DEVELOPMENT OF A WHOLE LIFE CYCLE COST BENEFIT (LCCB) MODEL FOR ENHANCED PERFORMANCE SURFACING MATERIALS

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ABSTRACT

Enhanced or modified bituminous binders for asphalt have an influence on the characteristics of the asphalt mix and its performance in the surfacing layers of road pavements. Modified binders typically cost more than unmodified binders and it is therefore desirable to demonstrate, and quantify, the economic benefits of modified binders, in order to justify their higher cost. A deterministic Whole Life Cycle Cost Benefit (LCCB) model was developed to investigate where modified binders could have a life cycle cost benefit in the UK. The model includes deterioration relationships, a range of maintenance treatments and calculation of road user costs due to delays through maintenance sites. Based on the input data, the model can identify the maintenance scenario that gives the lowest life cycle costs over an analysis period or the maintenance scenario that yields the greatest economic return (life cycle cost savings) against the initial investment costs. Using the model, the proportional improvements in resistance to rutting, skidding and structural deterioration (residual life) required to justify the increased cost of modified binders were evaluated. A translation layer was also developed; this allows the input performance parameters required by the model to be derived from the results of laboratory testing of the binder and reference asphalt mixes.

Keywords: whole life costing, polymer modified bitumen, life cycle assessment, modified binders, performance testing

1 INTRODUCTION

Polymer-modified bituminous binder products (PMBs) have long been used to extend the performance characteristics of asphalt mixes. However, the process costs associated with introducing polymers results in a higher purchase price compared with conventional paving-grade bitumen. The gap is widened further when "Premium" binders, using combinations of modifiers and processing techniques, are considered. In the current financial climate, with public spending cuts and other financial austerity measures affecting infrastructure investment in the UK, the need to demonstrate the products' cost effectiveness is becoming greater. Higher up-front material costs need to be offset against cost savings, either immediately (e.g. faster installation, reducing user delays and plant and labour costs) or over the whole life of the pavement (e.g. reduced maintenance requirements due to greater longevity), when compared to conventional binders.

One approach to demonstrating these benefits is life cycle cost benefit modelling, the systematic consideration of all costs over a project's lifetime (or a specified analysis period) to identify the minimum total outlay over that period. To model a road pavement over a specified analysis period, the likely deterioration must be known; typically, this will be a function of the elapsed time, the previous condition and the level of traffic using the pavement. Established deterioration relationships are available for conventional materials in use in the UK but, although binder and asphalt mix tests are available to measure a range of the properties of PMBs, no reliable methodology currently exists to relate these material test results to the behaviour of the road pavement.

Typically, life cycle pavement cost analyses have used historical data or engineering expertise to determine performance [1]. Academic research has focused on performance prediction models [2]. However, none of these methods apply when considering new materials. The behaviour of newly-developed materials in road pavements can be established using full-scale trials, but this is a time-consuming and expensive process. By contrast, if the pavement performance can be adequately predicted by determining the critical material properties based on laboratory testing, the economic modelling can be carried out quickly to demonstrate the benefits of these products.

In 2009, Nynas Bitumen launched its Performance Programme™ initiative. Its objective is to help foster a greater understanding of cost-benefit delivery and facilitate product selection based on best value for any situation. To this end, Nynas Bitumen commissioned TRL to develop a modelling framework to translate asphalt mix test results into pavement properties and run a comparative life cycle cost analysis based on these results, demonstrating the most cost-effective maintenance profile for polymer-modified binders compared to their conventional equivalents.

2 PAVEMENT MODELLING FRAMEWORK

The pavement modelling framework developed by TRL consists of two principal components:

1. An **input file generator**, developed using Visual Basic for Applications (VBA) and contained in a Microsoft Excel spreadsheet; and

2. A **life cycle cost optimiser**, developed using the Python programming language and GTK user interface toolkit.

The input file generator allows the user to specify the application scenario, analysis settings, pavement design and asphalt mix test results, producing input files in an extensible mark-up language (XML) format. Advanced users of the tool can develop complex analyses by editing the user input data file directly, combining multiple construction options into a single analysis file to perform a sensitivity analysis.

The life cycle cost optimiser takes this user input data file, along with a country-specific default data file, and calculates the optimal maintenance profile for the modified binder and conventional designs. The life cycle cost optimiser also enables the utilisation of a sensitivity analysis-based "reverse life cycle costing" approach; varying a range of pavement performance parameters and associated costs to identify the desired material characteristics that generate the greatest benefits in life cycle cost terms.

Although the model has been developed for use in a UK context, the modular design of the life cycle cost optimiser and flexible nature of the data input files mean that the system can easily be adapted for use in other countries; plans are underway to extend the project to include continental Europe and Nordic regions. Future developments will also see the adaptation of the asPECT protocol to add carbon emission calculations to the outputs, adding a consideration of sustainability to the decision making process. This paper focuses on the application of modified binders in the surface layers; similar analyses could be applied to the base or binder layers.

3 INPUT FILE GENERATOR

3.1 Application scenario

The application scenario provides the context for the analysis, specifying the type of road (e.g. dual carriageway), initial traffic levels for each carriageway, and the location of the road (this is used to select appropriate traffic growth rates from the forecasts in the UK Department for Transport's National Transport Model (NTM) [3]). This allows the rapid tailoring of an analysis to a specific client or the modelling of a developmental product across several scenarios to see which of the scenarios would benefit most from the use of the product.

Traffic is specified as a starting average annual daily flow (AADF) and the proportion of these vehicles that are heavy goods vehicles (HGVs), along with the year in which these data were recorded. The road is specified as dual or single, along with the number of lanes and whether or not it is a motorway. The location is specified as a region (e.g. North-East) and an area (e.g. Urban), reflecting the options in the National Transport Model. The model automatically assigns the appropriate proportion of each carriageway's heavy vehicle traffic to each lane, and includes a maximum traffic capacity for each road type, beyond which the traffic will not be grown.

3.2 Analysis settings

The analysis settings cover the basic attributes of the analysis; specifically, the analysis period (i.e. the length of the period over which costs will be considered) and the base year (the starting year) for the analysis. The former is set to 60 years for UK central government procurement (as mandated by current guidelines [4]), but would probably be shorter for private sector clients, who want to realise an earlier return on their investment. The latter defaults to 2008, the base year for the default cost data (taken from Spon's [5]) used in the model calculations. Selection of a base year other than 2008 would require indexation of the model cost data from 2008 to the required year.

3.3 Pavement design

The pavement is modelled as containing three layers; base course, binder course and surface course. The user specifies the thickness of each of these layers and whether the modified or conventional binder product is used in the layer. This allows, for instance, a design incorporating conventional materials in the base and binder courses and a modified binder in the surface course. The overall cost of the modified material (as a proportion of the cost of the conventional material) is also set by the user; this is the total unit cost of the asphalt mix, allowing the variation of both binder and aggregate costs.

3.4 Asphalt mix test results

Results from a range of asphalt mix tests are entered and are converted to equivalent pavement performance. Some of these conversions use simple relationships; for instance, the ratio between rutting rates (mm per year) for conventional and polymer-modified pavements is assumed to be proportional to the ratio of either wheel-tracking slope (µm per cycle at 60°C) or proportional rut depth (% at 50°C). Others conversions are more complex; two of these are discussed in sections 3.5 and 3.6.

3.5 Deformation and output rate

Among the benefits of asphalt mixes using modified binders are lower working temperatures and a greater resistance to deformation. Combining these attributes suggests that the road could be opened to traffic earlier after the laying of the surface course, leading to reduced costs of user delays, labour and plant hire. To model this benefit, wheel-tracking rates (µm per cycle) are measured for asphalt mixture samples at various temperatures (70°C, 50°C and 30°C). A logarithmic regression is then used to provide the relationship between wheel-tracking rate and material temperature (Figure 1).

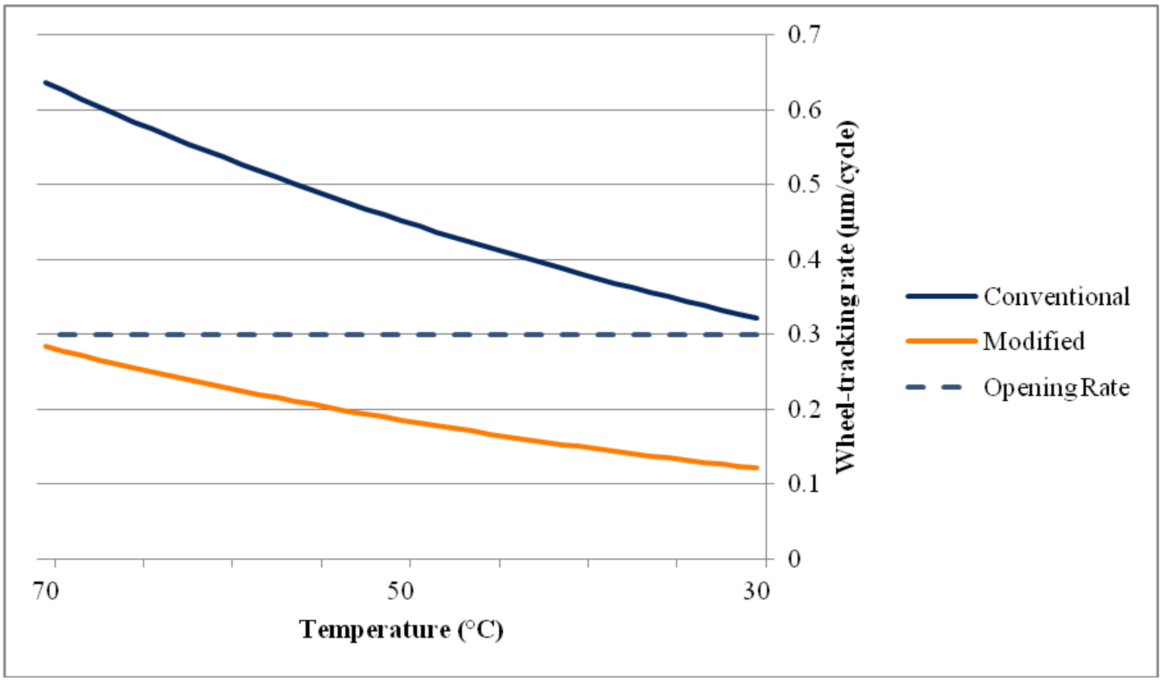

Figure 1: Example relationship between mix temperature and wheel-tracking rate

Combining this relationship with the laying temperatures of the conventional and modified materials (e.g. 140°C in Figure 2) and a wheel-tracking threshold, below which the road will be considered suitable for opening (e.g. 0.3μm per cycle in Figure 1), allows the calculation of the difference in time (from laying the surface layer to opening the road) for each product, using equations developed by Nicholls *et al*. [6]. The ratio of the cooling times (Figure 2) is assumed to be the ratio of the output rates (i.e. the rates at which the pavement can be constructed, measured in m^2 per hour) of the surface courses for conventional and modified materials. To ensure that the pavement is not modelled as opening at too high a temperature for safe vehicle operation, a maximum opening temperature is set (e.g. 50°C in Figure 2).

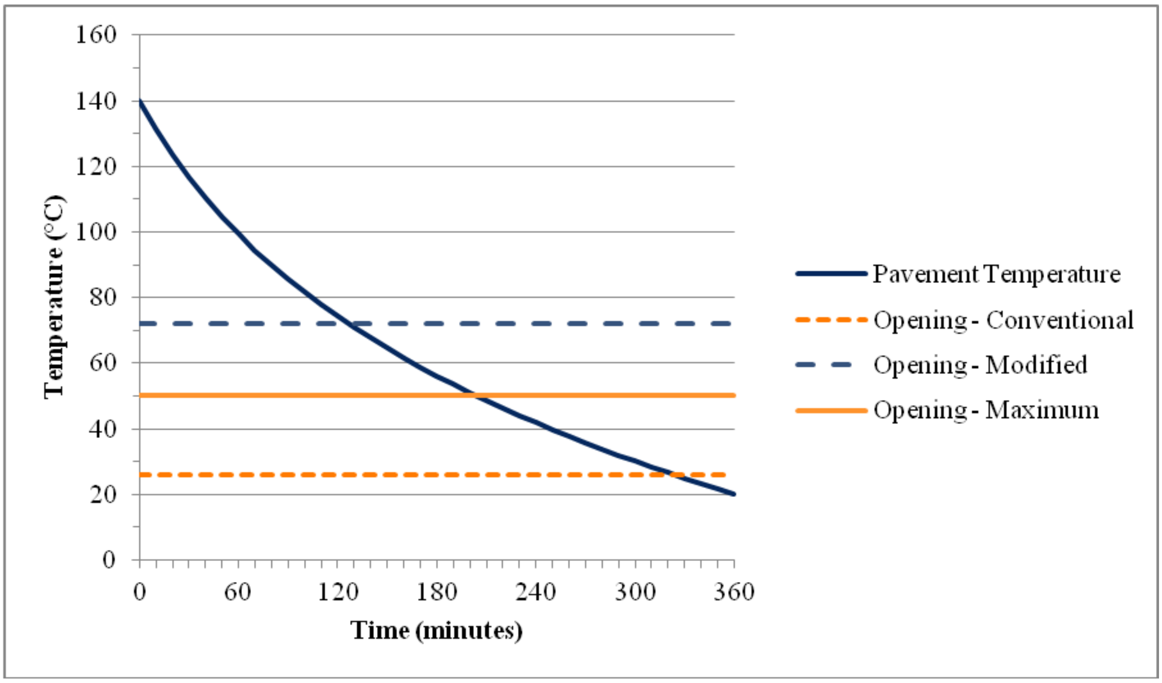

Figure 2: Example pavement cooling curves (assuming 15°C ambient temperature, 10km/h windspeed)

The output rate will affect the unit cost of laying the material (as the per-unit labour and plant hire costs are reduced for higher output rates) and the traffic management and user delay costs (as the traffic management arrangement will be in place for a shorter period of time). Based on the values in Figure 1 and Figure 2, for instance, the surface course output rate for the modified binder would be approximately 159% of the rate for the conventional material.

3.6 Independent factors

For some pavement performance parameters, such as cracking and fretting, the various contributing factors are separate causes, one of which will prove to be the "weakest link" and start the deterioration. Determining which factor this will be requires significant site-specific knowledge; gathering this information is not considered practicable for modelling at this level. To combine these factors, therefore, a root mean square (RMS) method is used to calculate the total comparator R as shown in equation 1:

$$R = \sqrt{\frac{f_1 r_1{}^2 + f_2 r_2{}^2 + \cdots}{f_1 + f_2 + \cdots}} \qquad (1)$$

where r_x are the individual ratios for the constituent test results and f_x are weighting factors (currently all set to 1).

4 LIFE CYCLE COST OPTIMISER

The life cycle cost optimiser uses the concept of maintenance profiles, lists of the years within the analysis period in which maintenance is performed, along with the specific maintenance activity to be applied in that year. For each construction option (i.e. conventional or modified), carriageway and lane the optimal maintenance profile is calculated by selecting the valid profile with the lowest Net Present Value (NPV) using an exhaustive, depth-first search.

4.1 Net Present Value

The NPV is the sum of all costs incurred through the analysis period, discounted back to the base year. The optimiser includes both direct (those that must be paid by a specific party) and indirect (those that are not paid by a specific party) costs. The following are included:

- **Works costs**, the direct costs for both the initial (re)construction of the pavement and any ongoing maintenance requirements, including the costs of materials, plant hire and labour;
- **Traffic management costs**, the direct costs of providing and maintaining the traffic management (TM) arrangement necessary to protect the road workers during each maintenance intervention;
- **User delay costs**, the indirect cost (to the economy as a whole) of delaying vehicle occupants through the TM arrangements; and
- The **residual value**, at the end of the analysis period, of any maintenance interventions that have been carried out.

For the discounting, needed to equitably compare costs in different years, the optimiser uses a "time preference model of real discount rates" [7]; specifically, the first 30 years use a 3.5% p.a. discount rate, the next 30 use a 3.0% p.a. discount rate. These rates are set by the UK Treasury for central government procurement; as with the analysis period (see §3.2), a private sector client may use a higher discount rate to drive an earlier return on investment.

4.2 User delay costs

The user delay costs used within the model are based on suites of analyses performed using the UK Department for Transport's Queues And Delays at Roadworks (QUADRO) closure modelling tool. For each road type and traffic management arrangement (e.g. a single lane closure on a three-lane motorway) a delay curve maps the flow-capacity ratio of the road to an average per-vehicle delay time, as shown in Figure 3.

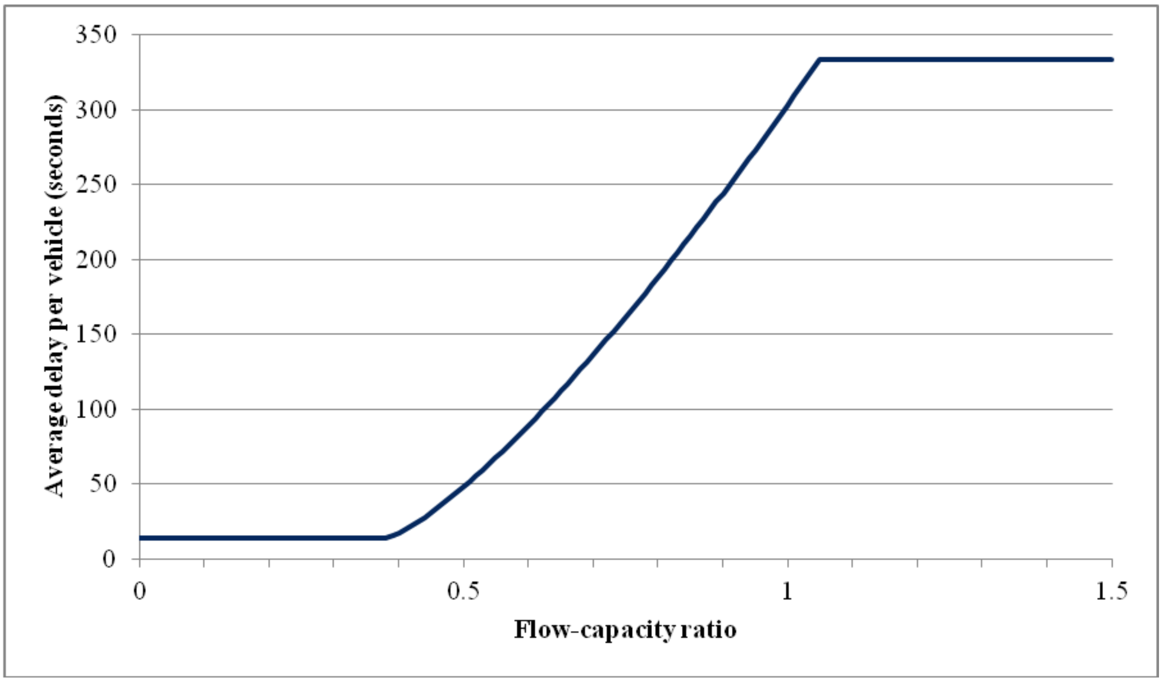

Figure 3: Delay curve for a single lane closure on a three-lane motorway

Lookup tables provide the breakdown of traffic into various road user and vehicle types; each of these categories has a value of time, as shown in Table 1 [8]. Using the proportions of vehicles in each category, which vary depending on the time of the day and the day of the week, the model calculates the delay costs for each day in a complete week in the appropriate year (seven days starting from the 1st of July) then combines these to give an average per-day delay cost for that closure type. This assumes that the maintenance is carried out under a constant closure, rather than a day-only or night-only arrangement.

Table 1: Value of time by road user and vehicle type

Road user type	Value of time (£ per hour, 2002 values)				
	Car	Light Goods Vehicle	Other Goods Vehicle (2- or 3-axle, rigid)	Other Goods Vehicle (more than 3 axles or articulated)	Public Service Vehicle (e.g. bus)
Working	24.99	10.10	8.42	8.42	59.16
Commuting	4.75	6.63	n/a	n/a	n/a
Not Working	6.81	5.85	n/a	n/a	n/a

The delay cost model also includes rates for the growth in value of time from the 2002 baseline.

4.3 Residual value

To make an equitable comparison between different maintenance profiles and ameliorate the effects of applying an arbitrary analysis period (rather than using a "cradle-to-grave" approach, which is complex with a life-extensible asset like a road), the remaining value of the maintenance activities carried out during the analysis period is credited back to the NPV in the final year of the analysis. The last maintenance activity within the analysis period is assumed to lose value linearly from the point of intervention to the point at which the next intervention will be required. To ensure that the differing service lives of the pavement's surface and structure are captured appropriately, if the last intervention in the analysis affects only the surface, the remaining value of the last structural treatment is also included.

An example of this calculation, assuming linear deterioration of both the surface and the structure of the road, with surface and structural treatments costing £250,000 and £900,000 respectively (and lasting 15 and 40 years respectively) and a 40-year analysis period, is shown in Figure 4; the residual value is the sum of the surface and structure maintenance values at the end of the analysis period (£485,000, which would be discounted to £128,574 before being subtracted from the NPV).

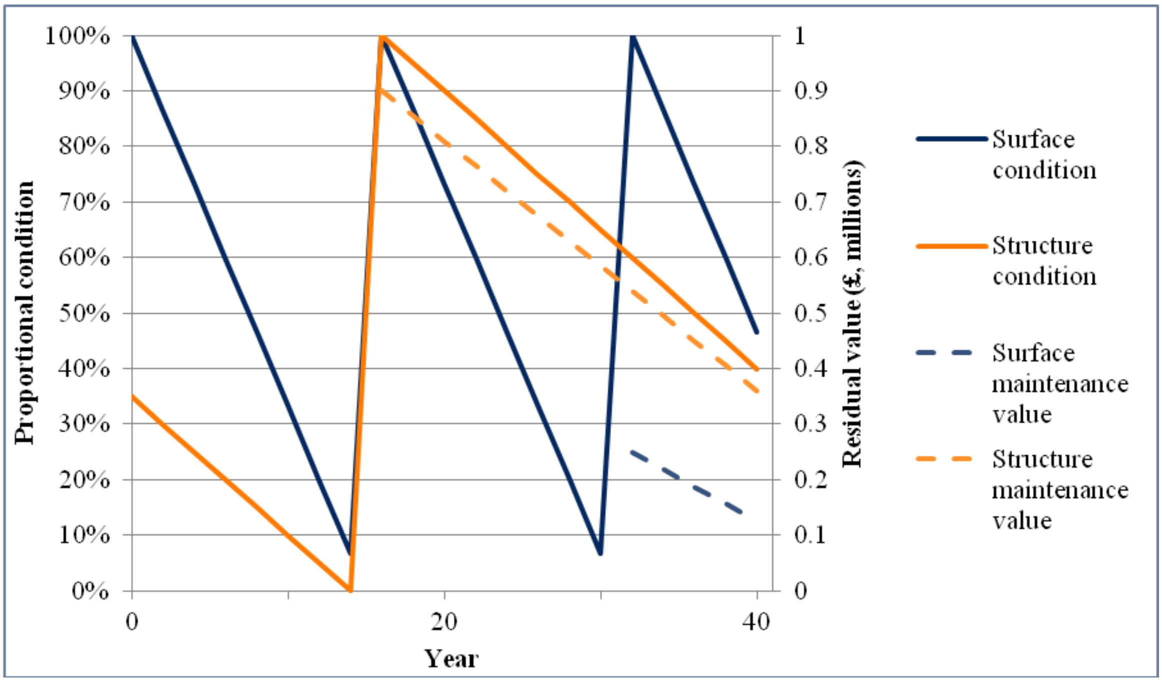

Figure 4: Example residual value calculation

The residual value ensures that the last maintenance intervention is not automatically pushed beyond the end of the analysis period; it attaches a value to leaving the pavement in good condition.

4.4 Performance modelling

The performance of the pavement is modelled as a set of independent condition parameters, each of which has a starting value, a deterioration relationship and intervention criteria. The deterioration relationships are specified in the model in terms of elapsed time Δt (linear only), condition C (up to the fourth power) and traffic T (up to the fourth power, either AADF, commercial vehicles (CV) per day or million standard axles (MSA)), along with a constant, as shown in equation 2:

$$C_t = x_0 + x_1\Delta t + x_2 T_{t-\Delta t} + x_3 C_{t-\Delta t} + x_4 {T_{t-\Delta t}}^2 + x_5 {C_{t-\Delta t}}^2 + x_6 {T_{t-\Delta t}}^3 + x_7 {C_{t-\Delta t}}^3 + x_8 {T_{t-\Delta t}}^4 + x_9 {C_{t-\Delta t}}^4 \quad (2)$$

For each performance parameter, either larger or smaller values can be set to represent better condition.

The intervention criteria for each parameter consist of an investigation level and either an intervention level (where specific values are known) or investigatory period (where estimates of the lifetime of the parameter must be made). Once a parameter reaches its investigation level, applying a maintenance activity to improve it becomes an option. Once the parameter reaches its intervention level, or the investigatory period has elapsed since reaching the investigation level, maintenance must be applied to improve the parameter. For example, the investigation level, investigatory period and intervention level for rutting are shown in Figure 5; note that maintenance is carried out in 2020, resetting the rut depth to a smaller value.

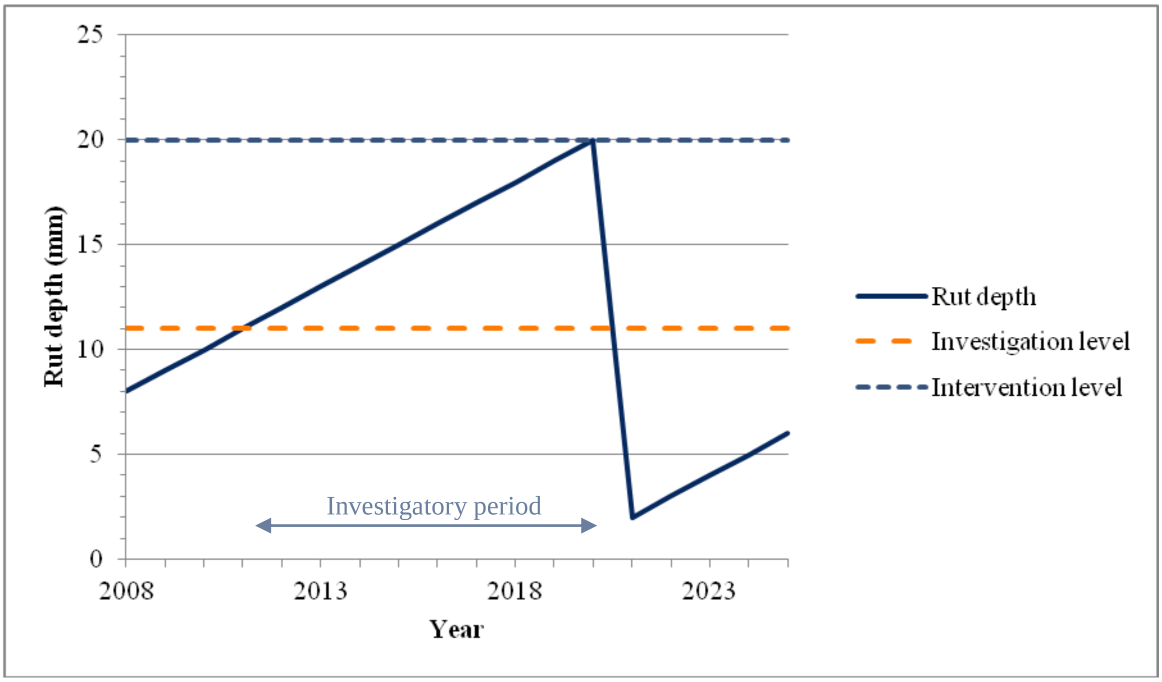

Figure 5: Deterioration, investigation level and intervention level for rut depth

4.5 Maintenance activities

Each maintenance activity is represented as a works cost (£ per m^2), an output rate (m^2 per hour) and a set of parameter resets, which can either be a value (e.g. rutting is reset in mm) or a lifetime to the next investigatory period. Each activity also specifies a number of lanes which must be closed for a single lane to be treated; this is automatically converted to a traffic management arrangement by the model, according to the road type selected for the analysis.

For each year in the analysis period, one or more maintenance activities (including no activity, if no parameters have reached the intervention level) can be selected by the model. The model selects appropriate maintenance activities based on the parameters which are at the intervention level or in the investigatory period and which of those parameters are affected by each activity. To ensure that maintenance activities are being used effectively, precedence is given to those activities where at least half of the reset parameters are at the intervention level or in the investigation period (e.g. reconstruction, which resets three parameters, will only be carried out if at least two of the parameters need investigation or intervention).

4.6 Optimisation

The model works through every valid maintenance profile, according to the selection rules outlined above. Each year is considered in turn; appropriate deterioration is applied to all condition parameters, then a list of appropriate maintenance activities is generated. If more than one treatment option is available in that year, the model picks one to complete the current run and adds the other, part-completed maintenance profile(s) to the end of a list. As each profile is completed, the model retrieves the part-completed profile most recently added to this list and continues the analysis from the last maintenance activity listed in the profile.

Throughout the optimisation process, the model tracks the maintenance profile with the lowest NPV to that point; if a newly-completed maintenance profile has a lower NPV, it replaces the previous profile. At the end of the optimisation process, the profile with the lowest NPV is considered to be the optimum. A snapshot of this process, showing the NPVs of a number of analysed profiles, is given in Figure 6.

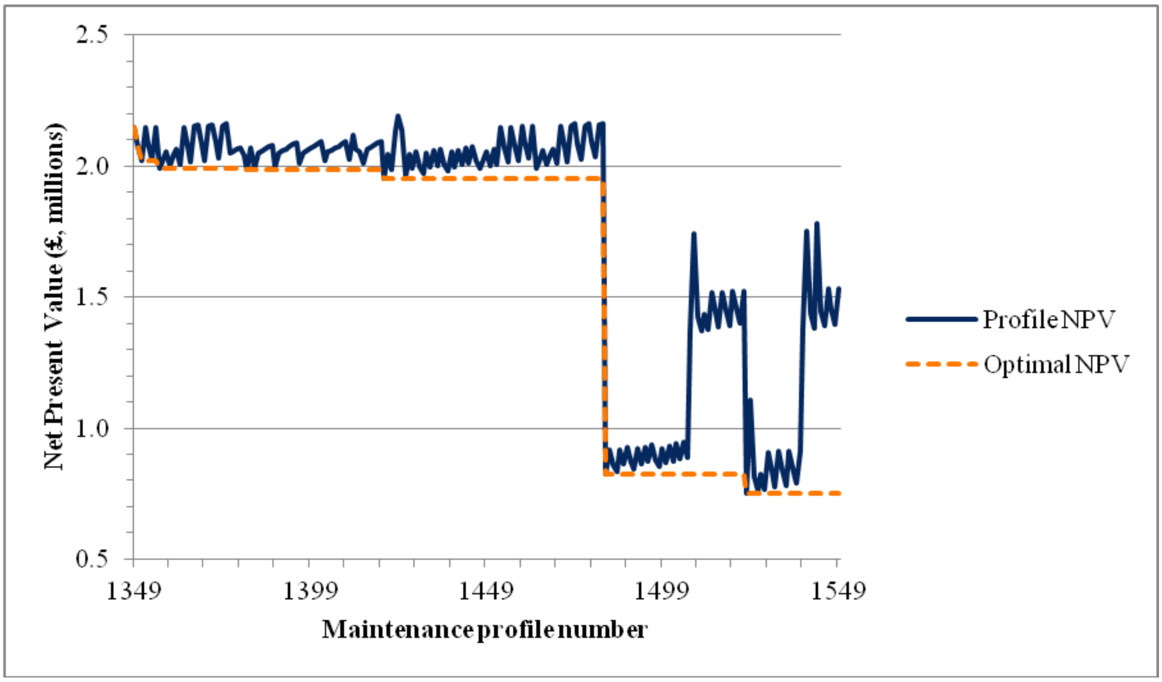

Figure 6: Snapshot of the optimisation process

5 RESULTS

To demonstrate how the framework can be used, two sets of results have been produced, comparing Nynas' Endura Z2 Premium binder to a standard 40/60 binder. This polymer-modified binder is relatively hard, with a penetration value of 25, and combines additives to improve workability with a specially-selected bitumen suitable for heavily loaded areas. The modelled road comprised 10km of dual carriageway with around 37,000 vehicles per carriageway per day, of which 15-20% were heavy goods vehicles. Traffic growth rates for large urban areas in the East Midlands were used.

For all of the analyses, three pavement performance parameters have been modelled; sideway-force coefficient (SFC, also referred to as surface friction), rutting and residual structural traffic capacity. Other performance parameters that may be affected by the choice of binder (e.g. cracking and ravelling) have not been modelled. The available maintenance activities were thin surfacing (resets only SFC), 50mm inlay (resets rutting and SFC) and reconstruction (resets all parameters).

Only the surface course was modelled as including modified materials, so only the rate of rutting is affected by material choice (lower layers affect structural capacity and the binder was assumed to have no effect on the rate of SFC deterioration). All maintenance is like-for-like (i.e. modified materials are replaced with new modified materials and conventional materials are replaced with new conventional materials).

5.1 Comparative analysis

Figure 7 shows the cumulative Present Value for baseline and modified construction options; the total NPV for each option is the cumulative total in 2068. The proportional material cost for the asphalt mix using polymer-modified binders as opposed to penetration-grade binders was set to 139%, based on a conventional asphalt price of £80 per tonne. Overall, using the modified binder leads to life cycle cost savings of over £2.5 million, approximately 6% of the baseline NPV, with maintenance being deferred towards the end of the analysis period. Particularly in the second half of the analysis, the increased durability of the asphalt mix using the modified binder allows maintenance to be deferred

To show the relative contributions to the NPV, Figure 8 separates the direct costs (of works and traffic management) from the indirect costs (of user delays). Throughout the analysis, the user delay costs form a significant fraction of the NPV; from around 2040, the indirect costs due to a maintenance intervention are larger than the direct costs. It is also clear that the cost-effectiveness of the modified binder does not rely on the effects of indirect costs; both direct and indirect cumulative Present Values are lower.

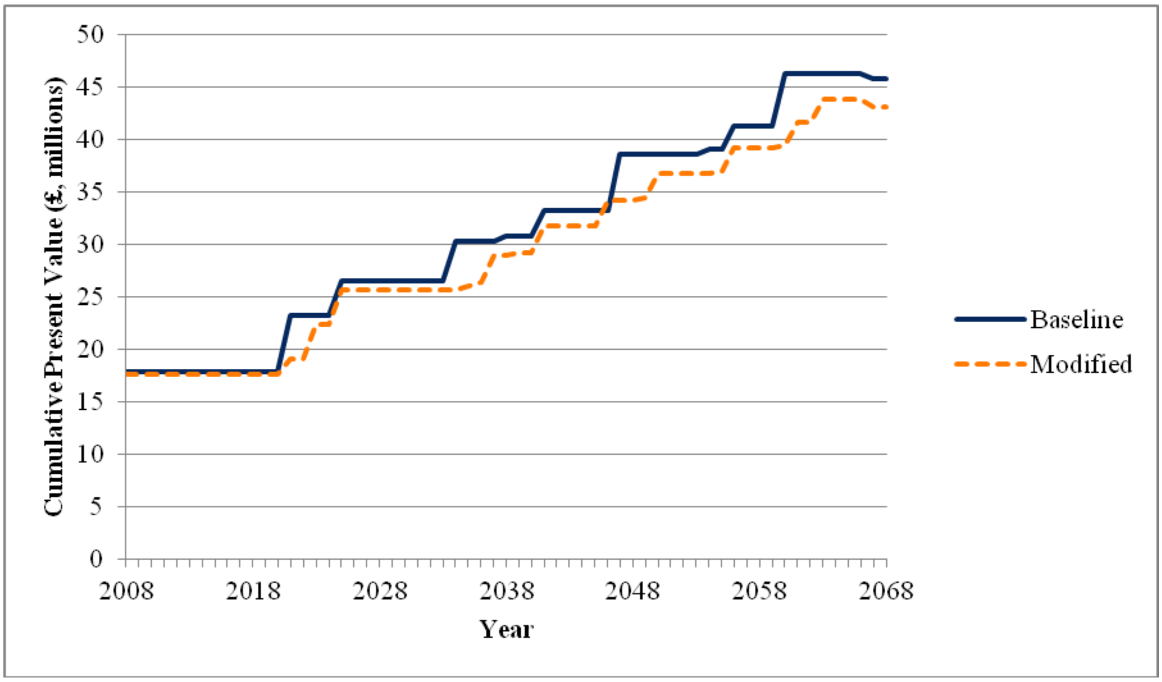

Figure 7: Cumulative Present Value of comparison options

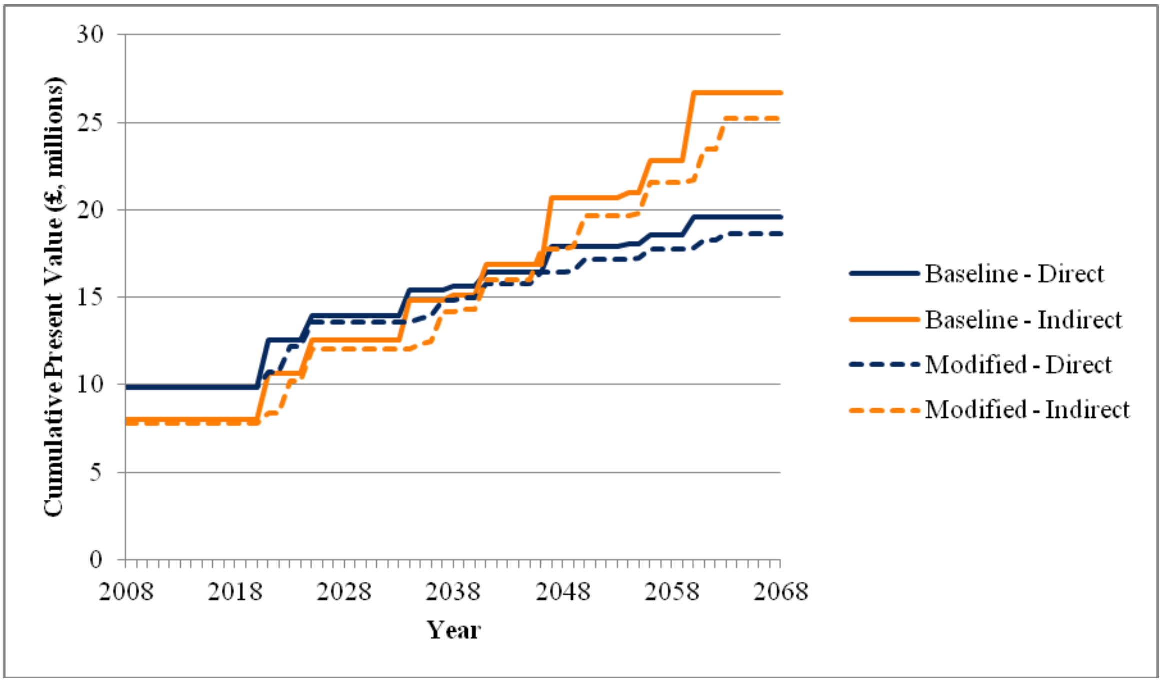

Figure 8: Cumulative Present Value of comparison options by cost type (excluding residual value)

The longevity of the material has a significant effect on the results. These results show that, if the modelled performance gains can be demonstrated through appropriate testing, the use of modified binders in the surface course asphalt mix can be justified from a life cycle cost approach, despite the higher material costs.

5.2 Sensitivity analysis

The second, "reverse", modelling approach involves running near-identical analyses with one or more parameters varied over appropriate ranges. This allows the potential outcomes from the use of modified binders to be understood before all of the appropriate material performance information is available from testing or other means; for instance, predicting an appropriate cost point for a material of known properties.

First, the analysis performed in §5.1 was repeated with various costs, increasing in ten percentage point increments from the 120% to 160% (Figure 9) and including the calculated 139% price point. By running analyses with the costs varied in this way, it can be demonstrated where the break-even points lie and what appropriate prices for the material would be. In this case, even if the modified asphalt mix is 60% more expensive than a conventional mix (implying a modified binder 213% more expensive than the conventional equivalent), its whole life cost is lower.

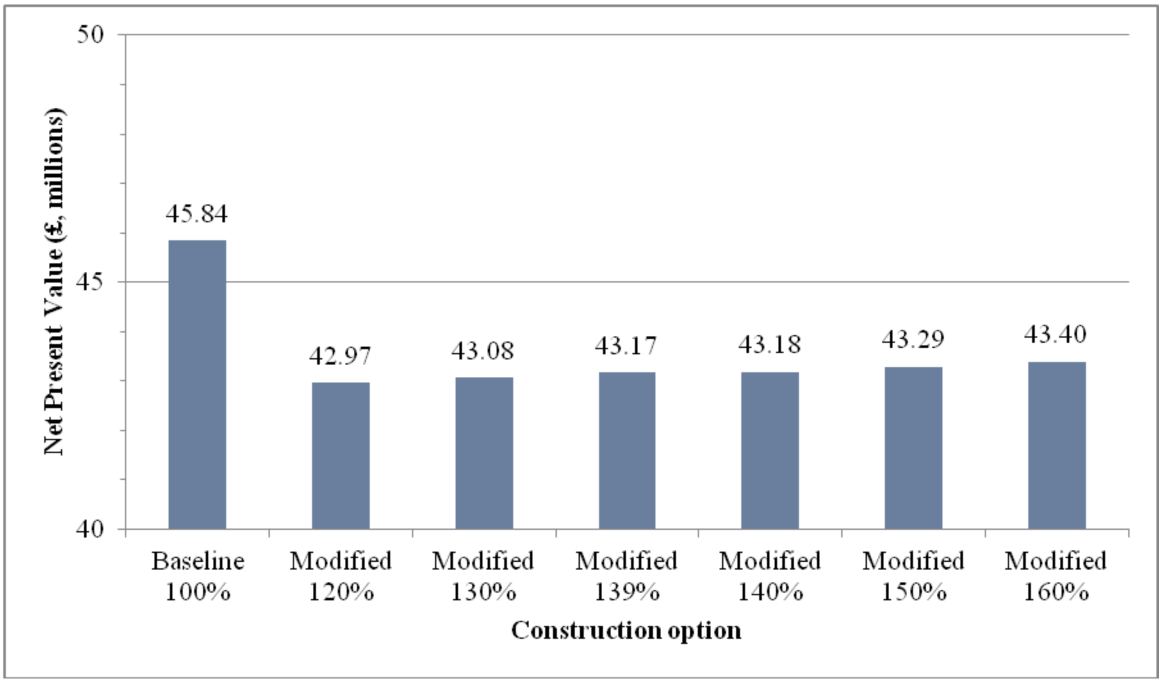

Figure 9: Net Present Values for varying modified material costs

Next, the impact of the rate of rutting on the results was examined. Using the test data, a relative rutting rate of 0.344mm per year, compared to the baseline 1.0mm per year, was calculated for the modified pavement. The rutting rate was varied at 0.2mm increments between 0.2mm and 1.0mm; even with the same rutting rate as a pavement constructed using a penetration-grade binder, the modified pavement is more cost-effective (Figure 10); significant savings are seen from around 0.6mm per year, As the rutting rate affects the frequency of maintenance (and, therefore, the traffic management and user delays), the NPV is more sensitive to variation of rutting than of material cost.

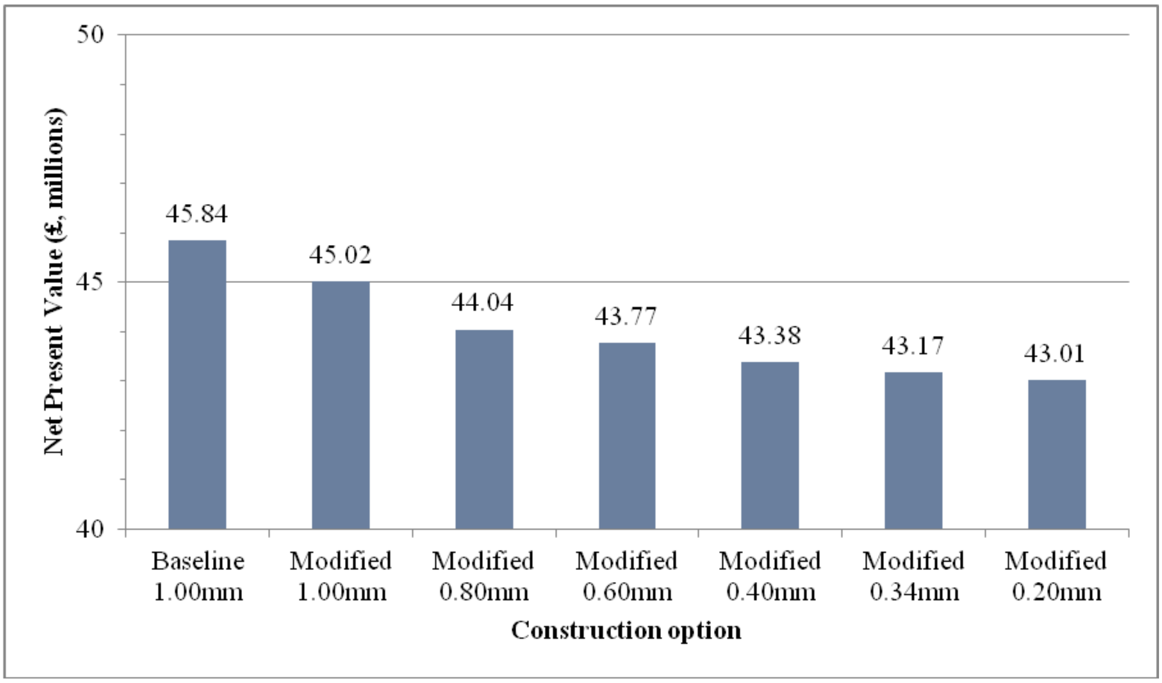

Figure 10: Net Present Values for varying modified rutting rates

Lastly, the output rate of the surface course was varied between 120% and 160% of the conventional rate in ten percentage point increments (Figure 11). Also included is 159%, as this was the value calculated from the test results (see §3.5). The premium binder is cost effective with all of the modelled output rates.

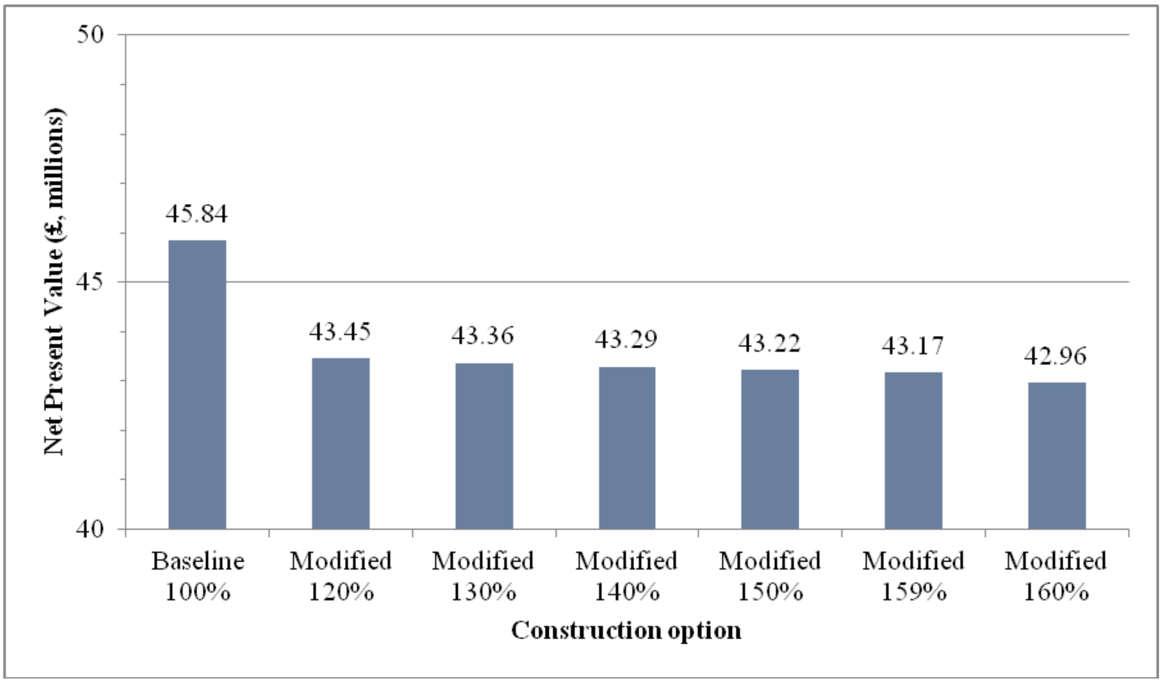

Figure 11: Net Present Values for varying modified surface course output rates

The sensitivity analysis demonstrates that improved durability to rutting and increased surface course output rate can each separately justify the use of a modified binder from a life cycle cost perspective.

6 CONCLUSIONS

Although the modelling framework is still in a developmental phase, it has already shown the potential benefits of the approach. The results show how the comparative life cycle costing approach can be used to demonstrate the cost-effectiveness of polymer-modified binder products in asphalt mixes based on material tests. They also show how the same model can be used to perform sensitivity analysis, either for further investigation of established results, to represent predicted future products or to guide development and testing efforts.

Establishing a formal approach for modelling allows the assumptions within the modelling to be made explicit and exposes them to discussion and refinement, as will no doubt happen as the model is deployed and used. For instance, the factors referred to in §3.6 are currently all set to 1; as more information is gathered, these can be altered to more closely match real-world outcomes. Being open about the assumptions made and the optimisation techniques used also provides reassurance that the results of the comparative analyses treat the modelled materials equitably.

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