

The Application of Life Cycle Assessment Technique in the Investigation of Brick Arch Highway Bridges

by

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ABSTRACT

Surrey County Council is the principal owner of highway infrastructure within its boundaries and is directly responsible for over 2,000 bridges across the County highway network. Historically the management of this asset has been governed by technical and economic constraints. More recently, reflecting the changing perceptions of society and concerns that now exist towards the ecological environment, Surrey is examining ways in which to minimise the environmental impact of its activities.

This paper provides dialogue as to why environment should be considered within bridge management and focuses on brick arch bridges as a category in presenting a case for how environmental improvement can be achieved.

A framework that provides a structured way to assess environmental impact associated with structure management decisions is discussed. This method applies life cycle assessment methodology as a means to evaluate environmental performance. Findings are discussed objectively and a series of conclusions encompassing structure life cycle decisions towards construction, maintenance and strengthening strategies are reached.

Keywords: Highway Bridge, Structure Form, Brick Arch, Life Cycle Assessment, Environmental Impact.

1. INTRODUCTION

Highway bridges are an integral part of our modern society. These most essential of civil engineering structures provide the invaluable service of facilitating and enabling movement and transportation. In the day-to-day operation of these structures, a series of traditional management issues exist. Encompassing safety, economic and technical themes, these issues are the most influential to management and policy decision-making.

However, with the advent of sustainability and the recognition that a wider perspective is needed, it is understood that environment should be included as an additional variable within decision-making; for if we are to improve and maintain our natural environments, then we have to consider and understand the consequences of our interactions on these environments.

2. SUSTAINABILITY

'Sustainability' is only one of the many buzzwords in the civil engineering industry over the last decade, but one, which has the greatest potential to affect change. Definitions exist in literally hundreds of different forms and are used in an equally large number of different contexts. The reason is not so much the complexity of the concept; a simple definition can be provided (Box 1), but in implementation. This can be achieved through sustainable development: the advancement and development of our society in harmony with the natural environment. It is in this field where the complexities of the subject become apparent.

It is painfully clear that today's society is not developing in a sustainable manner. If we do not curb our consumption and emissions, protect the environment and improve on our record on social progress, then the world will turn into an exceedingly unattractive and perhaps uninhabitable place in which to live. These trends started global debate on the subject and have helped develop consensus that sustainable development is a necessity, rather than merely desirable. For the UK an important milestone was the 1992 Earth Summit. In the ten-year period since the UK government has become increasingly focused on meeting sustainability criteria and through initiatives such as Local Agenda 21 [1], many of these objectives have been passed down to local government. Surrey County Council (SCC) like all local authorities must now consider its activities from a sustainable perspective, in short local authorities have a duty to contribute to the achievement of sustainable development in the UK.

Box 1 - A Definition of Sustainability

Humanity has the ability to make development sustainable, to ensure that it meets the need of the present without compromising the ability of future generations to meet their own needs.

World Commission on Environment and Development [2]

2.1 Sustainable development

The implementation of sustainable development: in essence it represents a road for society advancement in which progress must be in harmony with the natural world rather than in conflict with it. Therefore to achieve sustainable development we must consider human progress; we must place ourselves into context alongside the natural environment, and consider what drives our society and what the outcomes and impacts of our activities will be. When applying conceptual thinking in this area three broad themes arise: environment, economy and society. Each is intrinsically linked and will to a greater or lesser extent impinge on decision-making at every level. The relationship of these themes is best illustrated in a diagram, Figure 1. Regardless of the level at which an activity is being evaluated, the crux is that equal consideration is given to each theme and that no hierarchy exists. It is only then that a truly sustainable decision will be made. Sustainable development therefore falls at the centre of the diagram where all three themes overlap. When evaluating an activity from this perspective it is often found that the social and economic themes provide the greatest pull. These are traditionally the issues of greatest importance to an industrialised society. This concept can be applied at any level and for any decision-making process. When considering a highway bridge operator's objectives, traditionally it is the socio-economic aspects that are fundamental to management of the network. In contrast environment, and the consequence of decisions toward environmental impact, are rarely if ever considered.

The adoption of a truly sustainable decision is more complex and conceptual thinking merely provides the guidelines for making a decision. However, by adopting this form of strategic thinking a first step has been taken towards arriving at a sustainable solution.

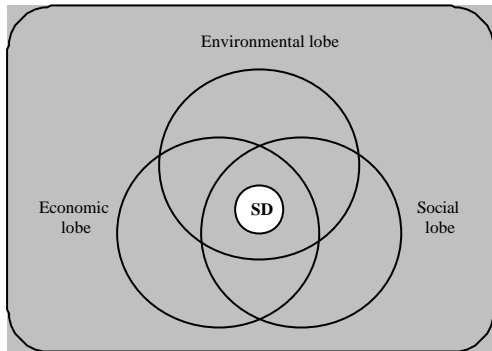


Figure 1 – Sustainable development lies at the centre of the diagram (SD).

2.2 The driver for research

When assessing structure management practice, it is evident that the aspect of environment is the one field where knowledge is lacking. The consequences of everyday decision-making are not evaluated on environmental performance. Therefore to adopt sustainable working practice, knowledge of this third theme must be developed and integrated into the decision-making process. SCC recognises this as a major need in order for it to deliver a sustainable bridge management strategy for the future.

3. LIFE CYCLE THINKING

To investigate, research has applied a life cycle evaluation method to identify environmental impacts. This ‘cradle to grave’ technique ensures a holistic approach enabling the assessment of environmental burden throughout any product, system or process under analysis. The technique, a form of system analysis, Figure 2, tries to consider all the environmental impacts, from primary raw materials right through to ultimate waste disposal. This approach formed the basis for the development of the environmental management tool Life Cycle Assessment (LCA), which has been used to evaluate environmental performance of highway bridges in this study. It is necessary to adopt such an all-embracing perspective because there is little legitimate understanding of where the greatest environmental impacts occur within a bridge life cycle.

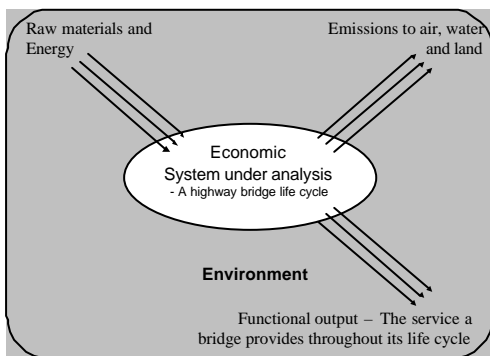


Figure 2 – The systems approach in LCA, adapted from [3].

In part this stems from the highly complex nature of bridge life cycles. Although the function of a bridge is simple, discrete structure life cycles can show great variance, and different

bridges that provide a similar or common service can have very different life cycles. Structure life cycles are defined and influenced by physical, economic, technical, symbolic, historic, commercial, political, safety and social concerns and issues. These can be termed life cycle ‘influencing factors’. In essence every structure is unique and there exists a cocktail of different reasons and influences that will dictate and define any one-bridge life cycle.

Past studies that have applied LCA to investigate highway bridges [4,5] have been case specific studies. As such the many issues that influence bridge management have not been considered nor discussed. The objective of this work has been to consider these influences in greater depth to determine how they effect structure life cycles. By following a structured approach a framework has been developed from which a series of planned and mapped LCA studies have been completed.

4. BRIDGE FORM AND DEVELOPMENT OF A PROJECT METHODOLOGY

The core of this framework and the point from which the project methodology starts is structure form. It is considered that this and material of construction define a structure life cycle and hence environmental performance. Bridge form and structural classification are well reviewed and most subject reference books cover in detail the evolution of bridge form and design. Classically bridges can be categorised into the three ‘forms’ of beam, arch and cable designs [6]. Within these categories material fabrication, initial construction processes, and end of life options vary. It can also be shown that each demands an inherently different maintenance strategy through its service life. As a result of these differing life cycles, each structure form will have a different environmental performance. Hence following investigation, a judgement can be made with respect to optimum design, material and service life strategy.

Although the influencing factors will be of issue from initial structure design onwards, the environmental ‘footprint’ of the bridge will be fixed within broad guidelines based on form. It is within these broad guidelines that a project methodology has been developed. An indexing system has been constructed to represent bridge designs. It focuses on arch and beam structures because they are the only two forms that exist within the SCC bridge inventory. This index system progresses from initial structure form to include material and material subsections and then method of construction.

The next phase of a structure’s life cycle is service life. To include assessment of this it was necessary to undertake a case study review exercise to fully understand bridge operation in the County of Surrey. This review included consideration of structure deterioration and faults, and potential service life works activities. Using data developed from this process, it was then possible to undertake realistic LCA studies encompassing entire bridge life cycles.

It should be recognised that the case studies could only provide a guide to bridge service life. Service life can be hugely variable and hence have great influence on overall environmental performance. To consider all potential strategies would be time intensive. A definitive assessment of all bridge types and material constructions is not within the remit of this project.

The project framework and the methodology developed within it works well. It is possible to compare bridge life cycles at various levels analysing specific structure form and material constructions and also to investigate form specific service life maintenance strategies. Demonstration of this can be provided with an LCA of one structure class: brick arch bridges.

5. BRICK ARCH BRIDGES IN THE COUNTY OF SURREY

Brick is an extremely versatile construction material that when combined with the arch form can result in constructions of assorted shape. These can be classically divided into semicircular, segmental, elliptical and semi elliptical forms, as shown in Figure

3. A further category is the pointed arch although this structure form is not shown here as it tends to be much older in construction and rarely encountered on highway bridges.

Typically Surrey brick structures tend to be of semicircular or segmental construction. It is assumed that although the arch form varies in design, the basic life cycle is common across all four designs. Therefore the analysis of a specific structure will give a good illustration of the environmental performance of the structure form. Although various designs of masonry arch have been built in Surrey, by far the greatest in number are the traditional clay brick structures. As a specific category, these account for approximately 40% of the total SCC owned bridge inventory, a number equivalent to 430 bridges.

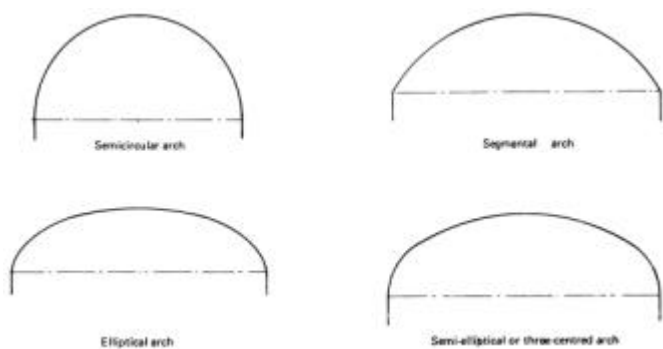


Figure 3 - Classic arch forms [7].

In managing this bridge inventory, resources are spread between general maintenance activities, and replacement and major renovation and strengthening projects. Each year SCC will undertake replacement, major renovation or strengthening works on 10 to 15 structures. At a maximum this represents works to 1½ percent of the total SCC owned bridge inventory, a very small proportion of the network. Total expenditure of these activities tends to vary between two and three million pounds. In contrast, minor maintenance is undertaken on anything up to 250 different structures with the total cost of this typically budgeted at half a million pounds.

These activities represent two very different groups, both of which it could be argued form the major focus of the Council's activities. In terms of knowledge to facilitate informed environmental decisions, little exists for either group. Knowledge in both areas is required so that practical improvements in both areas can be delivered. From a brick arch perspective the case is even clearer. The case study review indicates that as structures they tend to be 200 years old and as such have historic and symbolic significance to the locality in which they exist. For these reasons it is rare that a brick arch is demolished and replaced. When refurbishing and strengthening these structures there is a real need to know how to undertake these activities in an environmentally sympathetic manner.

5.1 A brick arch bridge service life

As previously discussed, information on structure service life has been developed by case study review. Ten real brick arch bridges were investigated and extensive background text and a management history of each was compiled. Information was sought from bridge records and document archives. The frequency of maintenance activities undertaken on individual structures was noted and trends for key maintenance activities across the whole structure group were found. This was achieved by noting maintenance frequency values for each case study. These values were then aggregated across all case studies such that the group average could be found. Information could then be consolidated into an 'idealised' service life representative of, in this case, a 'typical' brick arch bridge. This life cycle then formed the basis of the model used for environmental

assessment. The baseline strategy developed from this exercise and recognised as a typical Surrey brick arch bridge is illustrated in Table 1.

Table 1.
Brick arch bridge service life strategy developed from case study review.

Maintenance Activity	Activity Frequency (years)
Vegetation removal	5
Coping stone replacement/realignment	10
Brickwork maintenance – repoint/renewal	15
Parapet repairs/replacement	15
Invert clearance	20
Cutwaters replaced	40
First refurbishment scheme	120
Second refurbishment scheme	200

Although it consists of a number of activities, only brickwork maintenance and the first refurbishment scheme are considered by modelling in this paper. The reasons for this focus are discussed in Box 2.

Box 2 – Reasons for a simplified study

- The more minor activities do not involve replacement of materials. Hence environmental impact is negligible.
- It was considered that parapet repairs and cutwater replacement were adequately accounted for by brickwork maintenance modelling.
- Bridges are presently constructed for a 120-year design life [8]. Modelling a refurbishment and strengthening scheme at this interval is consistent with the anticipated life of a bridge built at the present time, and is also consistent with conclusions drawn from case study review.

To follow up on the final point it was found that of the ten structures reviewed, to date only two have been replaced. The average age of the bridges investigated stood at 200-years. Historically it was found that they underwent a major refurbishment scheme on average 126-years into their service life. Strengthening at this point (including saddling) was a common activity although it was found on average that concrete saddles were built 190-years into the structure service life. Over time these structures have experienced great differences in live load demands. It is a testament to their engineering and natural durability that they have lasted this long and continue to support highway loadings in the 21st century.

6. LIFE CYCLE ASSESSMENT

A life cycle assessment attempts to determine environmental impact by considering the flow of raw materials and energy into a system over a life cycle and relate these activities to environmental impacts, Figure 2. In a complex system such as a highway bridge life cycle this may involve many hundreds of different material and energy flows. Each flow will have an impact on the environment that is determined based on the flow 'inventory profile'. An inventory profile references all the chemical, substance and emission outputs that result when a defined quantity of the flow is specified. Through a system of classification and categorisation these outputs are aggregated into impact categories to determine environmental impact. The method is complex in detail and can involve classification and aggregation of many hundreds of substances. It is important that the method used to do this is structured and transparent such that the boundary determining what is, and is not included in the study can be clearly identified. It is for this reason that this LCA has been completed in general accordance with the Management series BS EN ISO 14040 [9]. It provides broad guidelines and advice for undertaking such a study.



Figure 4 - Elevation of Cascade Bridge, age 175-years. The structure has a clear span of 10.5m and a width of approximately 12.5m. The bridge is entirely of brick construction apart from a concrete slab footpath on one side. The structure provides for a single lane carriageway of width 9.5m and spans a small stream with large seasonal flow differences.

At concept level LCA can be broken into a series of stages. Broadly speaking these include planning, data collection and data treatment, evaluation and improvement assessment [10]. It is generally recognised that the planning stage is extremely important and the result of an LCA can be heavily dependant on the decisions taken towards planning issues such as system boundaries, evaluation method and choice of environmental parameters. These points in the context of this LCA study will be discussed in more detail.

6.1 LCA objectives

There exists a need for knowledge of the environmental consequences of decisions made in highway bridge management. This coupled with the scope for great variation in the strategies applied in the management process makes a definitive LCA study into all highway bridge life cycles an unfeasible goal. Therefore, rather than focus on this, the major objective has been to develop a methodology that applies LCA to consider environmental impact. This methodology has been tested through a series of simplified case studies. The scope of this study is to illustrate that LCA can be used to measure environmental performance of a highway bridge and provide relevant, interesting and influential results to decision-makers.

6.2 Life cycle representation and functional unit

All LCA studies are constructed around a functional unit. This is the unit of analysis and it provides a basis for comparison if more than one alternative is being studied. In the investigation of highway bridges it is logical that a bridge of defined size and service life (time span) be the functional unit. Therefore in undertaking this LCA study the model has been built around a real bridge design. A case study like this is used because it provides for accurate material and construction process estimates. Cascade Bridge was used to represent the brick arch form, Figure 4. The service life has been considered to be 120-years. The replacement of the structure and wastage material that would occur from demolition has not been included in the

study. Reasoning for this is provided by present management philosophy, which attempts to extend structure service life once a bridge approaches obsolescence; in effect after a 120-year service life the structure would be refurbished and strengthened rather than replaced.

6.3 Life Cycle Inventory (LCI) data

The software programme SimaPro has been used for LCA modelling. This is supported by three data sets, including PRé4, BULWAL and IDEMAT databases. These are databases of environmental information on materials and processes. Although comprehensive, the information in these databases is not entirely relevant to UK circumstances. To overcome this problem there has been a drive to secure UK specific profiles. The difficulty is that very little data are available. Environmental profiles for specific products such as pre-batched mortar or coating systems, materials like fill or recycled aggregate and processes like excavation or concrete vibration settlement either have not been developed, or will not be released on commercial grounds.

One group that has undertaken a large amount of work in the field is the Building Research Establishment (BRE). With their Environmental Profiles project they are overseeing the development of a LCI database specific to UK construction materials. This represents the only known UK specific data. With careful negotiation it has been possible to secure the release of a series of key material profiles. Those relevant to arch bridge construction include brick, cement, hydrated lime and reinforcing steel materials. The brick profile is representative of 'average bricks' and was developed with support from the Brick Development Association and leading UK brick manufactures. The profile is characteristic of continuous and intermittently kilned clay flettons, specials and engineering brick. It offers the only good representation of a generic UK brick as might be used in highway bridge construction and maintenance. In modelling bridge life cycles a mix of BRE and SimaPro profiles have been used.

6.4 System boundaries and scenario description

The boundaries to the LCA are presented in Figure 5; this illustrates the background and foreground levels to the study. Three life cycle stages are analysed. These are bridge construction, service life and structure strengthening. The strategy and assemblies within the foreground system have been developed around the SCC baseline scenario. In contrast, the inventory

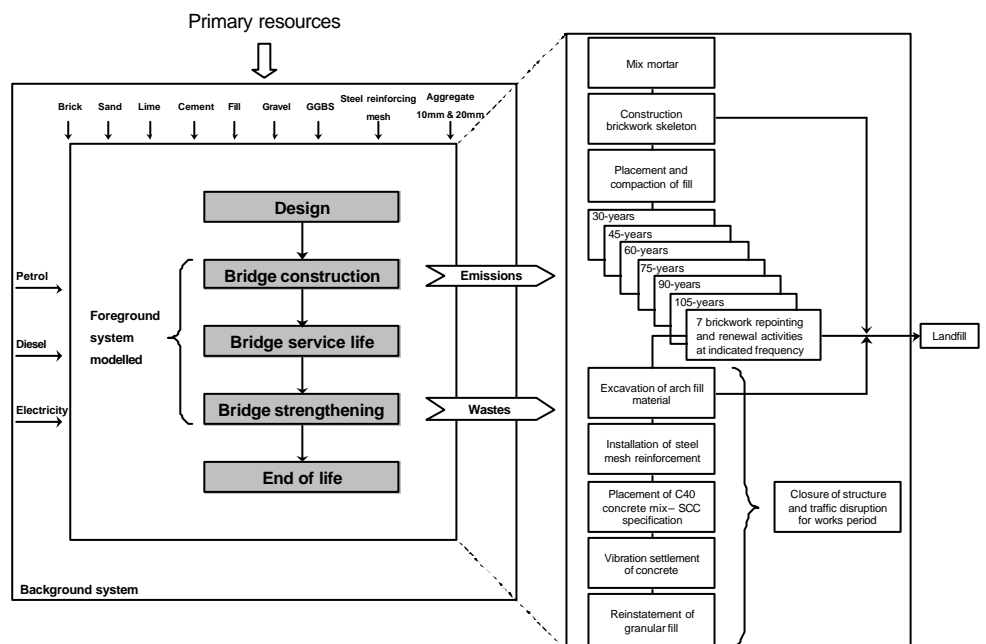


Figure 5 – The background and foreground systems of study.

Table 2.
Life cycle material demands (tonnes).

	Construction	Maintenance standard*			Strengthening	
		Good	Average	Poor	Saddle	Anchors
Brick	475					
Mortar (repointing work)	150	6.2	4.1	3.1		
Brick & mortar demand (brick renewal work)		122	54	26		
Fill	1790				416	
Steel reinforcing bar					2.92	1.18
Grout						2.64
Concrete					620	
Polyester fabric						0.036

*Represents aggregate material quantities for brick renewal and repointing activities over 120-year life cycle.

profiles that feed this system have been sourced from BRE and SimaPro databases. Using these profiles and the scenario outlined in Figure 5 a series of estimates were developed for the bridge life cycle. Consultation of structure drawings, a site visit, review of assessment reports and other archived literature enabled this activity to be completed with accuracy. Bridge construction estimates were developed for brick, mortar and fill material, Table 2. Mortar was considered to consist of cement, lime, sand and water components; a mix classification (ii) was assumed [11]. Site mixing of mortar material was anticipated and accounted for by an energy demand from a site mixer running off a diesel generator. The other site process considered at construction was compaction of fill material over the arch barrel. A small smooth wheeled roller was considered to complete this job [12]. Transportation demands for material supplies to site were also accounted for.

Brickwork maintenance activities are based on the concept of poor, average and good maintenance strategies. At an elemental level, each part of the structure is considered. Percentage surface areas are defined for brickwork repointing and brickwork renewal. What distinguished a good strategy from a poor strategy is the percentage area of structure receiving attention. Regardless of strategy, work was considered to take place at a standard 15-year frequency (apart from an initial 30-year maintenance interval following bridge construction). Repointing and renewal of brickwork are essentially material replacement activities. Both require mortar input, but brickwork renewal also has a brick demand. By assuming a 1m² area and defining a raking out depth

Box 3 - Brickwork maintenance strategy

Maintenance Activity	Maintenance rates (%)*		
	Good	Average	Poor
Repointing of brickwork	37	27	20
Renewal of brickwork	17	8	5

*These rates represent the percentage of structure surface area receiving works at the maintenance interval period of 15-years.

- A good maintenance strategy will see the structure through a 120-year service life after which only standard brickwork repairs would be necessary.
- An average maintenance strategy will see the structure through a 120-year service life after which an entire structure brickwork repair scheme would be necessary.
- A poor maintenance strategy would not afford a structure life span of 120-years. If this strategy was adopted it is anticipated that intervention to repair brickwork would be necessary earlier than the 120-year design life.

of 15mm [13], mortar demands for repointing can be determined. Likewise, for brickwork replacement across 1m², mortar and brick quantities can be calculated. Factoring these values by a defined life cycle strategy enables material quantities for brick and mortar to be calculated in volume and then mass terms, Table 2. Mixing and transport of materials to site were also considered. The distinction between poor, average and good brickwork maintenance strategies is important and can have implications to structure life span. Unfortunately the reality is that it is impossible to accurately predict a structure life span purely on the grounds of brickwork maintenance strategy. Despite this an attempt has been made to put a perspective on these differing maintenance strategies, see Box 3 for further discussion.

The final focus of modelling has been on structure strengthening methodologies. Two techniques have been compared. The first

examined traditional concrete saddle construction and the second reviewed a newer technology consisting of anchor bracing across the arch barrel. SCC has used concrete saddles for decades but the newer anchoring technique looks set to be used with increasing regularity in the future. With the consideration of a specific design, a series of material estimates were produced for the construction of a concrete saddle. The main material demand was for concrete, although a small amount of steel reinforcement was also included in the model. The process of concrete vibration settlement was included. The actual processes of excavation and disposal of granular fill material in a landfill were not considered. This was because profiles for material disposal and excavation plant were not available. As with many high volume construction waste materials (brick, mortar, sand, gravel, crushed stone, concrete materials and general construction rubble), arch fill material can be classed as inert [14] and therefore exerts no environmental impact apart from land take upon disposal. As an impact this issue has not been assessed in this LCA model. Therefore, in considering disposal of fill, the burden is associated only with transport of material to a landfill site at 10km distance. In modelling the saddle scheme, potential traffic disruption was considered. It was possible to do this by making the assumptions outlined in Box 4. Using these, it was possible to determine the total distance of extra journey kilometres travelled by road users as a result of the works scheme. The figure equated to 945,000 km.

Box 4 – Traffic disruption

- Structure location - Highway of B classification
- Vehicle flow rate - An average Surrey B road has a flow rate of 9000 vehicles per 24 hours [15]
- Detour distance - Conservatively assumed as 5 km
- Structure closure time - Following consultation it was assumed to be 21-days

The procedure for modelling the anchor scheme was similar in concept. The material volumes associated with its implementation are much less and include quantities of grout (sand, water, cement), steel reinforcement and polyester fabric, Table 2. However, the process of installation has high site energy demands. Primarily these are associated with the coring of the anchor holes and the mixing and pumping of grout. It was anticipated that the anchor design would consist of a series of diagonal anchors spaced at 2m intervals longitudinally across the structure; each with a length of 6m. To complement these, in a transverse direction through the arch barrel there would be a total of 12 further anchors (per side) spaced around the arch barrel; each would have a length of 3m. The benefit of the anchoring scheme is that the arch can be strengthened without having to close the structure to traffic. There is thus no

impact from traffic diversion. Assemblies were created for each of the activities associated with the anchor scheme. As with other models, materials were based on BRE profiles and the construction processes were represented by energy demands placed on a site diesel generator. Consultation on specifics such as coring times, material quantities and material mixes were sought from a series of commercial groups.

7. IMPACT ASSESSMENT

Impact assessment is highly influential to the final conclusions drawn from modelling. It is the point where wastes and emissions from the system under analysis are interpreted as environmental impacts. This is achieved with the use of impact categories, where, through characterisation, substances are grouped into categories where it is known they have a contribution to environmental impact. By the use of a damage factor the quantity of each emission is weighted to show the contribution of that emission to the impact category. In this investigation, the study has adopted eight impact categories classified into three further damage categories; Human Health (HH), Ecosystem Quality (EQ) and Resources (R), see Box 5 for further discussion. The units of these categories also require description; this is given in Box 6.

Box 5 – LCA impact categories

- HH – Carcinogen: cancers due to toxic chemicals in air, drinking water and food.
- HH - Respiratory organic: respiratory diseases due to toxic chemicals in air, drinking water and food.
- HH - Respiratory inorganic: respiratory diseases due to toxic chemicals in air, drinking water and food.
- HH - Climate change: infectious diseases, cardiovascular and respiratory diseases and forced displacement.
- HH - Ozone layer: cancer and eye damage due to ozone layer depletion.
- EQ - Eco-toxicity: the potentially affected fraction of species in relation to the concentration of toxic substances.
- EQ - Acidification and eutrophication: a measure of reduction in plant and animal diversity.
- R - Fossil fuels: qualitative structure of resources and continued decreasing concentration.

Two further stages to impact assessment remain. Once results have been characterised it is possible to add a perspective of size to an impact through normalisation. This is typically done by dividing each impact category by the total impact for the category in a given geographical area (results are thus expressed as percentages). In this study the figures are normalised to the effects of an average European inhabitant over one year. Evaluation adds the important final step. By applying weighting factors the relative importance or seriousness of a category is determined. With this phase, results are represented as a single score in eco-indicator points (Pt). Eco-indicator values can be regarded as dimensionless figures. The absolute value of a point is not really relevant because the main purpose of scoring is to express total environmental load for a product or process. The ability to score categories is important because it enables aggregation or comparison between different impact categories, but also the ability to score whole systems on environmental performance e.g. a highway bridge design, maintenance strategy or strengthening procedure. This is a useful function that provides results which can be easily interpreted for decision-making. In adopting this method the subjective nature of evaluation should be recognised. There is no pure scientific basis to using weighting factors to assess impact categories such as climate change and ozone layer depletion. The weighting factors are based on subjective choices and the reader should be aware of this.

Impact assessment has been conducted using Eco-indicator '99 methodology [16]. This is integral to SimaPro and provides the framework for undertaking the three impact assessment stages. Results in this paper will focus on evaluated data. However, discussion towards characterised results will also be presented.

Box 6 – Damage category units

Human health – This is expressed as the number of Disability-Adjusted Life Years (DALYs). It is a measure of the total amount of ill health, due to disability and premature death, attributed to specific diseases and injuries. This can be easily explained: a flow of toxic substances in tons per year will result in a number of DALY per year. If the per year is left out, then a mass loading is equivalent to a number of DALY.

Ecosystem quality – For toxicity the Potentially Affected Fraction PAF is used. This can be interpreted as the fraction of species that is exposed to a concentration equal to, or higher than, the No Observed Effect Concentration. To harmonise with the acidification and eutrophication categories this is converted to the Potentially Disappeared Fraction (PDF) of species. This can be interpreted as the fraction of species that has a high probability of no occurrence in a region due to unfavourable conditions. In summary, a toxic flow will have an observed effect on plant and animal species; this is translated to the PDF/m².

Resource damage – Market forces ensure that deposits with the highest concentrations of a given resource are depleted first, leaving future generations to deal with lower concentrations. Thus, in theory, the average ore grade available for future generations will be reduced with the extraction of every kilo. The unit used to measure resource damage is the 'surplus energy' in MJ per kg extracted material; this is the expected increase of extraction energy per kg of extracted material.

7.1 Results and discussion

The results from environmental analysis of bridge construction are presented in Figures 6 and 7. It is evident that brick demand represents the biggest single burden in five of the eight impact categories, Figure 6. This is perhaps not surprising given the large quantity of material required and the industrial processes associated with its manufacture. In many impact categories this is closely followed by burden from mortar demand. This is significant because of cement and lime use in the mix.

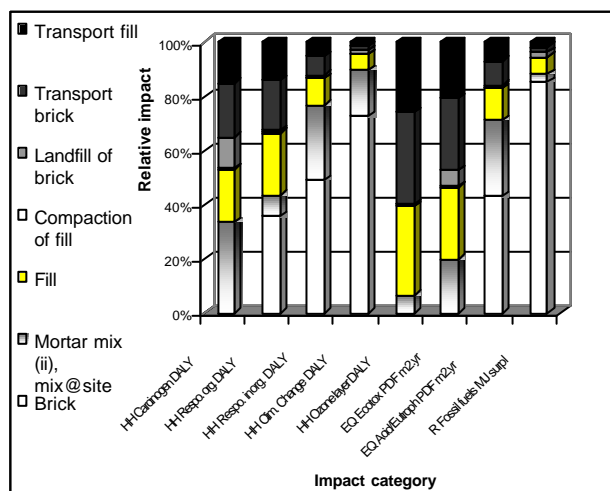


Figure 6 - Characterised data for the environmental impact of constructing the brick arch bridge. Compaction of fill has negligible effect in every impact category.

During construction, transport of materials is an issue, particularly in the categories of carcinogenic, ozone layer and eco-toxicity impact. However, the evaluation process reduces the weight of these categories and it is clearly shown in Figure 7 that transportation issues are of less importance environmentally when contrasted with material manufacture. The fact that transport

emissions are small is a reflection on the transport distances used in modelling. Brick materials are often locally produced and sourced from local suppliers (the model assumed a 50km transport distance for brick supply to site).

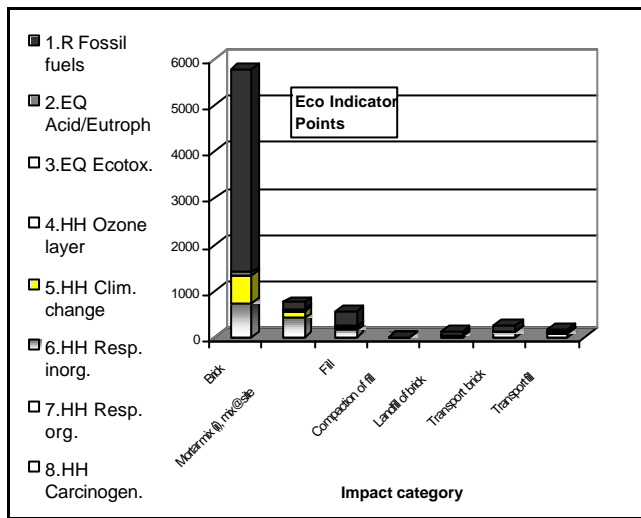


Figure 7 – Evaluated data for the environmental impact of constructing the brick arch bridge. Category 1, fossil fuel reduction is dominant. Impacts in categories 3,4,7 and 8 are negligible.

However, in some cases particularly for aggregate and cement provision, materials are often supplied from remote locations and have travelled long distances by ship or rail prior to being delivered to site. Sensitivity analysis which involved assessment of greater transport distances found that environmental impact did rise, but, it continued to remain minor when contrasted against the manufacture of the materials themselves. When reviewing data at a materials specific level, it should also be noted that proportionally, the environmental impact of transporting industrialised products like brick has less of an aggregated effect to the overall impact score than it does for non industrialised products; e.g. in this case 4% of the burden of brick is associated with transport, in contrast 24% of the burden of fill is attributed to transport.

There is 1790 tonnes of fill in Cascade Bridge. However, despite the large quantity, the impact it produces is small. This is because the functions associated with providing the material (quarrying and cleaning), do not have a large impact, e.g. the energy demand for one tonne of fill is 48MJ. In comparison the energy requirement for one tonne of brick is 3300MJ. When aggregating these figures for total scheme material requirements, the differences and hence environmental impacts are further accentuated. Compaction of fill barely figures in any impact category; an eco-indicator score of 2Pt. This is an indication that materials rather than processes of construction are the greater source of environmental impact.

For bridge construction the impacts associated with the quantities of solid waste produced on site are not large when considered against the impact of the completed structure. In general, wastage rates are not high, indeed historically granular and aggregate waste would be consolidated into the arch as fill material; total wastes leaving site would be small. However, this practice is no longer acceptable and the 2% wastage rate for brick (equivalent to 9.5 tonnes) has been modelled as removed from site to a landfill at 10km distance.

Apart from transport of materials to site and fill compaction, the only other process considered was mortar mixing. The impact of mortar mixing is included within the mortar category. When reviewing results at a more detailed level, it is found that the mortar-mixing element of the assembly is negligible in all

environmental impact categories; it represents less than 1% of the total impact of the material placed in the structure. For the mortar assembly the principal impacts come from cement (86% impact of mortar product) and lime (9% impact of mortar product). This would indicate that there might be only minor environmental benefit associated with the use of ready made or pre-batched mortars.

Despite the 120-year service life, brickwork maintenance through this period does not represent a large environmental burden. The primary reason for this is that the quantity of material used even for an average maintenance strategy is not great. Indeed, the total eco-indicator score across all impact categories for an average brickwork renewal and repointing strategy over an entire life cycle is 640 Pt. To put this in perspective, the eco-indicator score for bridge construction is 7630 Pt. In percentage terms the maintenance strategy represents only 8% of the environmental impact of the bridge construction. For a good maintenance strategy this figure increases only to 19% (equating to 1440 Pt). The conclusion to be drawn is that basic structure maintenance when compared with structure construction is not the major source of environmental impact. This finding has implications to maintenance policy. It is widely recognised that good general maintenance prevents structure deterioration; structure life span is extended. The result of this is that the time until it becomes necessary to invest in a new structure is lengthened. Brickwork maintenance should therefore be recognised as a form of environmental saving. The activities themselves exert a modest impact on environment, and extend the time to structure replacement and/or refurbishment; activities that do represent a much more significant impact. When comparing the two activities of brickwork renewal and repointing, the former represents significantly greater impact. Illustration of this is borne out in Figure 8.

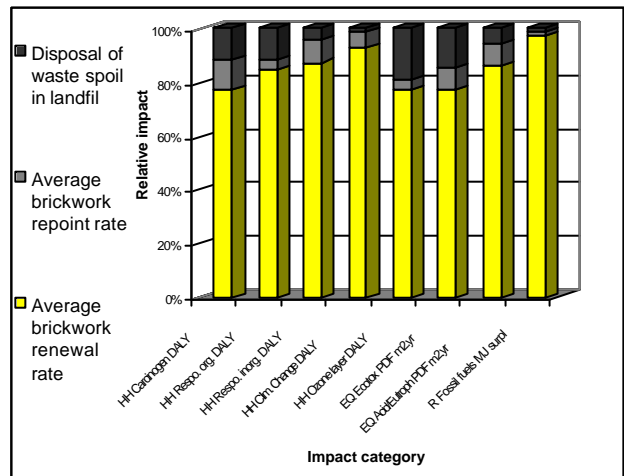


Figure 8 – Characterised impact data for brickwork maintenance. Note that waste spoil is inert and hence the impact of disposal comes from transportation of the material to landfill.

The graph illustrates characterised values for both activities and shows that in all categories the greatest burden is produced by brickwork renewal. Repointing represents less than 20% of the impact of brickwork renewal in all categories. If evaluated data are considered, this percentage figure drops further. Because replacement brick is not needed during repointing, on average, a good mortar repoint strategy through a 120-year life cycle will represent less than 0.5% of the impact of bridge construction. This presents a further reason for providing a structure with a good maintenance strategy. Repointing as an activity has only minimal impact on environment. The activity is ‘good value’ providing long-term environmental savings.

Service life deterioration or a change in load demand makes structure obsolescence a common problem on modern highway networks. The consequences of either occurring are similar; the

bridge is under strength and unable to carry the load requirements. To resolve the problem a number of options exist for continuing to provide a fixed transportation link at the location. They consist of bridge replacement or refurbishment/strengthening of the existing structure. In this paper two structure strengthening methods are reviewed. These are the construction of a concrete saddle and strengthening with anchors. The two methodologies are significantly different; saddle construction uses large quantities of materials and disrupts traffic flow during works. In comparison, anchor installation has much smaller material demand yet has high on site energy requirements. A major benefit with the latter technique is that no traffic disruption occurs. The impact results of these activities are shown in Figures 9 and 10, where they have been illustrated against a backdrop of bridge construction and service life.

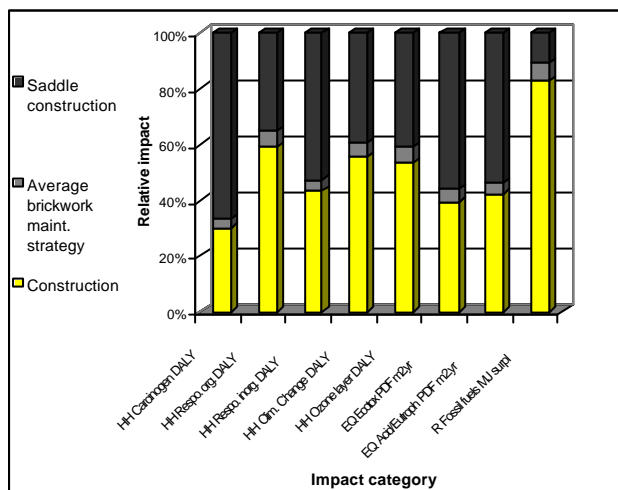


Figure 9 – Characterised data for structure life cycle. Includes construction (Figure 6), maintenance (an average brickwork maintenance strategy through a 120-year service life, Figure 8) and strengthening (a RC saddle of volume 270m³).

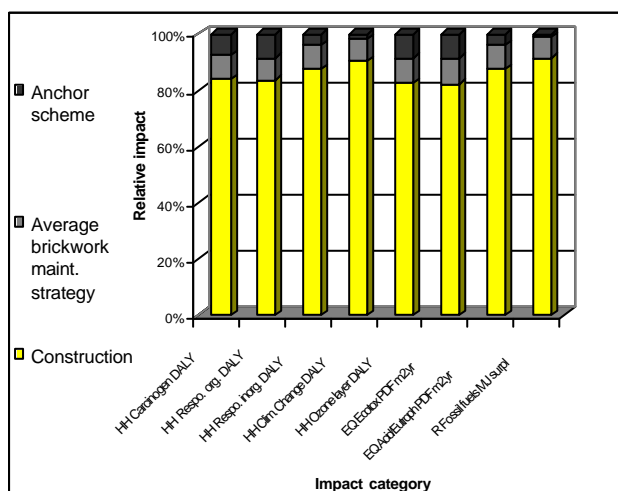


Figure 10 – Characterised data for structure life cycle. Includes construction (Figure 6), maintenance (an average brickwork maintenance strategy through a 120-year service life, Figure 8) and strengthening (installation of 228m of longitudinal and transverse anchors).

Of the two strengthening methodologies, the construction of the concrete saddle has greater environmental impact. The primary reason for this is the quantity of material used. Although an economical design of saddle was considered, the strengthening

method still used a ‘relatively’ large quantity of material, Table 2. It is the production of this material, principally the burden from cement, which causes this impact.

From investigation it can be shown that the impact of cement in the concrete mix accounts for 92% of the burden of the product; taking this further and considering a metre cube of placed and hardened reinforced concrete saddle, it can be determined that the burden of the concrete accounts for 85% of the impact, Figure 11; note this does not take account traffic disruption burdens and is specific to the saddle design considered in this model.

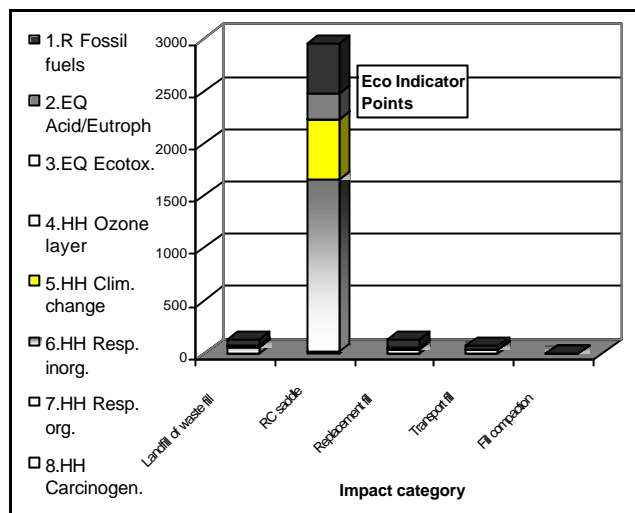
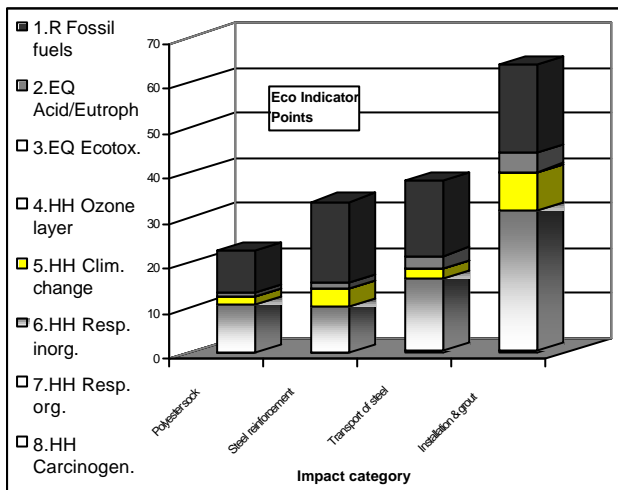


Figure 11 – Evaluated data representative of the construction processes associated with a RC saddle; the greatest impact arises from the RC saddle as a structural element. The RC saddle category includes the materials in the concrete mix, the steel reinforcement, the transport of steel and concrete to site, and the energy burdens for concrete vibration settlement. Across these contributions the concrete accounts for 85% of the environmental burden. Impacts in categories 3,4,7 and 8 are negligible.

The second bridge strengthening technique modelled was the installation of an anchor bracing scheme. It was found that this had relatively high site energy demands attributed to coring and grout pumping, Figure 12. However, despite this the entire scheme represented only a small burden to the environment; a total eco-indicator score of 158Pt was determined. Although the site energy demands could be considered as high, the majority of the impact still came from material demand. The major conclusion of the model was that the anchor scheme would account for only 2% of the life cycle burden of the structure after 120-years service life.

To date SCC has used the anchor bracing technique in only one structure-strengthening scheme. In this project, in accordance with design procedure, stainless steel was used as the anchor reinforcement material; interestingly an Italian supplier provided the product. Unfortunately, it was not possible to obtain an accurate profile for stainless steel reinforcing bar. A standard reinforcing steel product was thus assumed and the resultant breakdown of impact is illustrated in Figure 12. The steel has a burden, but is not the major impact creator. The use of stainless steel is an interesting issue and merits further discussion. Using adapted data, preliminary studies indicate that using stainless steel would increase the environmental burden particularly for impact categories carcinogen, organic respiratory and eco-toxicity. It is possible that the increases in these categories could raise the aggregated impact of the scheme by 50% or more. It was further found that the model was sensitive to transport issues associated with the supply of steel from remote locations. An attempt to account for this has been included in the study results presented in Figure 12, where it has been assumed that the steel had been supplied from Italy; transport distance 2000km accounting for an eco-indicator score of 35 Pt.

This value of 35 Pt is significant representing 22% of the impact of the entire strengthening scheme.



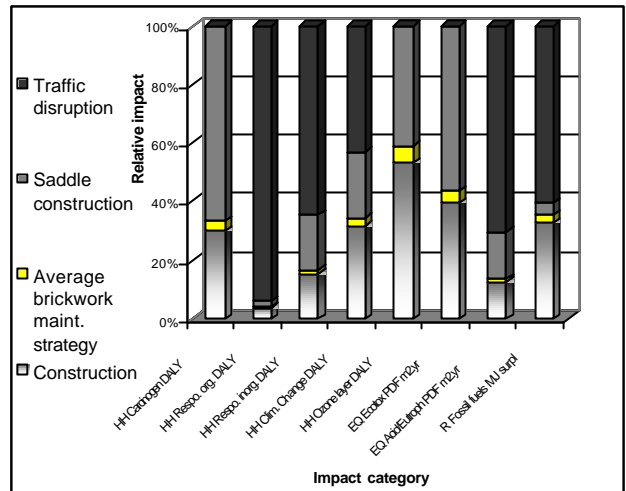
Figures 12 – Evaluated data representative of the construction processes associated with the anchor scheme. Impacts in categories 3,4,7 and 8 are negligible.

A further avenue of investigation not considered by this study, but of interest, is the superior reduced deterioration characteristic of stainless steel. Traditional steel might be expected to deteriorate faster and hence require earlier intervention for maintenance. Intervention and maintenance would incur environmental impact. In contrast, stainless steel might be expected to last longer and hence not incur these burdens. However, the material has an inherently higher burden on environment per tonnage produced. The environmental benefits of either strategy are evident although it is unclear which material would prove superior through a life cycle. This scenario may not be wholly appropriate for reinforcing bar used in strengthening anchors, but there are links to be made for using stainless steel in reinforced parapets or more widely in reinforced concrete structures. Further investigation into these applications is needed to determine if stainless steel offers a better life cycle environmental profile than traditional steel materials.

Site waste was considered in detail for all life cycle stages. Findings of the study indicate that waste removed from site at all stages would be inert, consisting of waste brick and fill or coring spoils. The impact of waste thus comes from the transport of material to landfill. A standard distance of 10km was adopted in all calculations. The significance of disposal was thus a direct result of the quantity of material being transported. The impact of waste brick disposal during construction, and fill disposal during saddle construction thus had the greatest burdens. In contrast, the 2m³ of waste spoils produced by the anchor scheme had no noticeable environmental impact. Although it is often (rightly) stressed that waste disposal is an issue, this study concludes that much greater environmental benefit could be achieved through efficient design (minimising use of material), good site practice (reducing the ten tonnes of waste brick created at construction) and if possible, the reuse of materials. It is the manufacture of materials, most noticeably brick, which generates the greatest environmental burden.

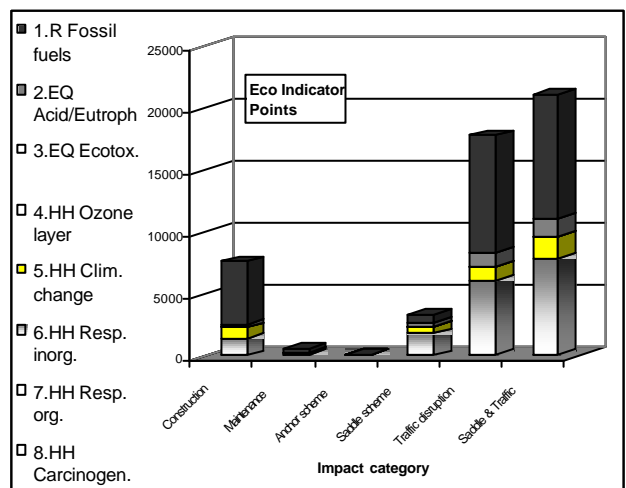
The greatest issue to arise from this study is the polluting effects of traffic disruption. The results illustrated for the saddle scheme in Figures 9 and 11 do not include traffic impacts; further discussed in Box 4. If the impact from traffic is included, the burdens associated with the saddling scheme rise significantly, Figure 13. Although traffic disruption is a contributor in only five of eight impact categories, the contribution is large in each case. This is despite modelling both a traffic volume and detour distance that might be thought of as conservative. Further, the sophistication of the traffic model is not great, and consists of a

select group of air emissions and fuel demands. Mix of traffic and knock on effects of congestion produced by detouring vehicles have not been included. If an assembly of greater detail were used it can be hypothesised that the impact from traffic disruption would be of greater significance still.



Figures 13 – Characterised data for structure life cycle. Includes construction, maintenance and strengthening with a RC saddle. Impact from traffic disruption, a direct result of undertaking the works has also been included.

The environmental effects of traffic diversion thus have important implications for structure strengthening; indeed, for any structural works that might close a structure. In reality it is not possible to divorce a maintenance/strengthening activity from the effects it might cause to traffic. If the works are undertaken, traffic disruption will occur with the resultant vehicle emissions. In this case study the environmental impact of the saddle scheme should include the impacts from traffic. Using evaluated data and aggregating the impact of the saddle construction and traffic disruption it can be clearly seen that the saddle scheme has a greater impact than any other activity associated with the structure life cycle; this includes bridge construction, Figure 14. It is possible to present a series of further interesting conclusions using the evaluated data in Figure 14.



Figures 14 – Evaluated data for structure life cycle. Includes construction and maintenance life cycle phases. Both structure strengthening methodologies are presented and the effects of traffic disruption are included. Impacts in categories 3,4,7 and 8 are negligible.

The anchor strengthening technique equates to a 95% overall environmental improvement against traditional saddling

technology. This figure increases to almost 100% if traffic disruption burdens are included in the equation. The environmental burden associated with the traffic disruption is of an order 5 times greater than that of the saddle construction. In other words, the greater environmental impact is from diverted traffic rather than site works. Finally, where long-term closures are necessary, the impact of traffic disruption may prove greater than the impact of bridge construction. In this case it was considered that the structure would have to be closed for 21-days in order to complete the saddle. However, findings concluded that after only nine days the impact from diverting traffic was greater than the impact of building the entire bridge. It can be concluded that if a standard Surrey A or B road is to be closed for any extended period of time, the greatest source of environmental impact will come not from the works themselves, but from the detouring traffic.

Results indicate that traffic disruption is an important consideration; constructing a saddle over a bridge will have a high degree of environment impact purely from this perspective. The anchor bracing scheme does not appear to suffer from this problem. However, if viewed differently, it does not offer the same level of advantage. Modelling has assumed that it would be possible to install the anchors by working across the structure and within a confined 2m wide workspace. Traffic would continue to flow in temporary lanes around this working island. But what if the structure were less than the 12.5m deck width, say 7.9m? It would not then have been possible to apply the scheme in the same way. Depending on the scope to use temporary traffic lights, it might be assumed that significant traffic congestion would occur. This scenario has not been investigated. However, it does serve to prove an interesting point; the advantage of adaptability. Cascade Bridge was built in 1827. The demands on the structure at this time were significantly different to those of today, yet by foresight or fluke the design of the structure has a quality that improves environmental performance. This is a quality that should be recognised and distilled into present design philosophy. By designing the quality of adaptability into a new structure, it should be possible to reduce environmental impact in the future thus helping towards a sustainable design. These qualities can best be factored in at the design stage, which can ensure that a structure will respond well to future uncertainties and the ravages of time [17].

8. CONCLUSIONS

The objective of this paper has been to present a methodology that enables the environmental impact of highway bridges to be investigated. By considering specific structure form and defining a structure life cycle, environment has been investigated under key impact categories. Life cycle assessment technique has been used to do this. Within the boundaries of a life cycle it offers a method to contrast and compare competing strategies and approaches. This has been demonstrated by investigation of a brick arch structure.

Results and discussion have reviewed bridge life cycle phases from construction through service life to structure obsolescence and the need for bridge strengthening technologies. The examples discussed are selective and relatively simple. However, in this context it should be recognised that the methodology is under development. A future objective is to provide greater detail to the methodology and case study examples. Further refinement and sensitivity analysis will also increase reliability and accuracy. Despite this, the case study illustrated here, demonstrates that the method can be used to evaluate environmental performance and develop coherent conclusions. Most notably, it has been found that bridge construction represents the single biggest contributor to environmental impact over an entire bridge life cycle. However, the environmental impact from structure closure and traffic diversion can be a source of greater impact. Maintenance has only minimal relative

impact on environment. The activities examined, which included repointing and brickwork renewal, provide 'good value' and represent long-term environmental savings. On a comparative basis, the anchoring methodology clearly exhibits distinct environmental benefit when contrasted with saddle construction.

The conclusions, although valuable in themselves, are a direct result of a developed project methodology. This has culminated in a framework that enables environment to be considered objectively within decision-making. It is only by applying life cycle thinking and extending our philosophies to take account of environmental as well as the traditional socio-economic criterion that we will begin to implement sustainable solutions in highway bridge management.

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