Design optimisation supporting sustainable link-road optioneering

ABSTRACT

This paper reviews a new link-road construction project in the UK, utilising the ORIS digital platform to optimise pavement design and minimise environmental impact over a 60-year lifecycle. The study adhered to the DMRB CD 225 and CD 226 design standards and evaluated the base design proposed by the client and three alternative design options. Multiple criteria were evaluated for each pavement design option including material consumption, costs, and carbon emissions. In addition, locally sourced materials like steel slag aggregates were prioritised for sustainability.

The optimal flexible pavement design with a Thin Surface Course System reduced construction and maintenance costs by 15% and lifecycle carbon emissions by 15% compared to the client's preferred design. The findings demonstrate the value of lifecycle analysis and the efficiency of digital tools such as the ORIS platform to reduce costs, emissions, and resource use through sustainable design. This highlights major potential for greener construction in future road infrastructure projects.

1 INTRODUCTION

Road networks are critical infrastructures that support national economies and facilitate the movement of people and goods. As population and economic growth continue, developing efficient and well-connected road systems is essential for reducing travel times and improving accessibility. However, road construction and maintenance present significant economic and environmental challenges, highlighting the need for sustainable solutions. In this context, the digitalization of the road sector has emerged as a vital area of study, offering potential to optimise construction processes and reduce costs. Understanding the importance of road engineering and exploring avenues for technological advancement is imperative for governments, policymakers, and industry stakeholders [[1],[2]]

This paper evaluates the application of value engineering and whole life cycle costing supported by digital tools in the road infrastructure design process through a real-world case study: the construction of a link road on the UK's Local Highway Network, also known as the Major Road Network.

The case study focused on optimising pavement design while minimising environmental impact using a comprehensive analysis that considered the construction phase, a 60-year analysis period and economic feasibility. By integrating factors such as material knowledge, resource consumption, environmental impact, construction cost, and maintenance needs, the study aimed to identify the most economically advantageous and sustainable pavement design that promoted efficient resource use based on whole life cycle costs and performance.

2 PROJECT OVERVIEW

To support AECOM's design for a new 1.6 km link road for the Major Road Network, collaboration occurred with ORIS, a decision support tool specialising in pavements, during the early stages. Based on several factors, including but not limited to the relatively low volume of traffic on this particular road (12 million standard axles) and a cost comparison analysis, rigid pavements were discarded as potential design options. Furthermore, an initial assessment highlighted the challenges associated with integrating a rigid pavement into the pre-existing fully flexible pavement.

The design options evaluated at the preliminary stage were fully compliant with the latest Design Manual for Roads and Bridges (DMRB) standards, considering a Class 2 foundation with subbase on capping. AECOM proposed the following pavement design options:

- Fully flexible pavement with a Thin Surface Course System (TSCS)
- Fully flexible pavement with a Hot Rolled Asphalt (HRA) surfacing with rolled in pre-coated chippings (performance design)
- Flexible pavement with a TSCS on a Hydraulically Bound Granular Mixture (HBGM category B) base.

Additionally, AECOM's client-preferred design served as the baseline or reference design for conducting a comprehensive comparative analysis, enabling informed decision-making based on quantifiable differences. **Table 1** provides a summary of the pavement designs evaluated using the ORIS platform.

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Base design		**Base design**	
Layer type	**Thickness (mm)**	**Layer type**	**Thickness (mm)**
SMA 6 with steel slag aggregates	30	SMA 6 with steel slag aggregates	30
AC 20 dense binder	50	AC 20 dense binder	50
AC 32 dense base	280	AC 32 dense base	60
Type 1 subbase	150	HBGM-B	170
Capping	600	Type 1 subbase	250
		Capping	430
Total thickness	**1110**	**Total Thickness**	**990**
Fully flexible TSCS		**Fully flexible HRA**	
Layer type	**Thickness (mm)**	**Layer type**	**Thickness (mm)**
SMA 6 with steel slag aggregates	30	HRA 35/14 surf PMB + PCC	50
AC 20 dense binder	60	AC 20 dense binder	60
AC 32 dense base	190	AC 32 dense base	170
Type 1 subbase	250	Type 1 subbase	250
Capping	430	Capping	430
Total thickness	**960**	**Total Thickness**	**960**

Table 1: Pavement designs evaluated by AECOM for the new construction of the link-road

Collaborating with ORIS, AECOM optimised the sourcing of local materials and, to support a circular economy, the permitted pavement designs with Thin Surface Course Systems utilised 6 mm steel slag aggregates obtained from nearby steelworks, replacing 50% of the coarse aggregates. This by-product waste offers several advantages as a sustainable material for asphalt road surfaces, including excellent rutting resistance, improved resistance to polishing and increased wear resistance. Its unique properties make it a cost-effective, sustainable aggregate alternative, reducing natural resource use while maintaining performance. Steel slag can also substitute aggregates with a minimum polished stone value (PSV) of 60, per CD 236 specifications.

The use of overlays was not feasible due to the inclusion of edging kerbs and ironwork in the proposed cross-section and the need to tie into the exiting construction to maintain continuity of the drainage system. Therefore, renewal options were limited to pavement inlays and the following maintenance programmes were derived for each of the proposed pavement designs:

- For the fully flexible TSCS design, a service life of 12 years [3] for the surface and 24 years for the binder course layer underneath were assumed based on local experience of these materials.
- For the fully flexible HRA design, both the chipped HRA and the AC binder course layer were expected to have a service life of 20 years [4].
- The proposed pavement designs were designed with a 40-year design life in accordance with CD 226, after which a full reconstruction would be undertaken.
- Routine maintenance activities for the fully flexible HRA design proposed surface dressing after 15 years of service to restore surface texture and skidding resistance, while the flexible pavement on the HBGM included reflective crack sealing after 9 years of service, again based on local experience.

The service lives were later adjusted as part of the whole life cost sensitivity analysis to determine how this would affect the evaluation of all three design options.

Table 2 summarises the pavement design option service lives.

3 METHODOLOGY

ORIS employed its unique material database to connect the project with locally available materials and sourcing locations, enabling efficient evaluation of different options. The road design assessment was also optimised through the ORIS platform using AECOM's concept designs. Different construction and maintenance scenarios were compared, contributing to informed decision-making, and several parameters were included in this assessment: road alignment, design sections, materials used, and appropriate maintenance activities for the pavement design options over the 60-year analysis period.

In addition, the Whole Life Costing was used by AECOM at the preliminary design stage as an additional factor for selecting the preferred pavement design, complementing the Key Performance Indicators implemented on the ORIS platform. These indicators include total construction cost, material consumption and carbon emissions over the full lifecycle of the pavement, encompassing installation, use, repair, and replacement.

3.1 Whole Life Cost

The Whole Life Cost (WLC) appraisal was performed following the England National Application Annex to DMRB CD 226 [5] and included producing a maintenance life cycle plan over a 60-year analysis period for each of the pavement design options, to then calculate the Net Present Service Value (NPSV) in terms of WLC. On this scheme, which encompassed a total pavement surface area of 23,675 m^2, the following factors were considered:

	Service Life (yrs) Scenario 1	Service Life (yrs) Scenario 2	Service Life (yrs) Scenario 3
Discounted costs (£)			
Replacement TSCS	12	12	12
Replacement BIN	24	24	24
Replacement BASE	48	48	48
Discounted residual value (£)			
Replacement HRA + BIN	20	18	25
Replacement BASE	40	36	45
NPSV (£)			
Replacement TSCS	12	12	12
Replacement BIN	24	24	24
Replacement BASE	48	48	48

Table 2: Pavement designs service lives of materials.

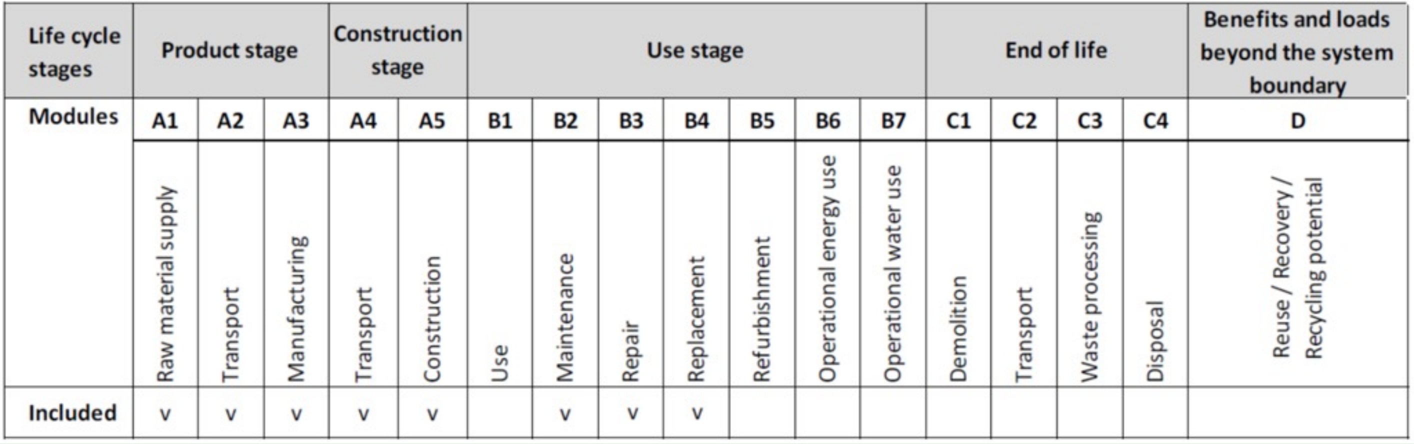
- The pavement costs evaluated by AECOM included the life-cycle stages based on **Figure 1**
- The preliminary works cost was assumed to be a fixed percentage of the construction or maintenance cost
- The life expectancy of the TSCS and HRA surfacing, as discussed in Section 2, were included in the sensitivity analysis
- The pavement design option with the lowest WLC based on NPSV was regarded as the most economically beneficial pavement option.

3.2 Whole Life Carbon

A comprehensive Life Cycle Analysis (LCA) was carried out in accordance with ISO 14040:2006 [6], ISO 14044:2006 [7], and BS 15804:2012 [8] standards. This analysis aimed to determine the Global Warming Potential (GWP) of the road pavement in kilograms of CO_2 equivalent, covering all stages from raw material extraction to end-of-life.

It should be noted that module B5 represents the refurbishment of the asset. This module covers all the technical and administrative actions undertaken to restore the pavement to a condition that enables it to perform its original required functions. These activities include a detailed maintenance program, repair, and/or replacement of a significant portion or complete section of the pavement. Hence, the B5 phase was not considered since there were no projections to extend the pavement's service life that require major refurbishment activities. Similarly, all end-of-life modules (C1-C4) would be accounted for in the relevant stages B2-B4 when individual pavement materials/layers have reached the end of their service lives or the 40-year pavement design life.

Lastly, B7 represents the operational water consumption. The assessment does not account for this module because water demand during the service life of pavement assets/infrastructure is not directly related to infrastructure use. The same water consumption would occur even without the infrastructure. Therefore, since operational water use is not specific to the pavement asset, it is excluded from the assessment.



Life cycle stages	Product stage			Construction stage		Use stage							End of life				Benefits and loads beyond the system boundary
Modules	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
	Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Reuse / Recovery / Recycling potential
Included	v	v	v	v	v		v	v	v								

Figure 1: Life cycle stages and modules used for the LCA of this scheme

The analysis utilised a unique database integrating the project location with local sourcing sites and available materials to undertake the transportation analysis. This approach considered logistical constraints of permitted Heavy Goods Vehicle routes, including weight limits, carriageway width, and height restrictions, to precisely calculate transportation distances and associated CO2 emissions. The sourcing environment involved eight asphalt plants within a 45-kilometre radius, three concrete plants within 20 kilometres, and 20 quarries within 30 kilometres, as illustrated in **Figure 2**.

Figure 2: Sourcing environment used within the analysis, from the ORIS platform

4 RESULTS AND DISCUSSION

4.1 Pavement construction cost

Among the evaluated options, the fully flexible pavement with a TSCS emerged as the most cost-effective choice in terms of direct construction cost, amounting to £2.33 million. This design option presented a reduction of 18% compared to the base design, which incurred costs of £2.83 million. The fully flexible pavement with a HRA surface offered another favourable alternative with a cost of £2.45 million, resulting in a cost reduction of approximately 13% compared to the base design. Similarly, the flexible pavement on a HBGM-B design proved to be cost-effective, with a total construction cost of £2.47 million, yielding a comparable reduction of approximately 13% also. **Figure 3**, taken from the ORIS dashboard, provides a visual representation of the pavement design option costs.

4.2 Whole Life Cost

During the WLC appraisal, the analysis took into account the maintenance activities required for each design option and their respective intervention periods (see **Table 2**), over the 60-year analysis. Based on the NPSV, the fully flexible pavement with a TSCS demonstrated the greatest economic advantage, with an NPSV of £3.23 million. Following closely was the flexible pavement on a HBGM-B base with a TSCS, which yielded an NPSV

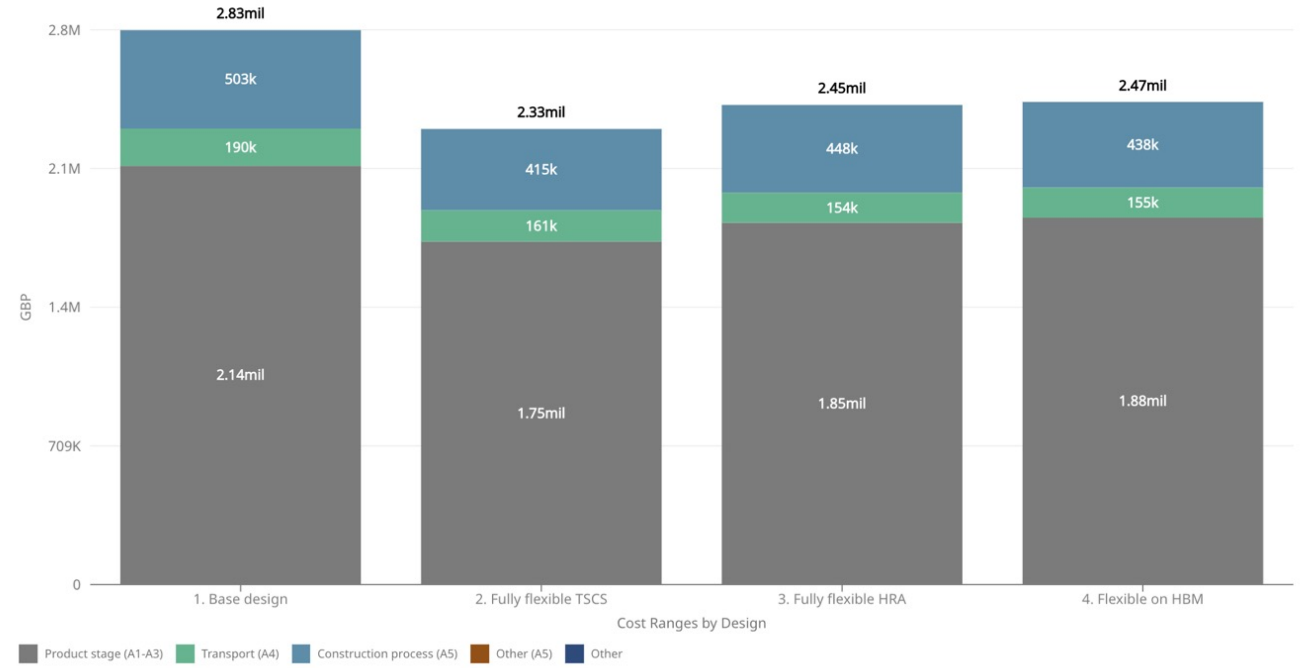
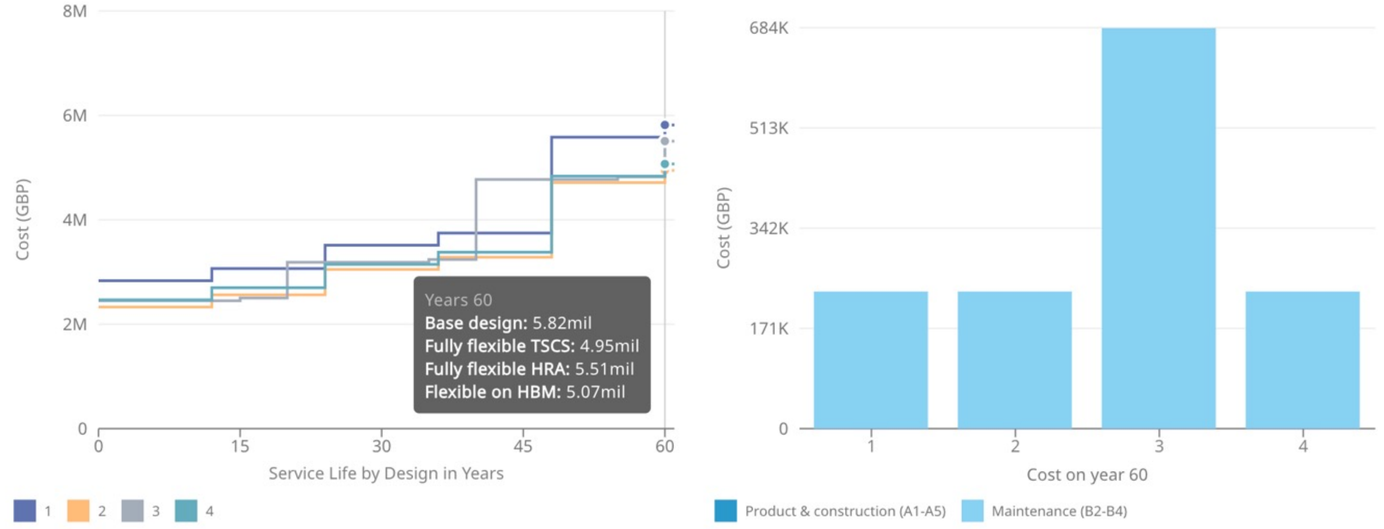


Figure 3: Total construction cost (£) of the pavement design options evaluated



(a) (b)

Figure 4: Cumulative construction and maintenance cost (£) of the pavement design options over the 60-year analysis period, and (b) maintenance cost in year 60.

of £3.36 million, as indicated in **Table 3**. Despite the higher residual value at the end of the 60-year analysis period due to the replacement of HRA surface and binder layers in year 60 (as shown in **Figure 4**), the fully flexible pavement with a chipped HRA surface proved to be the least economically beneficial option, with an NPSV of £3.42 million.

The WLC appraisal was supplemented with a sensitivity analysis that involved varying the surfacing life of the TSCS and HRA surfacing across the different pavement design options, as shown in **Table 2**. Whilst the selection of the preferred design option based on the lowest NPSV remained unaffected by the surfacing life expectancy, it did impact the ranking of the NPSV values among the options, as presented in **Table' 3 and 4**.

	Base design	Fully flexible TSCS	Fully flexible HRA	Flexible on HBGM
Discounted costs (£)	3,857,107	3,265,006	3,525,248	3,393,409
Discounted residual value (£)	35,228	35,228	101,280	35,228
NPSV (£)	3,821,879	3,229,779	3,423,968	3,358,181

Table 3: Results from the Whole Life Cost (WLC) sensitivity analysis in GBP (scenario 1 service lives).

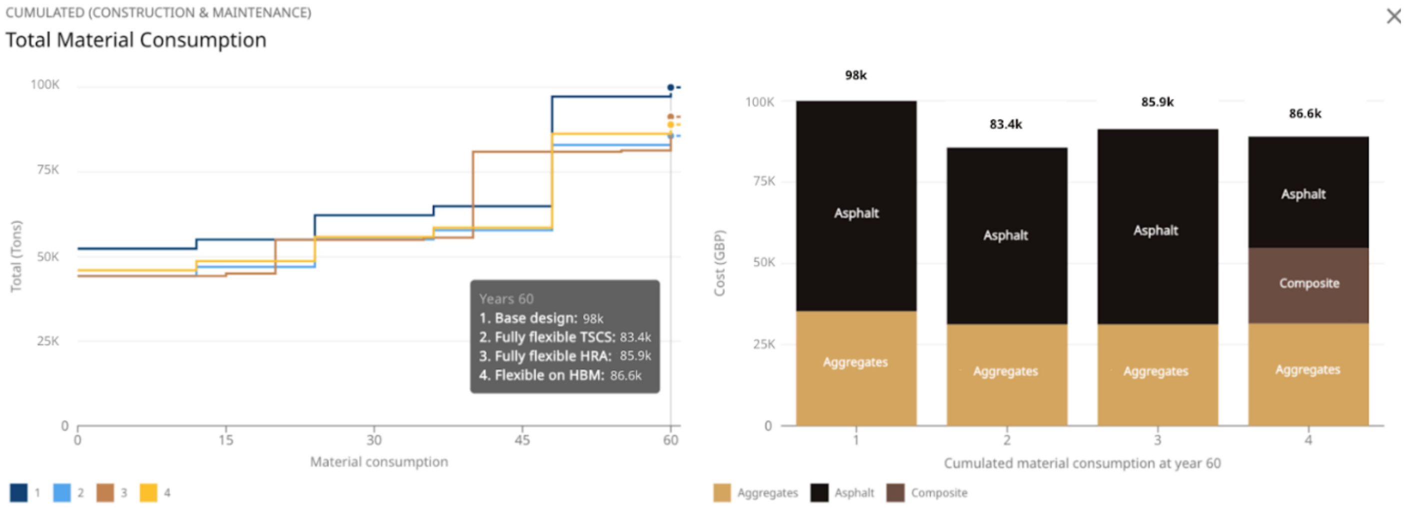
	Base design	Fully flexible TSCS	Fully flexible HRA	Flexible on HBGM
Discounted costs (£)				
Scenario 2	4,101,821	3,496,784	3,629,029	3,615,260
Scenario	3,765,319	3,160,576	3,298,150	3,293,674
Discounted residual value (£)				
Scenario 2	64,584	64,584	64,584	64,584
Scenario 3	35,228	35,228	35,228	35,228
NPSV (£)				
Scenario 2	4,037,237	3,424,861	3,558,407	3,550,676
Scenario 3	3,730,091	3,125,348	3,294,610	3,258,446

Table 4: Results from the Whole Life Cost (WLC) sensitivity analysis in GBP (scenario 2 and 3 service lives).

4.3 Material consumption

Throughout the 60-year analysis period, the fully flexible pavement with a TSCS demonstrated the lowest material consumption, amounting to 83,400 tonnes, as shown in **Figure 5**. This represented a notable reduction of 15% (98,000 tonnes) compared with the base design. Conversely, the flexible HBGM design required a total of approximately 86,600 tonnes of materials, making it the highest-consuming design option among those three evaluated against the base design. This higher consumption was primarily attributed to the materials needed for the (170 mm) HBGM layer replacements over the 60-year analysis period.

However, it is worth noting that the TSCS proposed for the fully flexible and for the flexible with HBGM base designs incorporated locally available steel slag aggregate, replacing 50% of the natural aggregates used in this TSCS layer. This replacement of natural aggregates with steel slag resources led to substantial savings, amounting to 3,900 tonnes in reduced consumption of natural materials. Lastly, the fully flexible with a chipped HRA design generated a material quantity exceeding 85,900 tonnes throughout its lifespan, as shown in **Figure 5**.

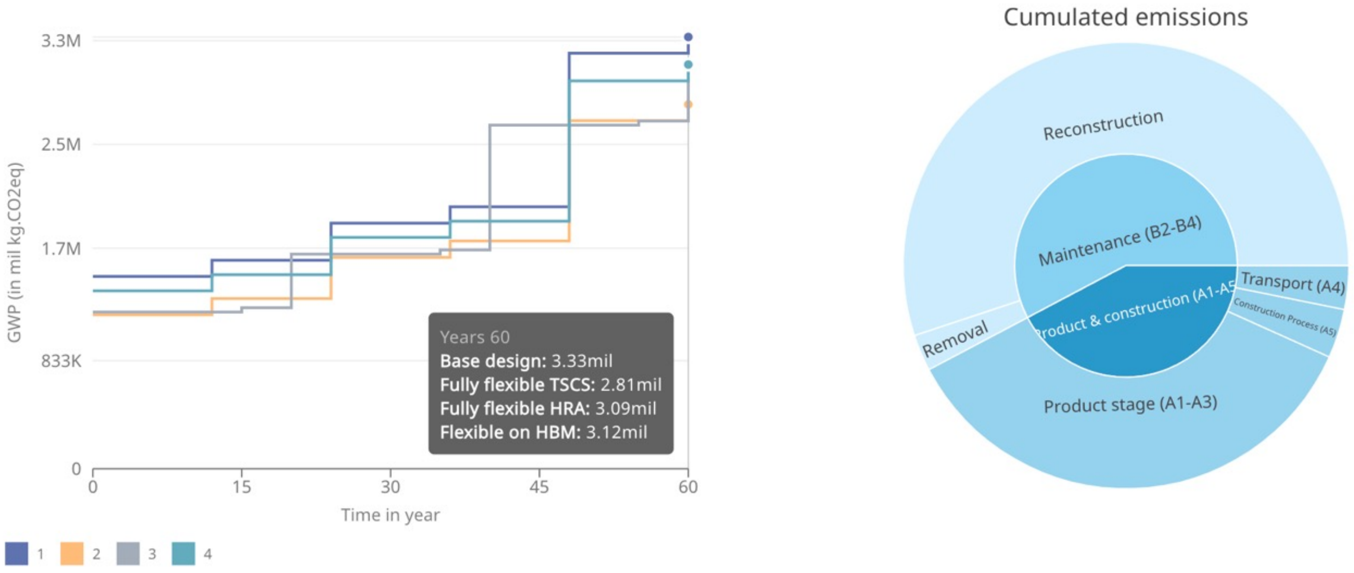


(a) (b)

Figure 5: Cumulative construction and maintenance material consumption (tonnes) of the pavement design options over the 60-year analysis period, and (b) total material consumption over the analysis period.

4.4. Whole Life Carbon

In terms of environmental sustainability, the fully flexible TSCS design proved to be the most favourable option among the pavement design alternatives, emitting a total of 2,810 tonnes of CO2 equivalent (tCO$_2$e) over the analysis period. Comparatively, the fully flexible HRA and flexible on HBGM designs resulted in carbon emissions that were 10% and 11% higher than the fully flexible pavement with a TSCS, with emissions of 3,090 tCO$_2$e and 3,120 tCO$_2$e, respectively, as depicted in **Figure 6**.



(a) (b)

Figure 6: Carbon emissions (kg.CO2eq) of the pavement design options evaluated by ORIS over the 60-year analysis period and, (b) detail of the cumulated emissions of the fully flexible TSCS design.

Furthermore, it is important to note that approximately 58% of the carbon emissions were attributed to maintenance activities, as illustrated in **Figure 6**. This emphasises the significance of evaluating the entire life cycle of an infrastructure project, as it allows for a comprehensive assessment of environmental impacts and underscores the importance of adopting sustainable practices throughout the project's lifespan.

5 CONCLUSION

The digitalisation of the value engineering, whole life costing and carbon equivalence analysis by AECOM, using ORIS technology, played a crucial role in the early-stage design of a link-road construction project. The assessment focused on evaluating the Whole Life Cost and environmental impact of various pavement designs over a 60-year analysis period. The appraisal not only bolstered AECOM's existing commitment to sustainability but also facilitated further optimisation by considering alternative options and local constraints/opportunities, including the utilisation of by-products from the local steel industry.

The impact assessment highlighted that the client's assumed "preferred" design option may not always be the most sustainable choice. It emphasised the significance of utilising local materials, which not only reduces transportation emissions and costs but also minimises the carbon footprint whilst supporting the local economy and alleviating the strain on premium natural resources. In this case study, the proposed pavement designs exhibited potential savings of approximately 15% in terms of cost, carbon emissions, and material consumption over the 60-year analysis period when compared with the client-preferred design. Additionally, the incorporation of locally available steel-slag in asphalt mixtures led to a 45% reduction in the consumption of natural resources.

Overall, the collaboration between ORIS and AECOM has demonstrated the significance of holistic sustainability assessments, the importance of local material utilisation, and the substantial benefits of digitisation in achieving cost-effectiveness, environmental preservation, and resource efficiency in highway infrastructure projects.

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