Project memo

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Abstract

SINTEF wants to explore how digitally supported work processes can promote environmental sustainability in early design of transport infrastructure projects. Particularly, this study explores three innovative approaches for early integration of environmental analysis in road projects along the use of automated environmental impact assessment, parametric modelling, 3D combinations and Geographic Information System (GIS). The approaches have demonstrated an enormous potential to streamline demanding tasks while facilitate the understanding of GHG budget analysis to all stakeholders through an intuitive visualization. This investigation contributes to sharing knowledge on advanced techniques that enable better informed decision-making for sustainability during the project scoping of transport infrastructure.

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SINTEF

1 Background

The construction of road infrastructure largely depends on carbon intensive materials (i.e., ordinary concrete, steel, asphalt) and fossil fuel machinery. To achieve the European Union´s climate goals, the Norwegian transport sector has committed to reduce its GHG emissions by at least 40% from the construction of road infrastructure by the year 2030 [1]. However, the increased demand on environmental sustainability of road construction raises challenges not previously addressed by the sector. Early design stages have high impact on the final performance of projects and require a thorough balance of trade-off decisions involving costs, risks, environmental and social impacts. The integration of GHG budget analysis at the early project phases is highly recommended as stringent environmental controls and major cuts in carbon emissions are becoming a top priority to minimize climate change impacts. It implies the management of large amount of data and the coordination of multiple goals, legislations, requirements, and resources towards an overall objective and priorities. The road infrastructure sector is expected to increase digitalization for better informed decision-making and improved socio-economic and environmental analysis from the outset [2] [3].

Traditionally, the prediction of GHG emissions is done with Life Cycle Assessment (LCA) tools but the integration of LCA at the early stages still has limitations and unsolved gaps [4] . Data input is manually intensive and time-consuming which can hinder the active use of results along the iterative design and planning process. Efforts have been made to develop automated LCA approaches based on Building Information Models (BIM). Different software can be used for the integration of BIM tools with LCA methodology to produce automated environmental calculations such as OneClickLCA, Tally or Solibri Model Checker. Although most of the applications have a strong focus on buildings design [5][6][7], or construction activities [8][9], further development is still needed to improve automation, interoperability and flexibility for data customization and integration [10][11]. While these advancements have demonstrated their benefits, transferring this methodology to transport infrastructure projects is often challenging due to discrepancies of LCA tools and other different methodologies between buildings and infrastructure. Nevertheless, research on infrastructure with BIM and LCA adoption remains limited [12].
In addition, the main analysed impacts in automated BIM-based LCA are from the production of consumed materials and energy during construction and operation while the impacts from transportation (materials and mass handling), maintenance or demolition are significantly less explored [5]. Accurate assumptions related to earthworks, land use and land use change, and mass transport (soil vs. rock excavation) are still challenging to obtain through existing LCA tools [13]. Yet, many automated LCA approaches based on BIM do not provide an intuitive visualization for non-LCA experts thus hindering the cooperation among working parties in early stages [14]. Therefore, there is a need for further research on solutions that integrate automated environmental analysis with other information technologies to enhance the sustainability of road infrastructure at early stages.

This study aims to explore three innovative approaches for early integration of environmental analysis in road projects, involving the use of automated environmental impact assessment along parametric modelling, 3D combinations and Geographic Information System (GIS). The approaches have an enormous potential to streamline demanding tasks while facilitates the understanding of GHG budget analysis to all stakeholders through an intuitive visualization. The design process is improved by facilitating a rapid decision-making and problem-solving, compared to traditional process. It also enables a better understanding regarding the impacts of the decisions, leading to more sustainable and cost-effective solutions in advance. An automated environmental impact assessment is a process of using algorithms, software tools and data-driven techniques to automatically assess various factors from different, large datasets and expedite the evaluation process thus reducing manual efforts and operational times [4]. In parametric modelling, objects are constructed using parameters such as dimensions, relationships, and constraints, which define their shape, size, and behaviour. The object-oriented parametric information of the project is represented in a 3D model [15]. GIS provides topological and georeferenced data, which allows for 3D analysis and spatial analysis such as, the calculation of the distance between two points, travel routes and the definition of the optimal location [16]. The combination of these three elements complements each other and reveal a great potential for improving the sustainability of infrastructure projects.

Only few studies discussed the use of automated environmental impact assessment along an integrated approach for early design and planning of infrastructure projects. D'Amico et al. [17] explored parametric modelling and GIS data integration for technical and environmental decision-making process in the design of airport facilities. Although the GHG budget was not accounted in this study the results enable to better understand the soil volume of "cut" and "fill" that the project requires. Already in the design phase, it was possible to evaluate the portion of land that can be reused, thus limiting the consumption of raw materials and maximizing the material balance. Zarubin et al. [18] proposed a GIS software module for environmental impact assessment of open pit mining projects. The integration of environmental assessment into the quarry 3D model improved the quality of mine planning to reduce negative impacts as well as to simulate missing data points from sparse and imperfect field datasets. Similarly, other studies developed solutions involving GIS, digital twins, or dimensional augmented reality models to monitor GHG emissions in later phases such as, during construction or for the assessment of a specific urban area [19][10][20].
This investigation focuses on three integrated approaches involving automated environmental impact assessment, parametric and 3D modelling, and GIS for early design and planning processes of transport infrastructure projects. The approaches go beyond automated LCA approaches based on BIM once provides an easy visualization of GHG budget along the entire extension of a project including roads, railways, tunnels or bridges. In addition, it enables a better comprehension of land use and mass handling thus overcoming the challenges faced by the standalone use of LCA tools.

2 Method

This study consisted of four steps: (i) literature review; (ii) selection of companies that use an integrated approach based on automated environmental impact assessment in addition to parametric and 3D modelling, and GIS for early design and planning processes of transport infrastructure projects; (iii) application of a survey to identify the benefits and opportunities of each approach; (iv) development of propositions based on step (i) and (iii).
Fist, a review of academic papers and professional reports was conducted to explore the state-of-the-art. Three consultancy companies were chosen to offer an integrated approach. Subsequent discussion meetings were conducted with each company to gather insights into their adopted approach.
Third, a survey consisting of two sections was applied. Table 1 illustrate the survey structure.
Finally, a set of propositions are presented based on both literature review and participants perspectives. These propositions focus on the benefits of the integrated approach for increased sustainability in transport infrastructure projects.

Table 1 – Topics and structure of the questionnaire.

Section 1 – Questions with examples
1.1. After implementing, has the tool helped to improve the achievement of the sustainability goals? If so, can you give examples of the improvement effects?

1.2 Has the tool helped to improve the way the GHG emissions are identified, visualized and assessed? If so, can you provide examples of the improved aspects?
1.3 Has the tool contributed to the management and dissemination of GHG emissions knowledge among the involved parties of a project? If so, can you give examples of such contribution?
1.4 Was a lot of training or new skills required to implement the tool? If so, can you give examples of the amount of training hours or special skills required?
1.5 Which are the main positive effects of the tool? Can you give examples?
Section 2 – Rate the areas where you believe the tool has introduced changes to the traditional way of performing:

2.1 Design and early planning	0 – 1 – 2 – 3 – 4 – 5 (0: no changes detected; 5: significant changes detected)
2.2 Conscious choice of products/materials	
2.3 Transport and logistics masses	
2.4 Construction processes	
2.5 Use and operation of the project	
2.6 Maintenance, reuse or decommissioning	
2.7 Collaborative work during project phase	
2.8 Increased awareness across disciplines	
2.9 Integration with other digital technologies	

3 Results

3.1 Overview of the tools

The explored approaches share similar benefits, such as: (i) supporting decision-making at early phase of projects (is of most value when used from the initial project scoping stage); (ii) processing a large quantity of data from different sources; (ii) improving the quality and speed of decision-making; (iii) facilitating real-time assessment of alternative project designs; and (iv) providing a more intuitive visualization of the GHG budget for the whole project and a more accurate analysis of land use and mass handling. Two of the companies used a self-developed application while the other used a commercial application. Despite these similarities, the approaches also cover differ aspects, as shown in Table 2.

Table 2 – Characteristics of each approach

Characteristics		Integrated approach: automated environmental impact assessment + parametric and 3D modelling + GIS		
		Trane (Company 1)	Infraspace (Company 2)	Trimble Quantum (Company 3)
Solution development		Customized	Commercial	Commercial (Trimble)
Indicators	GHG emissions	Yes	Yes	Yes
	Land use	Yes	Yes	Yes
	Mass balance	Yes	Yes	Yes
	Execution time	No	Yes	No
	Costs	No	Yes	Yes
	Traffic emissions	Yes	Yes	Yes
	Noise	No	Yes	Yes

Integration with other digital flows	Yes, open	Yes, open	Yes, within the products/services of the commercial solution
Interface	On-premise	Cloud-based	On-premise
Data generation	Algorithms	Artificial Intelligence	Algorithms

3.1.1 Trane

The first approach is based on industry tools "VegLCA" and "Tidligfaseverktøy" and is a customized solution that combines the use of empirical data and project-specific quantities in the calculation. Here, GHG calculations can be performed early, based on general knowledge of the project and its contents (Figure 1). As the project details and knowledge of ground conditions, geology, etc., become more refined, the calculation is continuously updated, with empirical data being replaced by increasingly accurate quantities and assumptions. This results in the gradual increase in the accuracy of the greenhouse gas calculation. The combination of empirical data and project-specific quantities allows Trane to be used in all planning phases. When the same tool is used across multiple planning phases, it becomes possible to track the project's development from one planning phase to the next without using different tools with different assumptions and characteristics.

What makes this solution unique is that complete GHG calculations can be presented along a reference line in the project (Figure 2), allowing for a meter-by-meter comparison of the calculation against previous calculations (e.g., baseline) throughout the project. It is also easy to adjust individual parameters in the calculation, and you can immediately see how this affects the greenhouse gas budget. With Trane, custom model visualizations of greenhouse gas emissions from land use change and from traffic in operation are produced (Figure 3). This is particularly useful in the early phase, as both of these categories result in significant GHG emissions that are largely related to the geometry of the road (or track). Small adjustments in alignment can have a significant impact on these emission categories. The automated environmental impact assessment is performed through algorithms including carbon footprint estimates from construction, operation, maintenance and traffic in operation (B8).

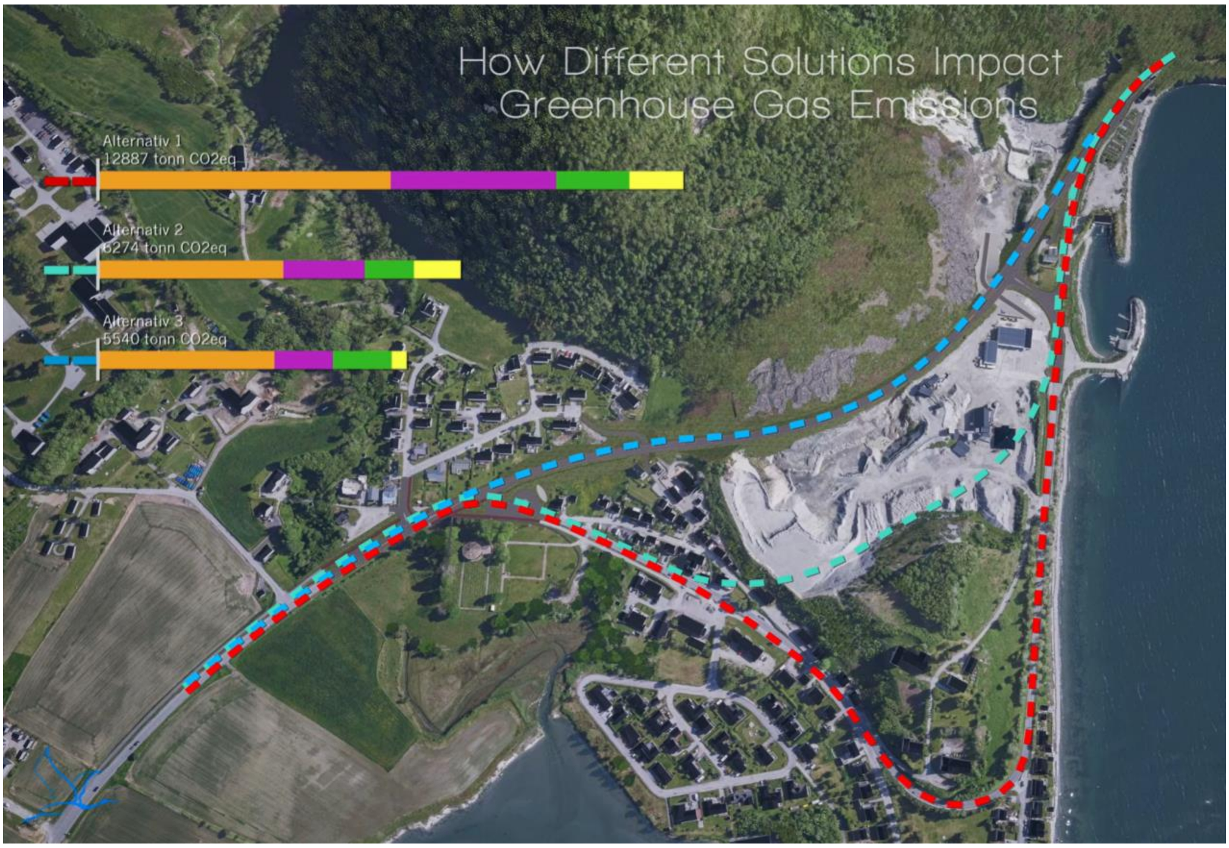

Figure 1 – GHG emission impacts from different road solutions (Source: Trane, 2024)

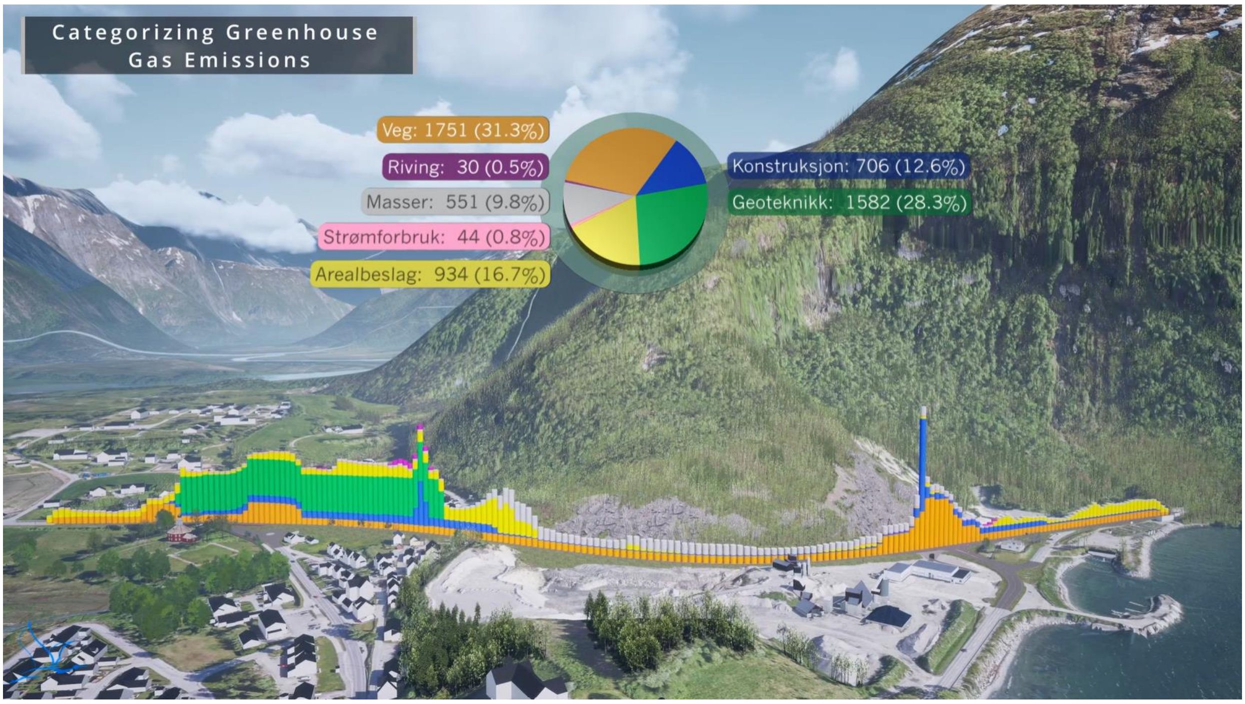

Figure 2 – GHG emission categorization allowing for a meter-by-meter comparison (Source: Trane, 2024)

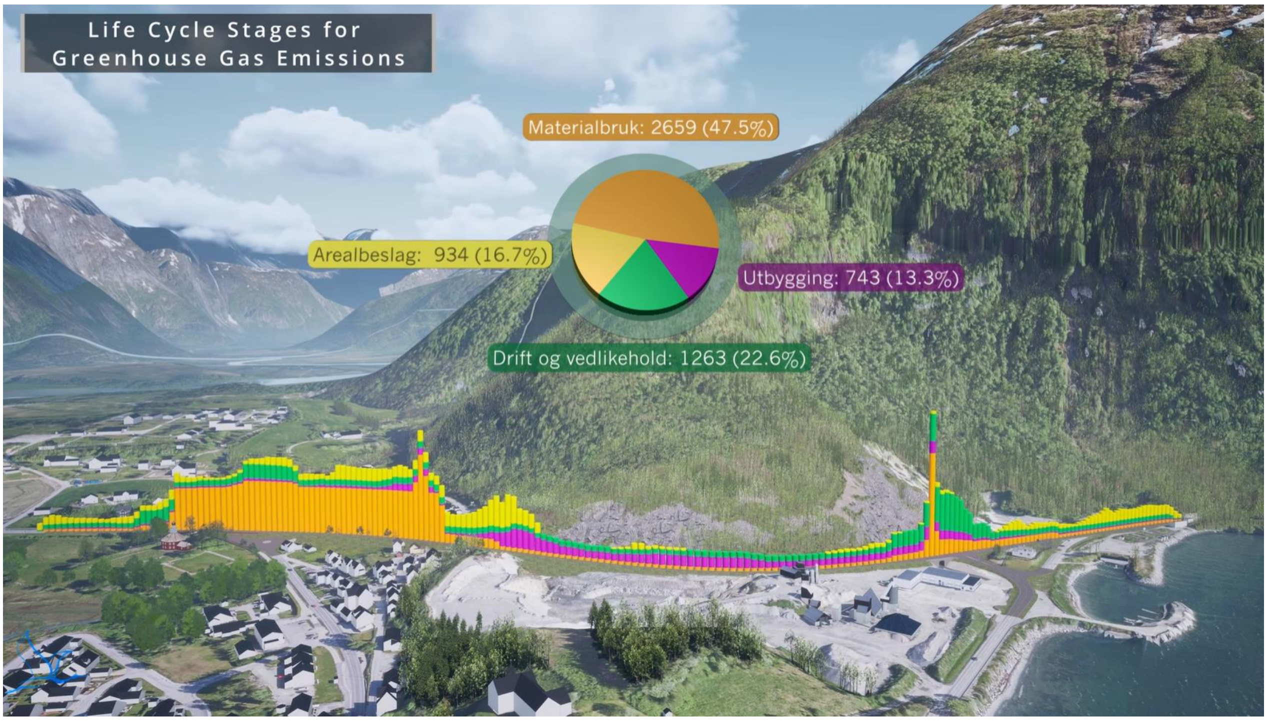

Figure 3 – GHG emissions from critical lifecycle phases (Source: Trane, 2024)

3.1.2 Infraspace

Infraspace is a commercial software offered as a cloud-based service with an accompanying web application. This solution utilizes artificial intelligence (AI) techniques, including advanced optimization algorithms and evolutionary strategies, to significantly enhance data processing speeds. This AI-driven generative design approach enables the rapid creation of multiple design variations, each evaluated against objectives such as cost, carbon footprint, environmental impact, and more (Figure 4). Optimal solutions are visualized through automatically generated 3D models, accessible via a web-based interface, and complemented by comprehensive metric dashboards (Figure 5). Infraspace's automated environmental impact assessments include calculations for carbon footprint from construction and operational phases, audiovisual impact, barrier effects, and land use. Moreover, it offers instant insights into construction costs and planning timelines by automatically analyzing earthworks and mass balances. The cloud-based computation, web-based interface, and multi-user functionality enhance collaborative and decision-making processes, enabling more informed and sustainable decisions regarding the localization of new infrastructure. Similar to the first approach, Infraspace can integrate data from external sources, facilitating automatic generation from varied data inputs.

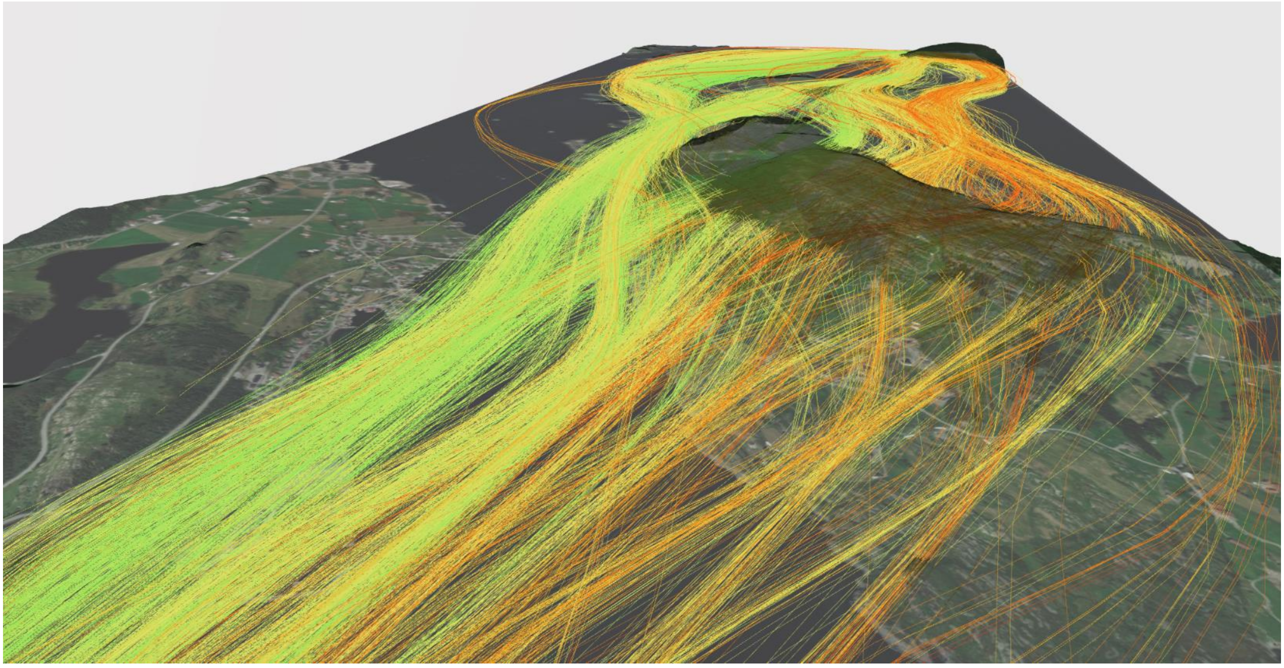

Figure 4 - Proposals created and evaluated with the AI-driven generative design software (Source: Infraspace, 2024)

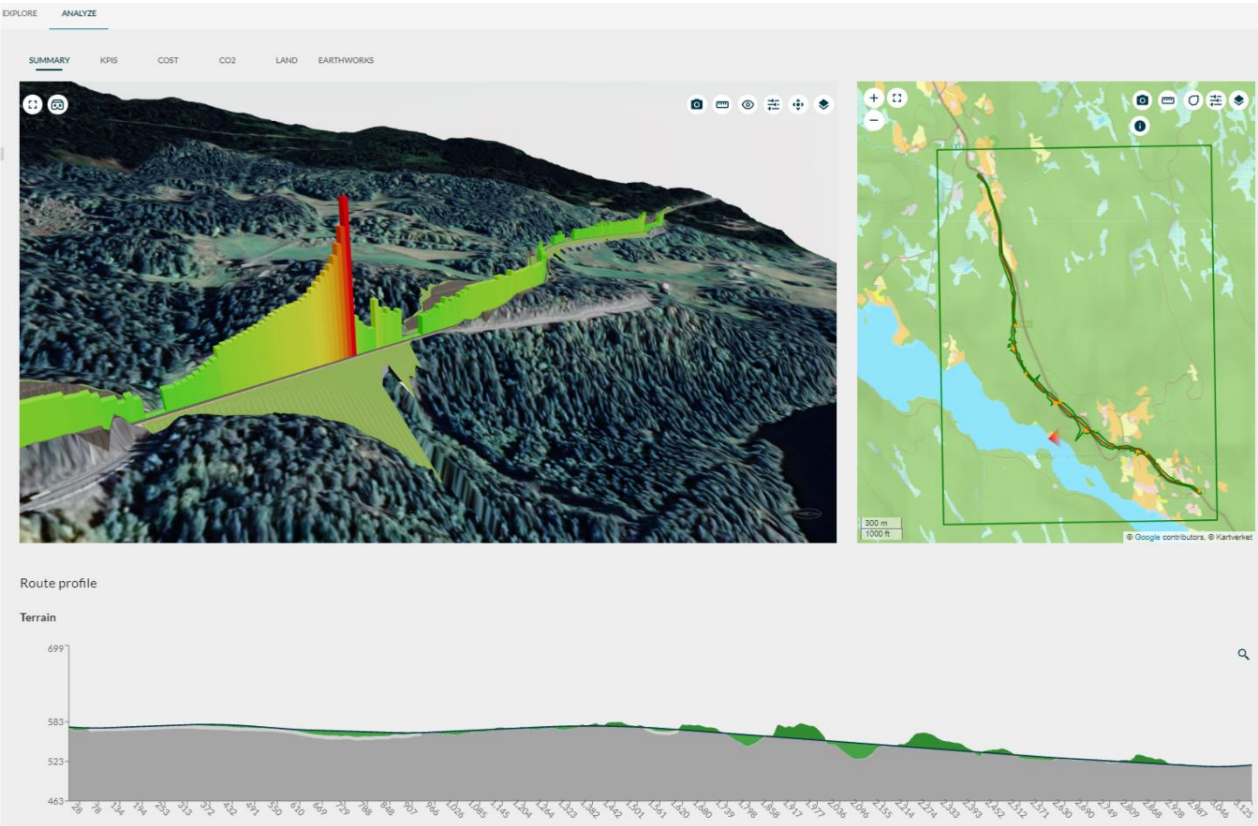

Figure 5 - Visualization of automatically calculated GHG from land take (Source: Infraspace, 2024)

3.1.3 Quantum Trible

The third is a commercial software, namely Trimble Quantum and it is useful for visualizing potential ideas for a road project. The automated environmental impact assessment include carbon footprint estimates from construction and traffic as well as noise indicators based on traffic, speed, geometry, etc. These factors are also combined with costs estimations from area use (kr/m^2) and traffic (kr/tonne CO_2). The software algorithms perform various tasks and efficiently present alternative routes for the required transport project and rank the options which best meet the various goals based on information about the terrain and geology, construction costs, carbon emission factors, GIS, environment and nature requirements (Figure 6). For each alternative route, it is possible to assess the different elements which make up the road project such as types of roads, tunnels or bridges (Figure 7). Differently to the aforementioned approaches, the input data is synchronized from a unique cloud-based platform which belongs to the same commercial software package, namely Trimble Quadri. The Quantum-Quadri connection provides a standardized, multi-discipline and concurrent work environment that facilitates quality control of contractual terms and national industry requirements. The input data in Quantum can be adjusted as desired, whether for a predefined template or for the customization of values.

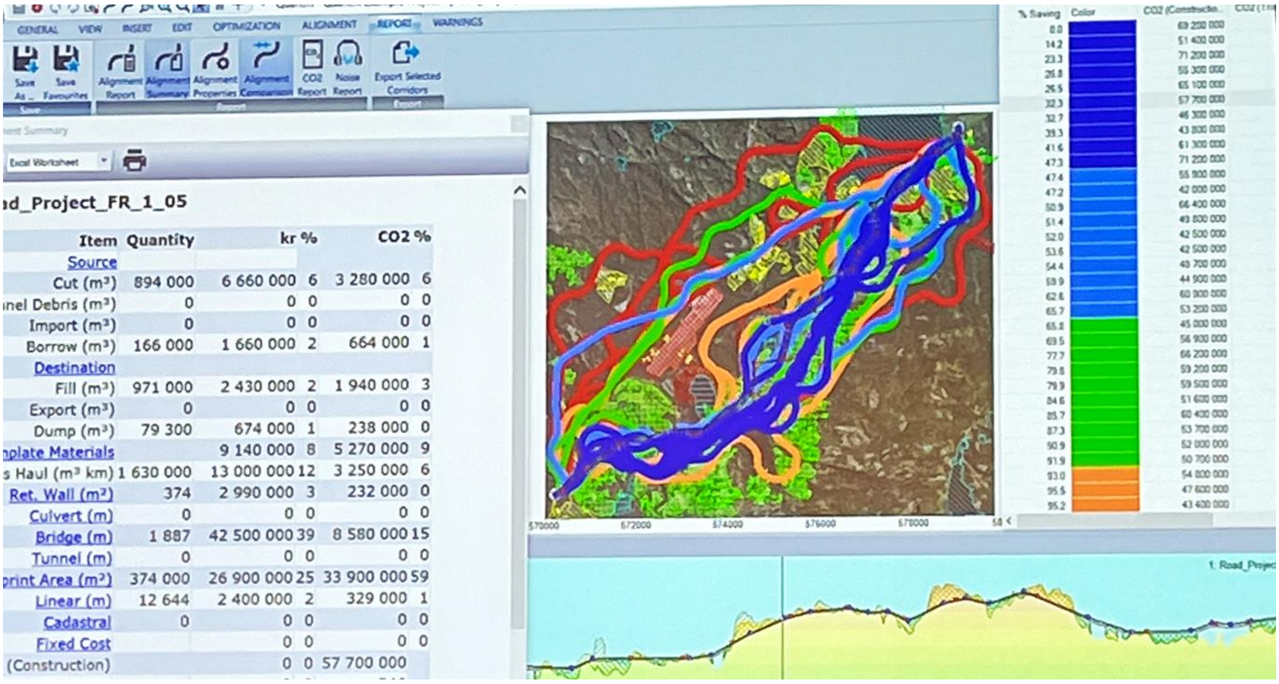

Figure 6 – Example of GHG budget visualization of alternative routes for a road project (Source: Trimble, 2023)

Figure 7 – Detailed report of bridge types within the road project (Source: Trimble, 2023)

3.2 Identification of benefits and opportunities according to participants' perspectives

The interviewed participated actively and provided genuine answers supported with practical examples. The results of the first section of the questionnaire are described by highlighting the topic of discussion and by citing the original answers.

All the participants agreed that the approach helped to improve the **achievement of environmental goals**. The reported improvement effects were related to:

> "*Visualisation of greenhouse gas emissions in a model (and which disciplines cause the various emissions) gives those working on the project a better understanding of what causes the greatest emissions and what their discipline/design contributes to. This helps to make the various disciplines responsible for their contribution, and my experience is that this awareness contributes to good collaboration to reduce emissions. Being able to quickly juggle between showing emissions per life cycle phase, per discipline and per material helps to increase understanding of the calculations and the opportunities for greenhouse gas-saving optimisations. We have so far used the tool in about 10 projects, and in most of the projects it has helped us to work much more purposefully with measures that make a difference than we would have achieved without using the tool. Often you are faced with choices in the design process where it is not easy to immediately say anything about the impact on greenhouse gas emissions. For example, we have used the tool to calculate and visualise the impact of alignment/vertical geometry and compared increased emissions from larger fill/cutting (mass transport + land use) measured against reduced emissions from traffic (slacker vertical geometry). This is a type of analysis that would have been significantly more difficult without our modelling tool*." (Trane user)

"Enabled faster insight into the impact of alternative route choices, including by automating land take calculations and using optimisation algorithms (e.g. supported by AI technology) to reduce the take of valuable land (e.g. marshland, agricultural and forest land)." (Infraspace user)

"Automatic generation of data in early phases free up time to manually optimise road lines. Better mass balance and better lines are usually better for greenhouse gas emissions." (Trimble Quantum user)

The participants also agreed that the approach has improved **the way the GHG emissions are identified, visualized and assessed.** It includes the provision of better figures, more accurate numbers, and enhancement of data quality control. Two detailed explanations were given, as follows:

"Effective calculations make it possible to follow a project (month by month) and continuously measure how the project is doing compared to the project's ambition for greenhouse gas reduction. Better quality assurance of the calculation is achieved, as the result is visualised geographically in the model, and it is easy to detect any errors in the calculation that affect one direction or another. In addition, the tool is designed to alert you if an object (a volume) is not calculated, which increases the certainty that everything that should be included is included in the calculation. Because the greenhouse gas emissions can be sorted by life cycle phase, by subject area or by material type, and at a level of detail adapted to the planning level of the project, it is easy and efficient to extract different figures and measure development/dashboard views." (Trane user)

"The approach can provide immediate insight into topics such as land take, greenhouse gas estimates, landscape visibility and terrain impact. Based on a centre line and open data (e.g. AR50), stakeholders can gain immediate insight into relevant KPIs for the proposals. By reducing the time it takes to gain such insight, enable to consider these topics early in the process - and better choices can be made early on." (Infraspace user)

Regarding this, the participants considered that the adopted approach contributed to better **management and dissemination of knowledge among the involved parties of a project**. For instance, the user of *Trimble Quantum* argued that visualizing GHG emissions from mass transport helps to easily identify the contribution of – e.g., adjustments of line routing, amount of filling/cutting, use of intermediate storage and transport distances, among others. An automated approach helps to get a quick and clear overview of the effects of multiple alternatives and measures, thus increasing the awareness on critical issues that are otherwise not easily detected and evaluated in early stages such as optimizing mass balance and handling to plan for the fewest possible routes, bridges or tunnels. Another example was related to the land use, as follows:

"Land use change causes emissions to varying degrees, depending on the type of area and whether the measure is temporary or permanent. By visualising the area emissions separately with colour coding according to which areas are affected, you get a very quick and clear overview of which areas cause high emissions and whether it is possible to avoid this in a rational way. This has been very useful in many projects and helps to increase understanding and focus on possible measures that reduce the impact." (Trane user)

"Making estimated greenhouse gas emissions visible and accessible with data visualisations in a web application that can be accessed by many people in a project (regardless of role) could be very beneficial.

Important elements of the tool are that the estimated values for greenhouse gas estimates are presented in a context together with the proposals, so that it is transparent and accessible. For example, Infraspace can calculate greenhouse gas emissions based on assigned emission factors for embankments, cuts, rock excavations and structures. And together with the estimates presented in tables and dashboards, you will be able to get automatically generated 3D visualisations and thus better understand what the calculations are based on. The fact that it is web-based and with a high focus on a simple user interface makes it accessible to many more people in the project compared to desktop software." (Infraspace user)

Regarding the **training load required to implement the approach**, different statements were reported. For *Trane* the users are the same who developed the solution and, until now, a user interface suitable for external users has not yet been created. The user of Trimble Quantum pointed that a 2-days course were sufficient while sporadic training based on last updates or new features may be required to maximize the benefits of the tool. For Infraspace, users are required to have a short training, according to answer given:

"*New users are normally given a 1-hour introduction. No special prior knowledge is required. To get started with generative searches, approximately 10 hours of training and self-learning with trials will be appropriate. The Infraspace team supports users, so there is minimal prior knowledge required beyond traditional professional knowledge of e.g., road planning."*

There was an overall consensus about the **positive effects of the approach** on time saving through automation of activities, and improved understanding through visualization. Some of the reported benefits were:

"Calculation of GHG emissions and subsequent updates (which can occur many times as the project idea progress) are obtained easily and faster. It enables to reduce time and resource related costs, allowing to focus on the causes and sources of emissions as well as on the saving measures that can make the difference." (Trane user)

"Time saved compared to traditional and more manual processes. The generative algorithm has come up with solutions with better mass balance and construction cost estimation." (Infraspace user)

Overall, the effectiveness and agility of the approach allows to focus on GHG emissions earlier in the project and take advantage of opportunities at speed – e.g., by encouraging the integrated work with different disciplines to assure that a theoretical estimation is compatible with what is expected in practice/real world. Also, an automated approach to GHG estimation of road projects generates new opportunities such as: (i) discovering better ways to solve problems through a smart visualization and comparison of multiple alternatives, and through the rapid processing of large amount data from different sources (emission factors, unit costs, geographic information, etc.); (ii) cope with challenges upfront – e.g., mass and energy balance can be assessed earlier to influence critical decisions that, otherwise, can be more challenging to address in subsequent phases; (iii) better understanding of the impacts of decisions and supporting the balance of trade-offs; (iv) different stakeholders (and non-experts) can be included in discussions due to the intuitive interface; among others.

The results of the second section of the questionnaire are illustrated in Figure 8. The figure summarizes the average percentage of the areas in which the approach introduced changes to the traditional way of performing, according to the participants perspectives.

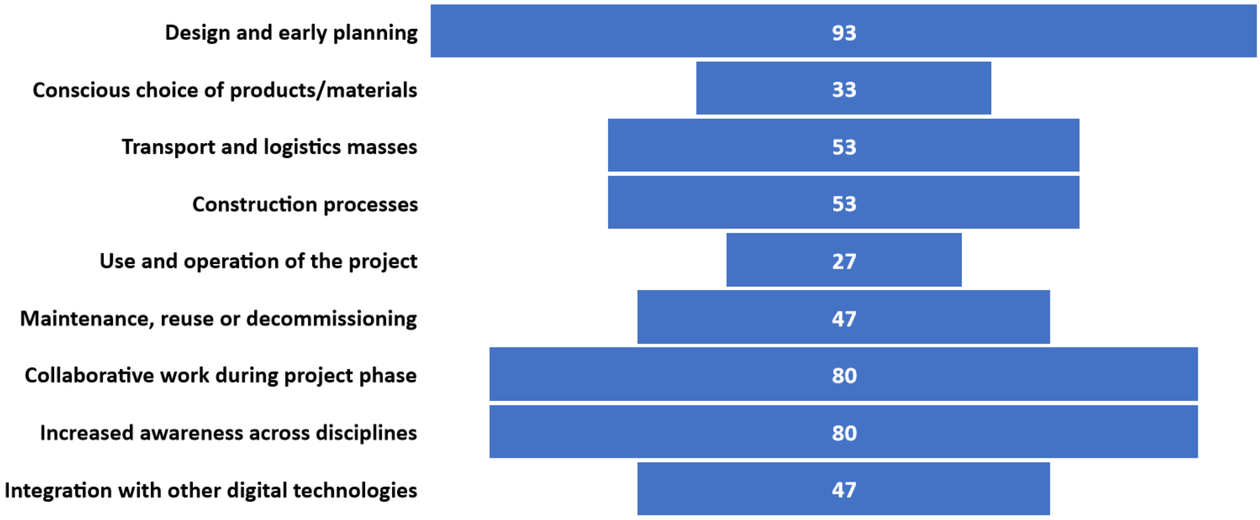

Figure 8 – Average percentage of the areas in which the approach introduced changes to the traditional way of performing

The three main categories in which significant changes were perceived are *Design and early planning, Collaborative work during project phase,* and *Increased awareness across disciplines*. It means a big step towards the increased demand of GHG emissions reduction for the construction sector. By 2030, the transport sector has committed to reduce its GHG emissions by at least 40% from the construction of road infrastructure (Norwegian Ministry of Climate and Environment, 2019). Thus, an automated approach not only support the reduction of GHG emissions through "the most optimal alternative" but also help project participants to understand the main sources of emissions and avoid problem shifting. By doing so, the environmental sustainability is integrated in early decision-making process, thus requiring the same attention as other crucial aspects (i.e., costs, productivity, etc.).

The categories in which the least changes were detected are *Use and operation of the project* and *Conscious choice of products/materials.* According to participants, decisions about speed limits or efficient ventilation and lighting has the potential to be early influenced through the approach. Yet, there were no major changes detected for the use and operation of the project. When it comes to influence a more conscious choice of products/materials, there are still some barriers even if there is a true intention to go for 100% low carbon solutions. For example, throughout the service lifetime of a road project the most emission intensive inputs are concrete, diesel and asphalt. Although low-carbon alternatives of these materials are available in the market, their adoption is not in full-scale yet. Uncertainties around the functionality or technical properties, lack of standards, increased costs or investment risks, are still some of the barriers of consumption.

4 Propositions

The innovative approaches appear to overcome the "problems" or challenges faced from the standalone use of digital tools or the lack of automated solutions for the efficient integration of environmental analysis during early project scoping of road infrastructure. Six propositions are summarized as follows:

(i) **GHG budget can be drawn up at the beginning of the design and planning phases** and take part of the decision-making process along critical variables such as construction costs, execution times and other critical factors.

(ii) **Calculations can be quickly updated and recalculated many times** during the scoping process, without taking excessive manual efforts and operational times. Integrating automated environmental impact assessment with parametric modelling enhances the accuracy and efficiency of impact predictions. It enables dynamic adjustments based on changing parameters ensuring that assessments reflect real-time changes and variations.

(iii) **Land use and mass balance can be better calculated and understood from a visual point of view** while the **3D representation and GIS combination contributes to better quality assurance by making errors easier to detect**. It facilitates a more comprehensive understanding of spatial relationships and potential impacts of large infrastructure projects in complex urban or natural environments.

(iv) The implementation of GIS along the automation of environmental analysis, parametric and 3D modelling **enables a more a holistic approach to decision-making along new ways of designing, planning and communicating through intuitive data visualization**. The demand for increased sustainability of transport infrastructure requires increased efficiency during project scoping to evaluate multiple scenarios and identify optimal solutions. Streamline the process on how environmental aspects are being calculated, visualized and understood by all relevant parties is also necessary for continuous improvement and adaptation to evolving (and unexpected) environmental challenges.

(v) **The integrated analysis and visualization of GHG emissions along critical data** (i.e., construction cost and schedule, land use, transport of masses, audiovisual and traffic impacts) **help to develop a more sustainable way of thinking** thus inspiring future project generations and disciplines which do not cover environmental requirements (at least, not at early stages). It facilitates scenario-based analysis, allowing planners and policymakers to assess the potential impacts and consequences of decisions, optimize resource allocation, mitigate risks and promote sustainable development.

(vi) It is worth noting that the inputs for the environmental assessment are obtained from conventional LCA tools or environmental product declarations, thus the GHG emission results are highly influenced by the adopted emission factors, calculation factors (materials/products, density of materials, etc.) and other factors and choices made by practitioners. Therefore, its recommended that project clients thoroughly **choose the LCA tool / procedures that will be used as inputs for the automated approach to ensure compatibility for further calculations withing the same project or for comparison with future projects**.

5 Conclusions

This investigation contributes to means for making transport infrastructure projects more environmentally sustainable. The explored approaches demonstrated innovative ways for better visualization and understanding of GHG budget along the project scoping of large and complex infrastructure. Multiple benefits and opportunities were identified, thus creating the basis for a set of propositions that aim to encourage the infrastructure sector towards integrated approaches for early implementation of sustainable practices and more comprehensive decision-making. This study is not intended to recommend one approach over the another once all of them serve for the same purpose: support early decision-making for transport infrastructure projects accounting for GHG emissions and optimization of land use and mass handling.

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