A DIGITAL TOOL TO SUPPORT DECISION MAKINGS AND TO REDUCE CARBON FOOTPRINT OF ROAD NETWORKS

K. NEGISHI, R. DE MONTAIGNAC, H. PLEY-LECLERCQ, N. MIRAVALLS
ORIS
koji.negishi@oris-connect.com

ABSTRACT

Roads are a material-intensive system with an ever-increasing material demand as evidenced by 700,000 km of new roads built around the world every year. Moreover, its particularly long service life of several decades implies maintenance needs with additional materials and energy consumption to secure vehicle safety and transport comfort. Meanwhile, climate actions and sustainable strategy in the infrastructure sector are of crucial importance to reduce material resource, energy consumption and associated carbon emissions, and to achieve targets set in the global agenda such as the Paris Agreement on climate change.

ORIS is the first digital platform connecting real and geolocalized material databases at an early design stage, allowing to measure, predict, and support informed decision making. A data science technique is used to find the best materials from locally available sources by optimising material transport. Based on the embedded local design catalogues and its automatized data-driven approach, an exhaustive Life Cycle Assessment (LCA) is performed on road for its whole life cycle, including material productions, transport, construction operations with customised options for pavement solutions, road use, maintenance, end-of-life and up to the benefit from demolished materials recovery.

Right decision makings on sustainable road strategy should be ensured by a holistic and systematic approach of the environmental assessment applicable to various projects. Over the past decades, significant scientific and technical efforts have been made to develop frameworks, tools and databases to estimate and reduce carbon emissions of road projects based on LCA. However, data collection and management still remains as one of the main challenges that leads to the unavailability of timely LCA implementation and poor results in identifying solutions for carbon emissions reduction.

In the use phase, a total of 6 use phase modules were built based on state of the art models to compute the impact of the road use due to specific pavement properties (albedo, carbonation and lighting) and the impact due to Pavement-Vehicle interactions (PVI). The PVI models take into account pavement degradation effect (deflection, roughness and texture) on vehicles fuel consumptions.

The article will expose how ORIS is thus capable of optimising the balance between material needs from construction and maintenance activities and vehicle fuel consumptions, while reducing life cycle carbon footprint, cost and material consumptions. Finally, a case study demonstrates the reduction potential of carbon by 6.69 million kgCO2eq. and cost by 2.6 million dollars.

1. INTRODUCTION

Materials and pavement design choices impact up to 60% of the cost of a road project and about 85% of its overall greenhouse gas emissions. Most roads are designed according to standardised and historical road design methods, where materials availability and adequacy are considered only later at the construction phase due to the difficulty in data collection and the lack of systematic approach. Such approach from the road ecosystem (owners, investors, designers, contractors) lacks to integrate sustainability requirements such as climate change mitigation, natural resources scarcity or social disparities. Connecting real materials databases at a very early stage enables to measure, predict and support informed decision making. ORIS is the first material platform, which is a web-based multi-user and multi-service that will enable more sustainable road building with optimised solutions for each local sourcing environment. Users are from the road ecosystem at large: material suppliers, road contractors, engineering firms or road authorities and even financial institutions and infrastructure financiers. Integrated in Building Information Modeling (BIM) workflow, an assessment of different pavement design options is instantly performed. First road alignment is loaded into the platform that geolocalises the project and material sourcing opportunities. Embedding local design catalogues, the user has the capacity to select several pavement structures from all visualised designs in order to compare and to choose their preferred design according to their priorities: carbon footprint mitigation, increased durability, local materials, cost reduction. Beyond pavement choice, the users can select several maintenance scenarii to be compared and assess the impact on the use phase. The key to success is the capability to combine planning, execution, maintenance and recycling on one platform. Our global approach is creating impact at every stage of the road life cycle. Furthermore, this data-driven approach and abundant geolocalised material databases enable to extend to rails or even other transport infrastructures, which are important public expenses for any country's budget.

Recent review works revealed the significant increase in the research on LCA applied to road construction projects in the last twenty years [1–4]. In fact, this shows the enhancement of the sustainable strategy on the infrastructure. Meanwhile, they also highlighted that the majority of published studies were involved in an inconsistency in the functional unit and an incomplete system boundary. Subsequently, main challenge in data collection and a significant execution time of an LCA study finally leads to the unavailability of results and decision makings before at the early design stage. To the best of our knowledge, none of existing studies provided a systematic approach enabling full and easier road LCA. In order to improve sustainability in road construction, the swiftness and data availability using data science techniques are of great importance and allow performing the project assessment at the very early stage.

To meet these challenges, an exhaustive and data-driven approach is required in order to promptly and seamlessly perform an extended level analysis of a road pavement design performance during its whole life cycle stages, conformed to LCA standards.

The application of the methodology demonstrates the potential of the tool to uncover the environmental impact of the different decisions made during the design of a project as well as the indirect effects that decisions made in one phase (e.g. construction or maintenance) can have on the subsequent use phase. Compared to most conventional road LCA approaches only covering a part of the life cycle, our solution scientifically based on data proves that holistic assessment over the full life cycle is a key to improve the overall sustainability of the road infrastructure. Besides carbon footprint criteria, material circularity (recycled materials used in the project and potential benefits from demolition waste) is monitored to support users even more sustainably and economically driven decision making.

2. DIGITISED FRAMEWORK FOR ROAD INFRASTRUCTURE PERFORMANCE ASSESSMENT

Negishi et al. [5] built a digitised framework applied to road infrastructure to simulate and measure a sustainability impact on multiple scenarios. The whole process is depicted in Figure 1. This advanced digital technology uses an innovative data management system and data science techniques allowing a quick assessment around a few key indicators : road safety analysis, identification of local material sourcing sites, pavement designing from digitised catalogues, material transportation analysis, life cycle carbon and cost analysis, natural resource consumption analysis and material circularity analysis. Its capability of an easy extension of databases serves to embed user data in the platform and thus allows multiple simulations, and scenario and sensitivity analysis of road construction projects. The platform developed aligned with this methodology is capable of combining the planning, execution, maintenance and recycling on one platform and greatly contributes to reducing the effort and assessment execution time and early stage decision makings.

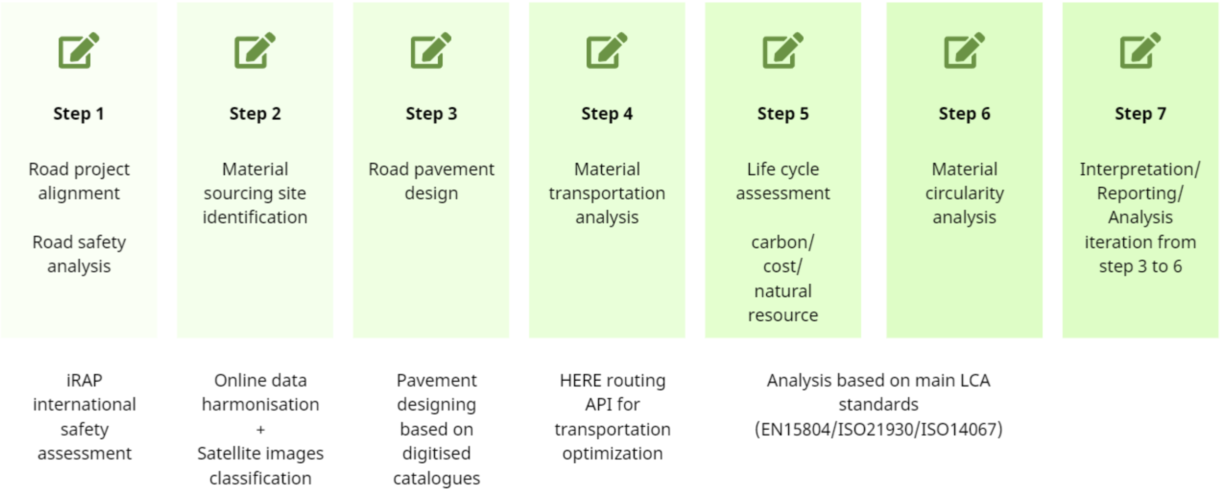


Figure 1 – Digitised process of road life cycle assessment methodology

The extensive database and automated calculations allow users to test, compare and visualise multiple solutions from the design (step 3) to the analysis (step 4 to 6), and come back to the design phase. The easiness of scenario analysis would reveal the huge potential of carbon, cost and material optimisations.

From the original construction - including material productions, transport and construction operations - with customised options in terms of materials actual properties and pavement solutions, the developed tool expands its analysis to the road use and maintenance phases, up to the end-of-life stage, compared to previously developed road LCA approaches that in most cases only consider production and construction stages. State of the art models are used to incorporate the impact of the road use due to specific pavement properties (albedo, carbonation and lighting) and the impact due to Pavement-Vehicle Interactions (PVI). The modules associated with PVI take into account not only pavement mechanical characteristics and the pavement ageing but also the evolution of annual average daily traffic (AADT) and local climate conditions over the road service lifetime in order to calculate increased vehicle fuel consumptions.

The whole methodology including the inventory calculation steps, input data, background carbon emission factors and representative case studies were verified by Intertek GmbH in

December 2022 and received the assurance statement regarding the alignment with eminent LCA standards ISO 14067 [6], EN 15804 [7] and ISO 21930 [8]. With these three standards and the material data management system connected to verified environmental datasets and cost data, the application of the methodology can cover road construction projects in most countries.

2.1. Digitised road safety performance assessment

Reducing fatalities on road sections is of utmost importance for road construction projects. The ORIS platform integrates safety evaluation using the international Road Assessment Program (iRAP) star rating system [9] regarding the safety target proposed by the United Nations. iRAP Star Ratings represents the relative risk of death and serious injury for individual road users and is measured through more than 52 road attributes. These parameters influence the safety for vehicle occupants, motorcyclists, bicyclists, and pedestrians. The evaluation considers the following parameters:

- Likelihood: referring to risk of a crash being initiated
- Severity: referring to the severity of crash when it happens
- Operating speed: referring to the degree to which risk changes with speed
- External flow influence factors: accounting for the degree to which a person’s risk of being involved in a crash is a function of another person’s use of the road
- Median ability to traverse factors: accounting for the potential that an errant vehicle will cross a median

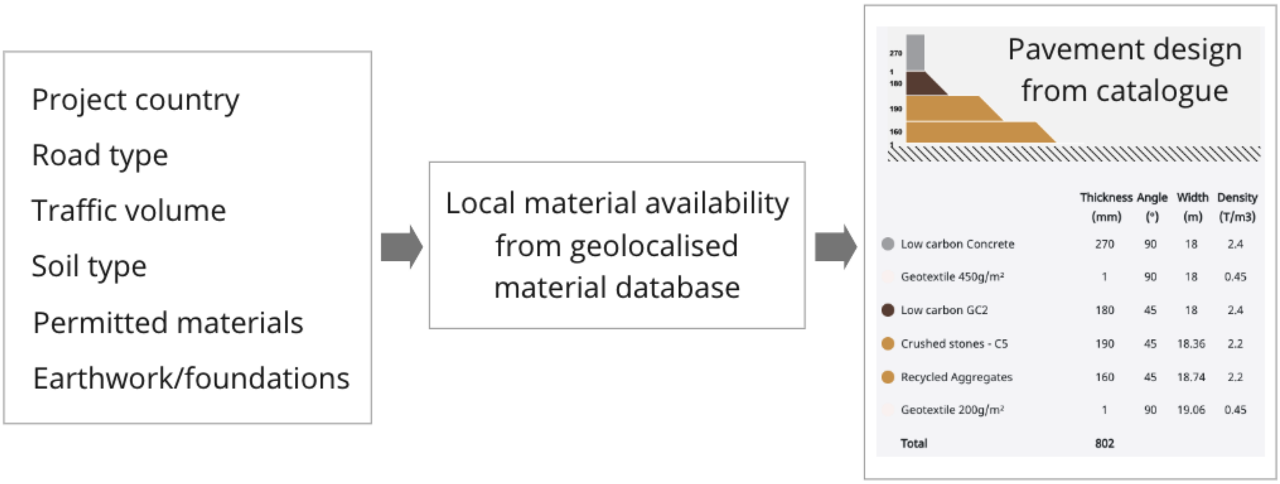
The safety assessment also comes after pavement design as the surface material will impact the road performance.

2.2. Building a database of local material sourcing sites

The first phase of a road construction project is the identification of local material sourcing capabilities. Each material sourcing site is recognised as material production sites such as asphalt, bitumen, concrete, cement and any other raw materials needed for a project. ORIS integrates an advanced level of database where geolocalised material sourcing sites are stored. The information of these sites are verified and completed by using data science techniques. Once material sourcing sites are identified, the attributes of materials required for the successful completion of the database is collected from various data sources including data provided by clients and data available in public. Each material is accompanied by the Declaration of Product (DoP) that provides material characteristics. Material prices are provided from contractors introduced in a cost table dedicated to a project, while environmental datasets associated are from the sources aligned with LCA standards and specific to the geographical context (e.g., ecoinvent, Base Carbone in France, industrial EPD).

2.3. Pavement design approach

Pavement structure can be designed either manually by entering the description of each layer of pavement, or automatically by selecting from the digitized local catalogues. Manual input to define layer by layer needs to feed the platform with information specific to each layer and materials used (e.g., dimension, material used, material density, internal transport costs, pavement cost). When it comes to the use of pavement catalogue, users need to feed the platform with the general road information required by the local regulations and catalogues (e.g., country, road type, traffic volume, soil classification, local climate conditions, material transport mode). Based on these parameters, the tool automatically selects pavement solutions prepared and stored in the database. It is important to note that the method of structural design, criteria of layer sizing and available materials differ from a country to another and not necessarily the same pavement designs are elaborated. From the solutions selected, the basic information on the dimension (width, thickness, and angles) and material density that allows the calculation of the reference flow are retrieved (Figure 2).



	Thickness (mm)	Angle (°)	Width (m)	Density (T/m3)
● Low carbon Concrete	270	90	18	2.4
Geotextile 450g/m²	1	90	18	0.45
● Low carbon GC2	180	45	18	2.4
● Crushed stones - C5	190	45	18.36	2.2
● Recycled Aggregates	160	45	18.74	2.2
Geotextile 200g/m²	1	90	19.06	0.45
Total	**802**			

Figure 2 - Digitised pavement design process combined with geolocalised materials data

This capacity to digitize a pavement design makes it possible to perform an LCA study at the very early stage of a project because it solves the unavailability of data for LCA modelling. An early assessment will bring higher potential of cost and carbon footprint reduction than the assessment in a later phase of the project.

To better anticipate how materials will perform under local weather conditions and over their lifetime, multiple material properties and factors were included in the model, in particular: flexural strength of concrete, fatigue behaviour of concrete, elasticity, subgrade reaction and albedo. These parameters combined with maintenance programs are used in the use phase models to compute these effects on vehicle performance and albedo effect [5].

2.4. Optimization of material transportation

In a life cycle of road projects, material transportation is needed in separate phases. Once a material sourcing sites database is built and a project location is recognised, the digital platform automatically simulates the transport distance, and associated carbon footprint and cost. ORIS identifies the right route from multiple possible solutions by considering road constraints (e.g., permitted truck size and weight, environmental avoidance zones) and traffic conditions.

2.5. Life cycle carbon, cost and material consumption assessment

The assessment of carbon footprint follows the LCA standards (ISO 14067, EN 15804 and ISO 21930) covering a full scope of road life cycle [5]. From the pavement designs selected, maintenance scenarios and end of life scenario, a life cycle inventory analysis is conducted to calculate material and energy consumptions through a whole life cycle. The use phase modules are divided into two categories. The first one is related to the properties of road surface material and calculates the albedo effect on global balance of atmospheric radiative forcing, the carbonation effect, and electricity consumption of road lighting. The second one is related to PVI effects and measuring the vehicle fuel consumption due to the fatigue of pavement over the pavement use. As the condition of pavement is a key factor to calculate the use phase modules, not only the degradation of pavement but also its improvement invoked by maintenance programs is taken into account for the use phase calculations. The methodology also includes a systematic estimation of benefit in terms of carbon emissions based on default materials recovery scenarios. The assessment with the use phase increasingly contributing to the overall result helps to better identify the potential for reduction in carbon footprint and avoid ramifications in the decision making.

Life cycle cost analysis takes into account operations and consumptions among the different stages of road projects and transforms them into cost. The material production stage considers the cost related to raw material supply, transport and manufacturing. The transportation cost includes the finished product transportation (from final material sourcing sites) to the project main access point, while the internal transport cost is also included to account for the product transportation from the main access point at the site to other work locations as needed. Then, the construction stage considers the energy consumption from equipment use converted into cost. The maintenance costs are also included in the analysis and to be considered as a key indicator for the global view as the maintenance program balances between life cycle cost and environmental performances of pavement use.

Finally, natural resource consumptions are calculated according to the project section length, layer widths, thickness and densities. By monitoring virgin and recycled materials incorporated into each layer of the designs, it is possible to evaluate the effect of recycled materials regarding carbon and cost performances.

2.6. Material circularity analysis

After the end-of-life of a road system, comes the measurement of material circularity potential from demolished waste. This gives additional information beyond the road lifecycle and indicates the environmental benefit obtained from the extension of materials service life by either reusing or recycling them. The scenario of demolished materials valorisation is specific to each project identifying potential transports up to recycling facilities and processing depending on scenarios.

2.7. Results interpretation

The final phase of road life cycle assessment is a result interpretation including results visualisation, comparison, and reporting. The tool helps decision-making thanks to different options of design comparison and scoring systems from the economic, environmental and material point of view through a whole road life cycle. Besides, the digital platform and its extensive database offers an easy implementation of alternative pavement scenarios so projects can return back to any previous steps.

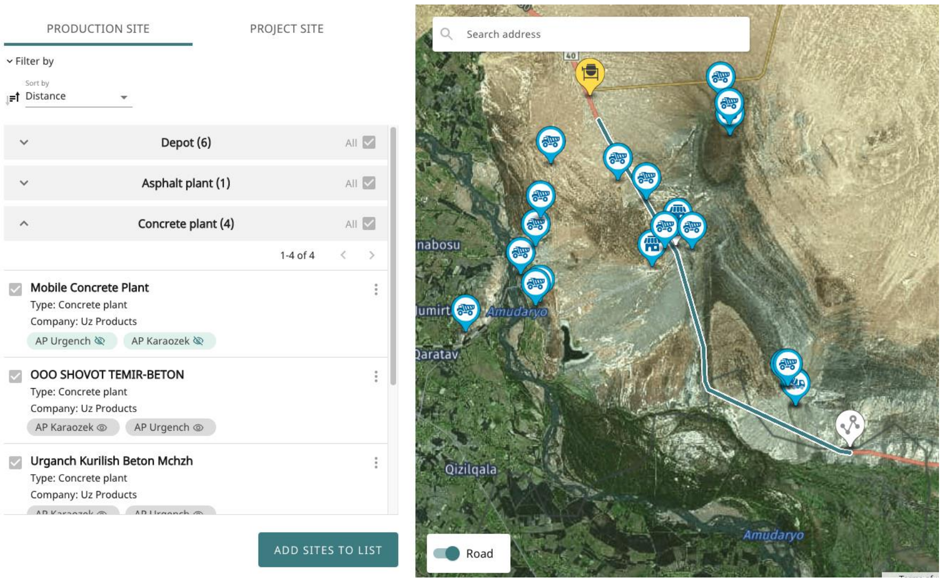
3. APPLICATION OF THE METHODOLOGY TO A HIGHWAY RECONSTRUCTION PROJECT IN CENTRAL ASIA

3.1. Road project alignment

The project is the reconstruction of the existing 24.3 km highway in Central Asia. The reference service life is 30 years. The pavement design catalogues were constituted based on a local standard [10] to reflect local conditions in addition to international standards [11, 12]. The traffic conditions were considered based on studies conducted between 2017 and 2021 [13] from which the following numbers were retrieved: average daily truck traffic per way is 1190, average growth factor constant during the studied period is 5.5%, and reference axle load type is 13 tonne. This case study does not include the material circularity analysis and the decision making is based on carbon, cost and material consumption through a whole life cycle.

1.1. Material sourcing sites identification

In total, 75 materials sourcing sites were identified for the project including 44 quarries and borrow pits, 9 concrete plants, 7 cement factories, 6 asphalt plants, 6 trains/road multimodal areas, 2 water sources and 1 geotextile factory. Figure 3 shows the road section to be reconstructed (blue line) and some extracted material sourcing sites around (blue points).



☑ **Mobile Concrete Plant**
Type: Concrete plant
Company: Uz Products
AP Urgench AP Karaozek

☑ **OOO SHOVOT TEMIR-BETON**
Type: Concrete plant
Company: Uz Products
AP Karaozek AP Urgench

☑ **Urganch Kurilish Beton Mchzh**
Type: Concrete plant
Company: Uz Products

Figure 3 – Material sourcing sites identified for the project (not exhaustive)

As the project is located in a water scarce area, water savings were identified as a key priority. The use of water is crucial to reach the optimum moisture content in road pavements but during geotechnical inspections, groundwater was absent in the pits dug up to three metres in depth. Therefore, two water sources away from the site were subsequently considered for the study. Water consumption for pavement construction was calculated with the following assumptions:

- Optimum moisture content for aggregate layers and treated layers
- Water for concrete layers in the mixed design

The pricing of materials was incorporated based on a local survey conducted in November 2021 and on local experiences as well as references for similar projects.

Regarding environmental data, in a local context where suppliers have not produced an Environmental Product Declaration (EPD) for their materials, ORIS complies local and international data to define the carbon footprint for each material. Based on these initial carbon evaluations, ORIS calculates the overall impact through a whole service life of the road.

3.2. Pavement designs selection

The base case design (design n°1) provided by the project was a rigid pavement structured with six layers of materials (Figure 4):

- 270 mm cement concrete pavement with sulphate-resisting Portland cement
- 1 mm nonwoven geotextile with a surface density of 450 g/sqm
- 180 mm crushed stone gravel sand mixture reinforced with sulphate-resisting Portland cement
- 150 mm crushed stone mixture
- 200 mm crushed stone mixture
- 1 mm Nonwoven geotextile with a surface density of 200 g/sqm

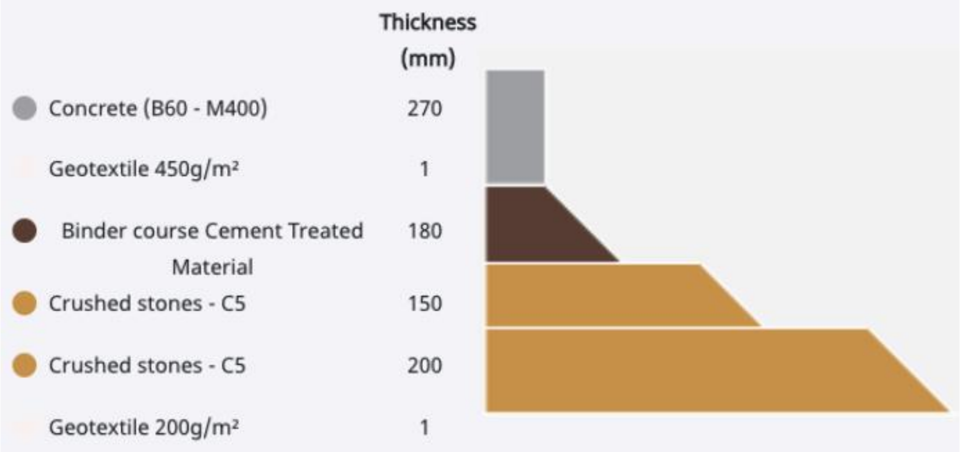


Figure 4 – Illustration of the base case design

To consistently compare with the base case, two alternative rigid structures were selected according to European standards:

- Alternative 1 (design n°2): This design is based on the RStO 12 German guidelines, with one layer of geotextile and the optimization of the base cement treated layer. To meet the expected performance, the aggregate layer thickness is increased.

- Alternative 2 (design n°4): The design is based on the French SETRA 98 pavement catalogue, with a suppression of one layer of geotextile and the optimisation of the concrete layer by reducing from 280 to 250 mm. To meet the expected performance, the aggregate and cement treated base course layer thickness are increased.

The comparison has been made between rigid pavements only at the request of the Uzbekistan Committee of road to follow the presidential decree stipulating that all new highway road pavements should be concrete-based design.

Through this assessment, the use of recycled materials from the existing road was identified as an opportunity for further optimization of the pavement design. In addition to the above 3 designs, the base case and the design alternative 2 (n°3 and n°5) were analysed with the use of recycled aggregates in different layers materials. Table summarises the base case scenario and four alternatives with materials specifications.

Table 1 - Selected pavement design scenarios for the case study

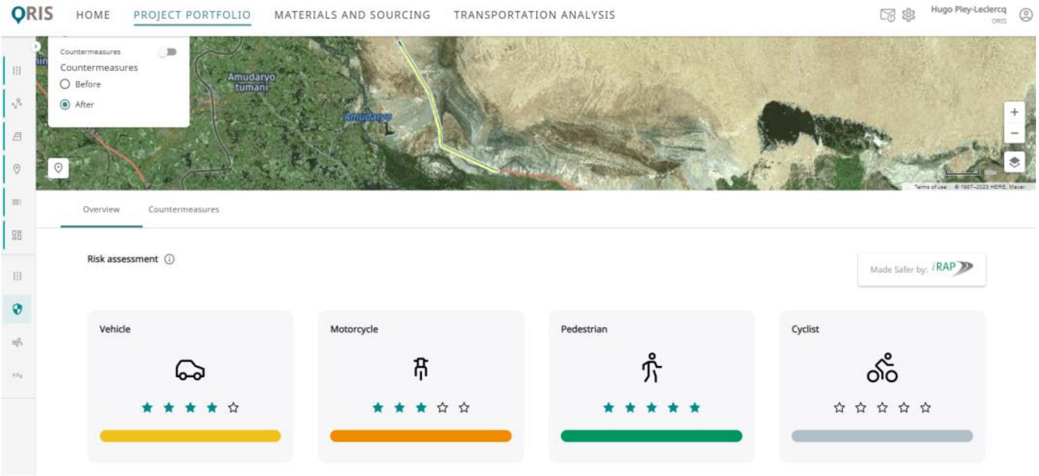
	Base case (n°1)	**Alternative 1 (Rsto12) (n°2)**	**Alternative 1 (Rsto12) recycled material use (n°3)**	**Alternative 2 (Setra98) (n°4)**	**Base case recycled material use (n°5)**
Layer 1	Concrete surface 270 mm	Concrete surface 270 mm	Concrete surface 270 mm	Concrete surface 250 mm	Low carbon concrete surface 270 mm
Layer 2	Geotextile 1 mm	Geotextile 1 mm	Geotextile 1 mm	Geotextile 1 mm	Geotextile 1 mm
Layer 3	Cement treated material 180 mm	Cement treated material 150 mm	Cement treated material 150 mm	Cement treated material 200 mm	Low carbon cement treated material 180 mm
Layer 4	Crushed stones 150 mm	Crushed stones 180 mm	Crushed stones 220 mm	Crushed stones 300 mm	Crushed stones 190 mm
Layer 5	Crushed stones 180 mm	Crushed stones 200 mm	Recycled aggregates 160 mm	Crushed stones 200 mm	Recycled aggregates 160 mm
Layer 6	Geotextile 1 mm	-	-	-	Geotextile 1 mm
Total thickness	**802 mm**	**801 mm**	**801 mm**	**951 mm**	**802 mm**

3.3. Road safety assessment

On this project, all 52 attributes were recorded for each 100-metre section of each road with the following assumptions:

- Average speed: 110 km/h
- Road users: mainly vehicles (trucks) and motorcycles
- User flow: 4.585 vehicle per direction per day
- Fatality rate: 11 fatalities per year

The Star Ratings were below 3, which is lower than the UN minimum targets [15]. Building on this assessment, the project team identified an improvement plan to reach the minimum iRAP Star Rating of 3 stars, shown in Figure 5. The implementation of those countermeasures increases the safety for all road users. The measures lead to a reduction in the potential of fatalities and serious injuries of 56%, which would avoid 1.845 fatalities over the 30 years' service life of the project.



Countermeasures
○ Before
● After

Vehicle ★★★★☆
Motorcycle ★★★☆☆
Pedestrian ★★★★★
Cyclist ☆☆☆☆☆

Figure 5 – Results of road safety assessment according to iRAP Star Rating system

3.4. Life cycle assessment and results analysis

Figure 6 represents the results from A1 to A5 phases and the ranking of five pavement solutions on three indicators: carbon, cost and material consumptions. The total material consumption has an insignificant variation (< 1%) except for the design from the French standard (n°4) that increases the use of aggregates while the clear influence of material choice on carbon and cost indicators appears differently from one solution to others. The adoption of the pavement solution from the German standard (n°2) has a gain of 3.8% in carbon footprint. The reduction potential in carbon footprint is maximised when recycled materials are introduced in the base case design (n°5) with a reduction of 16% (7.6M kgCO2eq.) compared to the base case. The German standard's solution with the incorporation of recycled materials (n°3) offers the less expensive alternative with a reduction of 12.9%.

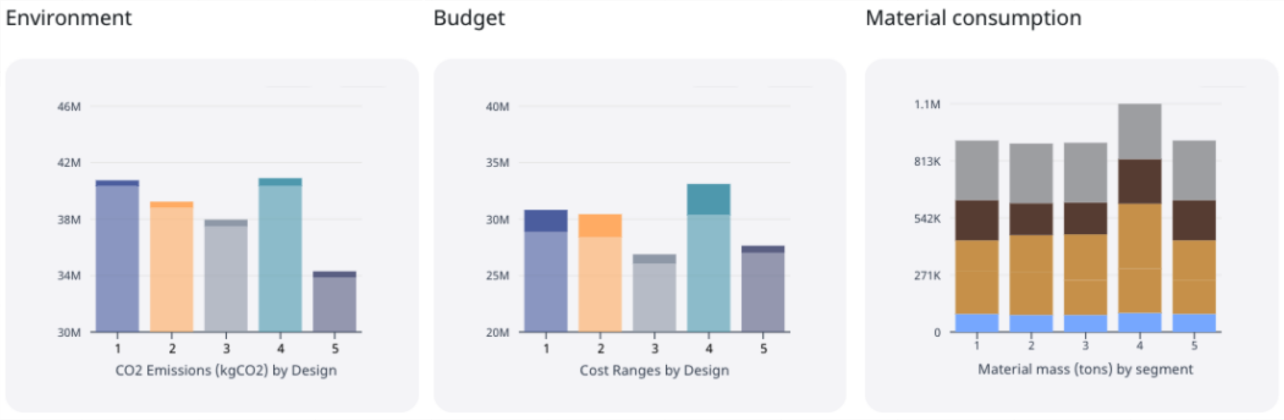
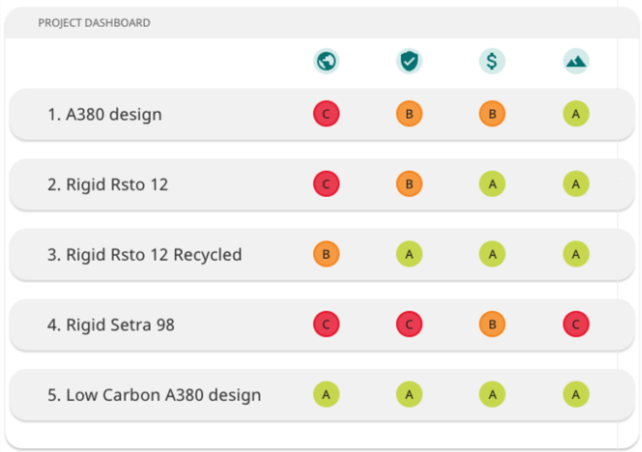


Figure 6 – Results of carbon, cost and material consumptions (M=millions, K=kilo)

The project evaluated that carbon emissions from the base case (n°1) cumulate to 39.2M kgCO2eq. for the product and construction phase while the use phase's emissions cumulate to 15.7M kgCO2eq.

The project is located in a water scarce area in Central Asia. The nearest source of water was located about 25 km from the construction site. Therefore, the water monitoring was of utmost importance in this project. With an analysis of the local material properties and the material mix design, alternative pavements can bring a reduction up to 4.8M litres of water.

Finally, Figure 7 proposes a simple representation of indicators evaluated in the project by scoring that ranges from A, B C to D the different solutions.



PROJECT DASHBOARD

	🌐	🛡	$	⛰
1. A380 design	C	B	B	A
2. Rigid Rsto 12	C	B	A	A
3. Rigid Rsto 12 Recycled	B	A	A	A
4. Rigid Setra 98	C	C	B	C
5. Low Carbon A380 design	A	A	A	A

Figure 7 – Project dashboard summarising the ranking of pavement solutions

4. CONCLUSIONS

Digitalisation and advanced technologies as data science techniques will contribute to the deployment of new solutions to support decision making for sustainable road infrastructure. The key to successful project implementation with a high reduction potential for carbon, cost and resource consumption resides in the capability to assess multiple design and maintenance scenarios from the very early stage of the project. The digitised framework presented in the current paper enables prompt and seamless analysis of a road project performance regarding carbon footprint, cost and natural resource consumptions through a whole service lifetime. The platform links real material markets with construction projects and embedded catalogue of multiple pavement solutions based on structural and local requirements. This disposition of data allows easing the pavement design process at a very early stage. The framework also ensures safer and smoother pavement solutions by incorporating iRAP methodology in the assessment flow.

The framework was applied to a real construction project consisting of upgrading a 25 km highway in Central Asia. The use of digital solutions allowed the project to assess and identify alternative road designs in a quick and efficient manner. The benefit of circular solutions (pavement solution n°3 and n°5) was obvious, demonstrating up to 16% reductions in carbon footprint compared to the base case. In economic terms, the best case scenario offers 10% cost saving, corresponding to 2.89 million dollars.

Furthermore, the current study demonstrated the following key learnings:

- The identification of local material sourcing sites makes data collection easy and their geolocation allows optimisation of material supplies.
- The use of recycled materials preserve natural resource consumptions while contributing to carbon saving by up to 6.69 million kgCO2 eq.
- Besides the material production and construction phases, a scope on full life cycle stages with a range of use phases should be considered to achieve even more significant reduction potentials in carbon and cost. It is crucial to consider an optimum program of maintenance counterbalancing between material needs reduction and vehicle emissions reduction.

REFERENCES

1. Balaguer, A., Carvajal, G. I., Albertí, J., and Fullana-i-Palmer, P. (2018). Life cycle assessment of road construction alternative materials: A literature review. Resour. Conserv. Recycl. paper 132, pp 37–48
2. Azarijafari, H., Yahia, A., and Ben Amor, M. (2016). Life cycle assessment of pavements: Reviewing research challenges and opportunities J. Clean. Prod., paper 112, pp 2187–97
3. Babashamsi, P., Md Yusoff, N. I., Ceylan, H., and Md Nor, N. G. (2015). Life Cycle Assessment for Pavement Sustainable Development: Critical Review Appl. Mech. Mater. paper 802, pp 333–8
4. Santero, N. J., Masanet, E., and Horvath, A. (2011). Life-cycle assessment of pavements. Part I: Critical review Resour. Conserv. Recycl. paper 55, pp 801–9
5. Negishi, K., De Montaignac, R. and Miravalls, N. (2022). Materials role in pavement design and its impacts in LCA of road construction and use phase. IOP Conf. Ser.: Earth Environ. Sci. 1122 012037
6. ISO 14067:2018 Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification
7. EN 15804+A2 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction product
8. ISO 21930:2017 Sustainability in buildings and civil engineering works – Core rules for environmental product declarations of construction products and services
9. Rogers, L. (2017). iRAP Star Rating and Investment Plan Implementation Support Guide. International Road Assessment Programme
10. Asian Development Bank. (2021). A Practical Guide to Concrete Pavement Technology for developing countries
11. French Standard (NF P 98-086) – French Association for Standardization (AFNOR). (2011). Road pavement structural design – Application to new pavement
12. German Standard (RStO 12) – Road and Transportation Research Association – Working Group Infrastructure Management. (2015). Guidelines for the standardization of pavement structures of traffic areas
13. Beruni TYFUK and Karatau ELUP. (2021). Traffic monitoring from 2017 to 2021.
14. United Nations. (2017). Technical document. Global road safety performance targets