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Tunnel Construction and Design

Designing more sustainable linear infrastructure projects using advanced digital technologies

This article outlines the significance of material optimisation in linear infrastructure construction, which accounts for a significant percentage of material use and CO_2 footprint. Advanced technologies and early design impact assessments offer opportunities for more sustainable infrastructure. A case study highlights the potential for substantial sustainability gains in infrastructure projects.

1 Introduction

Between 30 and 40% of all construction materials are used in the construction of linear infrastructure like roads and railways. The materials used in an infrastructure project account for 85% of its CO_2 footprint. A high footprint is, for example, linked to the production of cement, bitumen, and steel. To reduce the CO_2 footprint of a road or rail project, the right design choice is critical. The design choice is mainly dependent on the traffic load, surrounding factors like the local geology and locally available materials, and indirectly through the cost and location of local suppliers. The effect of changing climatic conditions, as well as the impact of alternative design options on the CO_2 footprint of a project, have not been in focus in the planning phase so far.

2 Current Developments

With rising awareness on the topic of climate change, through NGOs, citizens, entrepreneurs and politicians, the pressure to act is growing and the focus on the construction industry (especially cement and steel producers) is increasing heavily.

Environmental, social and governance (ESG) reporting – and therefore the need to track CO_2 emissions – is becoming mandatory for many companies. Current changes at European level, such as the new EU taxonomy, are leading to a massive focus on sustainable construction to guarantee the funding of a project. Additionally, requests from other stakeholders, like local interest groups, also lead to the need for rethinking how we source and use construction materials in a project.

3 Methodology

To be able to significantly reduce the footprint of an infrastructure project, the first step is to measure the impact of its design. It is important to use the same base for measurements to be able to directly compare different options later. To quickly calculate these footprints, algorithms and standard methodologies are necessary to automate these calculation processes.

To measure the impact, certain parameters need to be known, first of course the length, width, and height of a design. Second, the materials to be used need to be known (base layer, railway ballast, tracks, sleepers and so on). Combining the materials with the alignment of the track will give the quantities of the different materials needed.

The calculation of the impact of an infrastructure project follows the lifecycle assessment approach. It starts with the calculation of the CO_2 footprint of the production of materials which will be used in the project. If we use the example of an aggregate supplier, the production of this material would be subdivided into extraction or raw material supply (A1 stage), transport from extraction to manufacturing (A2 stage), and manufacturing (A3 stage) until the material is loaded onto the truck. For more complex materials such as concrete, the production stages (A1–A3) consider the CO_2 emissions of all the components in the recipe, including cement, additives, sand, coarse aggregates, fly ash and others.

In the next step, the potential sourcing sites need to be assessed. Several potential suppliers will be identified (different local quarries, precast producers). The transport distance from these suppliers to the construction site is calculated, enabling us to

Tunnelbau und Design

Gestaltung von nachhaltigeren linearen Infrastrukturprojekten unter Einsatz fortschrittlicher digitaler Technologien

Dieser Artikel befasst sich mit den Umweltauswirkungen von linearen Infrastrukturprojekten, wobei Materialien als primäre CO_2- und Kostenfaktoren im Vordergrund stehen. Er erläutert das aktuelle Bewusstsein für Klimaschutz, das sich auf das Bauwesen auswirkt, sowie den Schwerpunkt der EU auf nachhaltige Praktiken. Der Artikel beschreibt auch eine Methodik, die digitale Werkzeuge und die Lebenszyklusanalyse zur Messung der Auswirkungen des Designs nutzt. Anhand einer Fallstudie eines finnischen Eisenbahnprojektes wird gezeigt, wie digitale Modellierung und lokale Beschaffung die CO_2-Emissionen und Kosten erheblich senken und damit die Nachhaltigkeit verbessern können.

Construction et conception de tunnels

Concevoir des projets d’infrastructures linéaires plus durables à l’aide de technologies numériques avancées

Cet article examine l’impact environnemental des projets d’infrastructures linéaires, en mettant l’accent sur les matériaux en tant que principaux facteurs de CO_2 et de coûts. Il aborde la question de la sensibilisation actuelle au climat, qui affecte la construction, et l’accent mis par l’UE sur les pratiques durables. L’article présente une méthodologie qui s’appuie sur les outils numériques et l’évaluation du cycle de vie pour mesurer l’impact de la conception. Il présente une étude de cas d’un projet ferroviaire finlandais, montrant comment la modélisation numérique et l’approvisionnement local peuvent réduire de manière significative les émissions de CO_2 et les coûts, et améliorer ainsi la durabilité.

Costruzione e progettazione di gallerie

Sviluppo di progetti infrastrutturali lineari e sostenibili impiegando tecnologie digitali avanzate

Questo articolo si occupa dell’impatto ambientale dei progetti infrastrutturali lineari, sottolineando i materiali come fattori primari di CO_2 e di costo; Illustra l’attuale consapevolezza ambientale, che si riflette sull’edilizia, nonché l’accento posto dall’UE sulle pratiche sostenibili. L’articolo descrive anche un metodo che utilizza gli strumenti digitali e l’analisi del ciclo vitale per misurare l’impatto dell’progettazione. Sulla base di un caso di studio di un progetto ferroviario finlandese, verrà mostrato come la modellazione digitale e l’appalto locale riducono notevolmente i costi e le emissioni di CO_2 e dunque possono migliorare la sostenibilità.

evaluate the CO_2 emissions related to the transport of materials. This part is called the A4 module in the lifecycle assessment approach and covers transport CO_2 emissions from production to the construction site.

The last step of the initial CO_2 assessment is the A5 module, which covers the construction phase. This step includes the energy consumption of the vehicles used during construction (wheel loader, excavator, grader and so on). The lifecycle assessment continues with the use phase (B) and concludes with the end-of-life phase.

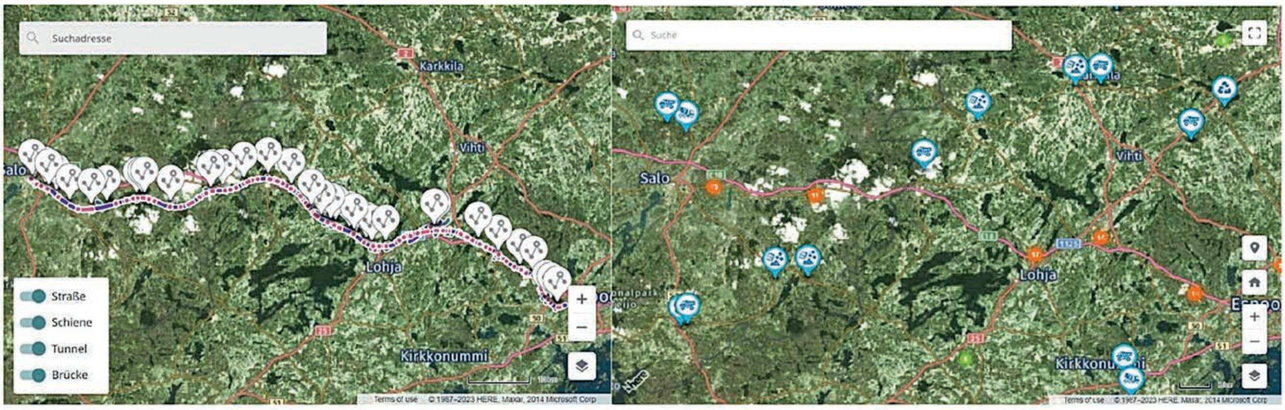
4 Case Study

The Länsirata is a partially double-track railway connection between Helsinki and Turku, currently in the planning phase. The new route from Espoo to Salo includes the construction of various section types, among them 100 km of new railway beds, over 20 tunnels, 100 bridges, and over 100 new roads. To optimise material flows, the ORIS software calculates the environmental impacts of different options, considering transport distances, interim storage, and other factors. The main tasks were to assess if a new alignment would be more sustainable than using and extending the existing track network and to assess the impact of possible use of the excavated materials from the track construction and tunnelling. This study focuses on the second aspect.

The key activities of the project encompass a broad range of analyses and strategies aimed at enhancing sustainability and efficiency. These include conducting a detailed carbon emissions and cost analysis specifically for the Espoo–Salo railway segment and evaluating the project's resilience to climate change over a 40-year period, which also involves deriving early adaptations to anticipated climate changes. Additionally, the project leverages the ORIS platform for a comprehensive assessment of emissions, costs, and material consumption, ensuring an informed decision-making process. A significant focus is also placed on the optimisation of resource use, notably through the reuse of excavated materials, alongside evaluating and enhancing the circular economy aspects of the project. Finally, the development of key performance indicators is prioritised to facilitate the reduction of CO_2 emissions and costs, underlining the project's commitment to environmental stewardship and economic viability.

4.1 Project Set Up

Local suppliers in the area were identified and the access points to the project were defined. As seen in Fig.1, many production sites are available around the project; different icons indicate different material types, for example the dumper truck for quarries and the RMX truck for ready-mix (concrete) sites. The problem we face is the accessibility to the project from the suppliers. For this reason, the project managers identified around 30 access points along the track length.

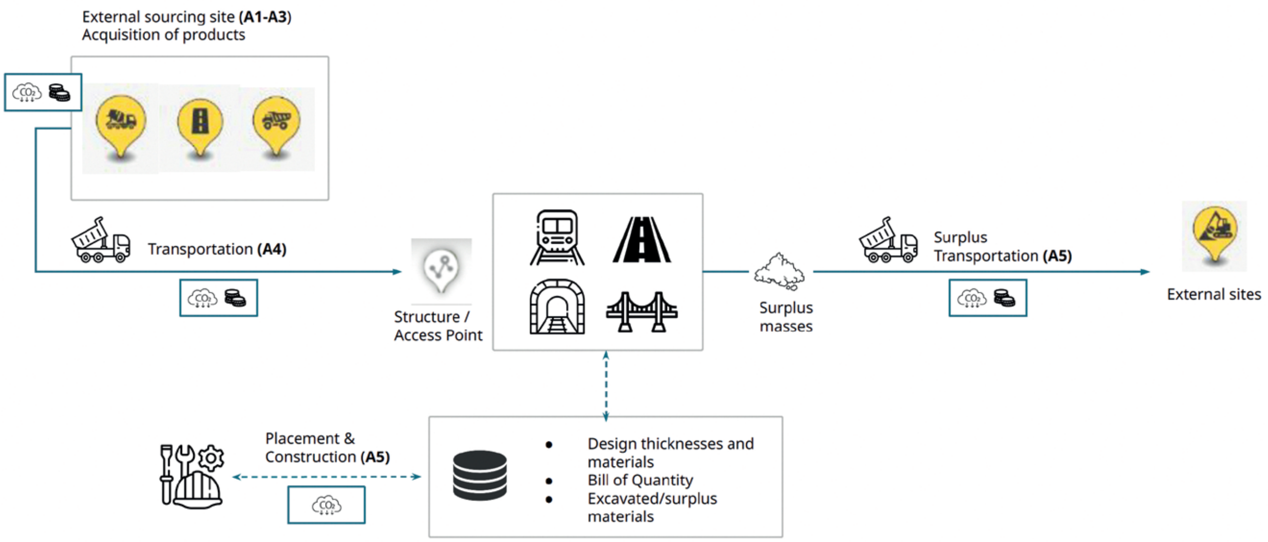


Credit: Own illustration, ORIS Platform Screenshot

1 Left image shows access points to the project; right image shows sourcing sites for different materials in the same area; numbers indicate the number of sites in the area.

4.2 Base Case

A base or reference scenario is essential for comparative analysis to serve as a benchmark for evaluating other scenarios and determining their degree of improvement or decline. The base scenario entails the sourcing of materials from external sites and typical materials suppliers, with no consideration of stockpiles in the analysis. Materials extracted from the project are transported to the nearest disposal sites with no use of surplus masses in the project.



Credit: Own illustration

2 This figure shows a process sheet for material handling.

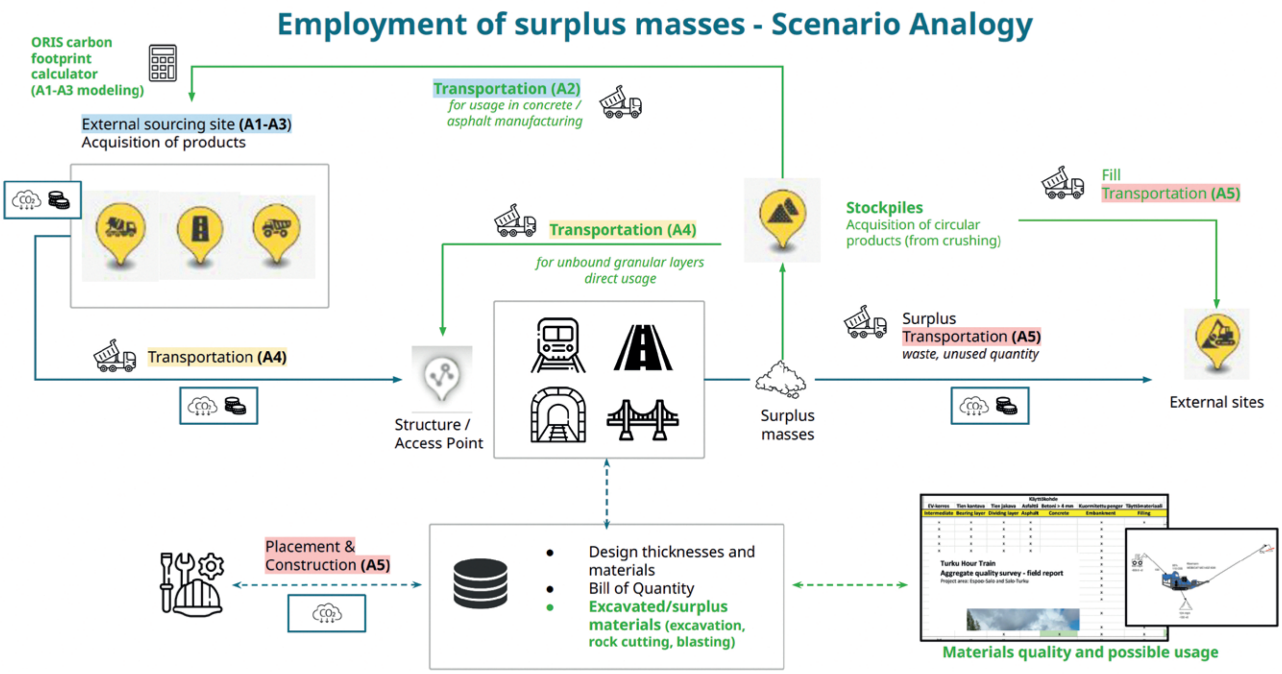
4.3 Optimised Material Flow and Low-Carbon Scenarios

Since significant volumes of rock materials will be excavated through tunnelling and other processes, the potential advantage of using these materials for the project was of great interest. This would offer several benefits, such as reducing the need to transport material from suppliers further away, which reduces CO_2 and cost.

To be able to validate the excavated materials regarding potential usage on site, different factors must be analysed. First, it was necessary to get a full understanding of the geology along the planned rail track. Local geologists and the Geological Survey of Finland retrieved a proper mapping of the in-situ geology. Samples were taken along the planned track and different laboratory analyses were performed to check the mechanical and chemical properties (for example, the Los Angeles test and the Micro Deval test). The material along the track was then categorised in different groups, based on the potential use: not usable at all, for use as base material, as railway ballast, as aggregate for concrete, or as aggregate for asphalt. In the next step, the amount of the different materials was quantified and compared with the volumes needed. The results showed that large volumes of the excavated materials could be processed and used during construction.

To estimate the impact of reuse of excavated materials, it was necessary to simulate the processing on site with different equipment. For this reason, software was used to model what mobile equipment (crusher, screens, and other equipment) must be used, how much of this equipment would be needed and where it should be positioned to reduce internal transportation in the project and therefore transport CO_2.

This alternative scenario entailed the reuse of surplus masses and was compared to the base scenario. As of this iteration, the starting point is the surplus masses (Fig. 4). When the quality and quantity allowed for it, the excavated material from tunnels or rock cutting was transported (A5) to a stockpile for processing (A1–A3). The processed materials from the stockpiles were then used in various applications, such as (1) immediate use in unbound granular layers or (2) processing into concrete or asphalt before being sourced to the structures based on demand. The transportation cost and carbon emissions are accounted for the A4 stage (1) as it is transported from the sourcing site (stockpile in that case) to the access point and in the A2 stage (2) as it concerns the transport of raw material used in concrete or asphalt production. To produce concrete or asphalt (A1–A3), this involved using



Credit: Own illustration

3 *This process map shows how excavated materials will be either processed and reused or transported to a landfill site.*

geolocated mixing sites that interacted with the sourcing environment of raw materials around, allowing for precise modelling of the concrete or asphalt production process. The location of the mixing sites was placed identically to the existing external concrete and asphalt plants.

Combining all the above-mentioned tasks and gathering all the information, it was possible to reduce the transport CO_2 footprint significantly. As an illustration, see Figures 4 and 5, which show the transport distances for two examples from the use of rock excavated from a tunnel in a road from the same project.

Credit: Own illustration, ORIS Platform Screenshot

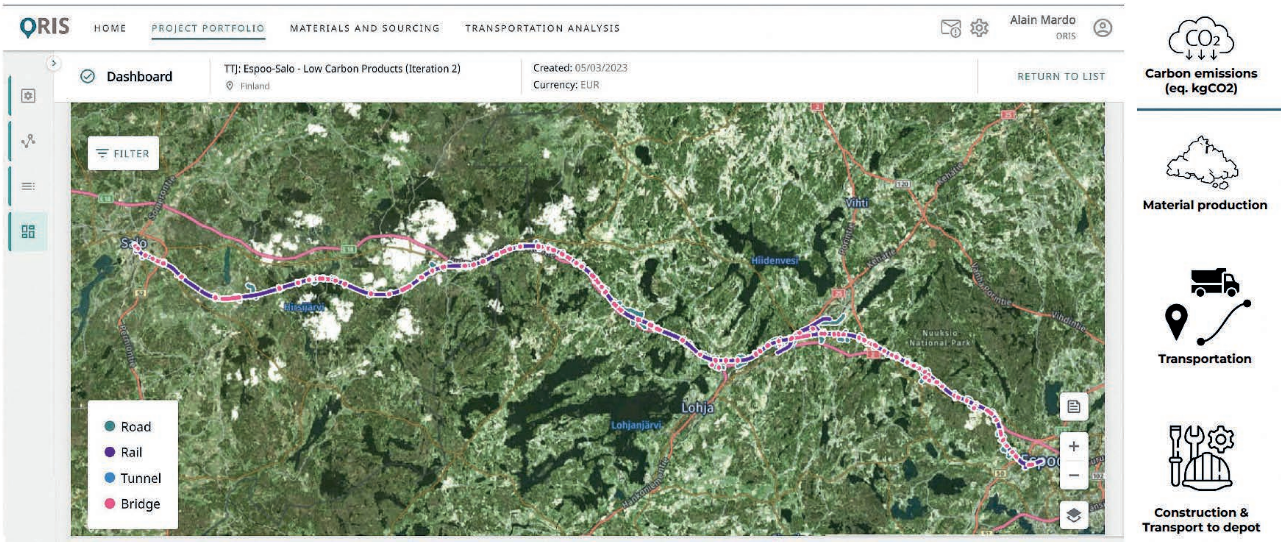
4 *This figure shows an example of transporting the excavated material to a disposal site (left) versus a stockpile (right) and their effect on the CO_2 footprint.*

Credit: Own illustration, ORIS Platform Screenshot

5 *This figure compares the use of virgin material which is transported 24 km (left) and taking the material from the stockpile (right) and their effect on the CO_2 footprint.*

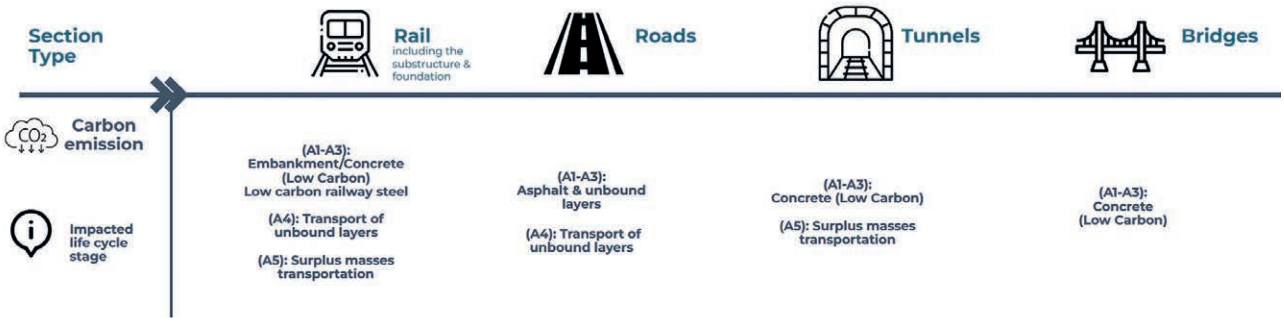
These examples can be applied to many different elements of the project, like obtaining virgin raw materials from quarries in the vicinity versus using ballasted rock sourced from nearby tunnels, which is a byproduct of tunnel construction. This not only enhances sustainability but also optimises transportation due to the strategic placement of the processing stockpiles.

Next to material flow optimisation, the project investigated the application of low-carbon products like low-carbon concrete and low-carbon railway steel. Carbon emissions can potentially be reduced by a low two-digit percentage at project level by implementing low-carbon materials.



Credit: Own illustration, ORIS Platform Screenshot

6 This figure depicts the scope of sections to which this principle has been applied. Actual reductions of the project cannot be disclosed yet.



Credit: Own illustration

7 This figure depicts the results of the study by section type of rail, roads, tunnels and bridges and the lifecycle stage affected in the scope of the study.

4.4 Resilience Analysis

In the pursuit of environmental sustainability, this project also included a comprehensive resilience analysis next to assessing the carbon footprint and circularity options. The analysis places a significant emphasis on understanding and mitigating the effects of climate change on the infrastructure. It predicts an average increase in yearly maximum temperature along the project line to 23.15°C by 2050, resulting in minimal structural impact with no countermeasures recommended. However, the analysis projects a more concerning 52% increase in freeze–thaw cycles, translating to 30 additional cycles per year by 2050. This substantial increase is expected to have a significant impact on structural integrity over time, necessitating adaptation and mitigation strategies at the design stage to avoid the need for increased maintenance and repairs. Unbound granular layers and concrete structures could face decreased resilience and integrity due to these climatic changes, with potential for increased rutting, cracking, and loss of bearing capacity. The analysis suggests using more resistant materials and improving drainage as possible adaptation measures. Additionally, a 40% increase in cumulative yearly rainfall is anticipated, necessitating further analysis to identify and mitigate flow level impacts based on terrain models and other factors. These findings underscore the critical importance of incorporating climate resilience into the project's design and planning stages.

5 Conclusion

Leveraging digital tools, infrastructure projects can incorporate circular options and self-sufficiency, further enhancing sustainability. These assessments, once digital systems are established, offer immediate insight into the impacts on key performance indicators of any adjustments made. Early-stage design planning and optimisation become crucial, allowing a broader range of alternatives to be explored swiftly, thus enriching the decision-making pool with more sustainable choices. Furthermore, scheduling emerges as a critical factor in maintaining the potential reductions in resources and avoiding conflicts related to material availability. As such, it is vital that scheduling considerations are integrated into later stages of project planning. Finally, adopting a Living-System approach invites a holistic engagement with the ecosystem, interlinking all project phases. This integrative strategy not only streamlines the planning process but also expands the scope of potential designs that can be evaluated promptly, fostering an extensive array of sustainable options for the project.