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Reducing the Carbon Footprint by Innovations in Tunnel Construction

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Abstract: Tunnels are a necessary transportation infrastructure element but substantially contribute to CO_2 eq. (Carbon) emissions and energy consumption. This paper is a gentle but fervent step towards minimization and better usage of resources that are the main "sustainable drivers" towards CO_2 eq. (Carbon) emission. An analysis of the carbon footprint was performed for drill and blast tunnelling near the Mratinje Dam in Montenegro. The life-cycle assessment (LCA) technique is employed to assess the environmental impacts associated with CO_2 emissions directly related to the materials production and tunnel construction activities. Two different alternatives were evaluated to identify where efforts should be focused to reduce the carbon footprint of the tunnel construction process. Different materials and approaches are examined to maximize sustainable opportunities. These examinations may help practitioners think differently and create new habits

Keywords: sustainability; tunnelling; carbon emission; resources, materials; drill and blast

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1. Introduction

In 2020, the famous fictional Doomsday Clock was set to 100 seconds to midnight, and in 2023, it was set to 90 seconds to midnight (Bulletin of the Atomic Scientists, 2024). This is primarily but not exclusively due to the increased risk of nuclear escalation, but it is also influenced by continuing threats posed by the climate crisis and the breakdown of global norms and institutions needed to mitigate risks associated with advancing technologies and biological threats such as COVID-19 (Bulletin of the Atomic Scientists, 2024).

Almost 80% of global warming gas emissions by volume are carbon dioxide (CO_2). Of that 80%, approximately a third arises from sectors relevant to transportation infrastructure, including transport, cement and steel manufacture, and commercial energy consumption (Sun and Park, 2020; Hunziker, 2024). Therefore, the construction sector is responsible for 38 % of global greenhouse gas (GHG) emissions (United Nations Environment Program, 2020). There are six greenhouse gases to be accounted for: CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide), HFCs (hydrofluorocarbons), SF6 (sulphur hexafluoride), PFCs (perfluorocarbons) and NF3 (Masson-Delmotte et al., 2021). Tunnels are a vital part of transportation infrastructure and our modern societies. However, since they utilize various high energy-consuming equipment, they also substantially contribute to CO_2 eq. emissions and energy consumption, highlighting the importance of our work in reducing their environmental impact. Some research shows that more than 80% of the CO_2 emissions in the construction phase of a tunnel are attributable to the construction materials cement and steel (Nasri et al., 2023), however the CO_2 eq. emissions and energy consumption aspects concerning tunnelling are very complex, and many factors must be considered.

This study employs the life-cycle assessment (LCA) technique to assess the environmental impacts of CO_2 eq. emissions directly related to the materials production and tunnel construction activities in a specific project. Two alternatives were evaluated to identify where efforts should be focused to reduce

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the tunnel construction process's carbon footprint. Different materials and approaches are examined to maximize sustainable opportunities and optimization potentials

2. CO_2 emission calculations

2.1. CO_2 emissions concerning the entire construction life cycle

Construction materials and activities in tunnel construction are significant sources of tunnel CO_2 emissions. The life-cycle assessment (LCA) technique is used to assess the environmental impacts of CO_2 eq. emissions related to all stages of a product's life (US Environmental Protection Agency, 2018). The life-cycle assessment (LCA) technique is defined by SRPS ISO 14040 (Institute of Standardization of Serbia, 2008) and SRPS ISO 14044 (Institute of Standardization of Serbia, 2009). CO_2 emissions are calculated by estimating the fuel consumed by machinery and transport equipment (diesel, electrical energy) and raw materials and then using the conversion factors to get kg CO_2 eq.

Transport and machinery equipment includes a wheel loader, waste dump truck, concrete mixer, concrete pump, lining trolley, shotcrete spraying machine, grouting pumps, drilling jumbos, power supply units, and axial flow fan.

Construction raw materials used in such analysis include cement, steel, sand, coarse aggregate, polyethene, silica fume, accelerators, plasticizers, polypropylene or steel fibers, polyester resin, etc.

The carbon emission factors are obtained from government organizations (Official Gazette of the RS, 2023), relevant international institutions (International Energy Agency (IEA), 2023), and literature. They mean the greenhouse gas emission per unit input expressed in kilograms of carbon dioxide equivalent (kg CO_2 eq).

The construction work and resource consumption analysis are done for a 1.0 m tunnel and can be applied to the entire tunnel length. The study includes and is limited to resource consumption for the following construction sequence: pre-grouting, excavation (i.e. drilling, loading, and blasting), ventilation, dewatering, scaling, spoil removal, installation of the initial lining (primary support – bolts, steel support or mesh and shotcrete), waterproofing, final (secondary) lining, and built-in parts, such as backfilling concrete, side-walk, kerbs, etc. Carriageway and subgrade works are not considered in this study.

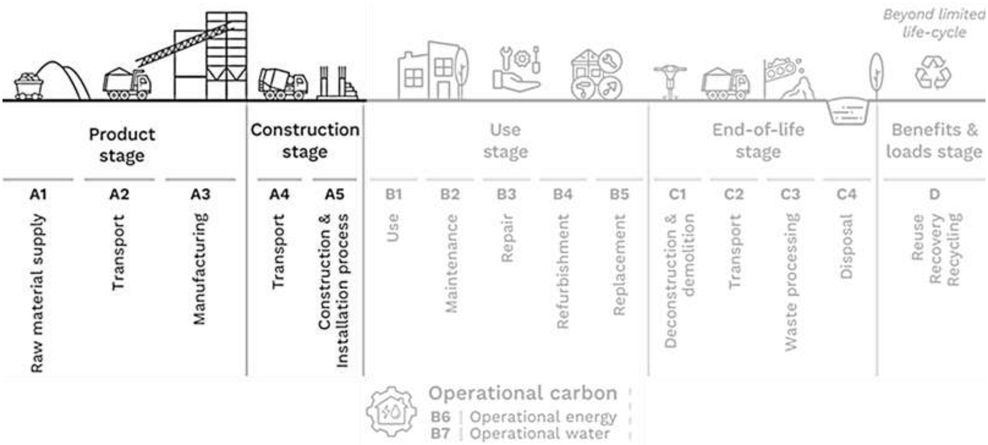

Fig. 1. Stages of a tunnel construction life-cycle according to SRSP EN 15978:2016 (Source: Institute of Standardization of Serbia, 2016), highlighting of phases considered in LCA calculations in this study.

The study is limited to the following life cycle phases: production stage (A1-A3), transportation (A4), and construction (A5) process stage, Fig. 1. The analysis does not consider the life cycle phase during usage of the object, repairing and managing (B1-B7), and the end-of-life (C1-C4), i.e., tunnel recovery or demolishing and removing materials to be recycled. The author of the final design gathered and estimated the input data for the LCA study from the basic design documentation and other working estimations from similar tunneling projects. No records were collected during construction since there were a couple of delays in executing the tunneling work. However, the actual results should be further refined as the project progresses.

2.1.1. Tunneling cross-section and load-bearing systems

The subject of this study is the tunnel No. 10 on the road from Plužine to Šćepan Polje in the Republic of Montenegro (Spasojevic, 2022, 2025). The tunnel is part of the road designed to extend straight into the mountain after the Mratinje Dam. The tunnel structure is a single-tube double-track tunnel with an approximate cross-section of 56,40 m^2 for the road infrastructure (the theoretically useful area) and a minimum service life of 50 years. The tunnel excavation is designed to be executed using the drill and blast technique.

The LCA tunnel study deals with two fundamentally different solutions for hard rock tunneling:

- two-layer tunnel lining
- single-layer load—bearing system,

A two-layer tunnel lining is designed as a double shell system. First, the outer layer is placed—the initial tunnel lining (rock support system). The initial tunnel lining consists of shotcrete, reinforcing steel wire mesh, and rock bolts (Spasojevic, 2022, 2025), Fig. 2. It is installed after the excavation and designed to provide controlled stress release and redistribution in the surrounding rock. After the initial lining is completed, the final (secondary) lining is executed. The final lining (inner layer) is made from cast-in-place reinforced concrete (Spasojevic, 2022, 2025), Fig. 3. The secondary lining is load-bearing for long-term loads.

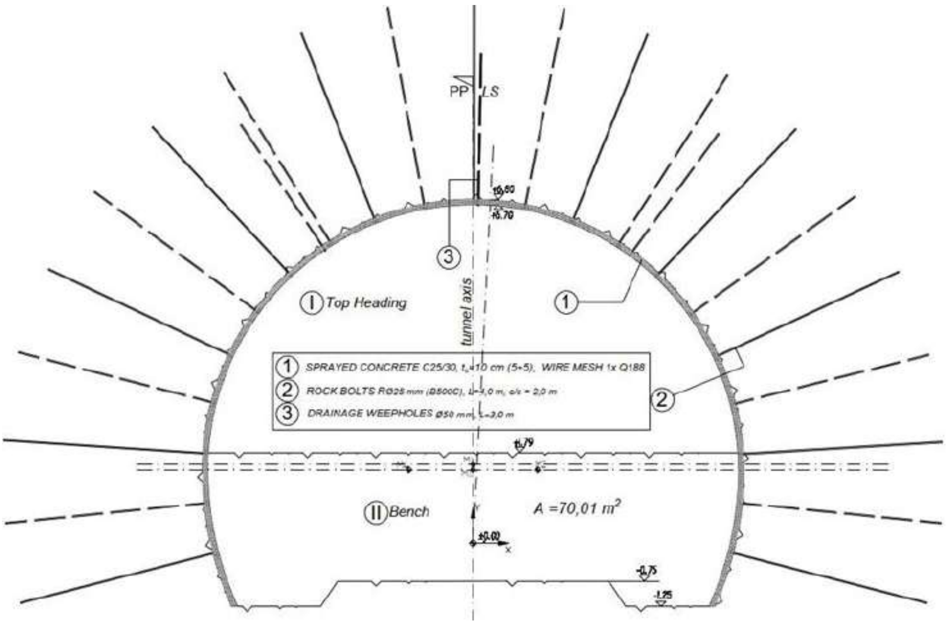

Fig. 2. Typical cross-section of the initial lining (rock support system) for a two-layer tunnel lining (Source: Spasojevic, 2022, 2025).

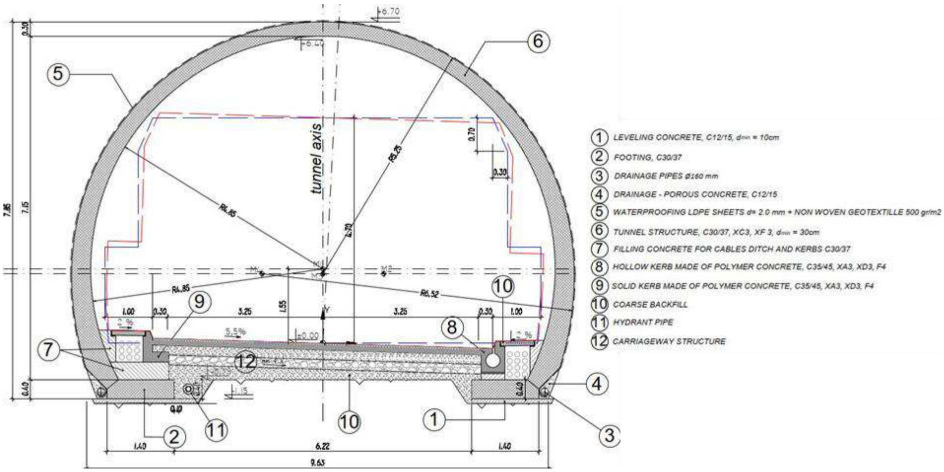

Fig. 3. Typical cross-section of the final (secondary) lining for a two-layer tunnel lining (Source: Spasojevic, 2022, 2025)

Single-layer load-bearing is similar to the initial lining of a double-shell lining, Fig. 4 and Fig. 5. The most significant difference is solving or reducing the presence of groundwater around the tunnel. Groundwater is the most important factor that leads to the decomposition of load-bearing elements of the initial rock support system in the case of a double shell system. This is solved by limiting groundwater inflow by pre-grouting the rock mass, Fig. 6. Further differences are the quality of the material properties for shotcrete and bolts. The quality of the shotcrete properties and bolts is much better. The compressive strength and durability of shotcrete are higher than those of the double-shell system. This is achieved by utilizing micro-reinforcement (fibers) and silica fumes. The rock bolts are characterized by a double protection system against corrosion, with a plastic tube and cement mortar (Spasojevic, 2022, 2025). In exceptional cases, an additional "protective" layer of shotcrete is designed to cover a single load-bearing system. This layer is not part of the load-bearing structure. It is designed with high compressive strength of C32/40 and includes polypropylene monofilament fibers (PP) to provide the required fire resistance and anti-spalling behaviour during fire or explosion accidents, Fig. 4.

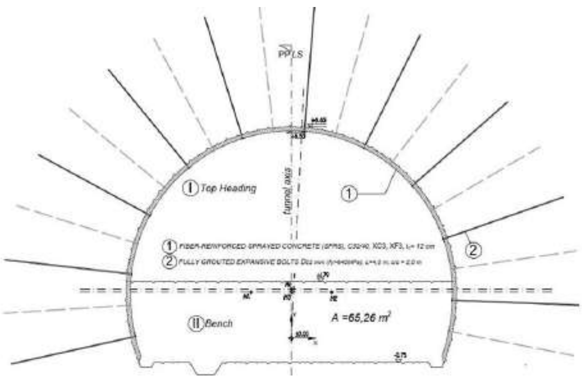

Fig. 4. Typical cross-section of the "protective" layer for the tunnel with the single-layer load-bearing lining (Source: Spasojevic, 2022, 2025).

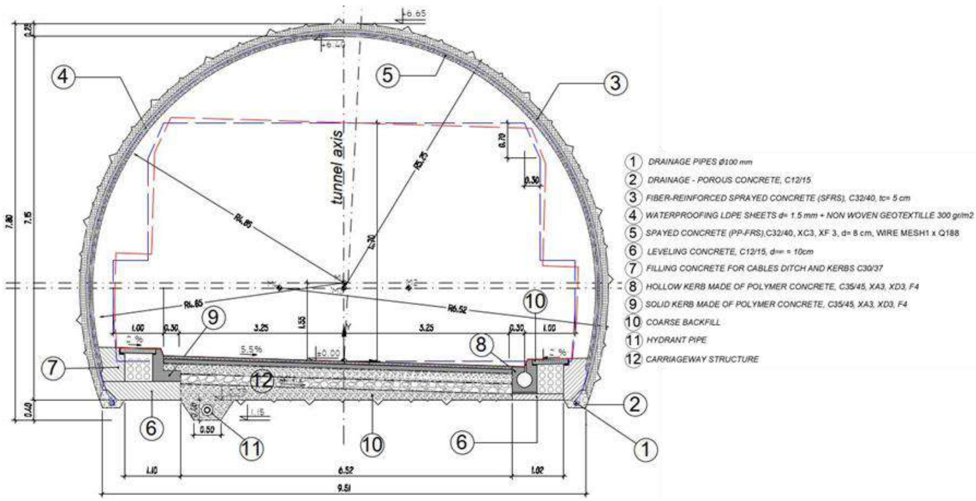

Fig. 5. Typical cross-section of the "protective" layer for the tunnel with the single-layer load-bearing lining (Source: Spasojevic, 2022, 2025).

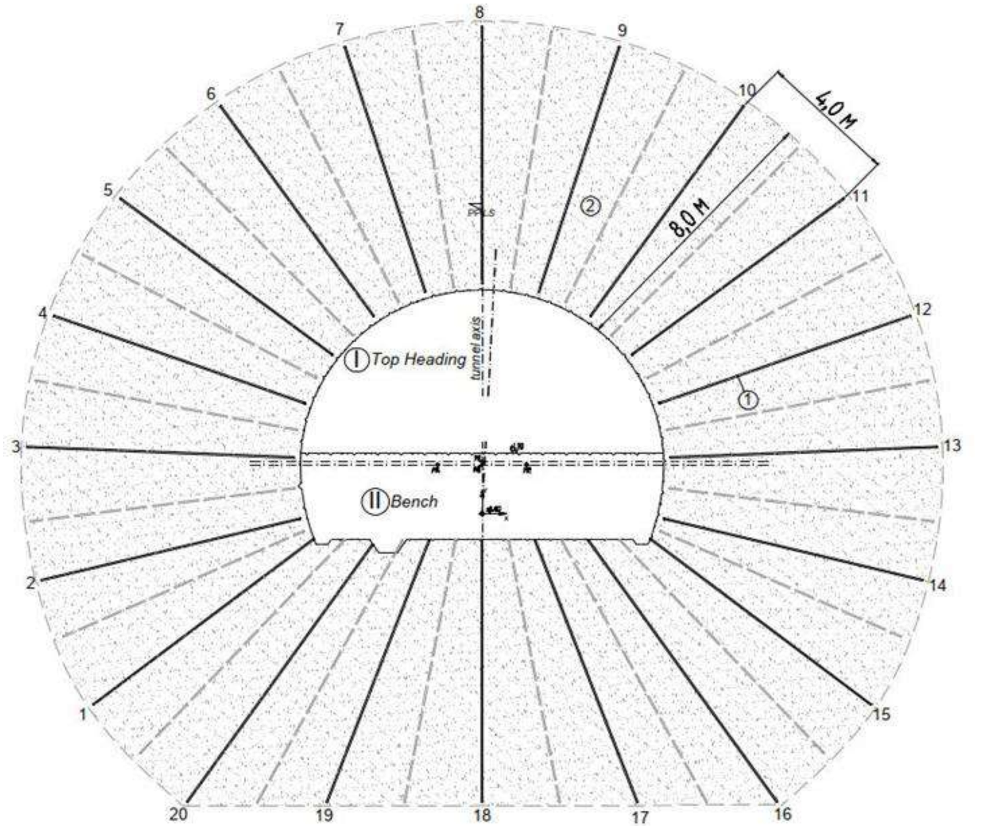

Fig. 6. Typical pre-grouting layout for the tunnel with the single-layer load-bearing lining (Source: Spasojevic, 2022, 2025).

3. Results and conclusion

The LCA tunnel study is divided into two main construction processes related to tunneling load-bearing systems or linings. The first process is related to constructing the load-bearing elements and rock support, which provide sufficient stability for the tunnel excavation. This is the initial tunnel lining for a two-lining tunnel system and rock support in the single-layer load-bearing system.

The second process is related to constructing the final (secondary) lining in a two-lining tunnel system and an additional "protective" layer of shotcrete in a single-layer load-bearing system. Fig. 7 and Fig. 8 shows CO_2 emission (kg CO_2 eq.) due to resource and raw material consumption for each defined construction process for the life cycle phases A1-A5.

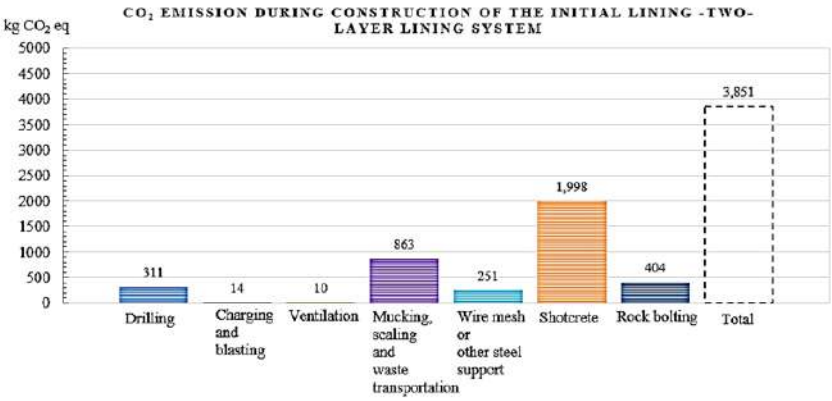

Fig. 7. Carbon emission (kg CO_2 eq) contributes to life cycle modules A1 - A3, A4, and A5 due to constructing the initial lining (primary support) in the two-lining tunnel system.

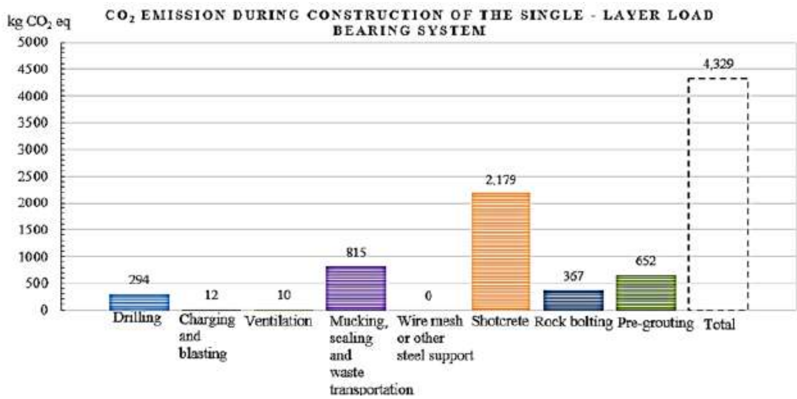

Fig. 8. Carbon emission (kg CO_2 eq) contributes to life cycle modules A1 - A3, A4, and A5 due to the construction of rock support in the single-layer load—bearing system.

Fig. 7, shows CO_2 emission due to the construction of the initial lining (primary support) for the case of a two-lining tunnel system. Fig. 8 shows CO_2 emission due to the construction of rock support in the single-layer load-bearing system.

The total CO_2 emission during the construction of the rock support in the single-layer load—bearing system is 4,329 kg CO_2 eq. The total CO_2 emission during the construction of the rock support in the initial lining (primary support) for the case of a two-lining tunnel system is 3,851kg CO2 eq. According to the estimates, the total CO_2 emission during the construction of the rock support in the single-layer load-bearing is 12.4 % higher compared to the initial lining (primary support) for the case of a two-lining tunnel system.

Fig. 9 shows CO_2 emission due to the construction of the final (secondary) lining for the case of a two-lining tunnel system.

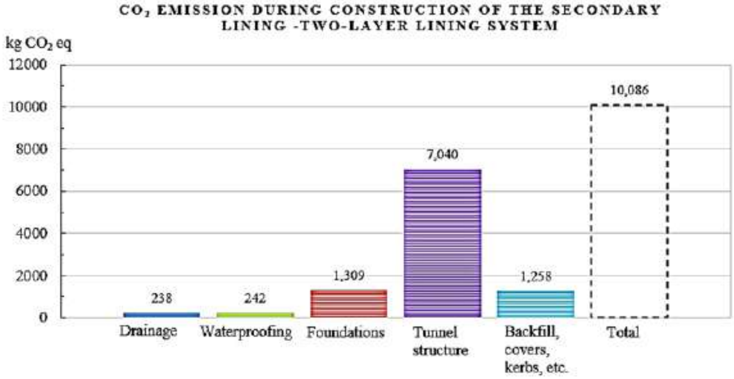

Fig. 9. Carbon emission (kg CO_2 eq) contributes to life cycle modules A1 - A3, A4, and A5 due to the construction of the final (secondary) lining for the case of a two-lining tunnel system.

Fig. 10 shows CO_2 emission due to constructing the "protective" layer for the tunnel with the single-layer load-bearing lining.

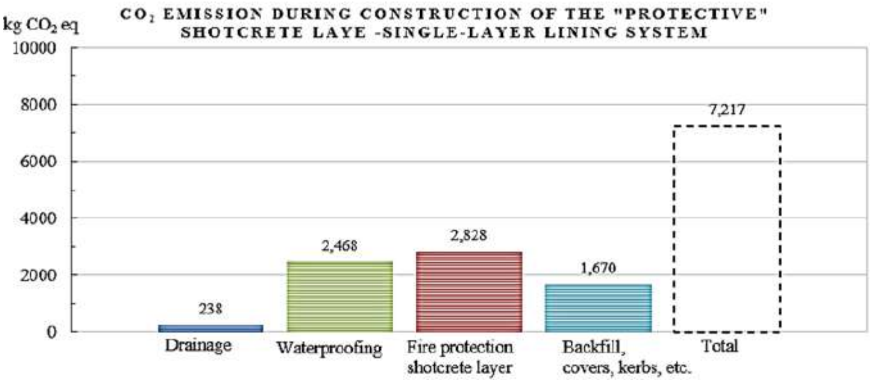

Fig. 10. Carbon emission (kg CO_2 eq) contributes to life cycle modules A1 - A3, A4, and A5 by constructing the "protective" layer of the single-layer load-bearing lining.

The total CO_2 emission during the construction of the final (secondary) lining for the case of a two-lining tunnel system is 10,086 kg CO_2 eq. The total CO_2 emission during construction of the "protective" layer for the tunnel with the single-layer load-bearing lining is 7,217 kg CO_2 eq. According to the estimates, the total CO_2 emission during the construction of the final (secondary) lining for the case of a two-lining tunnel system is 39.8 % higher compared to the case of a tunnel with a single-layer load-bearing lining. Collecting all estimations from Fig. 7 to Fig. 10, the total initial CO_2 emission of the construction of the two-lining tunnel system is 13,938 kg CO_2 eq, and for the single-layer load—bearing system is 11,546 kg CO_2 eq. The construction of the two-lining system produces 20.7 % more CO_2 emission than the single-layer load—bearing system. In rock conditions where a "protective" shotcrete layer is not required or pre-grouting works are insignificant, the total CO_2 emission drops to 8,066 kg CO_2 eq for the single-layer load-bearing lining. This is 30 % less. In this case, constructing the two-lining system produces 73 % more CO_2 emission than the single-layer load—bearing system.

The CO_2 emission distribution for the life cycle phases production stage (A1-A3), transport (A4), and construction (A5) process stage is shown below on Fig. 11.

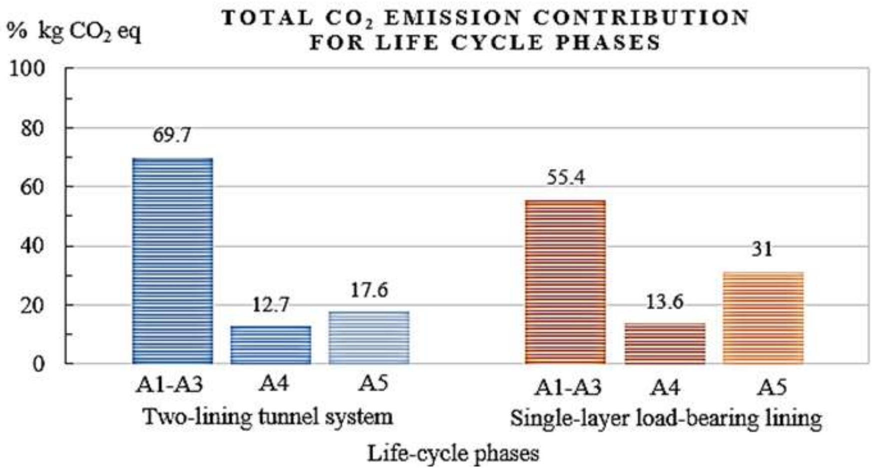

Fig. 11. The distribution of carbon emissions (in %) for life cycle phases production stage (A1-A3), transport (A4), and construction (A5) process stage related to tunnel lining systems.

The impact of life cycle phase A1-A3 dominates nearly all resource consumption in the CO_2 emission. According to Fig. 11, the carbon emission CO_2 from raw material input accounts for about 55.4-69.7%. The carbon emission CO_2 in life cycle phase A4 includes transporting all materials and products from producers and manufacturers to the construction site (Sun and Park, 2020). This phase generates similar share distributions for both tunnel lining systems. The life cycle phase "Construction" (A5) has a slightly higher impact for the single-layer load-bearing lining, 31%. This is due to increased resource consumption and activities necessary to construct an additional "protective" layer of shotcrete to cover a load-bearing system.

4. Conclusion

This paper compares the two fundamentally different tunnel lining solutions in hard rock tunnelling from a carbon footprint emission perspective.

The single-layer tunnel lining is operationally effective (time-effective) and results in cost savings (cost-effective) (Spasojevic, 2022, 2025).

Given the findings in this paper, it can be concluded that the carbon footprint emission can be reduced by at least 20.7% using single-layer load-bearing tunnel lining.

The study also reveals a very high carbon emission for a few materials and a very high contribution of the production stage (A1-A3) to all life cycle phases. Phases A1-A3 have a total share of 55-70 % of carbon footprint emissions. The influence of transport is comparable to other studies (Hopf et al. 2022). It follows that improvements in the production of raw materials are key to improving the life cycle assessment of tunnel structures. The usage of raw materials should be minimized by revising assumptions which are often conservative. Significant CO_2 reduction can be achieved by optimizing concrete mix design. This way, low-carbon or ultra-low concrete (or shotcrete) emissions of < 120 - 220 kg CO_2 eq./m^3 could be achieved. Reducing carbon related to steel is replacing steel bar reinforcement completely with structural fibers. The reduction in carbon related to grout could be by switching from a two-component system to a single-component grout with lower cement content where possible. To a certain extent, efforts should be made to equipment operation by considering and optimizing energy consumption.

This study can provide a reference for calculating carbon emissions throughout the life cycle of other tunnelling projects in hard rocks. The greatest hope is that it may help practitioners think differently and create new habits.

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