizing a Hybrid Life-Cycle Assessment Approach	Kou, L. Shi, X. Liang, H. Li, W. Wang, Y.	2024	◔	○	◕	●
Carbon Footprint Evaluation in Tunnels Excavated in Rock Using Tunnel Boring Machines (TBM)	Bascompta, M. García, H. Rodríguez, R.	2024	○	○	◕	●

● Fully addressed ◕ Mostly addressed ◔ Partially addressed ◑ Slightly addressed ○ Not addressed

Source: Based on Bullinger and Wächter, 2016, p. 84

A substantial body of literature exists within the scientific community addressing the subjects of sustainability, carbon accounting, and legal framework conditions in the context of tunnel construction. While general environmental and regulatory aspects are frequently covered, the analysis reveals a paucity of integrated and practice-oriented CO_2 accounting methods for tunnel construction projects, with the entire life cycle frequently insufficiently taken into account (Bascompta et al. 2024).

Life cycle analyses (LCA) and the Greenhouse Gas Protocol (GHG Protocol), which serve as the methodological basis for carbon accounting, are described in detail in specialist literature. Additionally, certification systems such as BREEAM, LEED, and DGNB have been developed to evaluate the environmental performance of construction projects more broadly (Bartels et al. 2022). However, the application of these extant accounting frameworks in the context of mechanized tunnelling has not yet been comprehensively established. This lack of alignment presents a substantial barrier to the implementation of effective CO_2 reduction strategies in tunnel construction. Addressing this gap necessitates further development and harmonization of existing accounting approaches and the systematic integration of sustainable practices at an earlier stage in the planning process. This approach would enhance the climate mitigation potential of tunnel infrastructure (Kou et al. 2024).

Empirical Study

An empirical study was also conducted to verify the general accounting approaches used in sustainability assessments, as well as research gaps identified through a literature analysis. The study aimed to supplement these approaches with practical assessments by experts. In order to ascertain the relevance of carbon accounting in tunnel construction, specific dimensions were examined, including understanding, acceptance and previous experience with the accounting methods currently in use.

The study was directed towards a specialized group of experts working in the field of sustainability assessment of tunnel construction. The experts were selected on the basis of their technical expertise and their current publication activities in the field of tunnel construction and carbon accounting. To obtain a comprehensive perspective, it was necessary to include experts from a variety of professional backgrounds. These included representatives from construction companies in Germany and Austria, engineering firms, public clients, specialists from the field of project planning and execution, and academic researchers with a university background.

Of the 21 individuals contacted for the expert survey, 6 experts agreed to participate, resulting in a response rate of 28.57%. Despite the restriction of participation, which diminishes the statistical representativeness of the data and precludes the drawing of generalizable conclusions for the entire tunnel construction industry, the responses nevertheless offer valuable qualitative insights into current practices and key challenges in the field of carbon accounting. Given the modest sample size, it is imperative to recognize the exploratory nature of the findings and to consider them as an inaugural step that prompts further research with more extensive empirical coverage. A thorough and candid discussion of these limitations is essential for maintaining the study's integrity and credibility.

Notwithstanding these constraints, the expert feedback reveals several consistent trends. The surveyed professionals highlighted significant discrepancies in the present utilization of carbon accounting within tunnel construction projects. These discrepancies are attributable not only to the absence of binding legal mandates, but also to the inconsistent and fragmented nature of prevailing guidelines. A conspicuous dearth of standardized, industry-wide methodologies exists to address the specific technical and operational features of mechanized tunnelling. Consequently, the assessment of CO_2 emissions frequently relies on approximate estimations, generic emission factors, or assumptions that do not align with the unique characteristics of tunnel construction projects.

The experts reached a consensus on the necessity of more precise and context-sensitive approaches to carbon accounting. These approaches should be grounded in project-specific data and capable of capturing the complex interactions of materials, machinery, and processes used in tunnel construction. Rather than relying on industry-unrelated blanket assumptions, a shift toward tailored methodologies is essential. These should include refined emission factors, differentiated by construction technique and project context, and data-driven calculation frameworks that reflect the full life cycle of tunnel infrastructure.

Moreover, the insights derived from the expert interviews are closely aligned with the findings of the preceding literature review. Despite the extensive documentation of foundational methodological frameworks, such as Life Cycle Assessment and the Greenhouse Gas Protocol, in academic literature, their application in tunnel construction remains in its initial stages. Certification systems also address environmental performance; however, their relevance to the specific challenges of mechanized tunnelling remains limited. The discrepancy between theoretical frameworks and their practical implementation underscores the necessity for methodological development that is explicitly oriented towards the tunnel construction sector.

Considering these results, it is evident that the process of carbon accounting in tunnel construction necessitates both structural and methodological advancements. Firstly, it is imperative to acknowledge the necessity for enhanced harmonization and standardization across various projects and institutions. Secondly, sustainable construction practices - particularly those related to emission reduction - must be incorporated more systematically and earlier in the planning phase. The integration of carbon accounting into the fundamental framework of project development is imperative for the meaningful contribution of tunnel construction to broader climate protection objectives.

The results of the expert survey support the conclusions drawn from the extant literature and underscore the necessity of developing a tunnel-specific, practically applicable, and scientifically robust methodology for carbon accounting. This would strengthen transparency and comparability across projects, thereby supporting the industry in meeting its climate responsibilities in a measurable and verifiable way.

Methodology to CO_2 Accounting in Mechanized Tunnel Construction

The findings outlined above constituted the conceptual foundation for the formulation of a customized methodology for sustainability assessment in mechanized tunnel construction. In order to identify suitable approaches, a comprehensive utility value analysis was conducted. This analysis employs a structured four-step process, as outlined by the German Federal Ministry of the Interior and Community (BMI 2023) to evaluate various CO_2 accounting models against a set of predefined criteria. The selection of criteria was predicated on the establishment of a foundation for evaluation, with the relevant criteria defined in accordance with project-specific requirements. These requirements encompassed a range of factors, including technical, ecological, economic, and regulatory aspects. A comprehensive set of criteria was meticulously evaluated, encompassing various dimensions such as relevance to the application, scalability, data availability and quality, model accuracy, uncertainty assessment, model complexity, user-friendliness, adaptability, transparency, support availability, system compatibility, data import/export, standards compliance, and stakeholder acceptance.

The selected approaches - process-based LCA, hybrid LCA, GHG Protocol, certification systems (BREEAM, LEED, DGNB), and databases - were each evaluated on a scale from 1 to 5 for each criterion, with equal weighting employed to ensure objectivity and transparency. The scores for each model were summed to determine their overall utility value. The results of the study indicated that the GHG Protocol (55 points) and the LCA method (54 points) were the most highly ranked, followed by the hybrid LCA approach (50 points), databases (49 points), and certification systems (41 points).

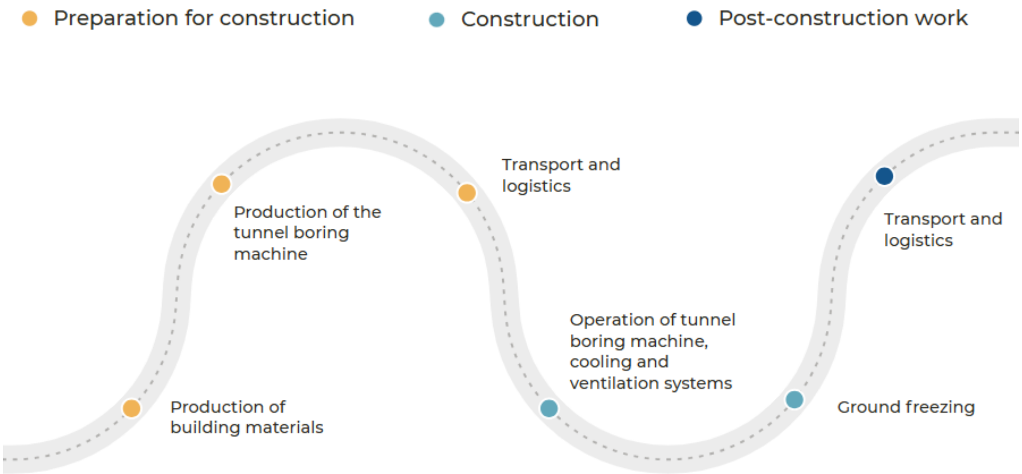
Consequently, the integration of the GHG Protocol and LCA is recommended as the optimal methodology for a comprehensive and pragmatic CO_2 accounting approach in tunnel construction. The integrative approach guarantees that the primary emission sources are meticulously documented, while also accounting for the indispensable holistic nature of the analysis.

The GHG Protocol provides a standardized and internationally recognized structure for recording and categorizing emissions (Benitz-Wildenburg et al. 2023). It distinguishes between three types of emissions: Scope 1 (direct emissions from owned or controlled sources), Scope 2 (indirect emissions from purchased energy), and Scope 3 (all other indirect emissions, including upstream and downstream value chain activities) (World Resources Institute (WRI) 2025). While this structure provides clarity and consistency for greenhouse gas reporting, it does not, on its own, offer the necessary granularity for analyzing the complex interdependencies of emissions in construction processes.

The LCA methodology is a complementary approach to the GHG Protocol, offering a comprehensive evaluation of the environmental impacts throughout the lifecycle of a construction project. This includes the extraction and production of raw materials, transportation, use, maintenance, and end-of-life disposal (VDI Center for Resource Efficiency 2019.).

This combination of both approaches enables the developed framework to benefit from the organizational logic and standardization of the GHG Protocol, while also acquiring analytical depth and contextual accuracy through the LCA perspective. However, both established approaches have shortcomings that necessitate context-related adaptation. Specifically, modifications to the system boundaries and balancing items are necessary to effectively map the specific emissions generated by mechanized tunnel construction. This tunnel-specific focus is essential, as several emission sources in TBM-based construction are highly specialized and rarely encountered in other construction contexts. These include not only the energy-intensive production of steel and concrete, but also the manufacturing and operation of the tunnel boring machines themselves - complex machines whose usage entails substantial electricity demand for cutting, cooling, and ventilation. Furthermore, emissions from upstream supply chains and downstream logistics, such as the transportation of excavated materials and prefabricated segments, contribute to the distinction of the carbon footprint of mechanized tunnelling from that of conventional infrastructure projects (see Figure 3).

Figure 3. *CO_2 Accounting Items in the Tunnel Construction Process*



Source: Own illustration

In accordance with the provisions of the German HOAI (Official Scale of Fees for Services by Architects and Engineers), the depicted emission sources are classified into three distinct phases of project development: preparation for construction, construction, and post-construction work, respectively. This phase-based structuring ensures that the methodology reflects the procedural logic of real-world tunnel construction projects and facilitates the integration of emission data into established planning and approval workflows. The strategic selection of key emission sources within these phases ensures the practical applicability of the framework without diminishing its analytical depth. Contributions from less significant emission sources, such as the production and operation of auxiliary machinery, are not adequately addressed due to the disproportionate effort required for data collection in comparison to their actual impact on overall emissions. Recent studies in construction-related

LCA confirm that auxiliary equipment typically contributes less than 1-2% of total project emissions (Lorse 2021, Kou et al. 2024), which supports the methodological decision to exclude these marginal sources. Moreover, emission quantification for such machinery often suffers from incomplete operational data and inconsistent reporting standards, which would compromise the precision of the overall balance if included without verified data. The precision of the results is contingent upon the availability of reliable, project-specific data, which remains limited at present. The enhancement of data collection methodologies and the formulation of consistent, widely accepted emission factors could augment the robustness and applicability of the methodology, thereby increasing its value for practitioners, policymakers and program funding authorities at multiple governance levels.

To operate this framework and illustrate its practical relevance, it is necessary to clearly assign emission sources to specific stages of the construction process. As illustrated in Table 2, the relevant emission sources and their allocation to items of the respective phases of the construction process are delineated.

Table 2. *Overview of Activities in the CO_2 Accounting Items*

Phase	**Work Package**	**Item**
Preparation for construction	Production of the TBM	Production of TBM components
	Production of building materials	Production of concrete (cement and aggregates)
		Production of structural steel
		Production of precast reinforced concrete elements
	Transport and logistics	Transport of building materials (concrete, steel, etc.)
		Transport of TBM components
Construction	Operation of the TBM	Mechanized tunnel excavation
		Operation of cooling and ventilation systems
	Ground freezing	Operation of the machines
Post-construction work	Transport and logistics	Spoil transport
		Removal of the TBM components

Source: Own illustration

This methodological approach enabled the reduction of complexity without compromising the validity of the results. The process of data collection presented a significant challenge, as the manufacturer's information was frequently incomplete and lacked standardization. To address this challenge, a methodology was developed that enables adaptability to diverse projects and ensures transparent documentation. Following the selection and elucidation of the pertinent items, a systematic calculation scheme was formulated (see Table 3).

This establishes a connection between the summarized items and the corresponding calculation approaches, thereby serving as a guideline for a structured approach to determining emissions.

Table 3. *Methodological Calculation approaches for identified CO_2 Accounting Items*

Position	Calculation Approach
Transport	$Total\ emissions\ E\ [t] = Emission\ factor\ e\ [t/km] * Total\ distance\ S\ [km]$ $Total\ distance\ S\ [km] = Distance\ per\ trip\ s\ [km] * Number\ of\ trips\ n$ $Number\ of\ tips\ n = \frac{Mass\ to\ be\ transported\ m\ [t]/Volume\ V\ [m^3]}{Transportable\ Mass/Volume\ per\ trip}$
Production of TBM and materials	$Total\ emissions\ E\ [t] = Emission\ factor\ e\ [t/t]\ or\ [t/m^3] * Mass\ m\ [t]\ or\ Volume\ V\ [m^3]$
Operation of TBM, cooling and ventilation systems	$Total\ emissions\ E\ [t] = Emission\ factor\ e\ [t/kWh] * Total\ energy\ requirement\ W\ [kWh]$ $Total\ energy\ requirement\ W\ [kWh] = Operating\ hours\ t\ [h] * Power\ P\ [kW]$
Operation of the machines for ground freezing	$Total\ emissions\ E\ [t] = Emission\ factor\ e\ [t/kWh] * Total\ energy\ requirement\ W\ [kWh]$

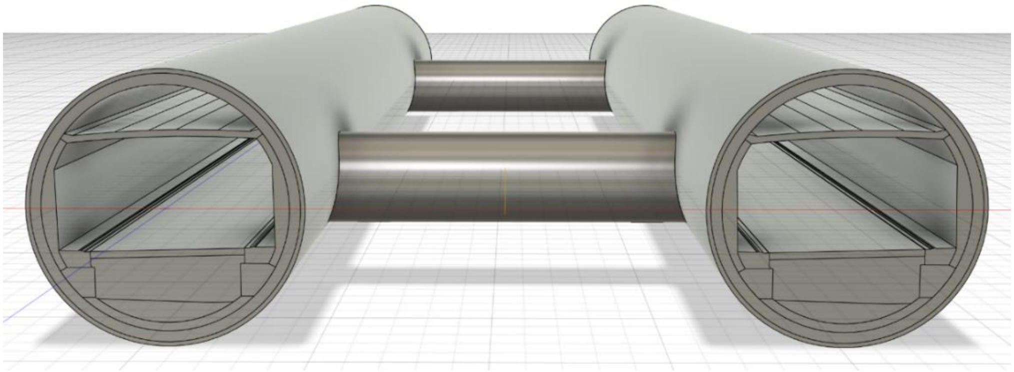
Source: Own illustration

In the next phase, the methodology is systematically implemented through the use of a case study exemplifying tunnel construction.

Validation

The validation process employs a real-world tunnel project situated in Munich, comprising two parallel tunnel tubes, each with an approximate length of 3 034 m, interconnected by cross-passages at 60-meter intervals. This configuration exemplifies a standard layout frequently implemented in urban tunnel infrastructure and functions as a representative case for assessing the applicability of the developed CO_2 accounting methodology. Figure 4 presents a three-dimensional representation of the tunnel structure, developed using Fusion 360 for the purpose of visualization. This depiction facilitates a more nuanced spatial understanding of the structural elements that are considered in emission accounting. The choice of this case study was guided by its practical relevance and the availability of generalized yet realistic design parameters, allowing the methodology to be tested under conditions that reflect actual construction practices while maintaining broad applicability to similar projects.

Figure 4. *Idealized Tunnel Cross-section with Two Tunnel Tubes and Cross-passages*



Source: Own illustration

To transition from the conceptual framework to practical implementation, the methodology was applied to the selected tunnel case. The primary challenge in CO_2 accounting in tunnel construction was the selection of reliable values that met the requirements of both realism and plausibility. Due to the extensive array of data sources and the significant discrepancies observed among public databases, a meticulous selection and validation process was imperative for the emission values.

Consequently, Table 4 provides a consolidated overview of all emission factors utilized in the analysis, including material production, energy consumption, and transportation.

Table 4. *Overview and Sources of all CO_2 Emission Values*

Building materials and electricity	**Emission factor e**	**Source**
Structural steel	2,875 $[t\ CO_2/t]$	*IOER Research Data Centre* of the Leibniz Institute of Ecological Urban and Regional Development, 2024
Reinforcing steel	0,615 $[t\ CO_2/t]$	
Asphalt	0,102 $[t\ CO_2/t]$	
Normal concrete C12/C15	0,063 $[t\ CO_2/t]$	
Normal concrete C25/C30	0,075 $[t\ CO_2/t]$	
Normal concrete C30/C37	0,082 $[t\ CO_2/t]$	
Normal concrete C35/C45	0,092 $[t\ CO_2/t]$	
Truck > 18t	0,0009454 $[t\ CO_2/km]$	Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, Umweltbundesamt GmbH, based on *GEMIS Austria*, 2024
Segments (concrete C40/50 and steel)	0,716 $[t\ CO_2/kWh]$	Own calculation based on Kou *et al.*, 2024, p. 18

Source: Own illustration

Table 4 (continued). *Overview and Sources of all CO_2 Emission Values*

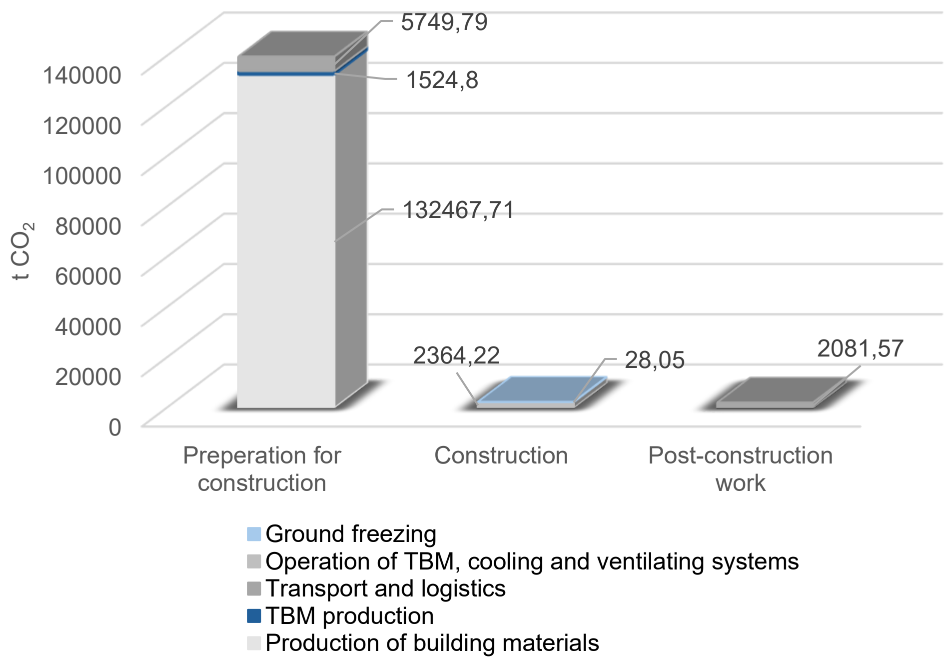
Gravel	0,002739 $[t\ CO_2/m^3]$	*ÖKOBAUDAT* of the Federal Ministry of Housing, Urban Development and Construction, 2024
Annular gap mortar (cement mortar)	0,314 $[t\ CO_2/m^3]$	
Green electricity	0,000032 $[t\ CO_2/kWh]$	Hakenes and Weißbach, 2023, p. 5
Electricity mix	0,000445 $[t\ CO_2/kWh]$	Icha and Lauf, 2024, p. 8

Source: Own illustration

These values form the empirical basis for estimating the magnitude of greenhouse gas emissions attributable to each element of the construction process and may serve as a point of reference for other tunnel infrastructure projects of comparable scope. A comparison with values reported in existing literature and applied in industry-standard approaches confirmed the methodological robustness and transparency of the selected parameters.

Preliminary to the calculation, geometric measurements of the tunnel components were conducted, and material volumes were derived accordingly. These volumetric data were utilized as input variables for the carbon accounting model, thereby ensuring consistency and precision in the quantification of emissions per unit process. Based on these data, Figure 5 provides a visual representation of the aggregated CO_2 emissions associated with each major accounting item, based on the emissions determined for building materials and electricity.

Figure 5. *Total CO_2 Emissions of the Exemplary Tunnel Construction Project*



Source: Own illustration

The total CO_2 emissions resulting from the tunnel construction project amount to 144 216.14 metric tons of CO_2. The most significant contribution originates from construction preparation, encompassing the production of construction materials, which generates 132 467.71 t CO_2. This is followed by transport and logistics emissions, accounting for 5 749.79 t CO_2, and the production of the tunnel boring machines, responsible for 1 524.80 t CO_2. During the construction phase, the energy required to operate the tunnel boring machine, cooling, and ventilation systems generates emissions of 2 364.22 t CO_2, while ground freezing contributes an additional 28.05 t CO_2. A total of 2 081.57 t of CO_2 emissions were documented during the post-processing stage of construction, attributable to transportation-related activities.

Even though transport and logistics, TBM operation, cooling and ventilation systems, and the operation of ground freezing machines generate substantial emissions, a direct comparison reveals that they account for a negligible proportion of total emissions, amounting to 8.15%. Consequently, the most significant potential for reducing emissions is identified in the domain of material production (Kou et al. 2024). The increased use of low-CO_2 cement and steel, as well as the incorporation of resource-saving segments, has the potential to significantly contribute to the reduction of emissions. This finding aligns with the results of the carbon footprint assessment of the Brenner Base Tunnel, which identified concrete production, tunnel excavation, material transportation, and construction equipment as the primary sources of emissions (Bergmeister 2022).

Overall, the results further indicate that the proposed methodology facilitates a consistent and transparent recording of all relevant emission sources, from material production to operation and logistics. The validation process confirms the conclusion that the calculation model is both logically consistent and practically applicable across a range of tunnel construction scenarios.

The calculated total emissions of 144 216.14 t CO_2 for the construction of the tunnel demonstrate the substantial climatic impact associated with an infrastructure project of this magnitude (Elbers 2022, Emig 2024). The high emissions prompt the critical question of how infrastructure projects can be reconciled with the objectives of sustainability and climate protection in a time of global climate crisis.

Discussion

The following discourse aims to provide a critical examination of the utility, limitations, and transferability of the proposed CO_2 accounting methodology for tunnel construction. It contextualizes the methodological strengths and data-related challenges, while addressing unresolved tensions between the need for standardization and the necessity of project-specific adaptation. The ensuing discourse delves into the foundational contributions of the developed framework, its practical relevance, and its future prospects for refinement and application.

Methodological Development

The proposed framework was developed to address the existing gap in standardized CO_2 accounting practices for tunnel construction projects, with a particular focus on tunnel boring machine-based excavation methods. In order to guarantee scientific robustness and practical applicability, the methodology synthesizes principles from the Greenhouse Gas Protocol and Life Cycle Assessment, integrating their respective strengths.

The approach prioritizes transparency, scalability, and simplicity. The study emphasizes major emission sources, primarily the production of construction materials such as steel-reinforced concrete and the operation of heavy machinery. It deliberately excludes minor sources whose accounting effort would not be proportionate to their emissions share.

A systematic, criteria-based selection process was conducted to evaluate different methodological approaches based on technical feasibility, ecological relevance, regulatory compatibility, and stakeholder acceptance. A utility value analysis revealed that the GHG Protocol (55/70 points) and the LCA approach (54/70) were the most suitable foundations, owing to their structured formats and scientific credibility. Alternative systems, including hybrid LCAs and certifications such as BREEAM and LEED, received lower scores due to their more limited scope and the presence of data inconsistencies.

A significant challenge encountered during the development process pertained to the limited availability of specific emissions data concerning tunnel boring machine components and processes. In several instances, particularly with regard to the manufacturing of tunnel boring machines and their subsystems, data had to be obtained through direct cooperation with manufacturers such as CREG TBM Germany GmbH or supplemented with estimations based on proxy processes. These discrepancies across publicly accessible databases necessitated rigorous validation procedures.

Key Findings and Limitations

The application of the methodology yielded several insights, as well as inherent limitations.

1. Scope Restrictions: At present, the framework's scope is confined to the analysis of CO_2 emissions, with a notable exclusion of more extensive ecological and socio-economic dimensions. These dimensions encompass, but are not limited to, land use changes, biodiversity impacts, and social externalities. This narrow focus fosters clarity and ease of use but limits the comprehensive evaluation of sustainability.
2. Data Uncertainty: However, reliable emission factors with a specific focus on tunnel construction are limited, leading to a persistent reliance on assumptions and approximations. For instance, the calculation of emissions from ground freezing operations for cross-passage construction necessitated sophisticated modeling approaches that employed tools such as MATLAB and GeoGebra to approximate energy demand and associated emissions.

3. Trade-offs in Practical Application: In order to maintain user-friendliness and enable practical implementation, the methodology involves simplifying assumptions. To illustrate, subordinate emission sources, such as auxiliary machinery, are excluded from this analysis. While this compromises completeness to some extent, their marginal contribution to total emissions justifies this exclusion within the current scope.

Case Study

To assess its real-world applicability, the methodology was implemented in a large-scale tunnel construction project in Munich. The case study confirmed the approach's utility in quantifying emissions and identifying mitigation strategies.

1. Material Optimization: The incorporation of recycled concrete and low-carbon cement types played a substantial role in the mitigation of embodied emissions.
2. Process Efficiency: The electrification of construction machinery, in conjunction with enhancements in logistics planning, has resulted in a quantifiable decrease in diesel consumption and operational emissions.
3. Support for Decision-Making: The framework facilitated a systematic evaluation of emission reduction measures in terms of their cost-effectiveness, providing a valuable instrument for planning and investment decisions. However, the high costs associated with certain mitigation options-imposed limitations on the full range of options that could be considered.

Broader Implications

The methodology has implications that extend beyond the individual project level.

1. Standardization Potential: The modular configuration of the framework enables its adaptation to diverse regional contexts, while maintaining a consistent template for TBM-based tunnel projects. This approach fosters transparency, facilitates cross-project comparability, and enables benchmarking.
2. Areas of Research that Require Further Exploration and Development: There is an urgent need to expand emissions databases that are tailored specifically to underground infrastructure. Furthermore, subsequent research endeavors should investigate the incorporation of life cycle costing and the monetization of ecological impacts to facilitate more comprehensive sustainability assessments.
3. The relevance of the policy is as follows: The methodology aligns with broader climate protection goals and can serve as a foundation for regulatory development. It furnishes public authorities and planning institutions with a structured approach to establish emission benchmarks and promote sustainable practices in infrastructure development. This alignment is consistent with the objectives set out in the European Green Deal and forthcoming regulatory frameworks that emphasize sector-specific decarbonization and life-cycle-

based assessment methods within the construction industry. The proposed framework therefore directly contributes to these evolving policy targets by providing a transparent, data-driven calculation and reporting structure that can be integrated into future sustainability assessment systems and environmental regulations.

Conclusions

The present study developed and applied a methodology for CO_2 accounting in tunnel construction, specifically tailored to mechanized tunnel construction. The proposed approach tackles the dearth of standardized practices by integrating the Greenhouse Gas Protocol and Life Cycle Assessment, thereby offering a balance between scientific rigor and practical usability. A systematic literature review and empirical data revealed significant methodological gaps, particularly the absence of project-specific data and consistent emission factors.

The developed framework places emphasis on significant emission sources, including material production (concrete, steel), tunneling machinery, and transport processes. It is designed to allow for modular adaptation to the specific conditions of each project. The application of the method to a real-world tunnel project in Munich demonstrated its practical relevance, highlighting that substantial emissions stem from segment production and logistical operations. The findings substantiate the efficacy of the method in the initial planning stages and accentuate the significance of transparent and reliable data as a basis for both technical optimization and funding-related decision-making.

Notwithstanding certain limitations, including incomplete data on minor emission sources, the methodology establishes a substantial foundation for CO_2 assessment in tunnel construction and demonstrates considerable potential for transferability to other infrastructure projects. Subsequent endeavors should prioritize the establishment of standardized, tunnel-specific emission databases to enhance comparability and support more extensive decarbonization objectives in the construction industry.

The future of tunnel construction must be characterized by a balanced integration of technological innovation and ecological responsibility. Tunnels, as pivotal components of contemporary mobility infrastructure, are required to incorporate environmental criteria into all phases of their life cycle to ensure sustained viability. The CO_2 accounting methodology developed in this study provides a foundation for such integration and could serve as a reference withing broader sustainable infrastructure and funding frameworks. With appropriate standardization and collaboration among stakeholders, the construction of tunnels has the potential to become a model for climate-aligned infrastructure development.

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