APPLICATION OF LIFE CYCLE ASSESSMENT TECHNIQUE IN THE INVESTIGATION OF BRICK ARCH HIGHWAY BRIDGES

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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 the concerns that it now possesses towards the ecological environment, Surrey has begun to examine ways in which to minimise the environmental impact of its activities

This paper outlines the project framework and explains the work behind a method developed and used to examine environmental issues associated with structure management activities. This will use Life Cycle Assessment methodology as a means to evaluate environmental performance. A strategy for the investigation of brick arch bridges will be presented. A series of conclusions encompassing construction, maintenance and strengthening strategies have been reached.

Keywords: Highway Bridge, Structure Form, Brick Arch, Life Cycle Assessment, and Environment.

1.0 Introduction

The definition of Civil Engineering has changed little with time. In the original Civil Engineering Charter of 1828 the definition of the profession is quoted as being ‘the art of directing the great sources of power in Nature for the use and convenience of man’. One hundred and seventy three years later, this definition still stands (a testament to how accurate it is), yet there is a growing realisation that these objectives cannot remain the primary focus.

In 1975 the subject of environment first appeared. The Charter definition of Civil Engineering was expanded to include the objectives of ‘making the best use of scarce resources in care for the environment and in the interests of public health and safety’. At the time this reflected the anxiety and concerns towards the ecological environment. In the 26- year period since, this theme has risen to prominence through the development of sustainability objectives and there exists today, a great awareness of the burden mankind is placing on the world environment.

In 1999 the Institution of Civil Engineers again refined its definition of the profession. Today Civil Engineering is presented as ‘the practice of improving and maintaining the built and natural environments to enhance the quality of life for present and future generations’. The significance of this should not be missed; the natural environment has equivalent status to the built environment. The objectives of this new definition are both ambitious and broad. They are also consistent with the now widely discussed and understood themes of sustainability.

These evolving definitions of Civil Engineering reflect the changing perceptions and direction of the industry and the society in which it is based. In its present form, it is true that the industry has large impact on the natural environment. But is it equally true of more specific engineering fields, and of the activities conducted within them?

2.0 Highway Bridges

Highway bridges are an integral part of our modern society. These most basic of civil engineering structures provide an invaluable service 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 largely recognised as the most influentia l to management and policy. They are also consistent with the traditional concepts of Civil Engineering. However, with the advent of sustainability it is understood that environment should be included as an additional variable within the decision-making process. In conclusion, if we are to improve and maintain our natural environments, then at a minimum we have to consider and understand the consequences of our interactions on these environments.

To do this research has applied life cycle methods to identify environmental impacts. This ‘cradle to grave’ technique ensures a holistic approach enabling the assessment of environmental burden throughout a system. The methodology further enables the environmental comparison of different structure form and of different life cycle maintenance strategies. These remain common research goals. However, it should be noted that this area of investigation is new to the industry. What is required is not simply knowledge of the benefit of a discrete structure or activity over another, but a structured method that will enable environment to be considered objectively within decision- making. Project aims are thus two fold:

1. To develop a methodology for considering environment in bridge management decision-making.
2. To provide definite answers to discrete questions on environmental performance.

This paper will outline the general project methodology explaining the work behind the evolved method and the various issues tackled in its development. The subject area remains remarkably wide due to the scope for different design and resultant life cycle strategies. A definitive assessment of environmental performance of all bridge types and material constructions is therefore out side the remits of this project. For this reason investigation of one structure class has been progressed. The primary focus of this paper will be brick arch structures. An organised environmental assessment of a brick arch bridge will be presented using Life Cycle Assessment (LCA) methodology as a means to evaluate environmental performance.

3.0 Masonry Arch Bridges in the County of Surrey

Bridge form and structural classification are well reviewed. Classically bridges can be categorised into three ‘forms’: beam, arch and cable designs. 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 throughout its service life. As a result of these differing ‘life cycles’, each structure form will have a different environmental performance.

To achieve valid comparisons of these structure categories, specific boundaries were set and the inventory of bridges managed by Surrey County Council (SCC) was classified under distinct headings. In effect an indexing system was constructed to represent all bridge designs. With a focus on arch and beam ‘forms’, a simplified model was developed. Although various designs of 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 structure inventory, a number equivalent to 430 bridges. These can be divided into semicircular, segmental, elliptical and semi elliptical forms. Typically Surrey structures tend to be of semicircular or segmental construction. It is assumed that although each varies slightly in design, the basic life cycle is common across all shapes. Therefore, the analysis of a specific structure will give a good illustration of the environmental performance of the structure class.

4.0 Life Cycle Assessment and Project Methodology

The initial focus of research has been to develop a project base and framework from which LCA work can be conducted. This has involved investigation and information collection in three key areas:

Ø Bridge form classification.

Ø The categorisation of bridge maintenance activities.

Ø The development of bridge life cycle models.

Literature review has provided input to all activities and case study investigation has produced the bulk of information for the categorisation of bridge maintenance activities and for the development of life cycle models.

4.1 Brick Arch Bridge Life Cycles

To develop life cycle models ten real brick arch structures have been reviewed in detail. Extensive background text and a management history for each have been compiled. Information has been sought from bridge records and document archives. The frequency of maintenance activities undertaken on individual structures has been noted and trends for key maintenance activities across the whole structure group have been 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’ life cycle 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 base line strategy developed from this exercise and typical of most brick arch bridges in Surrey is illustrated in Table 1.

Although it consists of a number of activities, only brickwork maintenance and the first refurbishment scheme have been considered by modelling.

The reasons for the focus on these activities include:

Ø The more minor activities do not involve replacement of materials.

Ø It was considered that parapet repairs and cutwater replacement were adequately accounted for by brickwork maintenance modelling.

Ø Bridges are presently constructed for a 120-year design life (1). 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.

Table 1. Brick arch bridge life cycle 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

4.2 Factors influencing Structure Life Cycle Models and Uncertainty

In the development of these life cycle models it was important to take account of the wider perspective particularly when interpreting individual records. The vast majority of highway bridges are single purpose structures. Although their functions are similar, discrete structure life cycles can show great variance, and different bridges that provide a similar or common service can have very different life cycles. These are defined and influenced by physical, economic, technical, symbolic, historic, commercial, political, residential, safety, recreational and social, concerns and issues. These can be termed ‘life cycle influencing factors’. The effect on structure deterioration and, by default, likely maintenance intervals is very difficult to factor into life cycle models. 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. This makes the environmental assessment of a highway bridge an inherently uncertain activity.

4.3 Life Cycle Inventory (LCI) Data

The software programme SimaPro has been used for LCA modelling. This is supported by three data sets, including Pre4, BULWAL and IDEMAT databases. Although comprehensive, the information in these databases is not entirely relevant to UK circumstances. To over come this problem there has been a drive to secure UK specific profiles. The difficulty is that very little data is available. Specific products such as paint or coating systems, materials like fill or recycled aggregate and processes like excavation or concrete vibration 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 over seeing the development of a LCI database specific to UK construction materials. The assemblies represent 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.

4.4 Life Cycle Representation

For comparative purposes LCA modelling has focused on three real bridge case studies. Although each structure is different in design and material construction, they have similar deck areas and load capacities and therefore provide the same operational service. Case studies are used because they provide for accurate material and construction process estimation. The brick arch bridge case study is Cascade Bridge (Figure 1). A series of estimates were developed for bridge construction and maintenance activities.

Figure 1. Elevation of Cascade Bridge. 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. The structure spans a small stream with large seasonal flow differences. The structure is presently 175 years old.

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 (2). Site mixing of mortar material was anticipated and accounted for by an energy demand from a site mixer running off a diesel generator. Transportation demands for material supplies to site were considered. Apart from the mortar mixing, no other site processes were considered at the construction stage. Although this places a focus on material components, it should be recognized that brick arch bridge construction uses very little, if any mechanization.

Table 2. Life cycle material demands (tonnes).

	Construction	Operation*			Strengthening	
		Good	Averg	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 (sand)	1790					
Steel reinforcing bar					2.92	
Grout						2.64
Concrete					620	
Stainless steel						1.41
Polyester fabric						0.036

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

Brickwork maintenance activities are based on the concept of poor, average and good, maintenance strategy. 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 works. Regardless of strategy, works were considered to take place at a standard 15-year frequency. 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 of 15mm (3), 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 both mass and volume terms, (Table 2). Mixing, and transport of materials to site were considered.

The final focus of modelling has been on structure strengthening methodologies. Two techniques were 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 and 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 modelling. The processes of concrete pumping and vibration settlement were included. Excavation and disposal of granular fill material were not considered. Profiles for material disposal and excavation plant have not been developed. In modelling the saddle scheme, potential traffic disruption was also considered. It was possible to do this by making a series of assumptions, Table 3.

Table 3. Determination of disruption associated with concrete saddle construction.

Structure location - Highway of B classification
Vehicle flow rate - An average Surrey B road has a flow rate of 9000 vehicles per 24 hours (4)
Detour distance - Conservatively assumed as 5 km
Structure closure time - Following consultation it was assumed to be 21-days
Using these values 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.

Procedure for modelling of 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), stainless steel reinforcement and polyester fabric, (Table 2). However, the process of installation has higher site energy demands. Primarily this is associated with the coring of the anchor holes and the mixing and pumping of grout. The benefit of the anchoring scheme is that the arch can be strengthened without having to totally 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 of specifics such as coring times, material quantities and material mixes were sought from a series of commercial groups.

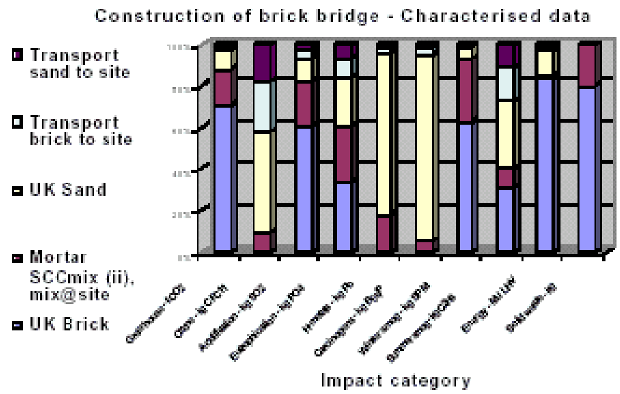
5.0 Impact Assessment

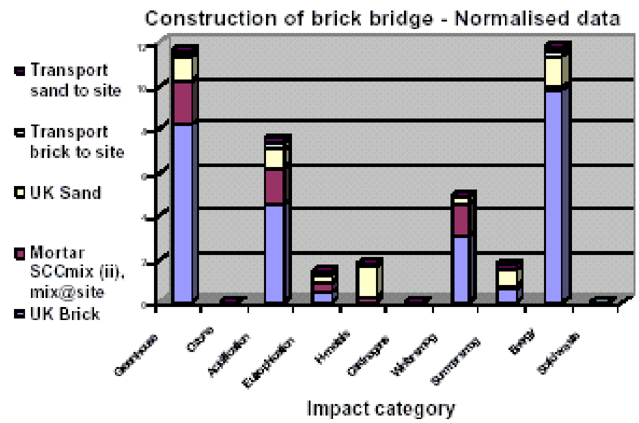
Impact assessment can be highly influential to the conclusions drawn from modelling. Through the processes of characterisation, normalisation and evaluation there exists opportunity to focus on specifics such as a particular chemical or substance, or alternatively take a much wider perspective with a focus on impact categories. Research has adopted the latter approach and ten categories have been used to investigate environmental impact. These categories are already pre-defined within SimaPro (5) and include:

- Eutrophication – kg PO4
- Solid waste production – kg
- Energy consumption – MJ
- Greenhouse gas – kg CO2
- Ozone depletion potential – kg CFC11
- Summer smog impact – kg C2H4
- Winter smog impact – kg SPM
- Heavy metals – kg Pb
- Carcinogens – kg B(a)P
- Acidification – kg SO2

They have the advantage in that they are recognisable environmental issues. Results in this paper will focus on characterised and normalised data in these categories. Elsewhere, particularly for presentation purposes, evaluated findings have been used. To develop these the Eco-Indicator 95 method has been applied, it offers an attractive method for representing the seriousness of life cycle impacts. This is particularly useful when presenting findings to an environmentally 'unsophisticated' audience. It also has potential as a scoring method that can rank a highway bridge design or life cycle on environmental performance. 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 is understood, and its limitations are accepted.

The results from environmental analysis of bridge construction are presented through Figures 2 and 3. It is evident that brick demand represents the biggest single burden in almost all impact categories. This is perhaps not surprising given the large quantity of material required (475 tonnes), and the industrial processes associated with its manufacture. In contrast, the impact from transportation of materials to site is small. This is a reflection of the fact that the model assumes that materials are locally produced. In most circumstances this is true, with the result that transportation distances are small (e.g. bricks are historically sourced from local suppliers). 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. In such circumstances the impact from transportation does rise, however, it remains relatively insignificant when contrasted against the material production processes.





Figures 2 and 3. Characterised and normalised impact data for construction of a brick arch bridge.

The demand for sand at construction is high and equates to 1790 tonnes. Despite this the impact it posses is relatively minor. This is because the only functions associated with sand provision are the dredging of the material, its cleaning, and its transportation to site. None of these activities require high-energy delivery and per tonne, the energy demand for sand is 31MJ. The result is total energy demand to supply sand to site is low, particularly when contrast against the energy demands for brick manufacture (energy requirement is 3300MJ per tonne). Despite this, sand is seen to have environmental impact within the carcinogenic and heavy metal fields. The reason for this is that a different energy profile has been used to represent energy delivery to sand producers. This profile contains emissions associated with national grid energy supply. Other materials have different energy profiles that do not represent a burden in these categories.

For bridge construction it can be seen that the quantities of solid waste are not large particularly when data is normalised. In general wastage rates are not high and it is considered that granular and aggregate waste materials produced on site would be consolidated into the arch as fill material following construction. Total solid wastes leaving site are therefore small. For example, a 2% wastage rate for brick has been accounted for, this equates to 9.5 tonnes yet this material would not be removed from site and would be used as fill material on completion of brickwork construction.

Apart from transportation of materials to site, the only other process considered was mortar mixing. The impact of this 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. For the mortar assembly the principal impact comes from cement and lime production. 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 life cycle, brickwork maintenance in relative terms does not represent a large environmental burden. The primary reason for this is that the quantity of material used even for a good maintenance strategy is not great, (Table 2). Indeed, the total normalised value across all impact categories for brickwork renewal and repointing activities over an entire life cycle is only 7.3. To put this in perspective, the normalised figure for brick provision (only) at bridge construction equates to 27. The conclusion to be drawn is that basic structure maintenance when contrasted against structure construction is not a major source of environmental impact. This finding has implications to maintenance policy. It is widely recognised that good general maintenance prevents structure deterioration; in short, 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 minimum impact on environment, and extend the time to structure replacement and/or refurbishment; activities that do represent significant impact. When comparing the two activities of brickwork renewal and repointing the former represents significantly greater impact. Illustration of this is borne out through Figure 4. The graph illustrates characterised values for both activities and shows that in all categories the greatest burden is produced by brickwork renewal. In all categories repointing represents less than 20% of the impact that brickwork renewal does. This provides a further reason for affording 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.

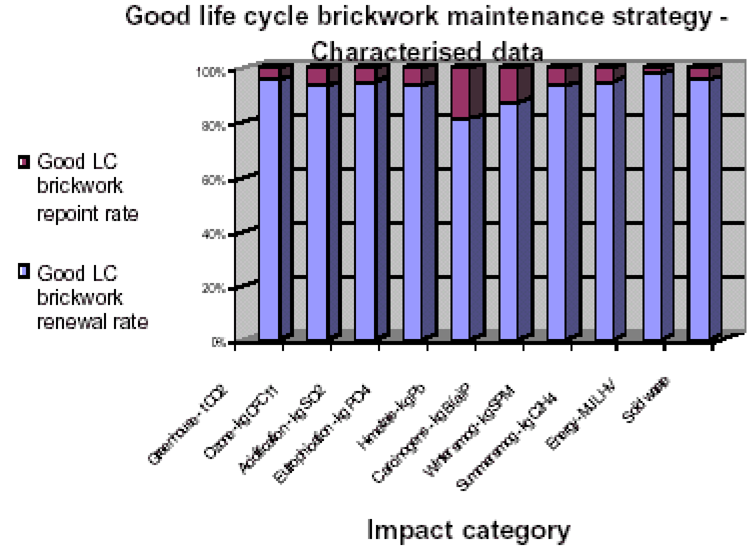
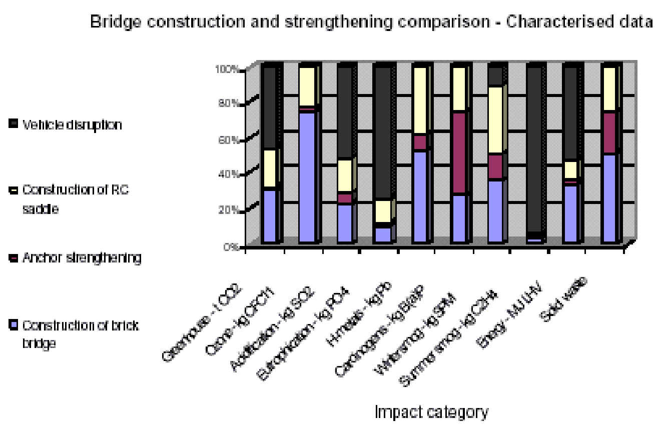
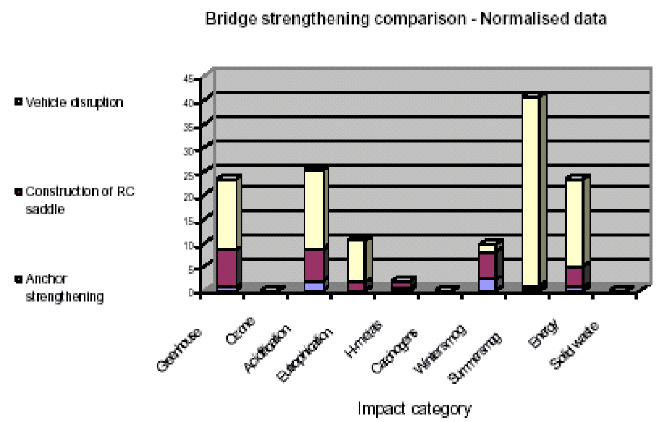


Figure 4. Characterised impact data for brickwork maintenance over a 120-year life cycle.

When a structure reaches obsolescence and is under strength, a number of options exist for continuing to provide a fixed transportation link at that location. Objectively, these consist either of bridge replacement, or refurbishment/strengthening of the existing structure. In this paper two structure strengthening methods are reviewed. These include the construction of a concrete saddle, and strengthening with anchor bracing. 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 demands yet has higher energy requirements on site, beneficially to the technique, no traffic disruption occurs. The impact results of these activities are shown through Figures 5 and 6.





Figures 5 and 6. Characterised and normalised impact data for construction of a concrete saddle contrast against an anchor bracing strengthening scheme.

From the results a series of key observations can be made:

- Construction of the bridge represents greater burden than both the works processes and material demands associated with the two strengthening methodologies. This is clearly shown in Figure 5. The conclusion to be drawn from this is that it is better environmentally to strengthen a brick arch bridge rather than replaced it with an entirely new structure of similar design.

- 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. Construction of the saddle uses a ‘relatively’ large amount of material. It is the manufacture of this material that causes the impact. Although the anchor installation processes have high site energy demands, on aggregate, because of the small amounts of material used, as a scheme it represents only minimal impact.

- The anchoring technique uses stainless steel reinforcement. The manufacture processes associated with the production of this material have a noticeable carcinogenic impact. However, once normalised this category becomes less significant, Figure 6.

- The solid wastes produced from concrete saddle construction have not been fully assessed by this model. For this reason the wastes produced from the anchor installation appear relatively large. In reality the volumes would be small in comparison to those that would occur from construction of the concrete saddle.

- The greatest issue to arise from this study is the polluting effect that occurs from traffic disruption. Clearly illustrated in Figure 6 the impact from traffic diversion is the biggest contributor in five of the ten impact categories. This is despite modelling both a traffic volume and detour distance that might be termed as conservative. It should also be recognised that the sophistication of the traffic model is not great, and consists of a select group of air emissions and fuel demands. If an assembly of greater detail were used it can be hypothesised that the impact from traffic disruption would be of greater significance still.

- The environmental effects of traffic diversion thus have important implications for structure strengthening. In reality it is not possible to divorce the saddle construction activities from the effects they cause on traffic disruption. If you undertake the works, traffic disruption will occur with the resultant vehicle emissions. The environmental impact of the saddle scheme should therefore include the impacts from traffic. By combining the two assemblies the saddle scheme is found to have greater impact in all ten environmental impact categories. Partial illustration of this point is made in Figure 6.

- This conclusion could be widened to encompass all maintenance/strengthening activities. 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. If the closure were long enough (greater than nine days in this case study) then the impact from traffic disruption becomes greater on aggregate than the construction of the bridge in the first instance.

6.0 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, defining a structure life cycle and using Life Cycle Assessment technique, environment has been investigated under key impact categories. A brick arch structure has been chose as a case study. From the study a series of key conclusions can be made.

- 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 diverting can on occasion (if the disruption period is long) be a source of greater environmental impact.

- It is the manufacture of the material components of a structure that is the source of greatest environmental impact. For a brick arch bridge the greatest impact arises from the clay brick production process.

- In contrast to the manufacture of materials, transportation of materials and site processes associated with construction, maintenance and strengthening all represent only minor burden.

- Basic brickwork maintenance has only minimal impact on environment. These activities including 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 contrast against saddle construction. The technique itself has less environmental impact than a saddle scheme and has the significant environmental advantage in that traffic disruption will not occur as a result of works.

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