Life Cycle Assessment of Use of Recycled Materials in Asphalt Pavements

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Thesis submitted to the Newcastle University for the Degree of Doctor of Philosophy

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Date: 31st July 2007

Abstract

The increasing use of recycled materials in asphalt pavements asks for prescriptive environmental assessment on associated impacts such as the energy and CO_2 footprint. Accredited by a number of industries already, life cycle assessment (LCA) is being accepted by the road industry to measure and compare the key environmental impacts of its product or process throughout the whole pavement life time, and present the results for communication with stakeholders.

This thesis reviews the technical performance of asphalt pavements containing recycled materials; searches for relevant LCA resources worldwide; identifies the gap for the road industry, and the key environmental impacts of recycling in asphalt pavements. It describes the development of a LCA model for pavement construction and maintenance that accommodates recycling practice and up-to-date research findings. Details are provided of both the methodology and data acquisition. 3 real case studies are carried out during the model development, and their findings described in this thesis. This is followed by a discussion of the challenges of applying LCA to road practice, and recommendations for further work.

Data in this model come from a mixed source of UK plants, EU standards and relevant LCA results. Methodology follows the ISO14040 norms. Unit processes in asphalt pavement construction are analysed and represented in this LCA model. The most significant variables in the process are identified, followed by data analysis and sensitivity check. This LCA model can be further tested and calibrated as a decision supporting tool for the asphalt industry. In order to achieve sustainable construction however, environmental assessment must be placed alongside the outcome of technical and economic studies.

Acknowledgement

I would like to thank my supervisor Mr. Roger Bird, Lecturer in Highway Engineering of Newcastle University, for his academic as well as professional advice throughout my PhD research. His wealth of knowledge, thorough attitude and innovative thinking has been, and will be, guiding me toward my further study and career development.

This research and model development is sponsored by Aggregate Industries UK Ltd. The data and the real case studies that the Company provided herein are greatly appreciated. Dr. Paul Phillips and Mr. Bob Allen have given this research invaluable advice on our regular progress meetings. I am also grateful for the cooperation and assistance from other staff of Aggregate Industries UK Ltd. including Dean Floyd, Darren Roddam, Mark Kirby, Phil Coupland and Mike Scott, to name but a few.

Also I owe a debt of tribute to my colleagues at Newcastle University, including Dr. Oliver Heidrich and Professor Tom Donnelly who advised me on the LCA and refined my research skills and outcomes, Mr. Sergio Grosso for his assistance with the micro-simulation work, and Professor Margaret Bell for her general advice and guidance on my thesis.

Last but not least, heartfelt thanks to my parents Mr. Guoyuan Huang and Mrs. Guoping Duan who have always been of strength, love and care, and emotional support to me.

CONTENTS

List of Figures

List of Tables

List of Abbreviations

General	**Emission Substances:**
ACEA (European Automobile Manufacturers Association)	As (Arsenic)
AI (Aggregate Industries UK Ltd.)	BOD (Biological Oxygen Demand)
BRE (Building Research Establishment)	CCl_4 (Carbon Tetrachloride)
C&D (Construction and Demolition)	
CML (Institute of Environmental Sciences, Leiden University)	Cd (Cadmium)
DALY (Disability Affected Life Years)	CFC (Chlorofluorocarbons)
DfT (Department for Transport)	CH_4 (Methane)
DTI (Department of Trade and Industry)	C_2H_4 (Ethylene)
DTU (Technical University of Denmark)	CH_3Br (Methyl Bromide)
EA (Environment Agency)	CH_3CCl_3 (Methyl Chloroform)
EAPA (European Asphalt Pavement Association)	Cl (Chloride)
EEC (The European Economic Community)	CO (Carbon Monoxide)
EMEP (Convention on Long-range Transboundary Air Pollution)	CO_2 (Carbon Dioxide)
EURELECTRIC (Union of the Electricity Industry)	COD (Chemical Oxygen Demand)
HMB (High Modulus Base)	Cr (Chromium)
HRA (Hot Rolled Asphalt)	Cu (Copper)
IBA (Incineration Bottom Ash)	HC (Hydrocarbons)
IIASA (International Institute of Applied System Analysis)	HCFCs (Hydrochlorofluorocarbons)
IPCC (Intergovernmental Panel on Climate Change)	Hg (Mercury)
IVL (Swedish Environmental Research Institute)	Mg (Manganese)
LCA (Life Cycle Assessment)	Mo (Molybdenum)
LCI (Life Cycle Inventory)	N_2O (Nitrous Oxide)
LCIA (Life Cycle Impact Assessment)	NH_3 (Ammonium)
LCM (life cycle management)	Ni (Nickel)
LHR (London Heathrow)	NMVOC (Non-Methane Volatile Organic Compounds)
LPG (Liquefied Petroleum Gas)	NOx (total of Nitric Oxide (NO) and Nitrogen Dioxide (NO_2))
MSWI (municipal solid waste incineration)	PAH (Polycyclic Aromatic Hydrocarbons)
NAEI (National Atmospheric Emissions Inventory)	Pb (Lead)
NCSA (National Crushed Stone Association)	PM_{10} (Particulate Matter <10µm)
NCHRP (National Cooperative Highway Research Program)	PO_4 (Phosphate)
NRC (Canadian National Research Council)	Sb (Antimony)
ONS (Office of National Statistics)	SO_2 (Sulphur Dioxide)
PG (Penetration Grade)	V (Vanadium)
PMB (Polymer Modified Bitumen)	VOC (Volatile Organic Compounds)
QPA (Quarry Products Association)	Zn (Zinc)
QUARTET (Quadrilateral Advanced Research on Telematics for Environment and Transport)	
RAP (Reclaimed Asphalt Pavement)	
RAINS (Regional Air Information and Simulation)	
RBA (Refined Bitumen Association)	
REAL (The Road Emulsion Association Limited)	
RIVM (National Institute for Public Health and the Environment)	
SAFEL (Swiss Agency for the Environment,	

Forests and Landscape)	
SAMI (Stress Absorbing Membrane Interlayer)	
SETAC (The Society for Ecological Toxicology and Chemistry)	
SMA (Stone Mastic Asphalt)	
TGCE-LCPC (Division for Civil Engineering and Environmental Technologies, the French Public Works Research Laboratory)	
TOE (Tonnes of Oil Equivalent)	
TRL (Transport Research Laboratory)	
UNECE (United Nations Economic Commission for Europe)	
UNEP (United Nations Environment Programme)	
USES (Uniform System for the Evaluation of Substances)	
VISSIM (VISual SIMulation)	
VTT (Technical Research Centre of Finland)	
WMO (World Meteorological Organisation)	

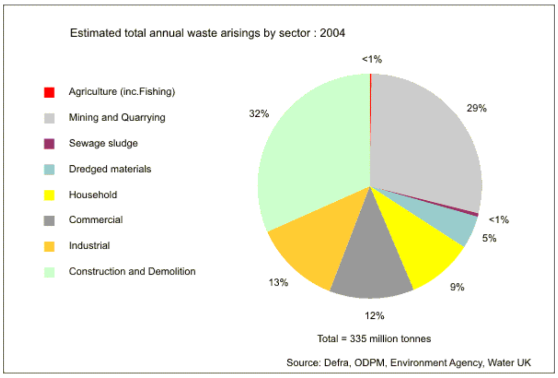
Chapter 1 : Introduction

1.1. Background

1.1.1. Quarrying and Waste - an “Inconvenient Truth”

Great Britain quarries each year approximately 200 million tonnes (Mt) of primary aggregates from land sources. Around 90% are used by the construction industry (QPA 2007). In 2005, roads accounted for, by value, about 3.5% of all construction works in the UK (DTI 2006). Some 95% of UK roads are paved with asphalt materials (IAT 2006). The construction and maintenance of these roads require large amounts of aggregates, which typically represent more than 90%, by weight, of the asphalt mixtures. The European Asphalt Pavement Association (EAPA) estimates that UK produced in 2004 some 27Mt of hot mix asphalt (HMA) (EAPA 2005). Millions of tonnes of aggregates are extracted and transported each year for use in roads. The Highways Agency for instance, consumes between 20,000-60,000 tonnes of aggregates in laying one mile stretch of motorways in England (The Highways Agency 2003).

Meanwhile in 2004, some 220Mt of waste were generated from industry and commerce, municipal/household and construction and demolition (C&D) in the UK, nearly 2/3 of the annual total of 335Mt (DEFRA 2006). A considerable percentage (industrial and commercial: 44%; municipal: 72%, etc) found its way to landfill, although the reuse and recycling rate is on the rise between 1998/9 and 2002/3 (industrial and commercial: from 39% to 45%; C&D: from 45% to 50%, etc) (DETR 2000; DEFRA 2006).



Source: Defra, ODPM, Environment Agency, Water UK

Figure 1-1 Waste Arisings by Sector in the UK (DEFRA 2006)

Such resource management does not seem to be in line with the Country's strategy for sustainable construction that requires the environment to be protected and the consumption of natural resources minimised (DETR 2000). There is concern that high specification aggregates (HAS) from UK permitted extractions could be exhausted as early as 2020 (Parker 2004). The situation seems even more urgent for approved landfill sites, as they are expected to run out of space in the next 5-10 years (The Environment Agency 2007). Based on such pressures, the UK government introduced the Landfill Tax[1] in 1996 and the Aggregates Levy[2] in 2002, providing financial incentives to the recycling drive. The Waste and Resources Action Program (WRAP) was established in 2000 as part of the Government's waste strategy to 1) create additional markets for recycled materials, 2) provide advisory services on recycling practice and, 3) encourage public participation in the nationwide recycling campaign (WRAP 2007). Besides these are peer pressure, Government's purchasing power, and requirement for reporting of Company's key performance, etc, in a concerted effort to prudent use of natural resources and effective management of waste, an essential step towards sustainable construction (Bird, Clarke et al. 2004).

Therefore the aim of this thesis is to investigate what approach the road construction industry can take to mitigate this 'quarry and waste' situation; to review what progress the industry has made so far; and to assess the technical and environmental aspects of the recycling practice in order to verify whether it meets the requirements of sustainable construction.

1.1.2. Use of Recycled Materials in Roads

Aggregates other than primary are defined as 'recycled' or 'secondary'. Recycled aggregates are reprocessed materials previously used in construction, recycled asphalt pavements (RAP) for example; secondary aggregates come from households or other industrial processes than construction, such as glass and steel slag (WRAP 2007). Table1-1 gives example of these types of aggregates. Apart from aggregates substitute,

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[1] A lower rate of £2/tonne applies to defined inert waste; a standard rate that increases every few years from £7/tonne as in 1996 applies to all the other taxable waste.

[2] A rate of £1.6/tonne is charged to all commercial extraction for construction aggregates including sand, gravel and stone.

a few recycled materials have the potential for replacing or modifying the bituminous or hydraulic binder in road structures.

Table 1-1 Types of Recycled and Secondary Aggregates (FHWA 1997; DMRB 2004; WRAP 2007)

Recycled Aggregates	Secondary Aggregates	
Recycled Aggregates	Blast Furnace Slag (BFS)	Pulverised Fuel Ash (PFA)
Recycled Asphalt	China Clay Sand	Recycled Glass
Recycled Concrete	Coal Fly Ash (CFA)	Recycled Plastic
Recycled Roofing Shingle	Colliery Spoil	Recycled Tyre
Spent Rail Ballast	Foundry Sand	Slate Aggregates
	Furnace Bottom Ash (FBA)	Spent Oil Shale
	Incineration Bottom Ash (IBA)	Steel Slag
	Kiln Dusts	

The use of recycled, instead of virgin, materials has the “dual sustainability benefits” of easing landfill pressure and reducing demand of extraction. This is an important means of getting the road industry on track towards sustainable construction. Design Manual for Roads and Bridges (DMRB) lists the permitted applications of recycled materials in road layers (DMRB 2004). The features of the road structure indicate that the lower courses (base, sub-base, etc) are able to absorb materials in larger quantity than upper layers. However, to maximise the proportion of recycled materials in construction supplies means more than quick burying of waste materials, possibly materials of greater value if used in other places.

For instance, the superior performance of steel slag when used as aggregates in asphalt surfacing, including strength and skid resistance, would be wasted by using it to replace cheap stones in granular base. The balance between new roads and maintenance that highway authorities in the UK are dealing with has moved towards the latter in recent years; and maintenance works affect mainly the upper pavement layers. In addition, the cost of transport and processing waste materials to have the desired properties is more likely to be justified by using the recycled materials in value applications such as the asphalt surfacing. The technical performance of asphalt layers containing some of the commonly used recycled materials is reviewed, and the cost implications assessed, in this thesis.

1.1.3. Key Indicators beyond the “Landfill Scheme”

The “dual sustainability benefits” are not to be achieved without a cost. Environmental concerns over recycling waste into pavement aggregates mainly have two aspects: 1) energy for transport and processing the waste in construction phase, and 2) leaching from recycled components in place during pavement life. Literature on these impacts will be reviewed in this thesis. Resource efficiency alone does not guarantee sustainable construction. Road works need to take into account a lot more social and environmental footprints than saving landfill space (WSP 2003). This is determined by the features of road works which include:

- Large volumes of quarry products and energy input;
- Long and linear geographic layout implying huge, as well as site specific, environmental and aesthetic impacts;
- Regular maintenance work during the long service life;
- Strong influence of technical performance on users’ cost.

Well defined targets and indicators, against which companies can measure their progress towards sustainable construction, are paving the way for an on-time and on-budget delivery of their ‘green’ goals. To put such a strategy into practice, companies need to identify, by means of hard evidence, the priority areas for action, and develop a set of targets and indicators for the best practice in all aspects and dimensions of the business. These then can be communicated to stakeholders, and used to benchmark their performance against competitors.

According to the Construction Industry Research and Information Association (CIRIA), the ideal indicators should be: “1) relevant, 2) representative, 3) repeatable, 4) responsive to change, and 5) reasonably easy to interpret” (CIRIA 2001). A consensus was recently formed around 6 key impact areas within the UK asphalt industry, based on the findings of a review workshop set up by the Refined Bitumen Association (RBA), the Quarry Products Association (QPA) and the Highways Agency, and published by the Transport Research Laboratory (TRL). These impact areas are (TRL 2005):

- Design for long-life pavements: promote resource efficiency by adopting quality paving materials and innovative maintenance techniques;
- Increase re-use and recycling in road works: use recycled and secondary materials where possible;
- Whole life cost analysis: address the life-time, rather than the short-term, cost considering both the agency's and the users' cost when selecting materials, layer thickness, interval of maintenance and the service level to restore, etc;
- Implement an effective environmental management system (EMS): reduce site emissions, pollution incidents and the waste volume; reduce water and energy use;
- Health and safety (H&S): improve H&S of the work place; provide employees with training and equal opportunities; enhance staff's environmental awareness;
- Responsible procurement, selling and marketing: know the clients' expanding expectation; engage suppliers and contractors in commitment to sustainable practice; provide unequivocal and backed statement for stakeholders.

1.1.4. A Life Cycle Approach to Sustainable Construction

Of those indicators above, some are obvious and paramount; others may be marginal and traded, in a project, against one another. Companies aiming for environmental labelling need to ensure their pursuit of 'green' product or process will not end up with undesirable consequences caused by simply shifting problems elsewhere or trading off one for another, possibly worse, impact. Claims of 'green practice' simply based on a certain aspect like materials saving or energy reduction are disputable and hard to compare. A life cycle approach is gaining ground in meeting the needs of sustainable construction (WSSD 2002). The tool developed as an outcome of this PhD project will analyse by accredited assessment technique all the key environmental impacts involved in the construction, use and disposal of asphalt pavements; test and calibrate the tool to industry needs; and present the results in a standard format.

1.2. Life Cycle Assessment (LCA)

The increasing use of recycled and secondary materials in asphalt pavements needs up-to-date studies on associated environmental impacts including the energy use, emissions and leaching, etc. Simply diverting the waste, such as glass, from other industries to aggregates supply is already questioned for its energy and carbon dioxide

(CO_2) footprint (Dacombe, Krivtsov et al. 2004; Grant Thornton and Oakdene Hollins 2006; WRAP 2006). Procurement documents for pavement construction regarding the laying technique, materials and maintenance option ask for prescriptive environmental assessment.[3] Already accredited by a number of industries, life cycle assessment (LCA) is being accepted and practiced by the road industry to measure and compare the key environmental impacts of its product or process throughout pavement life. These analyses provide the results for effective communication with stakeholders.

1.2.1. History of LCA

Life cycle assessment, developed in the 1970s, is a comparatively new technique. It objectively quantifies the total environmental burdens of a product across its life time from raw material acquisition, through production, use and final disposal: a cradle-to-grave analysis. The US Society of Environmental Toxicology and Chemistry (SETAC) works on the coordinated development of LCA across Europe and the States. International standards regarding LCA (the ISO14040 series) have existed since 1997. Through its growth, LCA is actively practised by a number of industries, such as house-building materials in France (B.L.P.Peuportier 2001), the German automobile industry (Mildenberger and Khare 2000), and world-renowned chemicals and consumer goods companies (BASF, Proctor and Gamble, etc), to monitor and report their eco-efficiency and environmental stewardship (BASF and Proctor& Gamble 2006).

Application in civil engineering, initially as a tool for assessing solid waste management (SWM) options, has started only in the last decade. Relevant practice in roads and asphalt pavements, particularly when recycled and secondary materials are involved, is limited (see Chapter Two). Besides giving the knowledge of products' environmental performance, LCA results are also able to support marketing or environmental labelling. For instance, the recently standardised Type III Environmental Product Declaration (EPD), which enables informed comparison between products fulfilling the same function, requires quantified environmental information based on independently verified LCA results (ISO14025 2006).

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[3] Personal communication with Bob Allen, Research Manager, Aggregate Industries UK Ltd on 25 September 2006.

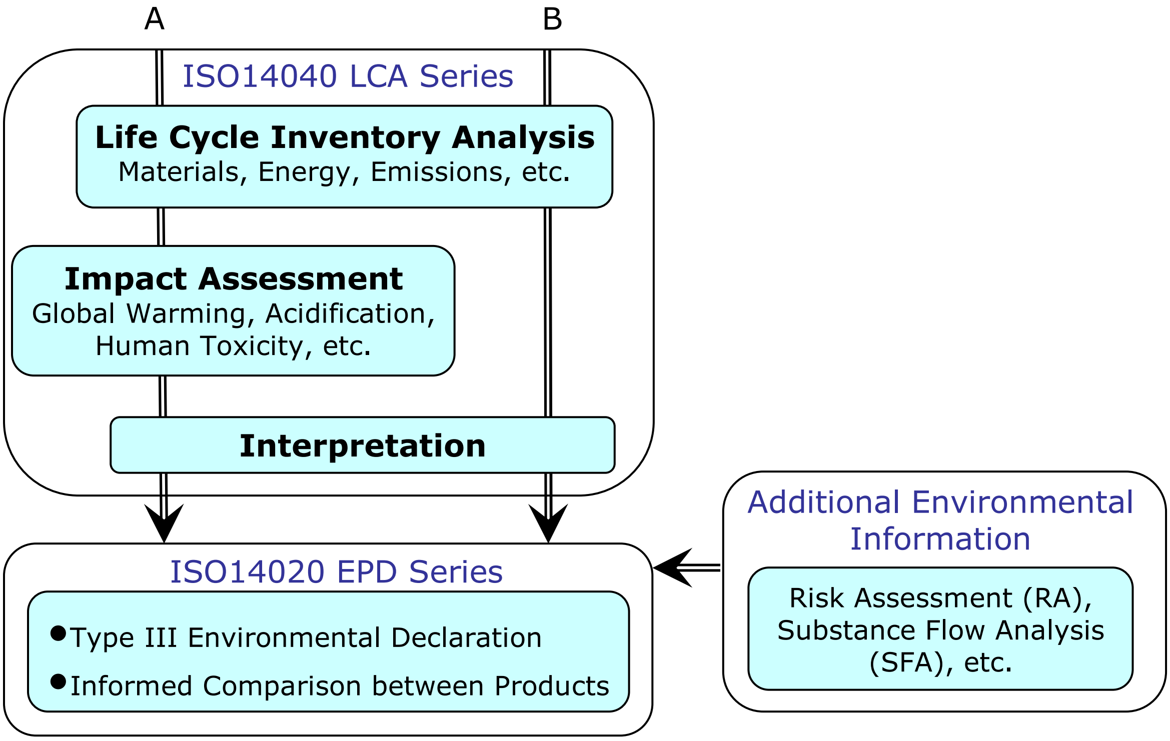

Figure 1-2 Role of LCA in Environmental Product Declaration (ISO14025 2006)

1.2.2. LCA Framework

The main work in LCA includes the development of an inventory, in which all the significant environmental burdens (input and output) will be compiled and quantified. This is followed by an impact assessment, calculating and presenting results in a predefined way that supports comparison or further analysis. The four phases of LCA are described below (ISO14040 2006):

1) Goal and Scope Definition – the first phase of LCA setting the boundary, level of detail, and time frame of the study. It also influences assumptions and options made throughout the study such as system boundary, data source and impact category.
2) Life Cycle Inventory (LCI) analysis – a relatively objective step that collects and compiles data of environmental input (raw materials, energy, etc) and output (emissions, leaching, solid waste, etc) within the system defined previously.
3) Life Cycle Impact Assessment (LCIA) – evaluation of LCI results during which an indicator and a characterization model will be selected for each impact category. LCI results assigned to the category are calculated using the

characterisation model, and the results presented by the indicator. This is a phase of LCA where some subjective choices are made to a particular application. It consists of both mandatory and optional elements that include:

a) Impact Category Definition – select a set of categories to which LCI results are allocated, alongside the definition of category indicator and characterisation model.
b) Classification – assign LCI results to impact categories.
c) Characterization – calculate indicator results within each impact category.
d) Normalization (optional) – calculate the magnitude of indicator results relative to reference information.
e) Grouping (optional) – assign impact categories into predefined groups (descriptive) and possibly rank them (normative).
f) Weighting (optional) – convert and possibly aggregate indicator results across impact categories using numerical factors based on value choice, a further step towards a single-numbered result.
g) Data Quality Analysis (optional) – understand the reliability as well as drawback of data used in the study, and the sensitivity of indicator results in significant areas.

4) Interpretation – a phase to compile, check and evaluate the results from LCIA or LCI phase, to form conclusion and recommendation.

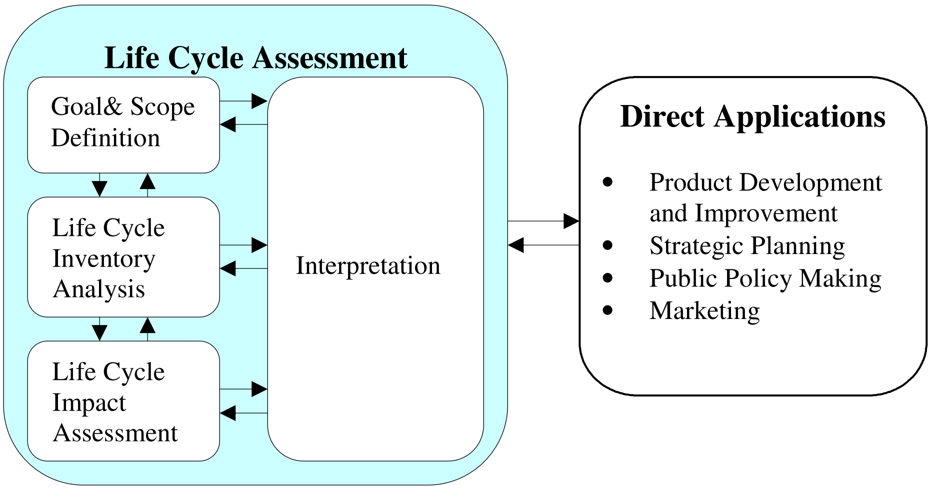

Figure 1-3 Framework of Life Cycle Assessment (ISO14040 2006)

In general, the results of LCA can assist in the following areas:

- Identify opportunities to improve the environmental performance of a product or process in the life cycle period;
- Decision-making in industry, government body or non-governmental organizations (e.g. strategic planning, priority setting, policy making) and;
- Marketing (e.g. environmental labelling, reporting, and product declaration).

Therefore some form of LCA work will be needed in this thesis, as the methodology and application meet the needs of environmental assessment of recycling practice in roads. Units in the construction process will be analysed and represented in the LCA model. Including CO_2 that makes the “inconvenient truth”, an environmental input-output inventory will be established for calculation and presentation of LCI results. The thesis will describe the development of an LCA model on top of existing databases, and through real case studies.

Chapter two reviews the technical performance of asphalt pavements containing recycled materials, availability of these materials and the cost implications. Also reviewed are the key environmental impacts of recycling in roads, the relevant LCA resources and the knowledge gap. Chapter three studies the unit processes in asphalt pavement projects; and describes the development of a LCA model (Excel spreadsheet) for pavement construction and maintenance. Details are provided of both the methodology and data acquisition. Chapter four includes a couple of case studies applying this LCA model to real asphalt paving projects in the UK. Chapter five introduces the micro-simulation model (VISSIM) and traffic emissions model (EnvPro), to compare the energy use and emissions of traffic to those of roadwork. This is followed by a discussion of the benefits of applying LCA to road practice and the risks of not doing it, the challenges in this application, and the scope of LCA and recommendations for further work (Chapter six and Chapter seven). Attached in the appendices are a couple of questionnaires completed by Aggregate Industries UK Ltd in response to data request for the case studies (Appendix One and Appendix Two), as well as a description of the calculation formulas, and relations between the worksheets, in this LCA model (Appendix Three).

Chapter 2 : Literature Review

The technical requirements specified by the road industry need to be met, by the recycled materials intended for use in asphalt pavements. The waste materials should be available, affordably recycled, and safely playing a role in the pavement structure. Waste glass, steel slag, tyre rubber and plastics are selected for detailed study in this PhD project including their arisings, management and application in asphalt pavements (Huang and Bird 2005; Huang, Bird et al. 2007). Recycling of these 4 materials for use in asphalt is commonly seen in practice. It is therefore assumed that similar research method can be taken for the study of other solid waste materials (SWM). Asphalt surfacing (surface and binder course) of the pavements is considered here to be a value application, as discussed in Chapter one, for these recycled materials.

The key environmental impacts of using recycled materials in roads are reviewed. Energy, emissions and leaching are selected for in-depth research (Huang, Bird et al. 2007). Relevant LCA resources worldwide are also reviewed, and the knowledge gap identified, for the asphalt industry. This will justify the need for the development of a new LCA model in Chapter three.

2.1. Waste Arisings and Management

The attributes of some waste materials from industry and commerce (steel slag, tyre, etc), municipal/household (glass, plastics, etc) and C&D (RAP, etc) sources give them potential for secondary use in road or building construction replacing natural aggregates. The waste arisings in the UK showed, in recent years, the sign of decoupling from economic growth (DEFRA 2007). The recycling rates have increased considerably since the Waste Strategy was put in place 7 years ago (DEFRA 2006), but the level of use of the recycled materials in transport infrastructure varies across the country, mainly due to the difference in local landfill space and access to natural quality aggregates (TRL 2001).

2.1.1. Waste Glass

WRAP estimated that in 2003, some 3.4Mt of glass entered the UK's waste stream of which about 2.4Mt (71%) was container glass, 0.76Mt (23%) was flat (or window) glass and the remaining 0.24Mt ranged from CRT (Cathode Ray Tube), fibre to lighting bulb. The recycling rate for container and flat glass was 36% and 30%, respectively. In total, some 1.1Mt (33%) of waste glass was recycled, among which 0.73Mt (66%) was fed to glass container manufacturers and 0.14Mt (13%) used as secondary aggregates. The majority of 2.3Mt (67%) of waste glass was disposed to landfill (WRAP 2004). The EU Directive on packaging waste (The European Union 1994) however, has led to a UK recycling target of 60% by 2008 for waste glass (British Glass 2004).

The lack of collection infrastructure is blamed for sending the majority of waste glass to landfill in the UK (British Glass 2005). The recycling infrastructure serves not only as a passive receptor of recyclable waste, but as a visual motivation that influences people's recycling behaviour (Gonzalez-Torre, Adenso-Diaz et al. 2003). Currently in the UK, Packaging Recovery Notes (PRNs) are acquired by 'obligated businesses' from 'accredited re-processors' as an incentive to recycle aluminium, glass, paper and plastics, etc. The value of PRNs fluctuates over time, and is currently (March 2007) about £21-25/tonne for glass (Letsrecycle.com 2007). The value is suggested to be raised high enough to cover the recycling cost (WRAP 2004).

Glass can be recycled indefinitely without loss of product quality (British Glass 2005). Returning recycled cullet to a glassmaking plant saves energy and mineral resources in great quantity (Edwards and Schelling 1999; Krivtsov, Wager et al. 2004). Using waste glass to substitute aggregates is perceived less sustainable in terms of energy and CO_2 footprint, based on the results of previous LCA studies of glass (Dacombe, Krivtsov et al. 2004; Grant Thornton and Oakdene Hollins 2006). However, the colour imbalance between glass production and waste arisings[4] encourages, in occasions even necessitates, seeking alternative markets for waste glass, such as use for aggregates (Hopkins and Foster 2003). Use of recycled glass as coarse aggregates

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[4] The largest volume of UK glass manufacturing is clear; the largest waste glass stream is green. The price of glass containers delivered to re-processors is in the descending order of clear > amber/brown > green > mixed.

in concrete gives rise to alkali-silica reaction (ASR) and as a result, cement replacement with PFA or ground granulated BFS was introduced to reduce the damaging ASR (BRE 2006). In addition to the above applications, waste glass can be used as aggregate in asphalt road construction should the technical specification as described later are being met.

2.1.2. Steel Slag

The amount of steel slag can be estimated based on the output from steel production process, assuming that the process is stable and the rate of slag generation consistent. According to US NSA (National Slag Association), steel slag accounts for, by weight, 7.5-15% of the steel produced (NSA 2001). The marketable slag is estimated by USGS (US Geological Survey) at a rate of 10-15% steel production (USGS 2001). One advantage of recycling steel slag is that the slag can be collected from a low number of steel plants, making the collection more efficient than for most other solid waste materials. In addition, this gate-to-gate process makes it possible to achieve controlled and consistent quality of the recycled materials. TRL reported in 2003 that some 1Mt of basic oxygen steel (BOS) slag was produced annually in the UK, with about 4Mt in stockpiles (TRL 2003). Recently in 2007, the figures were updated to be 0.75Mt and 1Mt, respectively (Roe and Dunford 2007). Owing to decades of research and practice, UK has now achieved a 100% recycling of steel slag, 98% of which are used as aggregates, mainly in concrete and asphalt (ODPM 2002). The UK's steel production saw a decline from some 18Mt in 1997 to not even reaching 12Mt in 2002, before rising to around 14Mt in 2004 (UK Steel 2006). Although steel slag in the UK is 100% recycled, application in asphalt surfacing is valued thanks to its mechanical properties as described later.

2.1.3. Waste Tyre

TRL estimated that the UK generates nearly 0.44Mt of waste tyre per annum, 100% of which has potential for use as aggregates. The fact is that about 21% is shredded and used for that purpose, 22% sent for energy recovery, and around 34% is disposed to landfill, stockpiles or illegal dumps where it is mixed with other waste makes the recovery difficult (Viridis and TRL 2003; WRAP 2003). Approximately 0.04Mt (or 9%) is combusted in cement kilns, as scrap tyres have a comparable energy value to coal, and have been used as an alternative fuel in cement production (UTWG 2002). According to TRL, the high processing cost is responsible for the existence of unregulated tyres disposal (Viridis and TRL 2003). European Tyre Recycling Association (ETRA) estimated the transport cost of post consumer tyre at about £1/tonne/km in average (Shulman 2000). The use of scrap tyres in asphalt or other road structures needs to be subsidised to compete financially with established aggregates in meeting the technical requirements for that use (Washington DOT 2003).

2.1.4. Waste Plastics

About 2.8Mt of waste plastics is generated per annum in the UK. Most of those reused or recycled (a total of around 5%) are from industry and commerce sectors; recycling from municipal sources (e.g. bottles) is less practised, for economic reasons (TRL 2004). An increase of recycling rate relies on the successful recycling of plastics mixed with other waste (British Plastics Federation 2006), and the support from robust environmental assessment method (Patel, Thienen et al. 2000). Similar to tyre rubber, a notable percent of waste plastics is recovered by retrieving its thermal content (38MJ/kg), comparing favourably to that of coal (31MJ/kg) and reducing energy as well as CO2 footprint (Patel, Thienen et al. 2000; British Plastics Federation 2006).

Data from WRAP indicate that about 0.4Mt of waste plastics generated each year is suitable for aggregates use. Presently only 0.008Mt is being recycled for that purpose. Recycled plastics are mainly used in the form of street furniture, insulation, ducts and pipes, etc. Very little so far is used in pavement construction (WRAP 2003). Similar to glass, the low value of PRN is blamed for the low recycling levels (DTI 2004). Recycled plastic packaging accounts for over 90% of all the recycled plastics each year in the UK (British Plastics Federation 2006). Financial incentives are believed to be more effective than specifications in affecting the recycling activity (WRAP 2003). Use for asphalt pavements may provide an important outlet for recycled plastics.

2.2. Technical Requirements for Materials in Asphalt Pavements

2.2.1. Requirements for Aggregates

A European standard (BS EN 13043 2002) for the specification of aggregates for use in asphalt was introduced in 2004 into the UK market. This standard specifies the technical requirements for aggregates alongside relevant test methods. Therefore materials recycled for use as aggregates in asphalt mixtures are subject to the same requirements for property classification and testing as are virgin aggregates. Pavement engineers are now responsible for defining categories for the technical properties of aggregates relevant to their specific application, and benchmarking the quarrying industry and other material suppliers. Examples of the requirements for aggregates in asphalt surfacing are presented in Table2-1.

Table 2-1 Requirements and Test Methods for Aggregates in Asphalt Surfacing (PD 6682-2 2003)

Property Category	Test Method	Property Requirements
Geometric	BS EN 933	Grading, Fines Content, Flakiness Index
Physical and Mechanical	BS EN 1097	Resistance to Fragmentation, Polished Stone Value (PSV), Aggregate Abrasion Value (AAV)
Chemical	BS EN 1744	Leaching
Thermal and Weathering	BS EN 1367	Water Absorption, Magnesium Sulphate Value

2.2.2. Requirements for Asphalt

To withstand the tyre and weather, pavement surface layers are made with the strongest and most expensive materials in road structure. Characteristics they exhibit like friction, strength, noise and ability to drain off surface water are essential to vehicles' safety and riding quality. Some are already associated with a standard test method (BS EN 13036 2002). Apart from the nature of the component aggregates and binder, asphalt performance strongly depends on the mixture type. Selection of a type for surface layers has to consider a multitude of factors including traffic, climate, condition of existing surface, and economics. No single mixture type could provide all the desired properties, often some are improved at the expense of others, making the selection difficult and contentious.

Stone mastic asphalt (SMA), porous asphalt or open graded friction course (OGFC) have a reputation for low tyre noise, high resistance to rutting and skidding, and therefore are preferred to hot rolled asphalt (HRA) for road surface that is subject to heavy traffic in terms of volume and loading (NAPA and FHWA 2000). For both mixture types, a number of properties are required of the component (particularly the coarse) aggregates such as PSV, resistance to fragmentation, affinity with bitumen, etc. Dense bituminous macadam (DBM) is commonly used in binder course and base.

2.3. Performance of Asphalt Pavements Containing Recycled Materials

Federal Highway Administration (FHWA) published in 1997 a guide manual for using 19 types of waste materials in all possible pavement layers (FHWA 1997). Recycled Materials Research Centre (RMRC) was established in 1998 under the partnership between FHWA and University of New Hampshire. The mission is to test, evaluate and develop guidelines for the use of recycled materials in roads considering long-term technical and environmental performance (RMRC 2007). In the UK, WRAP and TRL have been developing the potential applications of recycled materials in road structures, taking both the technical and marketing approach.

2.3.1. Waste Glass

Satisfactory performance has been observed of asphalt pavements containing 10-15% crushed glass in surface course mixtures. 4.75mm is the maximum size commonly accepted considering a range of engineering properties including safety issues (skin cut, tyre puncture) for that application. Anti-strip agent, typically 2% hydrated lime, is added to retain the stripping resistance. Glass particles in asphalt of higher content and larger size are reported to have led to a number of problems, particularly low friction and bonding strength, therefore are considered more suitable for use in lower courses. In practice, the same manufacturing equipment and paving method as designed for conventional asphalt can be used for the ‘Glasphalt’ (CWC 1996; FHWA 1997; Maupin 1997; Maupin 1998; Su and Chen 2002; Airey, Collop et al. 2004). RMC (now CEMEX) UK has been using recycled glass in DBM for binder course and base, with a 30% replacement rate. 20mm seems to be the maximum size of processed glass particles. In 2002, HMA containing 10% recycled glass sand was used in a pilot resurfacing project by Tarmac Situsec. Economics in these UK applications was reported to be ‘cost neutral’ compared with conventional asphalt paving (WRAP 2005).

2.3.2. Steel Slag

The angular shape, hardness and roughly textured surface give steel slag the characteristics to substitute coarse aggregates in asphalt to deliver the mix stability (resistance to rutting) and skid-resistance. Collaborative research carried out by US Strategic Highway Research Program (SHRP) and Universities in Saudi Arabia, found that mix durability (resistance to moisture, fatigue) was improved where coarse slag aggregates were used together with limestone filler and fine aggregates, and the bitumen prepared with polymer modification (Bagampadde, Wahhab et al. 1998; Khan and Wahhab 1998). Steel slag (≥9.5mm) after 3 years of aging (7-days expansion below 1%) replaced 62% of basalt aggregates in SMA mixtures in China laboratory. Surface performance (texture, friction, etc), resistance to rutting and low temperature cracking were improved, as a result (Wu, Xue et al. 2006). Nottingham Centre for Pavement Engineering (NCPE) studied the mechanical (resistance to rutting, cracking) and durability (susceptibility to aging, moisture) performance of asphalt containing slag aggregates. When 71% coarse steel slag particles were mixed with 21% fine BFS aggregates in SMA surfacing, the stiffness modulus was enhanced compared with the control mixture made of gritstone. However, the mix density and susceptibility to aging also increased (Airey, Collop et al. 2004).

In 1994, trial section of asphalt surfacing with 30% steel slag was laid in Oregon, followed by field inspection of the ride and skid performance over a period of 5 years. The trial section did not exhibit higher rutting and skid resistance compared to the control section. The report attributed the lack of measurable improvement to the low content and small size (6.3-12.7mm) of the slag particles, and it mentioned the economic disadvantage of using slag aggregates due to the increased mix density (implying higher transport cost) and mixing temperature (implying higher energy input) (Hunt and Boyle 2000). In the UK, following a 3-year investigation, TRL reported that BOS slag produced from main UK sources can be used in pavement surface where a minimum PSV of 60 is required. However, the report suggested that when assessing the anti-skid properties of asphalt made with slag aggregates, traditional PSV test should give way to 'known in-service performance under comparable situations' (TRL 2003).

A study conducted at the Research Association of Iron and Steel Slags (FEhS, Germany) confirmed that BOS slag asphalt exhibits superiority in bearing and anti-polishing performance over asphalt made with ‘established premium aggregates’ (basalt, flint gravel, etc) (Motz and Geiseler 2001). The presence of free Calcium oxide/Magnesium oxide (CaO/MgO) in slag makes it liable to expand in humid condition and therefore unsuitable for use in structures vulnerable to volumetric expansion. The common approach to overcome this problem is to expose the slag to spray water or natural weathering for a period of 12-18 months (FHWA 1997; Airey, Collop et al. 2004). The time span could be reduced if chemical treatment can be performed before the slag leaves the steel plant as is the practice in Germany (Motz and Geiseler 2001). European standard permits the use of steel slag in asphalt provided the 7-days volumetric expansion is no more than 3.5% (BS EN 13043 2002). Leaching is one of the main environmental concerns over the use of secondary materials in roads (Mroueh, Eskola et al. 2001). Research at FEhS has identified pH-value, electrical conductivity and Chromium concentration in the leachate as the main concerns for using slag aggregates (Motz and Geiseler 2001).

2.3.3. Waste Tyre

Generally, there are two distinct approaches to using recycled tyre rubber in asphalt. One is to dissolve crumb rubber in the bitumen as binder modifier, the other to replace a portion of fine aggregates with ground rubber that is not fully reacted with the bitumen. These are referred to as the ‘wet process’ and the ‘dry process’, respectively. Modified binder from the ‘wet process’ is termed ‘asphalt rubber’; asphalt made by the ‘dry process’ is ‘rubberised asphalt’ (FHWA 1997).

2.3.3.1. The Wet Process

In the wet process, crumb rubber (0.15-0.6mm) is blended with bitumen, usually in the range of 18-22% bitumen weight, for a minimum of 45 minutes at elevated temperatures prior to contact with aggregates (Hicks 2002). Light fractions of bitumen transfer into the rubber making the rubber particles swell and the bitumen harden. The binder viscosity is increased allowing for higher bitumen usage, which in theory can help reduce top-down thermal cracking and bottom-up reflective cracking, and improve the mix durability (resistance to moisture, oxidation and fatigue, etc).

The modification effect can be influenced by a number of factors including the base bitumen composition, blending time and temperature, volume and gradation of crumb rubber, and the grinding method (FHWA 1997; West, Page et al. 1998). These variables were studied following the SUPERPAVE (SUperior PERforming asphalt PAVEment) method at NCPE and US Texas DOT (Department of Transportation) (Texas DOT 2000; Airey, Rahman et al. 2003). FHWA believed that rubber particles in the 'wet process' will reduce the resilient modulus of the asphalt mixture, and therefore its resistance to permanent deformation (FHWA 1997). The opposite was observed in Brazil and India where the asphalt rubber mixture had lower rutting potential because of higher stiffness and tensile strength at high temperatures (Bertollo, Bernucci et al. 2004; Palit, Reddy et al. 2004). A study at Kansas State University (KSU) found that an 18-22% of rubber content was optimum for the low temperature performance of asphalt, and that a change within this range was less significant in affecting the tensile and fracture performance of asphalt than varying the binder content between 6-9% (Hossain, Swartz et al. 1999). This was confirmed by study at Arizona State University (ASU) that longer fatigue life of the asphalt rubber mixture was largely due to the higher binder content (Zborowski, Sotil et al. 2004). The University of Liverpool had the permissible rubber (0.3-0.6mm) content set at 10% of the binder made of pen-50 or pen-100 bitumen. Resistance to rutting, fracture and fatigue was increased as a result (Khalid and Artamendi 2006).

Some projects have revealed problems from the use of asphalt rubber in road surface. Bleeding and loss of coarse aggregates were observed on a Virginia SAM (stress absorbing membrane) trial section where the surface treatment contained 20% crumb rubber in the binder. The SAM did not hinder reflective cracking as expected (Maupin and Payne 1997). A chip seal (or surface dressing) project in Iowa indicated that the use of asphalt rubber reduced the friction of the finished surface (Iowa DOT 2002). A project in Texas indicated that OGFC represented the best application for asphalt rubber in terms of cost, resistance to cracking and ravelling (Tahmoressi 2001). NCPE suggested that asphalt rubber should not be used together with polymer modified bitumen (PMB), because the PMB-rubber interaction compromised the rheological properties of the aged binder and as a result, the durability of the asphalt mixtures (Airey, Singleton et al. 2002).

The design method for conventional HMA can be used for asphalt rubber mixtures, with mix stability being the primary design factor. A rule of thumb is that if 20% crumb rubber is used in the binder, the binder content would be 20% higher than unmodified. The binder content is recommended even higher in spray applications, for instance, 45% higher in stress absorbing membrane interlayer (SAMI) than that required for conventional asphalt (FHWA 1997). Placement of asphalt rubber mixtures can be carried out using standard paving machinery except for pneumatic tyre rollers as asphalt rubber will stick onto the roller tyres under paving temperatures (Epps 1994). The main concerns include the narrowed paving temperature window (e.g. no laying with ambient temperature below 13ºC), and potential toxic emissions (Hicks 2002).

Noise studies at Rubber Pavements Association (RPA) found that the use of tyre rubber in open-graded mixture reduced the tyre noise by at least 50% (RPA 2006). Rubber particles of multiple sizes were believed to have a better sound absorbing effect in spray applications (Zhu and Carlson 1999). A study by Emery demonstrated that by 1995 there was no such sign that mixing and paving asphalt rubber materials impose additional environmental burdens than conventional asphalt (Emery 1995). A more recent leaching test at Oregon State University (OSU) came to a different conclusion that about 50% of leachate contaminants from asphalt rubber mixtures were released into surface and ground water system within the first few days after laying, with 1,3-benzothiazole, Aluminium (Al) and Mercury (Hg) being detected at potentially harmful concentration level (Azizian, Nelson et al. 2003).

Projects in the late 1980s showed that asphalt rubber in dense-graded mixtures helped reduce the asphalt layer thickness by 20-50% without compromising the pavement performance (Kirk 1991). The potential for thickness reduction was confirmed by accelerated load testing (ALT) at University of California Berkeley and South Africa (Hicks 2002). Another benefit of using asphalt rubber is believed to prolong the pavement life. A project in Brazil having 15% rubber in HMA overlay binder found that cracking was developed 5-6 times slower than in conventional asphalt; and the asphalt rubber mixture outperformed in surface deflection, interface strain and rut depth (Nunez, Ceratti et al. 2005). Similarly, binder of 15% rubber (size of

0.2/0.4/0.6mm) was used in dense-graded asphalt in Japan. The mixtures exhibited improved performance in dynamic stability, 48-hours residual stability, flexural strength and strain value. Asphalt containing 0.2/0.4mm-sized rubber in particular provided the best laboratory results (Souza, Himeno et al. 2005).

On the other hand, FHWA stated that the production of crumb rubber modified asphalt is normally 50-100% more expensive than producing conventional asphalt (FHWA 1997). Practice by individual State DOT revealed a range of cost increase, presented by different means: 21% in Colorado (Harmelink 1999), 50-100% in Virginia (Maupin 1996), 25-75% for gap-graded and 80-160% for open-graded in Arizona (Way 1998), $10-15/tonne in Oregon (Hicks 2002), $16/tonne in California (Caltrans 2003), to name but a few. However, life cycle cost analysis (LCCA) was recommended by all practitioners for assessing the cost effectiveness of the use of asphalt rubber, taking an analysis period of 30-40 years including the maintenance and road users' cost. LCCA was conducted at ASU and OSU using the World Bank's Highway Development and Management model (HDM-4) and the FHWA's LCCA method (FHWA 1998), respectively. According to their results, the use of asphalt rubber was 'cost effective'. Meanwhile, both studies recognised that the results depend on many input variables which need to be studied on an individual basis (Hicks and Epps 2000; Jung, Kaloush et al. 2002).

2.3.3.2. The Dry Process

In the dry process, ground rubber (0.85-6.4mm) substitutes for fine aggregates in the asphalt, typically at a 1-3% replacement rate.

Asphalt properties of particular interest in the dry process include resilient modulus and noise. Where there was a 10-20% increase of binder content required for rubberised asphalt, the resilient modulus was reduced implying the need for an increase of layer thickness, compared with conventional mixtures (FHWA 1997). Other laboratory results showed a reduction of permanent deformation (Reyes, Reyes et al. 2005; Selim, Muniandy et al. 2005). Acoustic analysis and field measurement confirmed that rubberised asphalt paving is effective in reducing traffic noise from light-duty vehicles (Sacramento County 1999). A leaching test indicated that by replacing gravel of comparable size with rubber in the drainage layer, the nitrate concentration of leachate into ground water was reduced by more than half in sand-based root zones (typically seen in sports and recreation fields) (Lisi, Park et al. 2004).

The design method for conventional mixtures can be applied to rubberised asphalt containing 1-3% ground rubber particles. A target air void of 2-4% is the primary design factor (FHWA 1997). Both the time and temperature at which the bitumen reacts with rubber particles need to be controlled with care, to retain the physical shape and rigidity required for the dry process. A project in Turkey found that when Marshall stability, flow, VMA (voids in the mineral aggregate), unit weight and VFA (voids filled with asphalt) all were taken into consideration, the optimum technical parameters were: 0.95mm for tyre rubber gradation, 10% for tyre rubber ratio, 5.5% for binder ratio, 155ºC for mixing temperature, 15min for mixing time and 135ºC for compaction temperature (Tortum, Celik et al. 2005). However, rubberised asphalt generally does not show significantly improved performance to offset the additional cost (FHWA 1997; Hunt 2002).

2.3.3.3. Other Applications in Pavement Structure

Tyre shreds have applications in the foundation of roads. Compared with compacted soil, tyre rubber is of: 1) light weight, 2) low thermal conductivity, 3) high hydraulic conductivity and, 4) high shear strength at large strains. Leaching potential seems to be the main concern. ASTM-D6270 and EN12457 procedures are followed in the States and Europe, respectively, to measure and characterise the leachate. Constituent analysis of tyre sample indicated that although it contained leachable hydrocarbons (e.g. PAH), heavy metals (e.g. zinc) and respiratory dust, the released concentration was not of a concern to human health or surrounding environment under normal operating conditions (open air, neutral pH value, etc) (Edeskar 2004). Tyre rubber used in lower pavement layers can help reduce the depth of frost penetration in winter time. Processing of scrap tyres has a by-product: waste fibre, which was added into SMA mixtures to prevent the ‘drain down’ of bitumen from aggregates, where stabilising additives such as cellulose or mineral fibre are commonly used (Putman and Amirkhanian 2004). The EcoLanes project under EU Framework Program 6 (FP6) is looking at the use of steel fibres recovered from shredded tyres in roller compacted concrete (RCC), with both laboratory works and demonstration projects planned ahead in 2007-2009 (EcoLanes 2007).

2.3.4. Plastics

Similar to tyre rubber, recycled plastics can either replace a portion of aggregates, or serve as a binder modifier in the asphalt. DBM with recycled plastics, mainly low density polyethylene (LDPE) replacing 30% of 2.36-5mm aggregates, reduced the mix density by 16% and showed a 250% increase of Marshall stability; indirect tensile strength (ITS) was also improved in the ‘Plastiphalt’ mixtures (Zoorob and Suparma 2000). Recycled LDPE of a size between 0.30-0.92mm replacing 15% aggregates in asphalt surfacing nearly doubled the Marshall quotient, and increased the stability retained (SR) by 15%, implying higher resistance to rutting and water ingress. A 20% increase of binder content was required in this case (Qadir and Imam 2005). The blending of recycled LDPE to asphalt mixtures required no modification to existing plant facilities or technology (FHWA 1997). Flexural behaviour of asphalt containing recycled plastics (polyvinyl chloride-PVC bottle) was studied. Bending strength was increased by adding 2-6% of the mixture weight of plastic particles; further investigation was suggested to depict a curve of the ‘bending strength against plastics content’ (Ergun, Iyinam et al. 2005). Recycled plastics (PE film) used at 0.4% of mixture weight (or about 8% of binder weight) as bitumen modifier, increased the Marshall stability before and after water logging (60ºC, 24hrs) by 3.3 and 2.6 times, respectively (Justo and Veeraragavan 2002).

2.4. Environmental Impacts of Recycling in Asphalt Pavements

Environmental impacts of using recycled and secondary materials in roads have two aspects. One is the energy used to transport and process the waste into desired properties; the other is the impact (e.g. leaching) on the environment from those materials in place. Evaluation of these impacts in Nordic countries has extended the view from merely studying the leaching behaviour to a wide spectrum of environmental items and in longer time span, consistent with the LCA approach (Roth and Eklund 2003; Petkovic, Engelsen et al. 2004). Nevertheless, energy use and CO_2 emissions are studied more than other impacts, for global warming (climate change) causes the most concern, and energy use usually a good indicator of key emissions

(SO_2, NOx, CO_2, etc) (Bjorklund and Finnveden 2005). The impacts of recycling are also assessed against such factors as leaching, quarry saving, and diversion of waste from landfill.

For instance, LCA on the use of MSWI (municipal solid waste incinerator) bottom ash replacing crushed stones in the sub-base indicated that while energy use and emissions in construction stage were reduced, leaching was still a risk, and the LCA results were sensitive to transport distance and the conditions that affect the leaching behaviour (nature of recycled materials, previous treatment, liquid to solid (L/S) ratio and pH value, etc) (Birgisdottir, Pihl et al. 2006; Olsson, Karrman et al. 2006).

2.4.1. Energy Use and Emissions

Recycling can save energy, and consequently the CO_2 emissions. This is more pronounced in countries where electric power is generated from thermal power (fossil fuels) plants (Pimenteira, Pereira et al. 2004). However, from a life time perspective, the operational energy needs, maintenance requirements and recycling potential of the products all need to be considered, rather than merely the energy input at construction stage (Thormark 2006). The UK Institution of Civil Engineers (ICE) suggests that CO_2 be adopted as the measure of resource efficiency when assessing the different waste management options (ICE 2006). Results from energy analysis speak more favour of close-loop recycling than alternative use such as aggregates. A case study of waste glass for example, carried out at University of Southampton indicated that returning cullet to glass furnace can reduce energy input by up to 6.6-8.4%, while use as aggregates gives a rise of that energy input by 4.5% (Dacombe, Krivtsov et al. 2004). A study at Manchester Metropolitan University showed a 4-5GJ/tonne energy saving with closed-loop recycling, compared to a saving of 70MJ/tonne when used for construction aggregates (Butler and Hooper 2005). The figure is close to a previous LCA study of glass at Loughborough University in which an energy reduction (the furnace temperature in glass manufacturing was lower than melting virgin materials) of 3.3-3.7GJ/tonne glass was observed in close-loop recycling (Edwards and Schelling 1999).

Glass for recycling is normally collected from bottle banks, after consumer transport (kerbside collection) and local transport. The fuel consumption for the two stages of transport was estimated at 0.25MJ petrol and 0.15MJ diesel per kg glass, respectively. The underlying assumption was that the glass is the only waste carried in both transport. If other waste (e.g. aluminium, paper, plastics) are included, the fuel consumption allocated to glass is expected to be less than the above (Edwards and Schelling 1999).

Relevant publications normally consider specific environmental loadings of the recycling applications. For instance, research at TGCE-LCPC (Division for Civil Engineering and Environmental Technologies, the French Public Works Research Laboratory) studied the emissions of VOC, PAH and odour from laying asphalt containing 10-30% of RAP. Results saw the emissions of VOC and PAH increased with the recycling rate, while the odour emission decreased (Jullien, Moneron et al. 2006). Over 100 compounds emitted from bitumen were measured at Auburn University from 23 PG (paving-grade) bitumen sources throughout the US under varying temperatures. Emissions from production and placement of HMA under 170ºC were found well below the occupational exposure levels (OELs). The concentration and speciation of emissions increased with the operating temperature; VOC and PAH became of major concern when it exceeded 190ºC (Lange 2006). Exposure to vapours and aerosols of bitumen was examined across bitumen-related industries (road paving, roofing, etc) in Germany. The similar temperature dependency was found, for the emissions level at 180ºC or below (Ruhl 2006).

2.4.2. Leaching

University of Nottingham concluded that besides materials characterisation, a number of factors have effect on the leaching behaviour of materials in road structure, such as the level of compaction, binder type, pH value and moisture content of the surrounding environment, etc (Hill, Dawson et al. 2001) (see Figure2-1). Static, or the less time consuming dynamic, leach test was carried out at Shell Research and Technology Centre Amsterdam to measure the aqueous concentration of PAH from the leachate of road asphalt. The PAH level was found well below the EEC's (European Economic Community's) limit on surface and potable water (Brandt and

Groot 2001). Similarly, very little amount of heavy metals was detected in the leach test by Lulea University of Technology on natural aggregates (Tossavainen and Forssberg 1999). Bitumen emulsion was used in the Czech Republic for its stabilising effect as a barrier against the leaching of certain heavy metals (e.g. Ni, Cd) from industrial solid waste (Sild, Vondruska et al. 2004). The retention capacity of Lead (Pb) was found 3-10 times higher than normal along highway corridors in Canada, although the Pb's mobility in highway soils was restricted mainly to the top 0.3m (Li 2006).

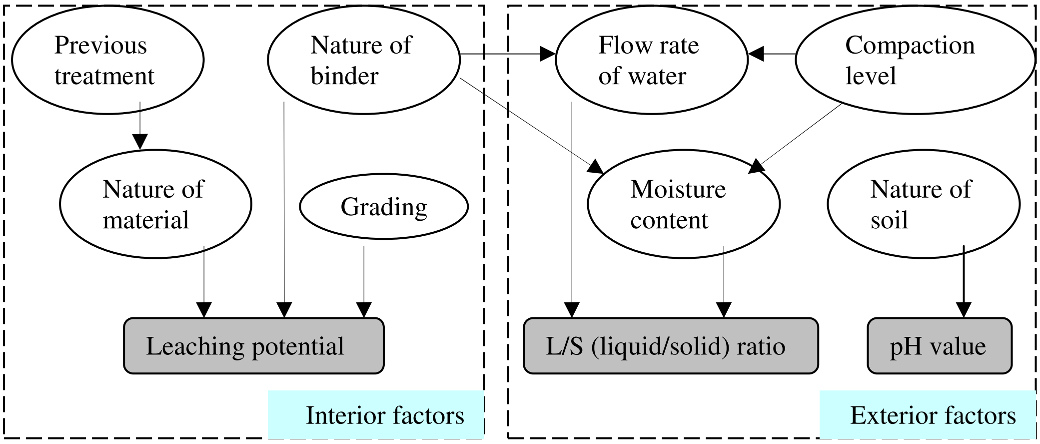

Figure 2-1 Factors That Affect Leaching from Materials in Roads

Some recycled materials, when used as aggregates in roads, may cause excess leaching into soil and ground water. Batch and column leach tests were carried out at LCPC on samples of asphalt containing RAP. It was found that the concentration of PAH and heavy metals were influenced by such factors as the grain size of RAP and the flow rate of percolating water. This was confirmed by field test of asphalt samples containing 10% and 20% of RAP (Legret, Odie et al. 2005). Chromium (Cr) and Vanadium (V) were of concern when BOS slag was used as road aggregates in France, with the V being in more toxic form and more mobile during natural aging (Chaurand, Rose et al. 2006). Leaching of heavy metals from asphalt containing recycled rubber increased at high temperature or low pH value, but generally below detrimental level (Vashisth, Lee et al. 1998), except for Hg which in OSU's study was released in potentially harmful amounts (Mohammad, Nelson et al. 2003).

Most leaching studies so far were focused on the MSWI bottom ash. Generally, MSWI bottom ash was assessed as ‘environmentally safe’ in road structure with regard to the leaching potential (Bruder-Hubscher, Lagarde et al. 2001; D'Andrea, Bonora et al. 2004). According to DTU (Technical University of Denmark), the leaching of Copper (Cu), Cadmium (Cd), Pb, and Zinc (Zn) was higher than control concrete where MSWI bottom ash was used in base layer (Cai, Bager et al. 2004). Compared with gravel by Lulea University of Technology, MSWI bottom ash in road fills beneath asphalt or granular layers led to higher loads of Cu, Cr and Chloride (Cl) in the leachate; and the L/S ratio and pH value were attested the conditions that dictate the materials’ leaching behaviour (Aberg, Kumpiene et al. 2006; Ecke and Aberg 2006). An array of treatment was tried in Belgium to reduce the concentration of Sb, Mo and Cu (assessed as critical substances) in the leachate from granular layers containing MSWI bottom ash including washing, heating and carbonation, with mixed effect on the leaching of those substances (Gerven, Keer et al. 2005).

2.4.3. Environmental Impacts for LCA Study of Asphalt Pavements

Environmental impacts selected for analysis in this LCA model are limited to a few categories as listed in Table2-2. This selection is based on the findings of previous LCA studies concerning the significance of the many environmental impacts involved in the life time of asphalt pavements (Mroueh, Eskola et al. 2001; Stripple 2005), the key pollutants listed in UK’s Air Quality Strategy (DETR 2000), as well as the availability of data.

Table 2-2 Environmental Impacts of Asphalt Pavement Construction

Environmental inputs	Materials resources	Crushed stone (coarse aggregates), Gravel/Sand (fine aggregates), Limestone filler, Bitumen (paving grade, foamed, emulsified), Recycled materials (RAP, glass, plastics, tyre rubber, steel slag, etc), Water[1]
	Energy resources[2]	Electricity, Natural gas, Petroleum products (LPG, diesel, heating oil, etc), Coal, Renewable energy (biomass fuel, nuclear, hydro, wind, etc)
Environmental outputs	Emissions to air	SO_2, NOx (total of NO and NO_2), CO, CO_2, HC (hydrocarbons), CH_4, NMVOC (non-methane VOC), N_2O, Particulate, NH_3, Heavy metals[3]
	Discharges to water	BOD (biological oxygen demand), COD (chemical oxygen demand), Phosphate, Nitrate, Nitrogen total, HC (hydrocarbons), Oil, Heavy metals[3], Chloride, Sulphate
	Products and wastes	Asphalt pavement surface, Solid wastes (Inert, Hazardous)

Notes:

1. Water is not normally represented in the building blocks of pavement structures except for the concrete at 150-230kg/m^3 (Deng and Huang 2001). When recycled materials are involved, water use might become significant due to the consumption in recycling process.

2. Petroleum, natural gas and electricity account for 47.5%, 32.5% and 17.5%, respectively, of UK's energy consumption in 2004 (DTI 2006). Energy from other sources, traditional (e.g. coal) or renewable (e.g. biomass fuel, nuclear, hydro, wind), contributes only to some 2.5% and is therefore assumed of low consumption by the asphalt industry. An exception is the coal which is the major type of energy input in cement production (Stripple 2001).

3. Living organisms need trace amount of some heavy metals such as copper (Cu), manganese (Mg) and zinc (Zn). Other heavy metals are threats to human well-being such as mercury (Hg), lead (Pb), arsenic (As) and cadmium (Cd) (UN System-Wide Earthwatch 2006). When this study mentions heavy metals, it is referring to the latter harmful group.

2.5. LCA Resources for the Asphalt Industry

Based on previous discussion, the main tasks that UK road industry has now are to maintain and repair the existing road networks. The concept of design for long-life pavements in the light of resource efficiency (materials, energy, etc) and the requirement for speed repair would make road works in the future confined to the top few layers of pavements only (TRL 2005). Recycled and secondary materials are increasingly used in new or rehabilitated pavement structures. An operating LCA model shall therefore reflect the maintenance and recycling in roadwork; and data specific to UK road industry are preferred. An ideal LCA model represents all the significant environmental impacts of asphalt pavement through its entire life time. On the other hand, to keep the amount of work manageable, a boundary needs to be set up, and assumptions made to informed users and audience. In summary, a working LCA model should be:

- Internationally recognised, including the methodology and supporting database;
- Populated with relevant and up-to-date data;

- Having as many as possible variables represented in the road practice;
- Easy to use and understand by industry;
- Flexible for data revision and model development in the future.

2.5.1. Previous LCA Models and Databases

US Environmental Protection Agency (EPA) is hosting an index of LCA resources worldwide including books and journals, websites and conference proceedings, software and databases, and case studies since 1998 (EPA 2007). EPA's pilot study in the late 1990's demonstrated that LCA can help select the environmentally preferable method for asphalt pavement treatment, even on a tight budget and time schedule (Schenck 2000). A hybrid I-O (input-output) model was used in Japan looking at the life cycle emissions of CO_2 from a motorway covering both the construction and operation stage (Inamura 1999). The potential values of 'generic data sets', 'technology assessment' and 'marketing' are viewed by the cement industry as 'high' or 'mid-high' in using LCA (WBCSD 2002). In addition to compliance with the standards (the BS EN ISO14040 series), a practical LCA study must also be supported by good quality data, which normally come from LCA databases or previous studies.

In 1993-1995 IVL (Swedish Environmental Research Institute) developed the first of its kind LCI model of road construction and maintenance for Swedish National Road Administration. The 2nd version was released in 2001 (Stripple 2001). A LCI study focused on asphalt pavements, including the use of recycled materials (RAP), was initiated in 1998 by EAPA (European Asphalt Pavement Association) and Eurobitume. IVL was commissioned to carry out the project. The 3rd draft was released in 2005 (Stripple 2005). Meanwhile, Eurobitume in 1997-1999 carried out a partial LCI study on bitumen (straight run, paving grade 50/70), covering the life period from crude oil extraction to refinery deposit (Eurobitume 1999). VTT (Technical Research Centre of Finland) published in 1996 a comparative LCA study on environmental impacts of asphalt and concrete pavements (Hakkinen and Makela 1996). Later in 2001 a LCA model was developed by VTT for Finnish National Road Administration addressing the use of industrial by-products (coal fly ash, blast furnace slag, etc) in roads (Mroueh, Eskola et al. 2001). In 2005, a LCA model of road construction including the use of MSWI bottom ash was developed by DTU (Technical University of

Denmark) (Birgisdottir 2005). In the UK, BRE (Building Research Establishment) published the 'Environmental Profiles' in 1998 providing a database on environmental performance of building materials and products, as well as the methodology for applying LCA to the construction sector (Howard, Edwards et al. 1999). More details of relevant LCA models including the strength and weakness of each are described below:

- BEES (Building for Environmental and Economic Sustainability) model, developed by National Institute of Standards and Technology (NIST), USA. It measures the economic and environmental performance of building products following the ISO14040 norms. Initially designed for the entire building industry, it does not provide much data relevant to asphalt paving. Version 4.0 updated in 2007, together with technical manual and user guide is now available to download and use free of charge (NIST 2007).
- PaLATE (Pavement Life-cycle Assessment Tool for Environmental and Economic Effects), a Microsoft Excel model developed by University of California Berkeley, USA. It takes user inputs for the design, construction and maintenance of pavements (materials, layer thickness, equipment use, etc), and presents outputs for the life cycle costs and environmental effects (energy, emissions, leaching, etc) (UC Berkeley 2007).
- Life Cycle Inventory of Asphalt Pavements spreadsheet model, developed by IVL. It builds up the life cycle inventory of asphalt pavement object with a statement of the source of data selected for use; and allows input of alternative data to their particular project. Due to confidential restriction in the industry, it has only been distributed by and inside EAPA.[5]
- BRE 'Environmental Profiles', developed in partnership with the Government and 24 trade associations in UK's construction sector. It aims to provide a consistent approach for applying LCA to, and a UK database on environmental performance of, building related materials and products. Similar to the BEES model above, it is not specific to road asphalt materials.
- Boustead model, developed by Boustead Consulting UK Ltd. It consists of software and a database covering a number of materials and fuel production

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[5] Email communication with Håkan Stripple, IVL on 08 June 2004.

processes that enable the user to develop a life cycle inventory for a particular process. Boustead is a leading company in the UK specialising in emissions modelling for many years.[6] Version5.0 is now available for purchase (Boustead Consulting Ltd. 2007).

- Life Cycle Assessment of Road Construction model, developed by VTT in a two-stage study on the applicability of using secondary materials in earthworks. It builds up the life cycle inventory of use of industrial by-product (coal fly ash, crushed concrete, blast furnace slag, etc) in roads and earth works, and compares with that of using natural aggregates only, with a focus on energy use and atmospheric emissions.
- Road-RES model, developed with C++ programming at DTU. It is used as a tool to support decision making for both the road construction and disposal of bottom ash from municipal solid waste incinerator. Issued in 2005 containing a MSWI residues' leaching profile, the model is looking to data improvement and application in real projects.

2.5.2. Need for a New LCA Model

There are a few important findings from those LCA studies above, which can be taken as a starting point for applying LCA to the road and asphalt industry. These findings include:

- Environmental loadings of asphalt and concrete materials vary considerably depending on the bitumen and cement content, respectively, as the bitumen and cement production are the energy intensive processes in the construction stage;
- Transport is an important variable with significant influence on the LCA results, particularly where recycled materials are involved. The break-even point, whether the recycling saves energy and CO_2, is often sensitive to the transport distance and fuel efficiency during the waste collection;
- Environmental loadings that are assessed as being significant in a pavement project, particularly when recycled materials are involved (see Table2-2);

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[6] Personal communication with Professor Tom Donnelly, Newcastle University on 27 April 2005.

- As a whole, emissions and energy use by traffic vehicles on the road represent the majority of the total environmental loadings from a road, compared to materials production, transport, placement and maintenance.

Nevertheless, the problems of simply applying one or another of those LCA models to the UK road sector are summarised in Table2-3 (Huang, Bird et al. 2006).

I. Low relevance to the road and asphalt industry;
II. Data from non-UK sources may not comply with the UK's industry average;
III. Some data are quite old, and the underlying assumptions and calculation formulas not clearly stated;
IV. The models above are normally focused on one or a few environmental impacts, such as energy and air emissions in the VTT model, leaching in the DTU model;
V. The inclusion of recycled materials are varied, but generally limited (e.g. RAP in the IVL model, MSWI bottom ash in the DTU model);
VI. Some models are not accessible, due to commercial restriction.

Table 2-3 Summary of Relevant LCA Models

Model/Database	**Sector**	**Origin**	**Year of Release**	**Recycled Material**	**Accessibility**	**Limitation**[1]
BEES	Construction	NIST, USA	Current version: 4.0		Free	I, II
Boustead	Transport	Boustead Consulting Ltd, UK	Current version: 5.0		Commercial	I
BRE Environmental Profiles	Construction	BRE, UK	Data updated to: 2004		Free	I
LCI of Asphalt Pavements	Asphalt pavements	IVL, Sweden	Draft3: 2005	RAP	EAPA internal use	II, V, VI
LCI of Road	Road	VTT, Finland	2001	BFS, CFA	No access by public	II, , IV, V, VI
PaLATE	Pavements	UC Berkeley, USA	Unknown	Unknown	No access by public	II, VI
Road-RES	Road	DTU, Denmark	2005	IBA	PhD thesis at DTU	II, IV, V

Note: Limitation refers to the text above.

2.6. Summary of Literature Review

The use of waste glass, steel slag, tyre rubber and plastics in asphalt layers have been reviewed in this Chapter. Their availability for use, satisfactory performance in roads and at what content these performance was observed, are confirmed. These will help define the asphalt recipe, an important pavement parameter that needs to be brought into the LCA model. Also reviewed are the key environmental impacts of using recycled materials in roads and asphalt. These will help keep the life cycle inventory analysis (LCI) within manageable amount. It can be argued, after the review of existing and developing LCA resources, that there is nothing suitable to meet the needs of UK road industry available on the market, which justifies the need for developing a new LCA model.

Chapter 3 : LCA Model Development

In this Chapter, the unit processes in asphalt pavement construction will be defined. They make the units in the LCA model for which data will be obtained, from site engineers as well as literatures, and analysed. Following the ISO14040 guidelines described briefly in Chapter1, an LCA model is developed, based on the review of environmental impacts in Chapter2, to measure and present the key environmental loadings in an input-output inventory, and interpret the results by assigning them to, and characterising in predefined impact categories. This is followed by a discussion of the scope of this LCA model and what further work is needed.

3.1. Unit Processes in Asphalt Pavement Project

Depending on the nature and deliverables, asphalt pavement projects differ from one another in terms of materials and equipment use, transport and placement method. The construction and maintenance of asphalt pavements can be characterised having the following processes (waste glass taken as an example of secondary aggregates).

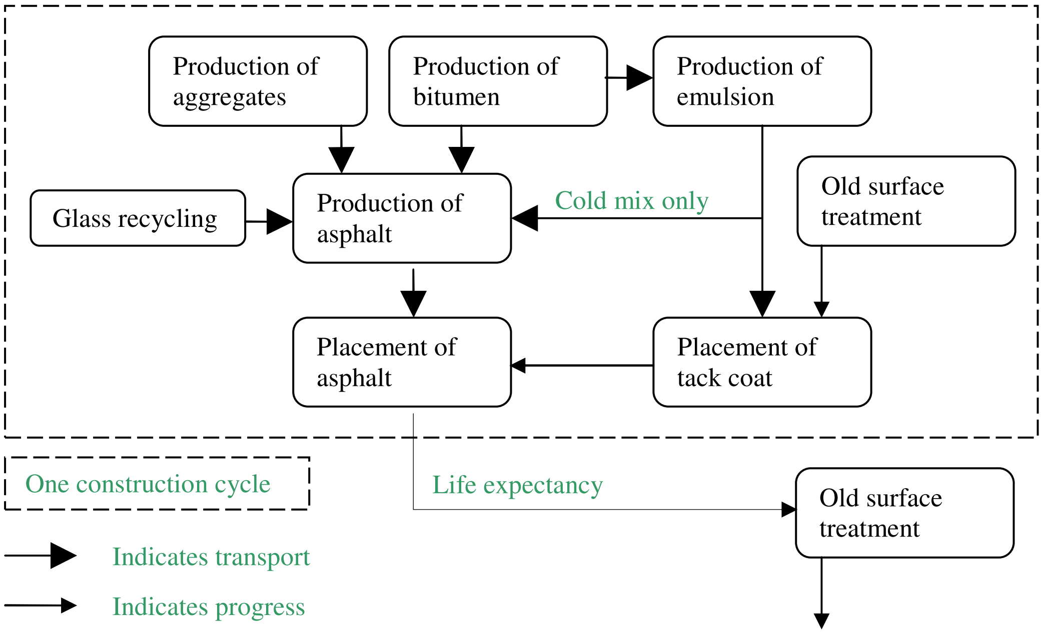


Figure 3-1 Construction and Maintenance of Asphalt Pavements

3.1.1. Production of Natural Aggregates

The common processes and machinery involved in quarrying aggregates are described by Quarry Products Association (QPA). Rock in a quarry is blasted from the working face (about 15,000t each time) with explosives, transported by truck or conveyor to crushing equipment where it is crushed and sieved into a range of sizes (with noise and dust control) to clients' needs. Sand and gravel sites are excavated from deposits in river valleys, usually by simple excavation. Action of the river has often done the grading, so particles tend to be of more similar size, and less crushing and sieving are required. However, crushed rocks from quarry are preferred by the road industry, due to their angular shape which provides higher friction and bonding with the bitumen. In addition to land quarries, marine dredging provides significant proportion of Britain's sand and gravel supplies (QPA 2007).

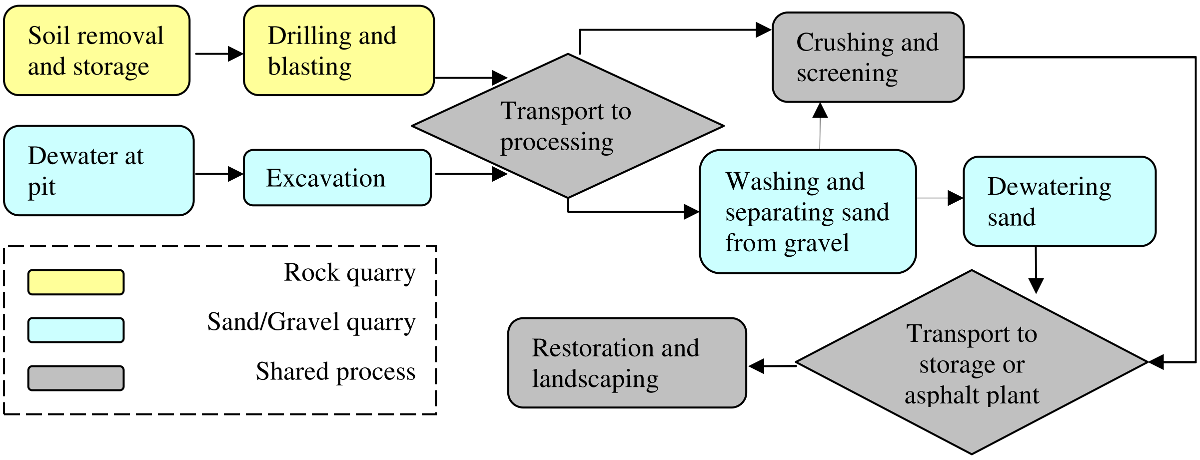


Figure 3-2 Production of Natural Aggregates for Use in Asphalt Production

3.1.2. Production of Bitumen

Bitumen is one of the many petroleum products from the refinery, during which the electric power is supplied to plants, diesel consumed in transport, and gas oil or natural gas combusted for heating purpose (Stripple 2005).

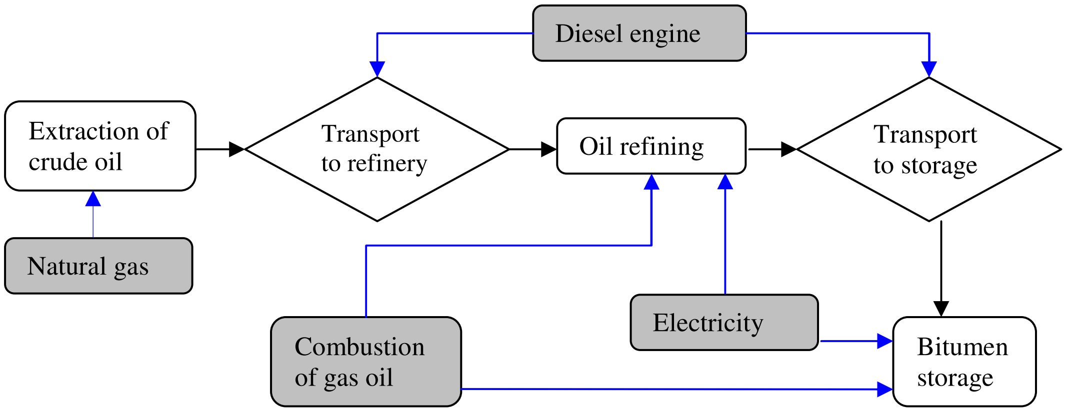


Figure 3-3 Production of Bitumen for Use in Asphalt Production

3.1.3. Production of Recycled and Secondary Aggregates (glass for example)

Waste glass is obtained through kerbside collection, bottle banks and commercial collection. Contaminants are removed before the glass is crushed to the required size for use as aggregates in asphalt. Waste glass for close-loop recycling (re-melt glass cullet and feed to glass making furnace) has more technical restriction such as colour sorting and impurity content (Hopkins and Foster 2003; Letsrecycle.com 2006). Energy data on thermal recycling of glass is available in the BUWAL250 database in SimaPro7 (PRe Consultants 2006). Depending on the goal and scope, the LCA study can include the environmental impacts of waste glass further upstream to raw materials acquisition for glass making.

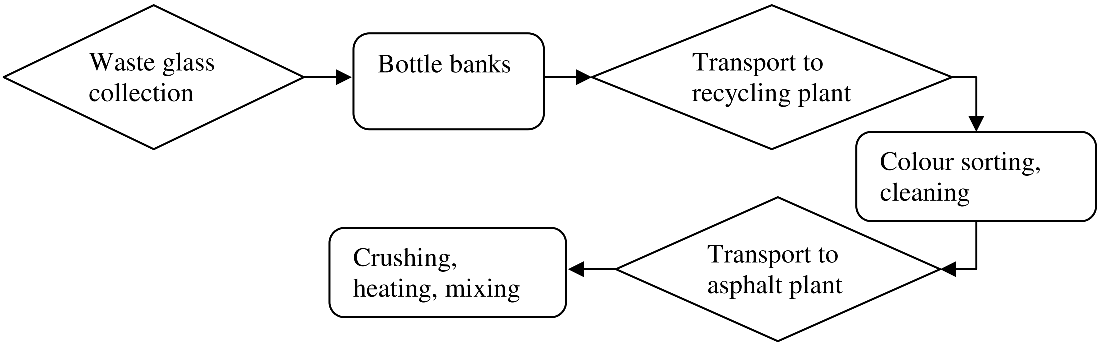


Figure 3-4 Production of Glass Aggregates

Generally, the life cycle of glass can be illustrated in Figure3-5:

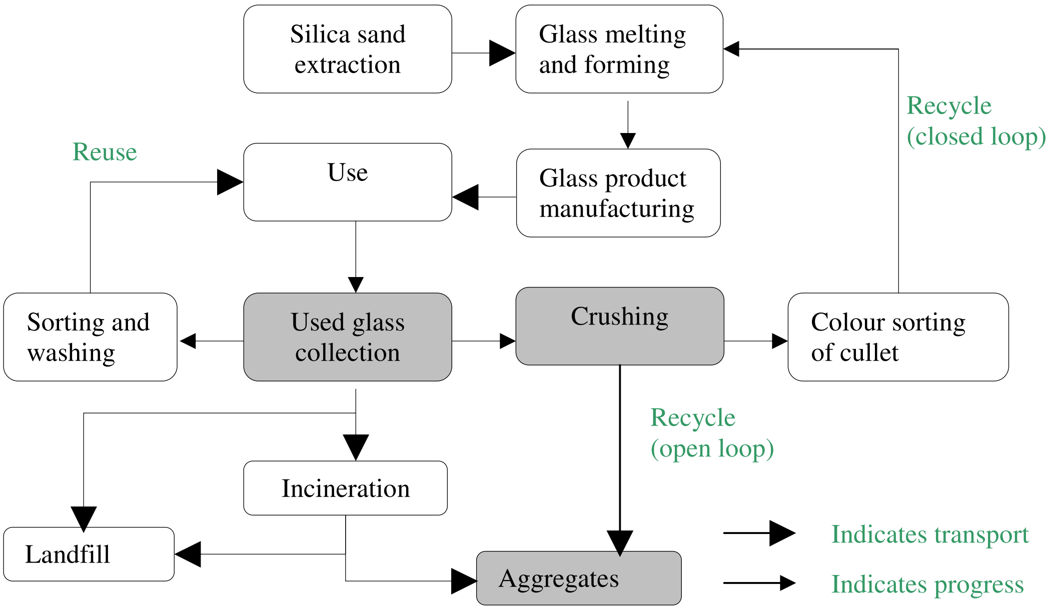


Figure 3-5 Life Cycle of Glass

3.1.4. Production of Bitumen Emulsion, Foamed and Rubber-Modified Bitumen

At an emulsion plant, paving grade (PG) bitumen is heated to below a certain viscosity (0.2Pa s) and fed into a colloid mill or a static mixer, along with the emulsifier solution made of liquid emulsifier and water. The bitumen globules disperse in the water phase, which is stabilised by the emulsifier. The low-viscosity liquid product is then ready for use in cold mix asphalt or surface treatment (tack coat, chip seal, etc). The bitumen and emulsifier content, and usage of the emulsion depend on which type of roadwork the emulsion is applied (see Table3-9). As for foamed bitumen, cold water 1-5% by weight of bitumen is pressure injected into hot bitumen (160-180ºC), to produce a large volume of foam that collapses gradually with time. Foamed bitumen is widely used in stabilising granular materials and cold in-situ recycling (Read and Whiteoak 2003; Wirtgen 2004; REAL 2006).

In the ‘wet process’, crumb rubber normally pulverised to below 1mm, is blended with heated bitumen in an agitated blending tank, for 45-60 minutes before coating aggregates to produce hot mix asphalt (Cooke 2002).

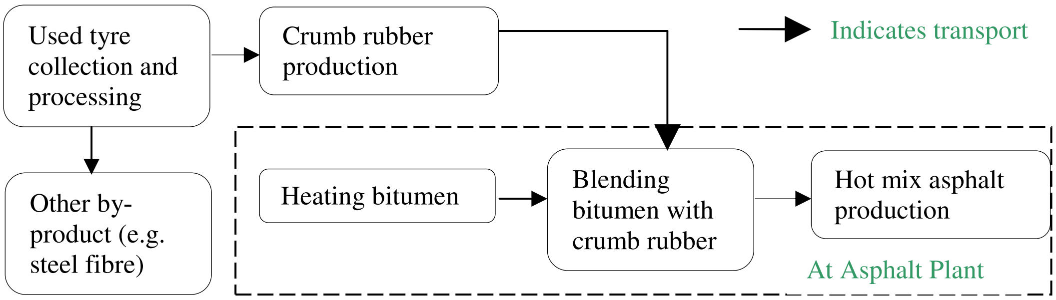


Figure 3-6 Production of Asphalt Rubber

3.1.5. Production of Asphalt

Aggregates are dried and heated before mixing with bitumen, in a batch or drum mix plant. Recycled aggregates (RAP, glass, etc) can be added providing the grading and binder content will meet the specification for use. Bitumen emulsion and foamed bitumen are able to mix with the natural or recycled aggregates without heating them (Read and Whiteoak 2003).

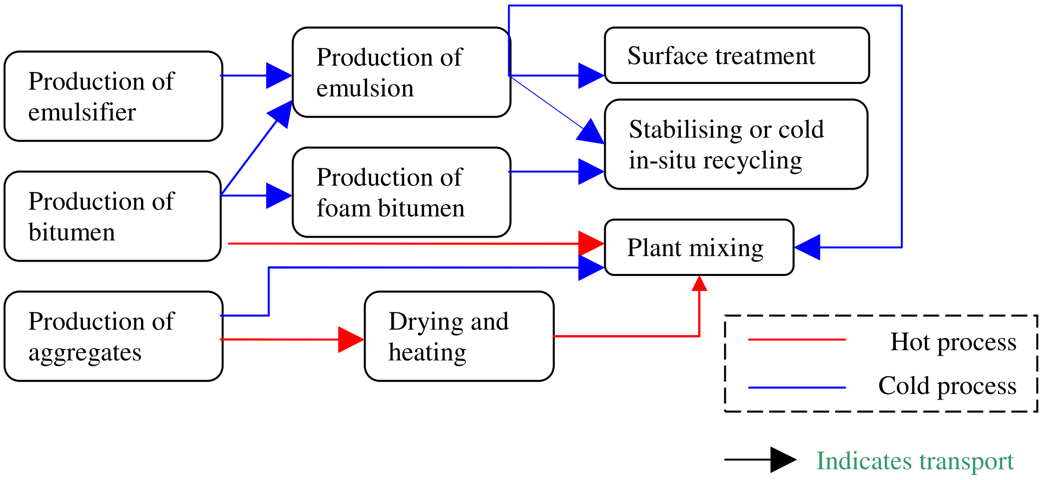


Figure 3-7 Production of Hot and Cold Mix Asphalt

3.1.6. Placement of Asphalt Layers

Surface treatment (e.g. milling, applying tack coat) is normally carried out before paving fresh asphalt materials. The nature and amount of work (which has energy use implications) depend on how the existing pavement surface is disposed, which might: 1) remain in place, 2) be milled, sent to asphalt plant as RAP, 3) be recycled in-situ and, 4) be milled and sent to landfill. This is followed by laying and rolling fresh asphalt materials at controlled temperature (TRL 2005).

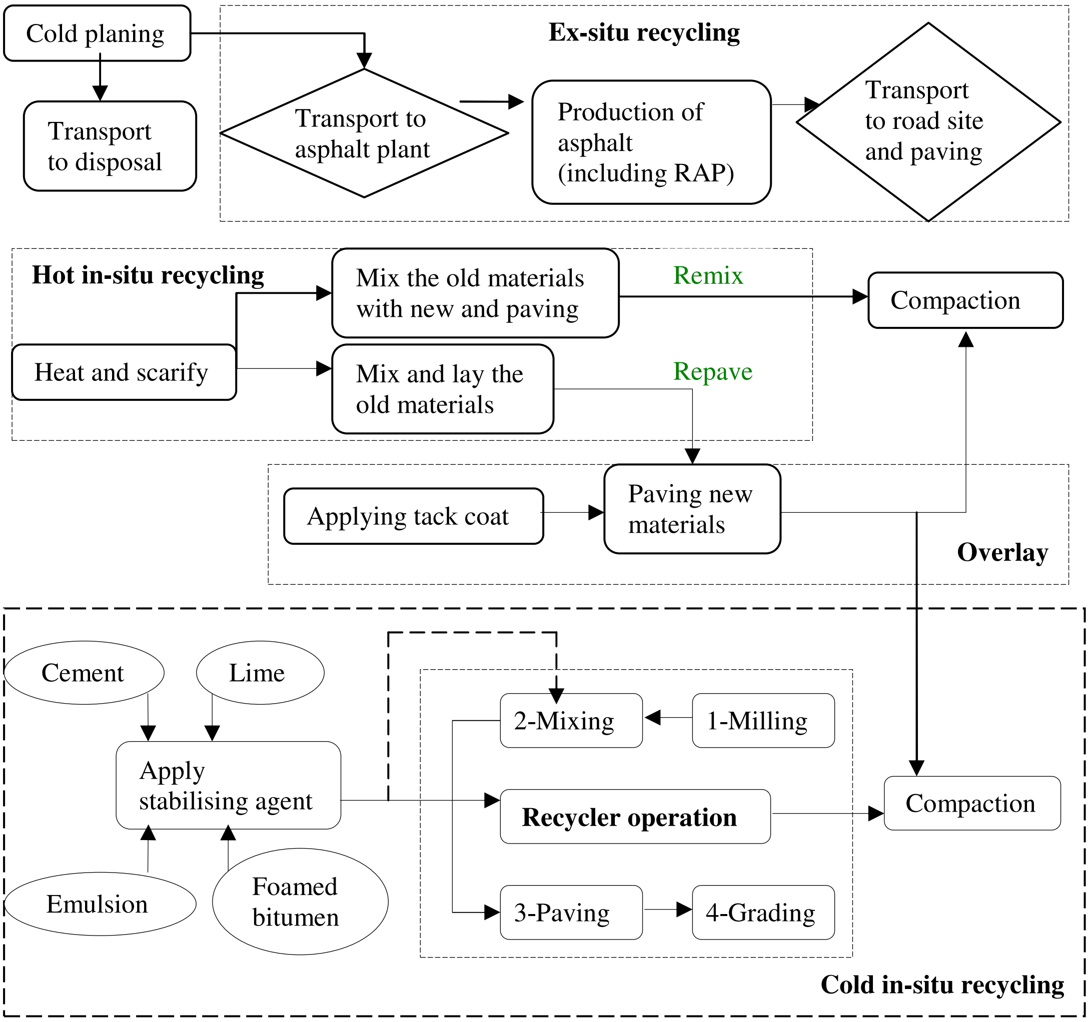


Figure 3-8 Treatment of Pavement Surface and Placement of Asphalt

Ex-situ (in-plant) recycling is capable of stockpiling, and has better control of the materials' quality; whilst in-situ (in-place) recycling reduces haulage and energy input, which is often carried out in a single pass by a purpose-built machine assembly (e.g. Wirtgen WR4200 Recycler). Recent years have seen cold in-situ recycling becoming preferable for its low energy input and speed delivery (Milton and Earland 1999; Merrill, Nunn et al. 2004). Care should be taken when choosing the stabilising agent, as the use of some types (hydrated lime, cement, etc) may eliminate the potential of the asphalt layers for a second time recycling in the future (Wirtgen 2004; TRL 2005).

Another type of pavement maintenance is the overlay of asphalt mixtures on existing concrete surface. Fractured concrete slab is broken by some breaker equipment (saw cutting first in the case of reinforced concrete pavements), compacted with pneumatic tyre roller, and then applied with the asphalt overlay. The broken concrete layer then will serve as the base or sub-base in the rehabilitated pavement structure, depending on its condition at the time of maintenance. In projects, where the concrete slab remains intact, an interlayer (e.g. stress absorbing membrane interlayer, SAMI) will be applied before laying the asphalt overlay. Alternatively, the 'saw cut and seal' treatment can be carried out on the asphalt overlay. Reflective cracking is a pavement defect commonly seen in asphalt overlaying concrete surface. The treatment categories and guidance, and machinery use are described in TRL report (TRL 2006).

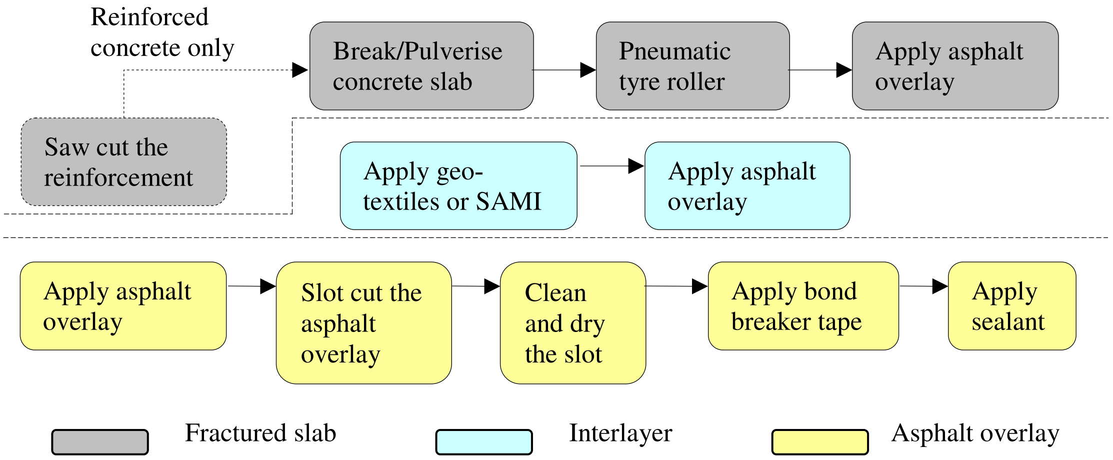


Figure 3-9 Laying Asphalt Overlays on Concrete Surface

3.1.7. Maintenance and Rehabilitation

To reduce subjective factors (e.g. aesthetics) to the minimum, the proposed LCA model deals only with the structural aspects of asphalt pavements which dictate the type of work involved, materials quantity and life expectancy of pavement layers. Functional aspects, such as road marking, accessories (lights, fences, signs, etc), maintenance salting and so forth, are not included for analysis. Neither included are the environmental impacts not specific to a particular project, such as the impacts from producing the machinery or plants.

In pavement maintenance, crack sealing or crack filling may be applied to cracks of 3-25mm wide. The sealing or filling materials can be applied hot such as PMB and asphalt rubber, or they can be applied cold like bitumen emulsion. If the cracks are less than 3mm wide, chip seal or slurry seal applies and if greater than 25mm, structural maintenance (patching or even full depth reconstruction) will be required (Lavin 2003). The processes and materials involved in maintenance and repair works are the same as placement of new layers, which are described above. The difference is that maintenance and repair works are carried out on existing roads, usually leading to land closure or diversion of traffic. This will cause additional fuel consumption and emissions from the traffic as a consequence, which are measured in this thesis using micro-simulation and traffic emissions model, and compared to those from road works (see Chapter5).

3.2. LCA Model Description

This section explains how the analysis of unit process in asphalt pavement projects, as described above, is applied in the LCA model. A Microsoft Excel spreadsheet (the computing tool) is developed alongside, with the calculation formulas in it described in more details in Appendix3.

3.2.1. Overview of the Model

Microsoft's spreadsheet, Excel, is a flexible computing tool that offers opportunities for modelling and graphic presentation. Also it is a widespread program that can be found on most computers therefore no need for investment in bespoke software. It is selected for calculating and presenting the LCI in this model.

This LCA model contains 5 worksheets: 'process parameters', 'pavement parameters', 'energy and emissions inventory', 'inventory results' and 'characterisation results'. Data in the 'process parameters' and 'pavement parameters' are primary inputs and likely to change between different pavement projects. Worksheet 'energy and emissions inventory' contains formulas and presents the life cycle inventory of unit process. The results of the calculation for each pavement project are shown in the 'inventory results' worksheet. For impact assessment, the inventory results are characterised; the characterisation model and factors can be found in the ‘characterisation results’ worksheet. Data in these worksheets are linked by calculation formulas. For instance, when energy data on a pavement process are altered, the inventory and characterisation results change accordingly. Only primary input data can be changed manually, others can not without changing the underlying calculation formulas. Data are provided alongside the statement of their source.

Table 3-1 Structure of the LCA Model

Worksheet	Description	Sub-worksheet
Process Parameters	Data on transport distance and fuel efficiency, energy consumption of unit processes in a pavement project	‘Energy in transport’ ‘Energy in materials production’ ‘Energy in pavement construction’ ‘Transport distance’
Pavement Parameters	Data on pavement dimension and materials recipe, determine the materials tonnage in a pavement project	‘Pavement dimension’ ‘Materials recipe’ ‘Pavement life time’
Energy and Emissions Inventory	Inventory data available for ‘primary’ processes are presented. LCI figures for unit operation of transport, materials production and pavement construction are calculated with formulas	‘Energy production’ ‘Combustion of fossil fuel’ ‘Transport vehicle operation’ ‘Construction vehicle operation’
Inventory Results	LCI data on ‘energy and emissions’ are aggregated into the unit of the pavement project	‘Production process’ ‘Transport process’ ‘Construction process’
Characterisation Results	LCI results assigned to defined impact categories, characterised by selected model and presented by category indicators	‘Global warming’ ‘Acidification’ ‘Photo-oxidant formation’ ‘Human toxicity’ ‘Eco-toxicity’ ‘Eutrophication’

Considering the features of a road project, the way the model is structured is for the purpose of convenient use, and in accordance with the ISO14044 (ISO 14044 2006). The units of calculation are presented in Figure3-10.

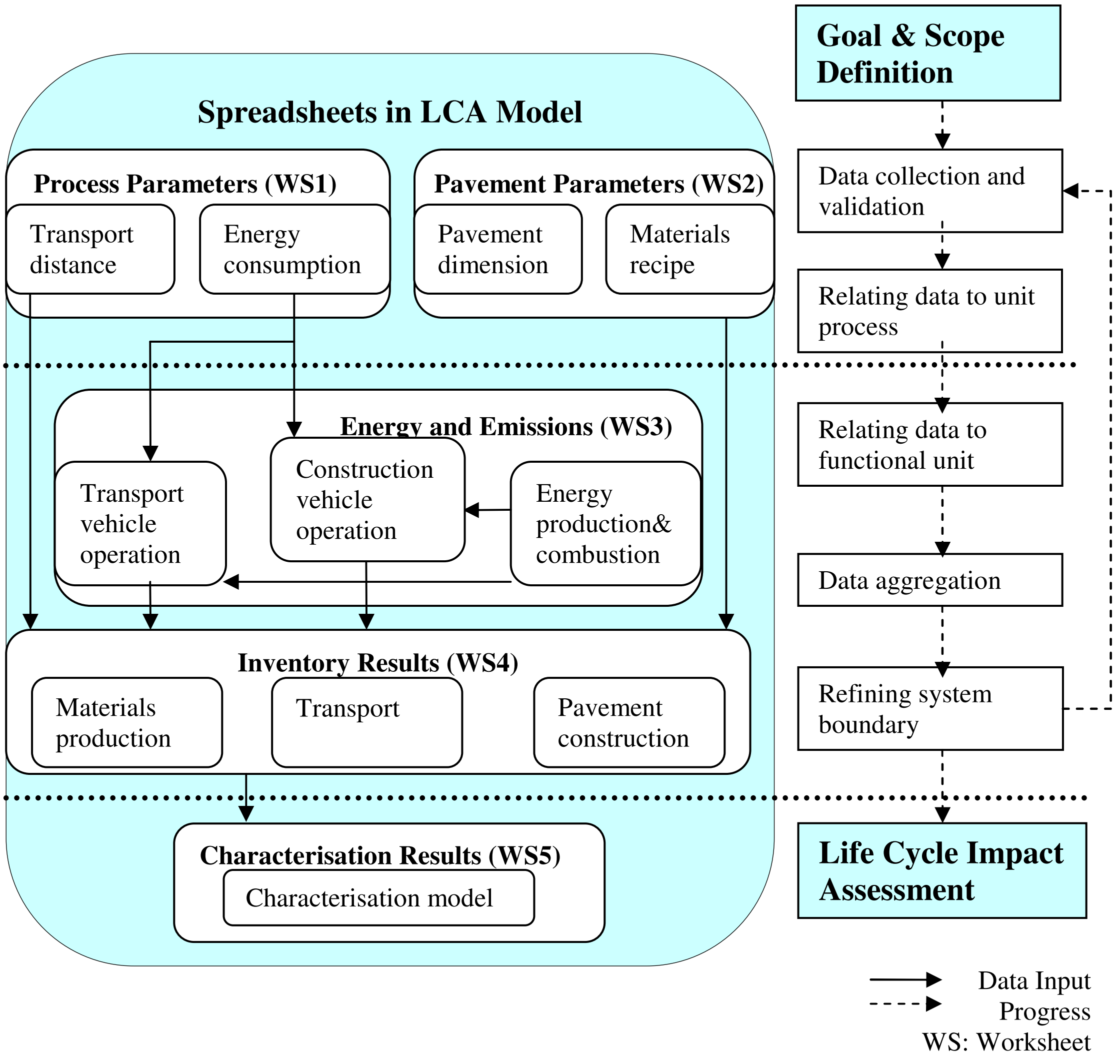
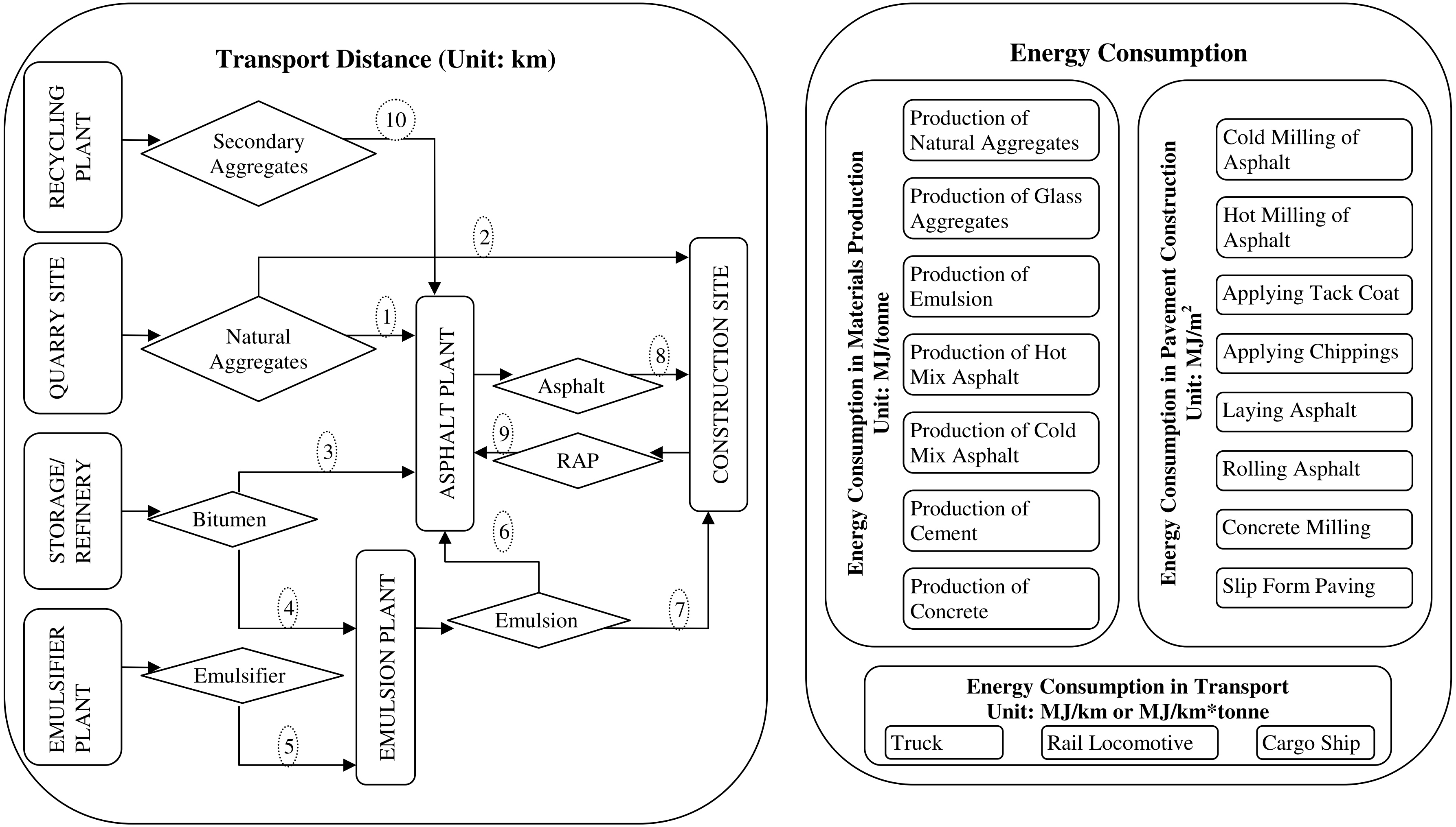
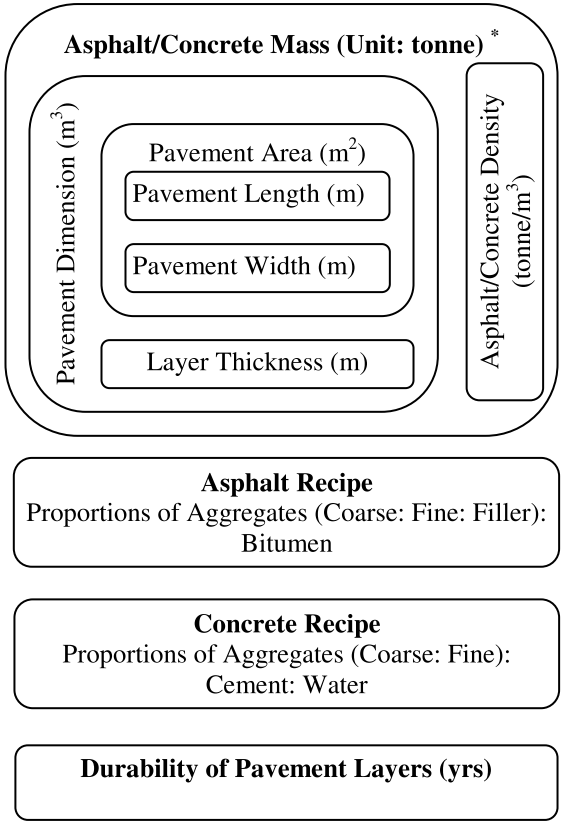


Figure 3-10 Structure of LCA Model and Procedures for Inventory Analysis



Process Parameters (Worksheet1)



Asphalt/Concrete Mass (Unit: tonne) *

Pavement Dimension (m^3)

Pavement Area (m^2)

Pavement Length (m)

Pavement Width (m)

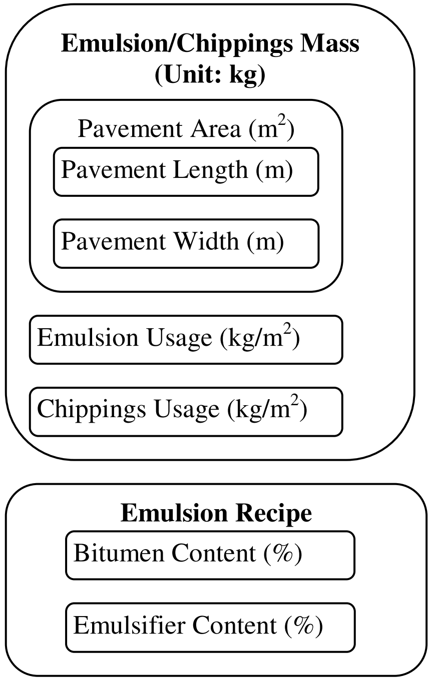
Layer Thickness (m)

Asphalt/Concrete Density (tonne/m^3)

Asphalt Recipe
Proportions of Aggregates (Coarse: Fine: Filler): Bitumen

Concrete Recipe
Proportions of Aggregates (Coarse: Fine): Cement: Water

Durability of Pavement Layers (yrs)



Emulsion/Chippings Mass (Unit: kg)

Pavement Area (m^2)

Pavement Length (m)

Pavement Width (m)

Emulsion Usage (kg/m^2)

Chippings Usage (kg/m^2)

Emulsion Recipe

Bitumen Content (%)

Emulsifier Content (%)

Refer to Appendix 3

Pavement Parameters (Worksheet2)

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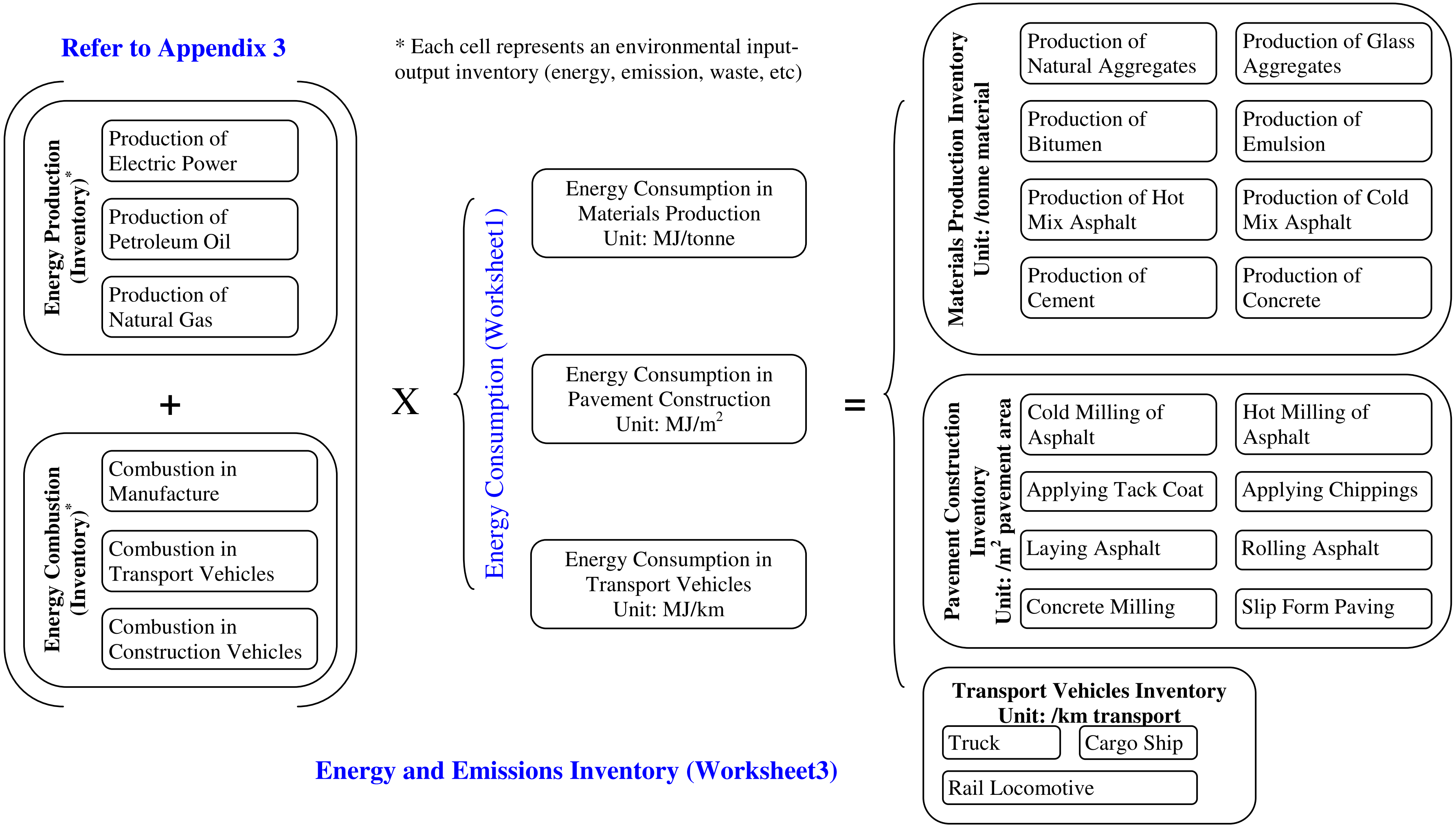
* Data normally known from contractors.

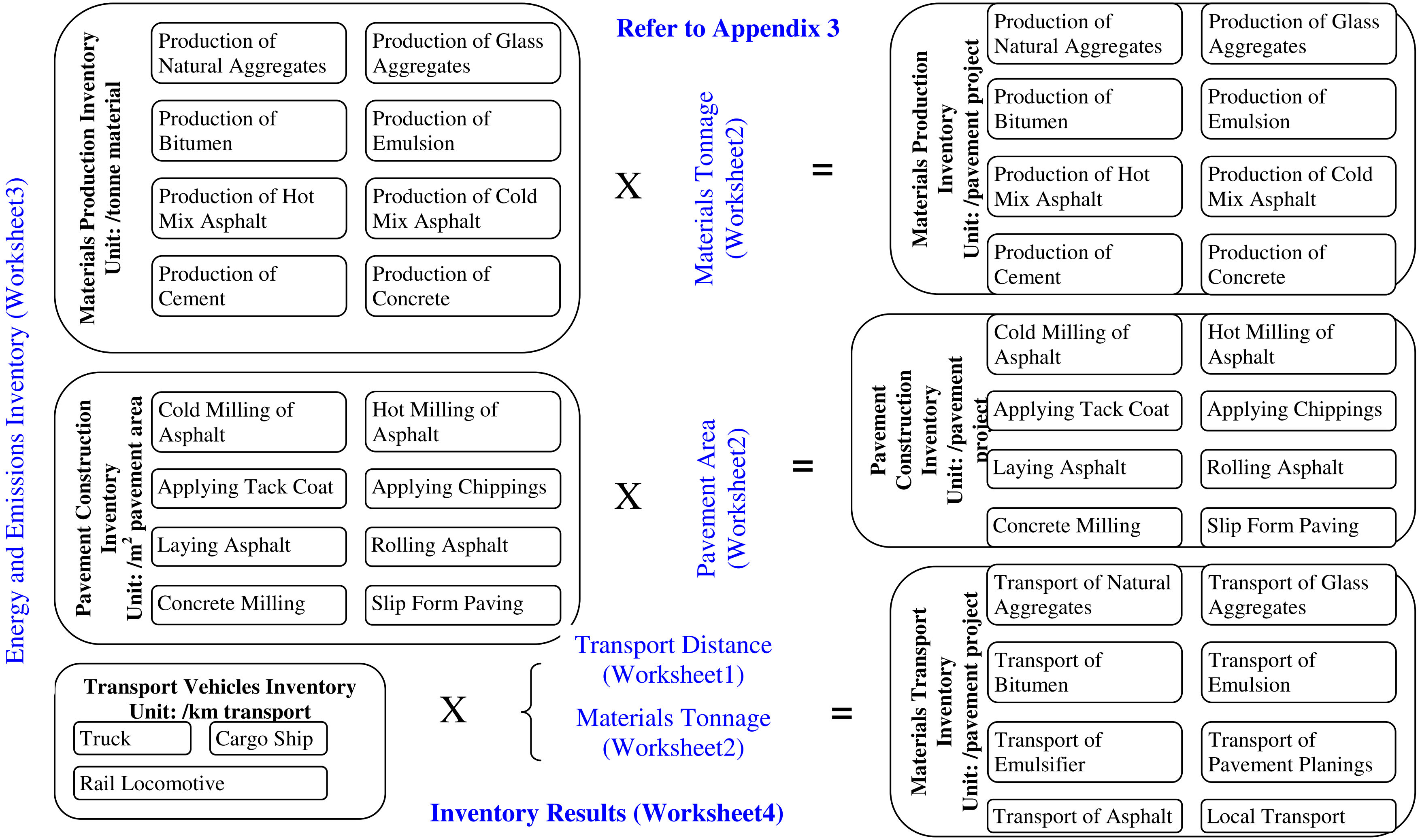
(Inventory of Energy Production + Inventory of Energy Combustion)* x Energy Consumption of Unit Process = Unit Inventory

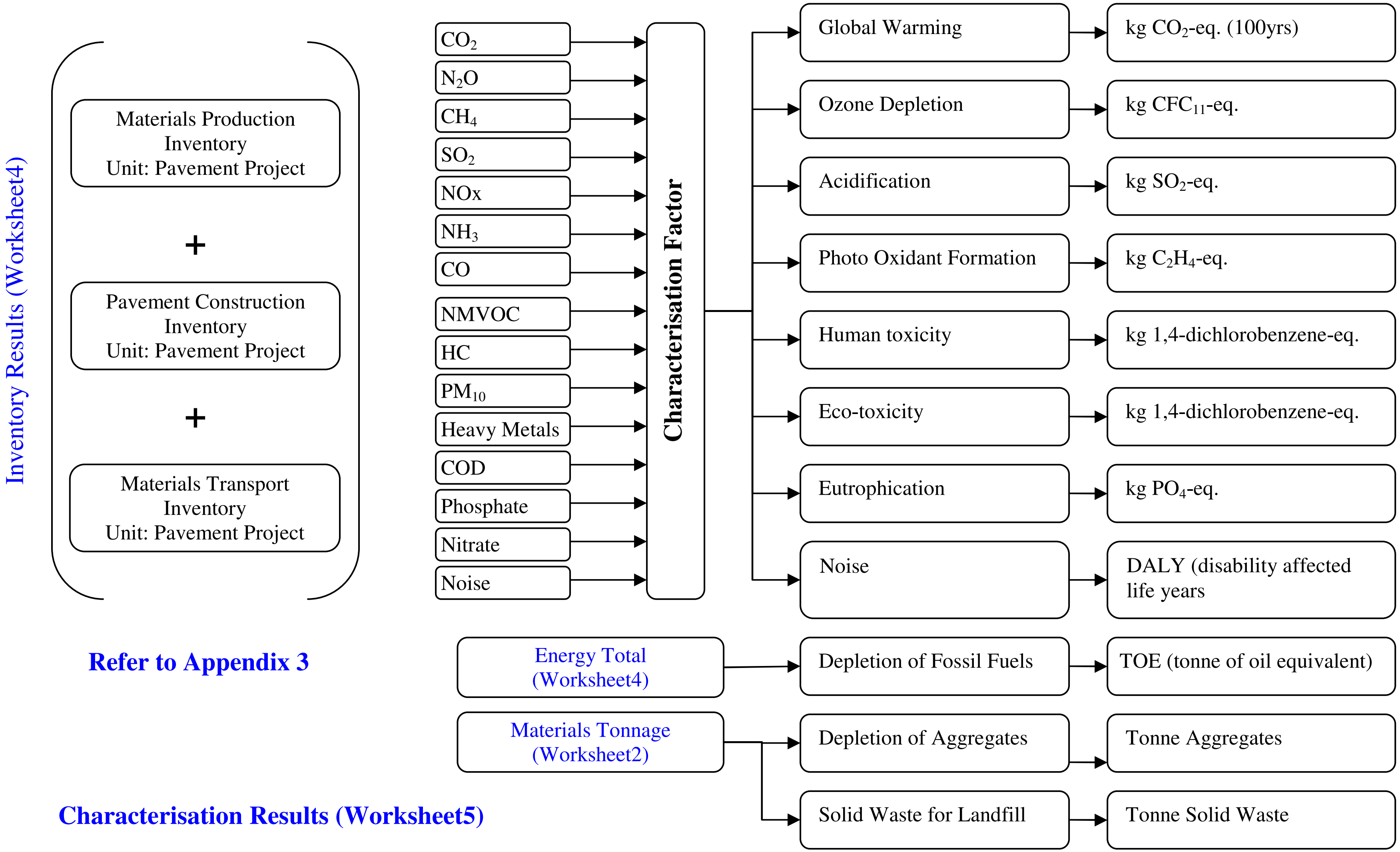


* Each cell represents an environmental input-output inventory (energy, emission, waste, etc)

Energy and Emissions Inventory (Worksheet3)

Unit Inventory x Quantity (Materials Tonnage, Transport Distance, Pavement Area) = Project Inventory Total




Inventory Results (Worksheet4)
Materials Production Inventory Unit: Pavement Project
+
Pavement Construction Inventory Unit: Pavement Project
+
Materials Transport Inventory Unit: Pavement Project
Refer to Appendix 3
Characterisation Results (Worksheet5)
CO_2
N_2O
CH_4
SO_2
NOx
NH_3
CO
NMVOC
HC
PM_{10}
Heavy Metals
COD
Phosphate
Nitrate
Noise
Characterisation Factor
Global Warming
Ozone Depletion
Acidification
Photo Oxidant Formation
Human toxicity
Eco-toxicity
Eutrophication
Noise
kg CO_2-eq. (100yrs)
kg CFC_{11}-eq.
kg SO_2-eq.
kg C_2H_4-eq.
kg 1,4-dichlorobenzene-eq.
kg 1,4-dichlorobenzene-eq.
kg PO_4-eq.
DALY (disability affected life years
Energy Total (Worksheet4)
Depletion of Fossil Fuels
TOE (tonne of oil equivalent)
Materials Tonnage (Worksheet2)
Depletion of Aggregates
Tonne Aggregates
Solid Waste for Landfill
Tonne Solid Waste

3.2.2. Process Parameters

The ‘process parameters’ worksheet includes data on transport distance (km), fuel efficiency in transport (litre/km or litre/km*tonne) and energy consumption per unit of materials production (MJ/tonne) and construction (MJ/m^2) in a pavement project. Energy data include both the amount and breakdown of energy types. Parameters can be grouped into sub-worksheets of ‘energy in materials production’, ‘energy in transport’ and ‘energy in pavement construction’.

A group of calorific values are fixed in the model for converting the volume of combusted fossil fuels into universal energy unit (MJ):

Table 3-2 Calorific Values of Fossil Fuels (DTI 2006)

	Electricity	**Diesel**	**Heating (gas) oil**	**LPG**	**Natural gas**	**Coal**
Unit	MJ/kWh	MJ/l (MJ/kg)	MJ/l (MJ/kg)	MJ/kg	MJ/m^3	MJ/kg
Value	3.6	43.3 (45.6)	41.1 (46.2)	49.4	39.6	26.7

Note:

The density of diesel and gas oil is assumed to be 950g/l and 890g/l, respectively.

3.2.2.1. Energy in Materials Production

Data are presented in the unit of ‘tonne materials’. Life cycle inventories for production of bitumen, bitumen emulsifier and limestone filler per unit are available in the ‘energy and emissions inventory’ worksheet.

Table 3-3 Energy in Materials Production

Materials production	**Unit**	**Quantity**	**Data source**
Production of crushed stone	**MJ/tonne stone**	42.16	IVL, Sweden
Electricity in production	MJ/tonne stone	21.19	
Diesel for vehicle/equipment operation	Litre/tonne stone	0.48	
Extraction of sand/gravel	**MJ/tonne sand/gravel**	27	IVL, Sweden
Electricity in excavation	MJ/tonne sand/gravel	11	
Diesel for vehicle/equipment operation	MJ/tonne sand/gravel	16	
Production of all-size aggregates[1]	**MJ/tonne aggregates**	41.85	Aggregate Industries Ltd. (AI), UK
Electricity in quarry	kWh/tonne aggregates	2.6[2]	
Diesel for vehicle/equipment operation	Litre/tonne aggregates	0.75[3]	
Production of bitumen emulsion	**MJ/tonne emulsion**	118.0	IVL, Sweden
Electricity in emulsion plant	MJ/tonne emulsion	21.2	
Combustion of heating oil	MJ/tonne emulsion	96.8	
Production of bitumen[4]	**LCI results**	N/A	Eurobitume
Production of emulsifier	**LCI results**	N/A	Akzo Nobel, Sweden
Production of limestone filler[5]	**LCI results**	N/A	VTT, Finland
Production of hot mix asphalt	**MJ/tonne asphalt**	400.8	EAPA's BAT[7]
Electricity in asphalt plant	MJ/tonne asphalt	23.5[6]	
Combustion of heating oil in plant	MJ/tonne asphalt	360	
Diesel for loading asphalt	Litre/tonne asphalt	0.4	
Production of hot mix asphalt	**MJ/tonne asphalt**	389.6	Aggregate Industries Ltd. (AI), UK
Electricity in asphalt plant	kWh/tonne asphalt	7.4[8]	
Combustion of heating oil in plant	Litre/tonne asphalt	8.3[9]	
Diesel for loading asphalt	Litre/tonne asphalt	0.5	
Production of cold mix asphalt	**MJ/tonne asphalt**	45.51	IVL, Sweden
Electricity in asphalt plant	MJ/tonne asphalt	1.27	
Combustion of heating oil in plant	MJ/tonne asphalt	5.81	
Diesel for electricity to mobile plant	MJ/tonne asphalt	21.1	
Diesel for loading asphalt	Litre/tonne asphalt	0.4	
Production of cold mix asphalt	**MJ/tonne asphalt**	36.4	Aggregate Industries Ltd. (AI), UK
Electricity in asphalt plant	kWh/tonne asphalt	1.7	
Diesel for electricity to mobile plant	Litre/tonne asphalt	0.7	
RAP pre-processing	**MJ/tonne RAP**	50.55	IVL, Sweden
Diesel for excavation	Litre/tonne RAP	0.29	
Diesel for wheel loader transport	Litre/tonne RAP	0.25	
Diesel for crushing in plant	Litre/tonne RAP	0.63	
Production of cement[10]	**MJ/tonne cement**	4290.6	Cementa AB, Sweden
Electricity in cement plant	MJ/tonne cement	390	
Diesel for vehicle/equipment operation	MJ/tonne cement	40.6	
Combustion of coal	MJ/tonne cement	3860	
Production of concrete[10]	**MJ/tonne concrete**	76.93	Cementa AB, Sweden
Electricity in concrete plant	MJ/tonne concrete	16.72	
Diesel for vehicle/equipment operation	Litre/tonne concrete	1.39	
Production of glass aggregates	MJ/tonne glass	441.85	
Transport from household to recycling	MJ/tonne glass	400[11]	Loughborough University
Electricity in production	kWh/tonne aggregates	2.6[12]	Aggregate Industries Ltd. (AI), UK
Diesel for vehicle/equipment operation	Litre/tonne glass	0.75[12]	

Notes:

1. Aggregates of required grading are often produced from a single quarry site, including coarse, fine and limestone filler components. Energy use is allocated by weight ratio to these components. Energy consumed in explosive production, drilling and blasting is excluded due to the relatively small amount (Hopkins and Foster 2003).
2. Mean value of Greenwich plant (2.8kWh/tonne) and Durham plant (2.4kWh/tonne).
3. Mean value of Greenwich plant (0.8Litre/tonne) and Durham plant (0.7Litre/tonne).
4. LCI data on bitumen (straight run PG50/70) did not include pre-combustion of heating oil and natural gas. 40% of LCI burdens of petroleum products are allocated to bitumen and 60% to lighter products, again based on the assumed weight ratio (Stripple 2005).
5. LCI data on limestone filler included the transport of products to asphalt plant (Hakkinen and Makela 1996).
6. Mean value of 18-29MJ/tonne.
7. EAPA's best available techniques (BAT) (EAPA 1996). Energy data on production of hot mix asphalt vary significantly between countries. Table3-4 has some examples.

Table 3-4 Energy Use in Hot Mix Asphalt Plant (Stripple 2005)

	Unit	A modern plant in Scandinavia	IVL, Sweden	EAPA's BAT	The Netherlands	The UK	Singapore
Electricity	MJ/tonne asphalt	25.2	36	18-29	38	32	320-390
Fuel oil	MJ/tonne asphalt	251.3	285	360	310	340	

8. Mean value of Greenwich plant (7.5kWh/tonne) and Durham plant (7.3kWh/tonne).
9. Mean value of Greenwich plant (9Litre/tonne) and Durham plant (7.6Litre/tonne).
10. A feature of energy use in cement production is the high percent of input from coal combusted in clinker (about 90% of the energy input). A feature in concrete production is the take-up of CO_2 by concrete in the carbonation process during its lifetime (estimated at 686g/kg cement or 274kg/m^3 concrete) (Stripple 2001).
11. 0.25MJ/kg glass (petrol) for consumer transport; 0.15MJ/kg glass (diesel) for local transport.
12. Energy input for processing glass aggregates is assumed the same as processing natural aggregates in a quarry.

Data on ‘energy in materials production’ are also available from other sources, including US Department of Energy, National Crushed Stone Association (NCSA), and Canadian National Research Council (NRC), etc (Zapata and Gambatese 2005). Data on some recycled materials by close-loop recycling are available in SimaPro7. BRE methodology suggests that the environmental burdens of recycled materials from open-loop recycling be allocated based on the residual value of the waste stream compared to the value of the product stream (Howard, Edwards et al. 1999).

3.2.2.2. Energy in Transport

Data for transport distance are presented in the unit of ‘km’. Mileage and vehicles for transport vary between pavement projects, so does the fuel efficiency presented in litre/km or litre/km*tonne. In the diagram below, the ‘surface dressing’ can also represent processes for unbound (or granular) layers (without emulsion), or application of tack coat (or adhesion layer).

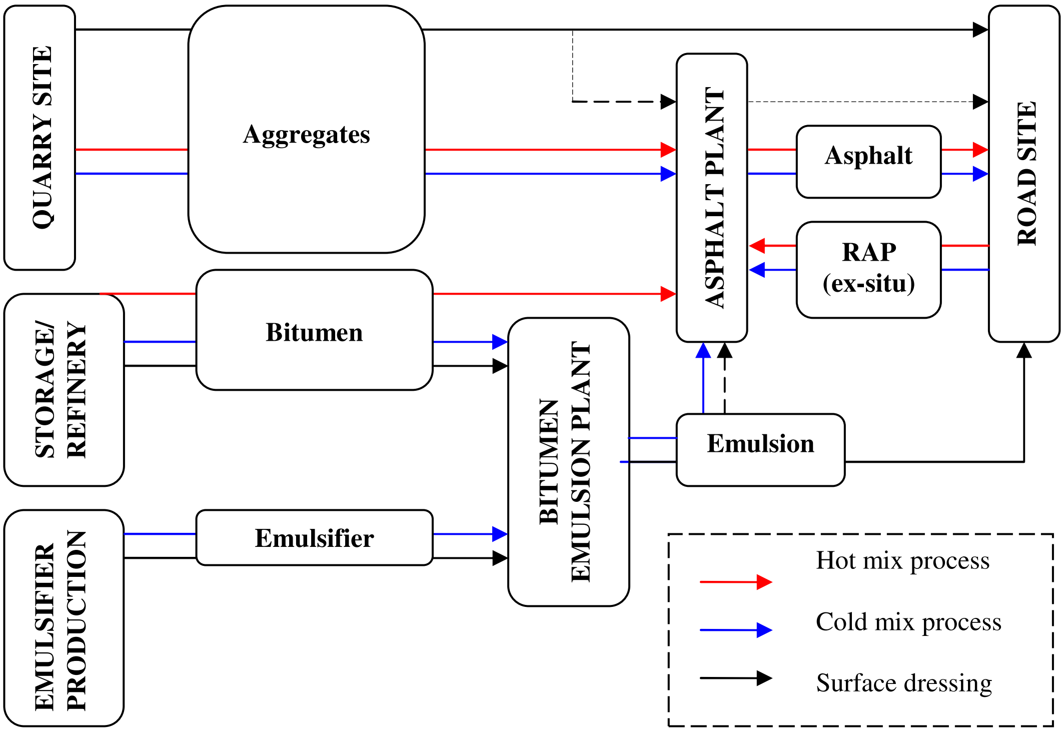


Figure 3-11 Transport in Asphalt Pavement Construction

When calculating the diesel consumption, transport vehicles are assumed to run at ‘full load’ and ‘empty on return’.

$$FC(MJ/km, F+E) = 43.3MJ/l \times \frac{FC(l/km, FL) + FC(l/km, EL)}{2}$$

FC (MJ/km, F+E): fuel consumption (MJ/km, full load + empty on return)

FC (l/km, FL): fuel consumption (l/km, full load)

FC (l/km, EL): fuel consumption (l/km, empty load)

In the IVL's study, 14t truck and 32t truck were selected for short and long distance transport, respectively. Also provided, was the energy for cargo transport (Stripple 2001). In Aggregate Industries UK Ltd's project, railway locomotive was used for long distance haulage of aggregates.

Table 3-5 Transport Vehicle Specification and Fuel Consumption

	Load limit (tonne)	FC (l/km, FL)	FC (l/km, EL)	FC (MJ/t*km, F+E)	Data Source
Distribution truck	14	0.39	0.29	1.05	IVL, Sweden
Long distance truck	32	0.47	0.29	0.51	IVL, Sweden
Cargo ship	n/a	n/a	n/a	0.13	IVL, Sweden
Railway Locomotive	1729	n/a	n/a	0.17[1]	AI, UK

Note:

1. The fuel efficiency is 0.85litre/tonne for a transport of 120 miles.

3.2.2.3. Energy in Pavement Construction

Data are presented in the unit of 'm^2 surface', except for local transport vehicles (wheel loader, excavator, etc). Normally, more than one figure is available for a process, depending on the vehicle/equipment in use in that project. Table below presents the available ones as an example.

Table 3-6 Energy in Pavement Construction

Pavement construction	Unit	Quantity	Data source
Application of tack coat	**MJ/m^2 applied surface**	0.59	Aggregate Industries Ltd. (AI), UK
Ramp width	m	2	
Application speed	km/hr	0.22	
Fuel consumption	litre/hr	6	
Application of chippings	**MJ/m^2 applied surface**	0.7	IVL, Sweden
Excavation of asphalt pavement[1]	**Litre/m^2 excavated surface**	0.35	IVL, Sweden
Cold asphalt milling[1]	**MJ/m^2 milled surface**	2.20	IVL, Sweden
Diesel for milling machine	MJ/m^2	1.75	
Diesel for sweeping machine	MJ/m^2	0.45	
Remixing	**MJ/m^2 remixed surface**	42.99	IVL, Sweden
Diesel for heater	MJ/m^2	0.5	
Diesel for remixer	MJ/m^2	1.0	
LPG for heating	MJ/m^2	41.49	
Paving[2]	**MJ/m^2 paved surface**	0.71	Aggregate Industries Ltd. (AI), UK IVL, Sweden
Width of screed	m	4.9	
Laying speed	m/hr	300	
Fuel consumption	Litre/hr	16.87	
Diesel for paver	MJ/m^2	0.53[3]	
LPG for heating screed	MJ/m^2	0.11	
Rolling[2]	**MJ/m^2 rolled surface**	0.45	Aggregate Industries Ltd. (AI), UK
Width of roller[4]	m	1.7	
Rolling speed	m/hr	6000	
Number of passes		6	
Fuel consumption	Litre/hr	12.5	
Slip form paver	**Litre/m^2 paved surface**	0.12	IVL, Sweden
Slip form paver (base stabilisation)	**Litre/m^2 stabilised surface**	0.03	IVL, Sweden
Concrete milling (12mm)[1]	**Litre/m^2 milled surface**	2.06	IVL, Sweden

Notes:

1. Fuel consumption varies with the depth of excavation.

2. Effective working time is assumed 50min/hr for paver and roller. Equation below is used to determine the upper limit of the paver speed provided the roller speed is known in the laying assembly, for the sake of a quality and efficient laying (Lavin 2003).

$$\text{Paver speed} \leq \text{roller speed x } 0.9 \,/\, \text{number of roller passes}$$

3. Calculated figure.

4. Effective rolling width is assumed 85% of the roller width.

3.2.3. Pavement Parameters

The ‘pavement parameters’ worksheet includes data on pavement dimension and materials recipe. It contains information on materials tonnage and together with data in ‘process parameters’, will determine the workloads in a pavement project, for LCI calculation. Parameters in it can be grouped into ‘pavement dimension’, ‘materials recipe’ and ‘pavement life time’ as described below.

3.2.3.1. Pavement Dimension

Data include pavement surface area and layer thickness. Thick pavement layers may be laid and rolled in more than one pass. ‘Swelling factor’ is the ratio of materials volume in loose state against that in compacted state (>1), and is used for the calculation of transport where the truck’s loading capacity is dictated by materials volume, rather than weight. A value of 1.3 was used, and the asphalt density assumed 2.3tonne/m^3, in the IVL’s study (Stripple 2005).

Table 3-7 Pavement Dimension

Pavement structure	**Unit**	**Surface**	**Binder**	**Base**
Pavement area	m^2	Project Specific Data (PSD)		
Pavement length	m	PSD		
Pavement width	m	PSD		
Layer thickness	mm	PSD	PSD	PSD
Asphalt density	tonne/m^3	2.3		
Swelling factor		1.3		

Alternatively, data on asphalt tonnage can be obtained from materials supplier, as was in both case studies in Chapter4.

3.2.3.2. Materials Recipe

Data include materials tonnage and composition. This model is using the ‘conditional formatting’ which is able to warn the user of any non-logical data input, e.g. the sum of components tonnage (or percentage) does not equal the total weight (or 100%).

Table 3-8 Hot and Cold Mix Asphalt Composition (%)

	Crushed stone (coarse)	Sand/Gravel (fine)	Limestone filler	Bitumen	Bitumen emulsion	Recycled (specify)
Hot mix	PSD	PSD	PSD	PSD	N/A	PSD
Cold mix	PSD	PSD	PSD	N/A	PSD	PSD

Bitumen emulsion can be applied to tack coat, chip seal, slurry seal and cold mix asphalt. Both the bitumen and emulsifier content vary between these applications. Emulsion usage in tack coat and chip seal is measured in the unit of ‘kg/m^2’, whilst in slurry seal and cold mix asphalt, by weight ratio. Data in the table below come from IVL’s study (Stripple 2005).

Table 3-9 Bitumen Emulsion Use

	Unit	Tack coat	Chip seal	Cold mix asphalt
Bitumen content	%	50[1]	65	60
Emulsifier content	kg/tonne emulsion	3	1.5	2.85
Emulsion usage	kg/m^2	0.1[2]	1.0-1.5[3]	(%)
Chipping usage	kg/m^2	N/A	15[3]	N/A

Note:

1. Bitumen content in the emulsion of Aggregate Industries’ project was 60%.
2. Emulsion in the tack coat of Aggregate Industries’ project was applied $0.4kg/m^2$.
3. The usage of emulsion and chipping in chip seal depends on the substrate and the nominal size of the chippings (Lavin 2003).

3.2.3.3. Pavement Life Expectancy

Mix design is out of the scope of this study, yet mixture properties and layer thickness are factors that, together with traffic and foundation strength, are used to predict the pavement life. Different service life should be applied to different pavement layers, e.g. 12yrs for surface course, 15yrs for binder course, etc. Pavement life expectancy is a key factor affecting the LCA results, as the functional unit is normally defined as below. This enables the comparison between asphalt layers of different life span.

Functional unit = pavement project / service life (yr)

3.2.4. Energy and Emissions Inventory

In the ‘energy and emissions inventory’ worksheet, a life cycle inventory (LCI) is built up for the processes in a pavement project. Inventory data that are available for some ‘primary’ processes (e.g. energy production, vehicle/equipment engine operation) are presented first, followed by progressive calculations to get the LCI data on other processes in the pavement project. Emission from a process has two parts.

One comes from the process itself (e.g. diesel engine, gas oil combustion), the other from the production of energy consumed in that process. The energy consumption figures of vehicles and equipments come from the 'process parameter' worksheet. This worksheet can be grouped into 'energy production', 'combustion of fossil fuel', 'transport vehicle operation' and 'construction equipment operation'. These are dealt with in turn below.

3.2.4.1. Energy Production

Data on production of electric power come from EURELECTRIC (Union of the Electricity Industry), using the average of 15 European countries with an assumed distribution loss of 5% (EURPROG 1998). It is noted that the emissions rate (emissions per kWh electric power generation) from UK power plants has declined since the early 1970s, thanks to the reduced use of coal (33%) in favour of natural gas (40%) and uranium (19%), as well as the emissions abatement measures at power plants (DTI 2006). A later version of 2005 is available, only to EURELECTRIC members (EURPROG 2006). Data on the production of diesel (pre-combustion) come from mixed sources in Norway covering extraction, refining and transport to the consumer (see Table3-10). LCI loadings for production of LPG are assumed to be the same as diesel (Stripple 2005).

Alternative sources of emissions data on energy production (electric power, natural gas, petroleum oil) include the NAEI (National Atmospheric Emissions Inventory) report (NAEI 2005), and the BUWAL250 (database in SimaPro7). This model did not include data from these two sources, for data presented in there are difficult to use for the LCI study.

Table 3-10 Inventory (selected items) for Energy Production

Energy type	Unit	Energy (MJ)			Emission to air (g)							Discharge to water (g)				Solid waste (g)	
		Electricity	Natural gas	Petroleum oil*	SO_2	NOx	CO	CO_2	NMVOC	N_2O	Particulate	COD	N-total	HC	Oil	Inert	Hazardous
Electricity	MJ	1	0.337	0.375	0.646	0.306	0.0281	137	0.0697		0.19		9.57E-04	0.0101		19.6	5.32
Diesel/Fuel oil	MJ			0.1	0.0036	0.01	0.0017	3.22		3.03E-03	8.86E-06	4.62E-06	8.75E-07		4E-04		

* Petroleum oil includes LPG, diesel and heating (gas) oil

3.2.4.2. Combustion of Fossil Fuel

Natural gas and petroleum oil (LPG, gas oil, etc) are combusted in production plants (asphalt, emulsion, etc) and construction equipments (paver, remixer, etc) for heating purpose. Of the key pollutants, emissions of SO_2, heavy metals and organic compounds are correlated with the content of certain components (e.g. sulphur) in the fuel, CO emissions are related to the combustion condition, and CO_2 emissions mainly depend on the fuel consumption. The same principle applies for fossil fuels consumed by diesel engine (see 3.2.4.3 and 3.2.4.4) (EEA 2005; Stripple 2005).

Relevant data are specified in EEA's (European Environment Agency's) standard Group3 – 'combustion in manufacturing industry', using the lower limit of Corinair90 data on combustion plant with thermal capacity of >300MW, 50-300MW and <50MW, regardless of the boiler type (EEA 2005).

Table 3-11 Emissions from Combustion of Fossil Fuel (CORINAIR90)

g/MJ	NOx	NMVOC	CH_4	CO	CO_2	N_2O	Heavy metals*
Gas oil	0.05	0.0015	0.0001	0.01	57	0.0006	3.8
Natural gas	0.022	0.002	0.0003	0.00005	44	0.0001	$0.05x10^{-6}$
LPG	0.035	0.002	0.001	0.01	57	0.002	n/a

* Data on 'heavy metals' refer to the total of As, Cd, Hg and Pb.

IVL data on those emissions did not differentiate the thermal capacity of the combustion plant either. The emissions level (emissions per MJ energy combusted) between different types of energy combustion was in the ascending order of: LPG/natural gas < fuel oil for general heating < fuel oil for heating in asphalt plant (Stripple 2005).

Table 3-12 Emissions from Combustion of Fossil Fuel (IVL)

g/MJ	SO_2	NOx	CO	CO_2	VOC	Particulate
Fuel oil in asphalt plant	0.05	0.05	0.52	78	0.196	0.026
Natural gas in asphalt plant	0.002	0.038	0.38	56	0.006	0.013
Fuel oil for heating, general	0.05	0.16	0.013	78	n/a	0.01
LPG for heating, general	0.002	0.038	0.38	56	0.006	0.013

Data from Corinair90 and IVL are aggregated for use in this LCA model. Corinair90 data are preferred, for: 1) The figures in Corinair90 are lower, which represent the tightening requirements under the EU Directive 2005/55/EC, and 2) Data sources in

Corinair90 are easier to identify. Where Corinair90 data are missing, IVL data are used. The aggregated data for use in this model do not differentiate the location of the combustion.

Table 3-13 Aggregate Data on Emissions from Combustion of Fossil Fuel (CORINAIR90, IVL)

g/MJ	SO_2	NOx	CO	CO_2	CH_4	NMVOC	VOC	N_2O	Particulate
Fuel oil	0.05	0.05	0.01	57	0.0001	0.0015	0.196	0.0006	0.01
Natural gas	0.002	0.022	0.00005	44	0.0003	0.002	0.006	0.0001	0.013
LPG	0.002	0.035	0.01	57	0.001	0.002	0.006	0.002	0.013

Data in orange indicated IVL's data.

3.2.4.3. Transport Vehicle Operation

LCI loadings for transport include two aspects: the vehicle engine, and the production of diesel it consumes. A number of vehicle features (fuel type, age, mileage, etc), operational condition (load, road layout, speed, acceleration, traffic flow, congestion level, etc) as well as environmental factors (altitude, ambient temperature, etc) have an effect on the vehicle's exhaust emissions level (TRL 2000). The many influencing factors were studied by TRL in 2006 for mapping the emission in west London (TRL 2006). To avoid confidentiality restriction and the difference between truck manufacturers, EU limit (effective from October 2005) on emissions from heavy-duty diesel engines is used in this LCA model as emissions from diesel engine operation (European Union 2005). An engine efficiency of 40% is assumed. Missing data on emissions (of SO_2, CO_2 and N_2O) come from IVL study (Stripple 2005).

Table 3-14 EU Emission Standard (Euro IV) for Heavy-Duty Diesel Engines

Tier	Unit	Test	Emission							
Euro IV	g/kWh	ESC&ELR*	CO	HC	NOx	PM	Smoke (m^{-1})	SO_2	CO_2	N_2O
			1.5	0.46	3.5	0.02	0.5			
g/MJ (40% engine efficiency)			0.167	0.0511	0.389	0.00222	0.0556	0.024	75	0.0021

* ESC: European Stationary Cycle; ELR: European Load Response

LCI loadings on transport vehicle operation (g/km) can be calculated by multiplying fuel consumption (MJ/km) by the sum of engine emission (g/MJ) and pre-combustion (g/MJ).

$$\text{LCI of transport (g/km)} = \text{FC (MJ/km)} * [\underset{\overset{\uparrow}{\boxed{\text{Table14}}}}{\text{engine (g/MJ)}} + \underset{\overset{\uparrow}{\boxed{\text{Table10}}}}{\text{pre-combustion (g/MJ)}}]$$

In the ‘energy and emissions’ worksheet, LCI data on IVL trucks are divided by their loading capacity, to obtain estimates in the unit of per km*tonne. Lower emissions level in unit of ‘g pollutants/ (km distance* tonne loading)’ comes from heavier trucks. This complies with the inventory data from ESU-ETHZ (PRe Consultants 2006).

Other modes of transport in a road project may include the ship (coast freight) and railway (locomotive). The diesel consumption is assumed (see in Table3-5) to be 0.13MJ/tonne*km and 0.17MJ/tonne*km, respectively. Their engine emissions (g/tonne*km) are presented in the table below (Stripple 2005). It is acknowledged that an alternative type of limit on emissions from diesel engine (including CO_2, CO, HC, NO_x and particulates) is presented by ACEA (European Automobile Manufacturers Association) and UNECE (United Nations Economic Commissions for Europe) in the unit of ‘g/km’. The relevant documents however, did not go into the same level of detail as this model does (UNECE 1999; ACEA 2007).

Table 3-15 Energy Use and Emissions for Diesel Ship and Locomotive (IVL)

Mode	Unit	Diesel use	Emission (g)				
			CO	HC	NOx	SO_2	CO_2
Ship	t*km	0.13 MJ	0.027	0.0075	0.252	0.063	9.5
Locomotive	t*km	0.17 MJ (source: AI)	0.049	n/a	0.4	0.018	18

3.2.4.4. Construction Equipment Operation

Similar to transport vehicles, an energy efficiency of 40% is assumed for the diesel engines in construction equipments. In cold mix asphalt plant, environmental burdens from ‘diesel for producing electricity to mobile plant’ are assumed to be the same as those from diesel consumed in construction equipments. The type and amount of energy consumed per unit by construction vehicle/plant can be found in Table3-16.

Table 3-16 Energy Consumption of (selected) Construction Vehicle/Plant

	Paver	Roller	Excavator	Tack coat applier	Chipping applier	RAP pre-processing	Cold milling	Remixing	Crushed stone production	Sand/Gravel extraction	Emulsion production	Hot asphalt production	Cold asphalt production
Unit	MJ/m^2	MJ/m^2	MJ/m^2	MJ/m^2	MJ/m^2	MJ/tonne	MJ/m^2	MJ/m^2	MJ/tonne	MJ/tonne	MJ/tonne	MJ/tonne	MJ/tonne
Electric power									21.19	11	21.2	23.5	1.27
Diesel	0.53	0.40	13.57	0.53	0.7	45.23	2.2	1.5	18.76	16		15.5	36.6
Fuel oil											96.8	360	5.81
LPG	0.11							41.49					

Again, EU standard on emissions from diesel engine is used in here. Relevant data are specified in Group8: ‘other mobile sources and machinery’. Formulas were used to calculate the emissions and fuel consumption (FC) of diesel engines, both varying with the engine power (P) (EEA 2005). The construction equipments are assumed to run at ‘operating capacity’. Missing data on emissions (of CO_2 and SO_2) come from the IVL’s study (Stripple 2005). The impacts of these assumptions on the final inventory results can be tested by data sensitivity check (see Case Study in Chapter4).

Table 3-17 EU Emission Standard (Corinair) for Stage II Controlled (20kW<P<560kW) Diesel Engines

Unit	Engine power (kW)	Emission									FC
		NOx	N_2O	CH_4	CO	NMVOC	PM	NH_3	SO_2	CO_2	
g/kWh	0-20	14.1	0.35	0.05	8.38	3.82	2.22	0.002	n/a	n/a	271
	20-37	8.50	0.35	0.05	5.50	1.50	0.80	0.002	n/a	n/a	269
	37-75	8.00	0.35	0.05	5.00	1.30	0.40	0.002	n/a	n/a	265
	75-130	7.00	0.35	0.05	5.00	1.00	0.30	0.002	n/a	n/a	260
	130-560	7.00	0.35	0.05	3.50	1.00	0.20	0.002	n/a	n/a	254
	>560	14.4	0.35	0.05	3.00	1.30	1.10	0.002	n/a	n/a	254
g/MJ (40% engine efficiency)	0-20	1.57	0.0389	0.00556	0.931	0.424	0.247	0.000222	0.024	75	
	20-37	0.94	0.0389	0.00556	0.611	0.167	0.0889	0.000222	0.024	75	
	37-75	0.89	0.0389	0.00556	0.556	0.144	0.0444	0.000222	0.024	75	
	75-130	0.78	0.0389	0.00556	0.556	0.111	0.0333	0.000222	0.024	75	
	130-560	0.78	0.0389	0.00556	0.389	0.111	0.0222	0.000222	0.024	75	
	>560	1.60	0.0389	0.00556	0.333	0.144	0.0111	0.000222	0.024	75	

Similar to transport vehicles, LCI loadings for construction vehicle/plant include both those from engine operation and pre-combustion of the diesel consumed. For processes where LPG or gas oil is combusted for heating, LCI data on both the combustion and production of the LPG or gas oil are included. Most road machinery work at an engine power of 20-560kW; LCI data for operation of vehicle/equipment are calculated in the worksheet assuming a P value of 130-560kW. Sensitivity check can be carried out on this variation.

In VTT’s LCA study, inventory data (energy, emissions) were provided on production of materials, namely hot mix asphalt (SMA, asphalt concrete), bitumen, crushed stone and gravel (see Table3-18). Also provided in the study were inventory data on asphalt paving, and maintenance in 50 years time span (Hakkinen and Makela 1996). Those data are not used in this model, for materials recipe in the VTT's study was fixed (see Table3-19), and details of some processes and machinery in use were not stated.

Table 3-18 Inventory Data for Materials Production (VTT)

	Emission to air								Discharge to water			Solid waste	Energy	
	CO_2	SO_2	NOx	CO	VOC	CH_4	Heavy metals	Particles	COD	Oil	N-total		Fossil fuel	Electricity
Unit	g/kg												MJ/kg	
SMA	51	0.19	0.41	0.043	0.17	0.044	9.2E-06	0.052	0.0062		0.00031	0.011	0.78	0.061
Asphalt concrete	43	0.18	0.34	0.036	0.13	0.035	8.6E-06	0.044	0.0044		0.00022	0.010	0.68	0.039
Bitumen	330	0.8	2.9	0.1	2.0			0.3	0.1	0.03	0.005	1.9	6.0	
Crushed stone	2.0	0.0065	0.012	0.0025	0.0047	0.0043	0.21E-06	0.0019					0.011	0.041
Gravel	1.7	0.0018	0.014	0.0031	0.0026	0.0017	0.43E-06	0.0027				0.003	0.0024	

Table 3-19 Asphalt Recipe (VTT)

%	Bitumen	Aggregates, of which			Cellulose Fibre
		Crushed stone	Sand	Limestone filler	
SMA	6.2	88.8		4.7	0.3
Asphalt concrete	4.4	90.8	4.8		

3.2.5. Inventory Results

In the 'inventory results' worksheet, inventory data in 'energy and emissions inventory' are aggregated into the unit of the pavement object, based on the workloads calculated from 'pavement parameters' (for materials tonnage and pavement area) and 'process parameters' (for transport distance). The results can be grouped into 'materials production', 'transport' and 'materials placement'. At the end of the worksheet is the total of each environmental input (e.g. energy, aggregates) and outputs (e.g. CO_2, PM) in that pavement object. If needed, the percentage that each process contributes to the total can be presented.

Table 3-20 Process Groups in Inventory Results (selected)

Materials Production	Natural aggregates Recycled aggregates (specify) Bitumen Emulsion/Foamed bitumen Hot mix asphalt Cold mix asphalt
Transport	Aggregates to asphalt plant Bitumen to asphalt/emulsion plant Emulsion to asphalt plant Asphalt to road site Emulsion to road site RAP to asphalt plant (ex-situ recycling)
Materials Placement	Planing Applying tack coat Paving Rolling Remixing/Repaving (cold in-situ recycling)

3.2.6. Life Cycle Impact Assessment (LCIA)

Energy, emissions and solid waste measured in mega joules, grams or tonnes do not tell how the human or natural environment is affected by these loadings. Also, information users normally want the meaning rather than reading the list of chemicals quantities from the inventory (Mundy 2006). This requires a method that can compile and interpret the inventory results, in a consistent and recognised way for decision-making. The life cycle impact assessment is able to perform such a function. It consists of both mandatory and optional elements as specified in ISO 14040.

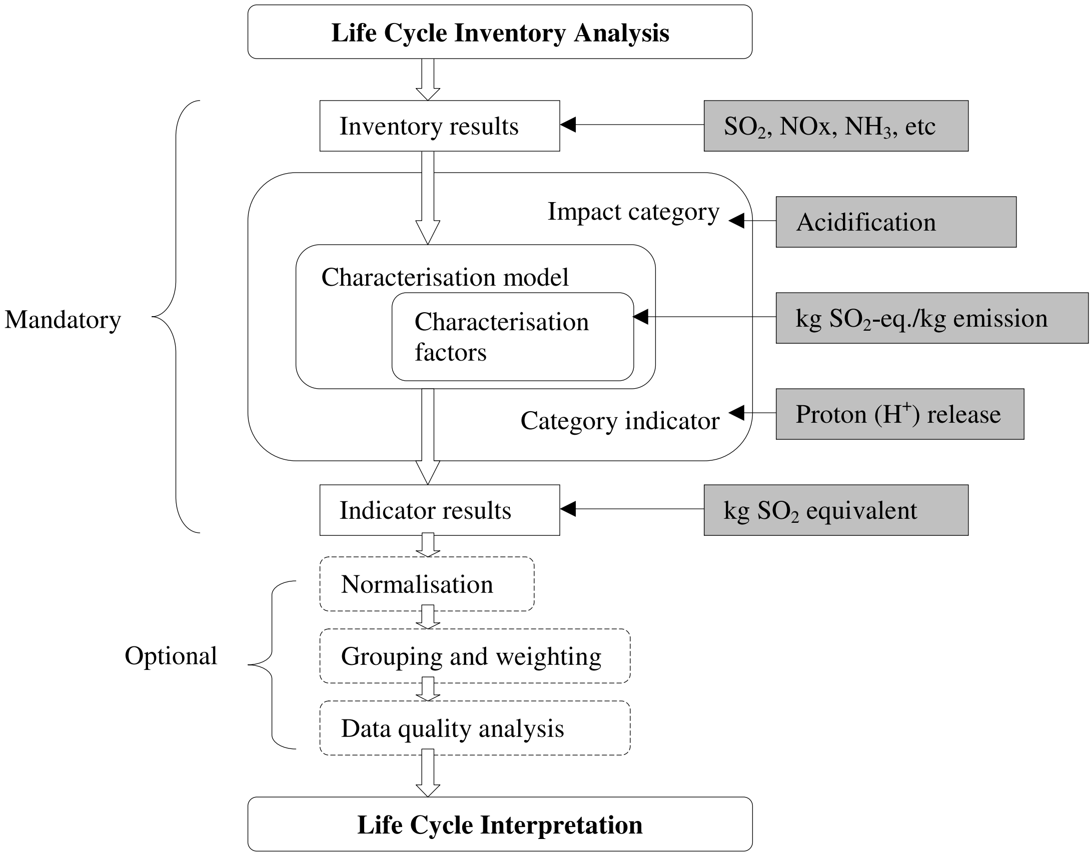


Figure 3-12 Procedures for Life Cycle Impact Assessment (Acidification for example)

3.2.6.1. Mandatory Phases

A consensus was recently formed around 6 key impact areas within the UK asphalt industry, based on the findings of a review workshop set up by the RBA, QPA and the Highways Agency, and published by the TRL (TRL 2005). The 1999 Gothenburg Protocol simultaneously addressed acidification, eutrophication and ground-level ozone by setting emission ceilings for 2010 on four pollutants: sulphur, NO_x, VOCs and NH_3 (UNECE 1999). SO_2, PM_{10}, NOx, CO and lead are defined in 1997 by Department of Environment as the air quality strategy pollutants (NAEI 2005). Based on the review of existing LCIA methods (Pennington, Potting et al. 2004), and the methods recommended by BRE and ISO standard (Howard, Edwards et al. 1999; ISO 14047 2003), a group of impact categories are selected for use in this model, alongside are presented the available or selected assessment method (characterisation model and characterisation factor).

Table 3-21 Methodology for LCIA[7]

Impact Category	**Characterisation Model**	**Category Indicator**	**Characterisation Factor**
Depletion of minerals			tonne aggregates/bitumen
Depletion of fossil fuels			TOE (tonnes of oil equivalent)[1]
Global warming[2]	IPCC model	Increase of infrared radiative forcing (W/m^2)	kg CO_2-eq./kg emission (kg CO_2 equivalent per kg emission)
Stratospheric ozone depletion	WMO model	Increase of stratospheric ozone breakdown	kg CFC_{11}-eq./kg emission
Acidification	IIASA model: RAINS	Release of hydrogen ion (H^+)	kg SO_2-eq./kg emission
Photo oxidant (ground-level ozone) formation	CML model[3]	Increase of tropospheric ozone formation	kg C_2H_4-eq./kg emission
Human toxicity	CML model[4]	Predicted daily intake	kg 1,4-dichlorobenzene-eq./kg emission
Eco-toxicity	CML model	Predicted concentration	kg 1,4-dichlorobenzene-eq./kg emission
Eutrophication	CML model	Deposition of N/P equivalent in biomass	kg PO_4-eq./kg emission
Noise[5]	SAEFL model	Health impairment	Disability adjusted life years (DALY)
Depletion of landfill space			m^3 landfill space

Notes:

1. 1 TOE = 41868 MJ (Howard, Edwards et al. 1999).
2. GWP_{100}: global warming potential with a time horizon of 100 years.
3. Another recognised model is the UNECE model: EMEP.
4. Another recognised model is the RIVM model: USES4.0.
5. Current European Directive 2001/43/EC (relating to tyres for motor vehicles, their trailers and fitting) is considered not strict enough for the tyre industry to limit tyre noise on the road (Prof 2007).

The selection of impact categories needs to consider also the availability of inventory data. Some pollutants (e.g. CO_2) are present in only one impact category; others (e.g. SO_2) may contribute to more than one impact category. There is a difference in

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[7] IPCC: Intergovernmental Panel on Climate Change; WMO: World Meteorological Organisation; IIASA: International Institute of Applied System Analysis; RAINS: Regional Air Information and Simulation; CML: Institute of Environmental Sciences, Leiden University; UNECE: United Nations Economic Commission for Europe; EMEP: Convention on Long-range Transboundary air pollution; RIVM: National Institute for Public Health and the Environment; USES: Uniform System for the Evaluation of Substances; SAFEL: Swiss Agency for the Environment, Forests and Landscape; DALY: Disability Affected Life Years.

pollutant concentration at the endpoint if the pollutant goes through a serial process or a parallel one (ISO 14047 2003). As the mechanism for allocating pollutants to parallel processes is unknown, substances in this model are allocated in their full amount to relevant categories as if they all go through the serial processes. Similarly, the characterised results of an impact category (e.g. Global Warming) may come from two or more pollutants (see Figure3-13, air emissions inventory taken as an example).

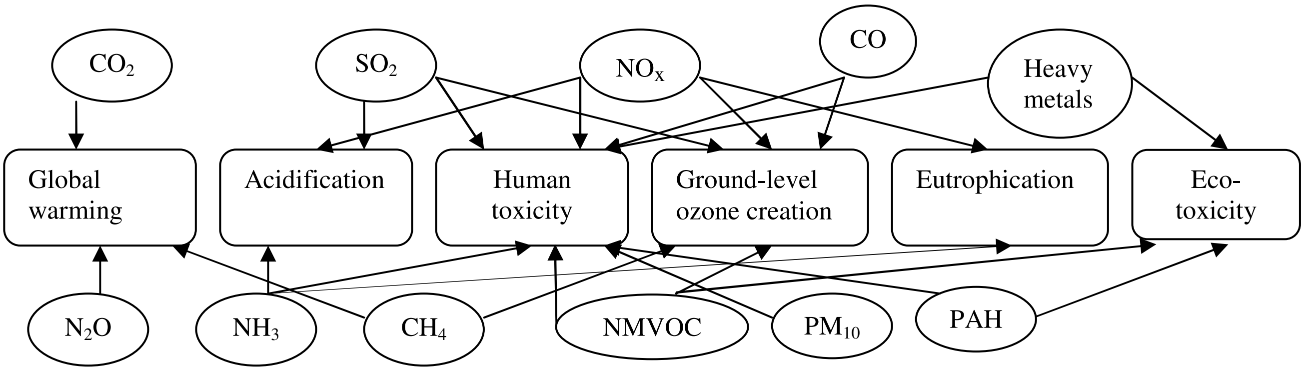

Figure 3-13 Assignment of Inventory Results (Classification)

The inventory loadings assigned to an impact category need to be characterised, by converting them to equivalents of indicator for that category. The characterisation factors in a category indicate the ‘severity’ of an emission to that category.

Table 3-22 Characterisation Factors for Emissions

Impact Category		Emissions	Characterisation Factor	Quantity	Source
Global warming		CO_2	kg CO_2-eq. (100yrs)	1	IPCC (IPCC 2001)
		N_2O		23	
		CH_4		296	
Stratospheric ozone depletion[1]			kg CFC_{11}-eq.		WMO (WMO 2006)
Acidification		SO_2	kg SO_2-eq.	1	IIASA (Huijbregts, Schopp et al. 2000) (BRE)
		NO_x		1.07 (0.7)[2]	
		NH_3		1.88	
Photo oxidant (ground-level ozone) formation		SO_2	kg C_2H_4-eq.	0.048	CML (CML 2004)
		NO_x		-0.427 (0.028)[2]	
		CO		0.027	
		CH_4		0.006	
		NMVOC		1.0	
Human toxicity	Emission to air	SO_2	kg 1,4-dichlorobenzene-eq.	0.096	CML (CML 2004)
		NO_x		1.2	
		CO		2.4	
		HC[3]		5.7E+05	
		NMVOC		0.64	
		PM_{10}		0.82	
		NH_3		0.1	
		Heavy metals[4]		5.1E+05	
	Emission to fresh water	HC[3]		2.8E+05	
		Heavy metals[4]		2.4E+03	
Eco-toxicity[5]	Emission to air	NMVOC	kg 1,4-dichlorobenzene-eq.	3.2E-11	CML (CML 2004)
		HC[3]		1480	
		Heavy metals[4]		8.6E+05	
	Emission to fresh water	HC[3]		1.1E+04	
		Heavy metals[4]		1.9E+05	
Eutrophication		NO_x	kg PO_4-eq.	0.2 (0.13)[2]	CML (CML 2004)
		NH_3		0.35	
		COD		0.022	
		Phosphate		1	
		Nitrate		0.1	
Noise		Noise/1000 vehicle*km	DALY	1.3(26)E-03[6]	SAEFL (Muller-Wenk 2002)

Notes:

1. The main ozone depletion substances (CFCs, Halons, CCl_4, CH_3CCl_3, HCFCs, CH_3Br) identified by WMO are not quantified in emissions inventory.
2. Figure in the bracket is for NO_2 and is used in this model as for NOx; figure out of the bracket is for NO.
3. Figure for carcinogenic PAH (polycyclic aromatic hydrocarbons).
4. Figure for the total of As, Cd, Hg and Pb.
5. Figures in Eco-toxicity are the mean characterisation factor of ‘freshwater aquatic eco-toxicity’, ‘marine aquatic eco-toxicity’ and ‘terrestrial eco-toxicity’.

6. Figure in the bracket is for night-time (10pm-6am) journey (sleep disturbance); figure outside the bracket is for daytime (6am-10pm) journey (communication disturbance). As for comparison, the DALY of truck emissions (CO, NOx, HC and PM_{10}) per 1000 vehicle kilometre is 1.14E-03. If the time of the day of the transport is unknown, a day/night time split of 95:5 is assumed. If the road traffic data are provided in the unit of tonne*kilometre, the following loading factors are assumed for conversion: 3.8tonne for a 16tonne truck, 7.0tonne for a 26tonne truck and 10.8tonne for a 40tonne truck (Muller-Wenk 1999).

The characterised result for an impact category is the total of all the individually characterised loadings allocated to that category. For example, in an inventory in which the SO_2, N_2O, CH_4 and CO_2 loadings are 25g, 17g, 4g and 520g, respectively, the characterised result (category indicator result) for ‘Global Warming’ (N_2O, CH_4 and CO_2 have a contribution) will be 17x23 + 4x296 + 520x1 = 1503g CO_2 equivalent.

$$Characterisation\mathrm{Re}\,sult = \sum_i Loading_i \times CharacterisationFactor_i$$

There are LCI loadings that have not been assigned to, and characterised in, any of the impact categories. Impact assessment of these loadings is expected in light of on-going development of environmental assessment techniques (the LCIA method). Most emissions to water (except HC and heavy metals) are of this type.

3.2.6.2. Optional Phases

In normalisation, the characterisation result of an impact category is divided by a reference value, which normally is the total input or output per UK capita. This model uses the latest data that can be sourced from literatures.

Table 3-23 Normalisation Factors

Impact Category	**Indicator Result**	**UK Total**	**Year**	**Data Source**	**Per UK Capita**
Depletion of minerals	Aggregates	214 Mt	2004	QPA (QPA 2007)	
Depletion of fossil fuels	TOE	246,884 TOE	2005	DTI (DTI 2006)	
Global warming	CO_2	559.223 Mt	2004	NAEI (NAEI 2006)	
Stratospheric ozone depletion	CFC_{11}	88,000 t[1]	2003	WMO (WMO 2006)	
Acidification	SO_2	979 t	2003	NAEI (NAEI 2005)	
Photo oxidant (ground-level ozone) formation	NMVOC (replace C_2H_4)[2]	1089 t	2003	NAEI (NAEI 2005)	
Human toxicity	NH_3 (replace 1,4-Dichlorobenzene)[2]	300 t	2003	NAEI (NAEI 2005)	
Eco-toxicity	Heavy metals (replace 1,4-Dichlorobenzene)[2]	339.479 t[3]	2001	EA (EA 2004)	
Eutrophication	NOx (replace PO_4)[2]	1570 t	2003	NAEI (NAEI 2005)	
Noise	DALY	499.4 billion vehicle*km	2005	DfT (DfT 2006)	
Depletion of landfill space	Landfill disposal	75 Mt[4]	2002	EA (The Environmental Agency 2007)	
UK Population		60,209,500	2005	ONS (Office of National Statistics 2007)	

Notes:

1. Global figure.

2. UK total emissions of C_2H_4 and PO_4 are difficult to obtain. Therefore, in LCIA where the normalisation phase is needed, NMVOC and NO_x are appointed instead as the indicator for ‘ground-level ozone formation’ and ‘eutrophication’, respectively. Characterised result presented as C_2H_4-equivalent and PO_4-equivalent is then converted, using the characterisation factor in that impact category, into NMVOC-equivalent and NOx-equivalent, respectively. For the same reason, NH_3 and Heavy Metals are used to replace 1,4-Dichlorobenzene as the indicator for ‘human toxicity’ and ‘eco-toxicity’, respectively.

3. Same as in the model, data on heavy metals refer to the total of As, Cd, Hg and Pb, the data on which are presented below:

Table 3-24 UK Total of Heavy Metals to Air and Water (The Environmental Agency 2004)

(Unit: tonne)

	Arsenic	Cadmium	Mercury	Lead	Total
Emission to air	N/A	5.070	8.820	194.000	207.89
Release to water	110.560	1.074	19.710	0.245	131.589
Total	110.560	6.144	28.530	194.245	**339.479**

4. Total tonnage of waste sent to landfill.

There is no scientific basis for presenting the LCA results with a single number (ISO 14044 2006). A consensus between all levels of decision makers within an industrial sector is normally needed for further assessment of normalisation/characterisation results. This model proposes a grouping and weighting method as in the table and figure below, in accordance with the 'Eco-points' developed by BRE through an expert panel for the UK construction industry (Dickie and Howard 2000). However, it should be noted that the weighting is not recommended by standards for use in comparative LCA study (ISO 14044 2006).

Table 3-25 Grouping and Weighting for Environmental Impact Categories

Impact Category	**Impact Area**	**Weighting (%)**
Depletion of minerals	Regional	3
Depletion of fossil fuels	Regional	11
Global warming	Global	35
Stratospheric ozone depletion	Global	8
Acidification	Regional	5
Ground-level ozone formation (fog)	Regional	3.5
Human toxicity	Local	8.5
Eco-toxicity	Local	4
Eutrophication	Regional	4
Noise	Local	
Depletion of landfill space	Regional	6
Others	Water, Freight	12
Total		**100**

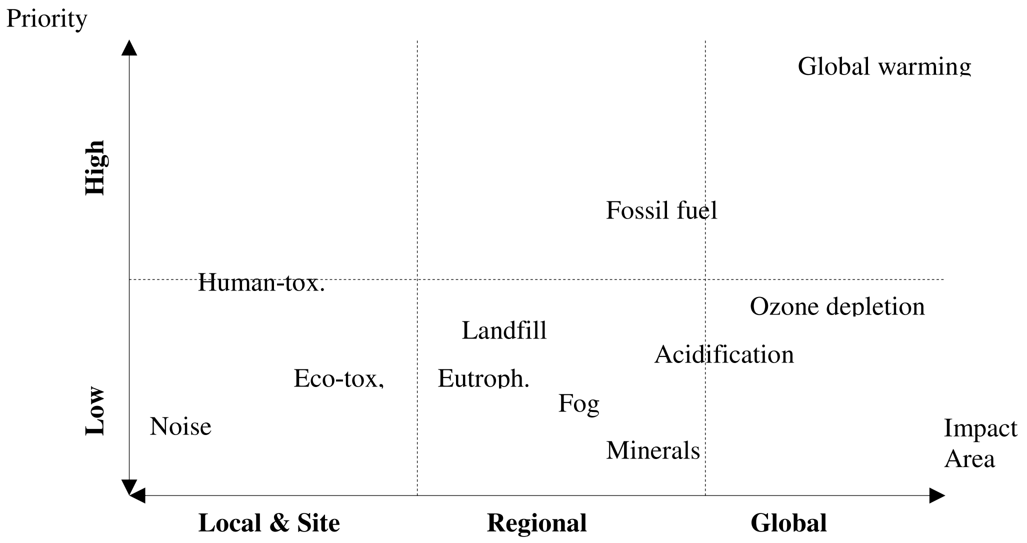

Figure 3-14 Grouping and Weighting for Environmental Impact Categories

Results of sensitivity analysis can be used to identify and, if needed, exclude life cycle stages or unit processes from the system that are demonstrated to have low significance to the LCA results. Also identified, is the significance of the many environmental impacts in a LCA study. The system boundary, or even the goal and scope, of the LCA study can then be refined based on these results (see Figure3-10).

3.3. Summary of LCA Model Development

This Chapter outlines the unit processes in the construction and maintenance of asphalt pavements; waste glass is given as an example of secondary aggregates in the practice. An Excel spreadsheet is built up as the computing tool for the LCA model. Case study of a real project will therefore be able to map the materials and processes to the units in this model, and replace default numbers in the spreadsheet with data specific to that project. Amends to the model and/or the spreadsheet will be made in each individual study to meet the particulars of that project, as shown in the case studies in Chapter4.

Chapter 4 : Case Study

A couple of case studies were carried out during the development of this LCA model, to 1) test the model's completeness and its ability to represent the environmental loadings in a real asphalt pavement project, 2) identify the significant elements in a pavement project and assess their sensitivity to the input variables, and 3) build up the scope and database of the model for further development.

Two projects were selected for analysis: a road inlay at Wolverhampton, and asphalt paving on an access road at London Heathrow Terminal 5 (LHR T5). Data in both studies came from site engineers from Aggregate Industries UK Ltd (AI). The case studies are presented the way they were first written, as a progress log of this LCA model. The road inlay was a simple exercise that built up the LCA framework and mechanism for data collection. The LHR T5 study went into more depth of the road project, and developed the LCA model into a more complex as well as flexible computing tool. Both case studies were supported by site visit and questionnaire (see Appendix1 and Appendix2). Lessons learned from the first case study were applied in the second one. Findings of both case studies are discussed separately. At the end of this Chapter is a discussion that compares the methodology and outcomes of the two case studies, indicating how the LCA model was improved during the progress.

4.1. Road Inlay at Chapel Ash, Wolverhampton

4.1.1. Project Background

From 16 January to 01 February 2005, Aggregate Industries UK Ltd supplied and laid materials replacing the asphalt surface and binder course on an urban junction at Chapel Ash, Wolverhampton. This case study investigated, using LCA, the environmental impacts of the process proposed by AI using company branded asphalt products (Bardon Superflex14), and made a comparison with the original thicker pavement and materials option proposed by Wolverhampton City Council (WCC). This case study described the analysing process and results, and provided advice on what measures can be taken to reduce the environmental impacts of the inlay process.

It used the collective findings of previous work and, where available, the real on-site data from the contractors. The LCA report was submitted on 02 November 2005 to Aggregate Industries UK Ltd (Huang and Bird 2005; Huang, Bird et al. 2006).

4.1.2. Process Analysis, Scope and Assumptions

The life time of asphalt pavement projects can be defined containing the following processes:

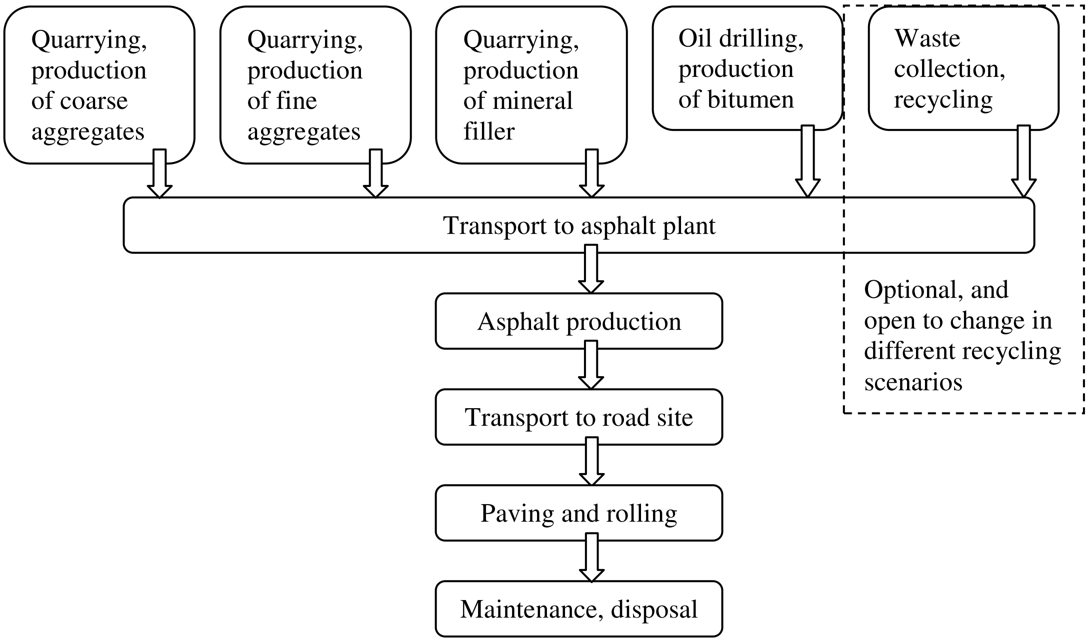

Figure 4-1 Life Time Processes of Asphalt Pavements

For each unit in the flowchart, the data on materials and energy that contribute to the Life Cycle Inventory (LCI) were as follows:

- Input: minerals, energy, water;
- Output: emissions to air, discharge to water, solid waste.

The normal processes and machinery commonly used in minerals quarrying are described by Quarry Products Association (QPA). Processes not specific to this project (e.g. restoration after quarrying) were not included in this LCA study. Bitumen is one of the many co-products of the oil refining industry (Shell 2005). Environmental burdens can be allocated between these products on a pre-defined basis: by volume of the product (ISO 14041 1998).

Table 4-1 Average Yields of Main Products from Crude Oil Refinery (API 2002)

Product	LPG	Gasoline (petrol)	Kerosene (jet fuel)	Diesel (gas oil)	Industrial fuel oil	Lubricating oil and wax	Coke	Bitumen	Others	Total
Yield (%)	4.5	46.2	10.7	23.1	4.5	1.2	4.8	3.3	1.7	100

The type and amount of work prior to paving fresh asphalt materials depends on how the existing pavement surface is disposed. In this project, tack coat was applied after the top 100mm had been removed by cold planing. In alternative scenarios, recycling for instance, scarified pavement materials might be recycled in-situ, or taken off-site for processing at an asphalt plant.

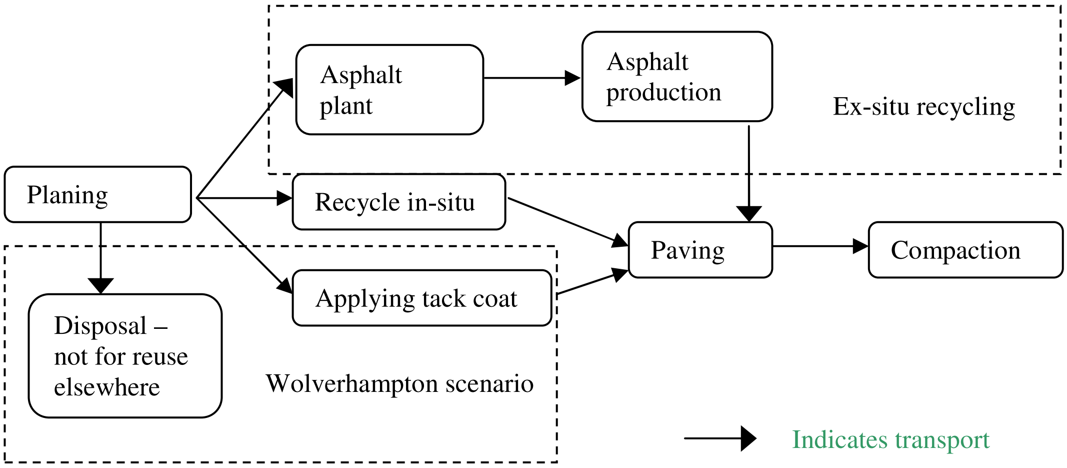

Figure 4-2 Disposal of Existing Pavement Surface

The two-step (Classification, Characterization) 'Environmental Problems' approach developed by CML (Institute of Environmental Sciences, Leiden University, the Netherlands) and SETAC (The Society for Ecological Toxicology and Chemistry, US) in the early 1990s for life cycle impact assessment (LCIA) was adopted by the ISO 14040 standards. This case study followed this approach. The methodology of 'BRE Environmental Profiles' also fits well with the ISO standards (Howard, Edwards et al. 1999). The scope and assumptions made in this LCA study are specified below:

Table 4-2 Scope and Assumptions in LCA of Wolverhampton Project

Inventory data	
Source and quality of data	AI, supplemented by industry average
Temporal coverage	See '**Project Background**'
Geographic coverage	See '**Project Background**'
Technical coverage	See **Table4,5** below
Product systems	AI proposal vs. Wolverhampton CC proposal
System boundary	Construction + in-service period
Functional unit	10,150m^2 of asphalt surface for 1 year's service
Allocation procedure	ISO 14040 and BRE allocation principle
Recycling	No recycling or use of recycled materials
Method of impact assessment	CML-SETAC-BRE methodology
Format of report	BRE format

4.1.3. Life Cycle Inventory Analysis

4.1.3.1. Procedure for Establishing the Inventory

Based on the BRE's Inventory Data Handling Checklist, the steps below were followed to establish the life cycle inventory:

1) Define the principal product(s);
2) Collect data from unit processes or defined process groups, and aggregate them;
3) Allocate the data to principal product(s);
4) Convert, where needed, the data to standard units (SI);
5) Divide the data by the principal product(s) in tonnes to obtain *per tonne* data.

4.1.3.2. Environmental Impacts for Analysis

According to the IVL's and VTT's research (Mroueh, Eskola et al. 2001; Stripple 2005), the environmental impacts of road construction for LCA case study can be limited to a few categories:

- Use of aggregates (virgin, secondary) and bitumen;
- Energy (gas, diesel, electricity, etc) consumption;
- Atmospheric emissions: CO_2, CH_4, NO_x, SO_2, N_2O, VOC, TOC, CO, HC, PM, etc;
- Leaching into soil and water (surface, ground, marine): heavy metals, chloride, sulphate, BOD, COD, N-total, HC, oil, etc;
- Others: noise, dust, land use, solid waste, etc.

The reasons for excluding other than the above environmental impacts were either the significance of those loadings was low, or the relevant data were not sufficient for further analysis (Mroueh, Eskola et al. 2001). If a different construction process is involved, (e.g. recycled rather than virgin aggregates only, maintenance rather than new construction), the category list would be expected to change.

Table 4-3 Emission Factors for Energy Production and Use (Howard, Edwards et al. 1999)

Grams/MJ	CO_2	CH_4	NO_x	N_2O	SO_2	VOC	CO	PM_{10}
LPG	67.81	0.019	0.092	0.00009	0.014	0.0656	0.0069	0.0030
Gasoline	74.23	0.021	0.088	0.00003	0.048	0.0702	0.0116	0.0058
Diesel	76.70	0.021	0.091	0.00059	0.107	0.0702	0.0117	0.0070
Electricity	150.4	0.404	0.422	0.00558	1.234	0.0175	0.1665	0.0328
Natural gas	53.88	0.112	0.093	0.00010	0.002	0.0090	0.0027	0.0011

4.1.3.3. Construction Parameters

The life cycle inventory is made of data presented in the tables below. This is a comparative LCA study. Unless stated otherwise, these process data were collected from contractors in charge of that process, such as the haulage companies (e.g. H&D Haulage), the construction contractors (e.g. Power Plane Ltd., HR International Crushing& Screening Ltd.) or the materials suppliers (e.g. Aggregated Industries UK Ltd).

Table 4-4 Pavement Parameters

	Pavement parameter	WCC proposal	AI proposal
	Life time expectancy	12 yrs	15 yrs
Surface course	Area	10,150m^2	10,150m^2
	Depth	40mm	40mm
	Mixture weight[1]	970t	969t
	Mixture composition (coarse:fine:filler:bitumen)	0/14mm SMA[2] 72.4:12.7:8.9:6.0	Bardon Superflex14 (64.5:23:7.6:4.9)
Binder course	Area	10,150m^2	10,150m^2
	Depth	110mm	60mm
	Mixture weight	2668t	1454t
	Mixture composition (coarse:fine:filler:bitumen)	0/20mm HDM[2] 66.7:20.0:8.6:4.7	Bardon Superflex14 (64.5:23:7.6:4.9)

Notes (assumptions):

1. The bulk density of surface course asphalt equals that of the binder course, in both proposals.

2. The materials breakdown of the surface and binder course asphalt in WCC's proposal equals the mean value in British Standard for 0/14-surface course (BS 594-1 2003) and 0/20-binder course (BS 4987-1 2003), respectively.

3. The weight of planed pavement materials equals that of the compacted fresh materials, in both proposals.

Table 4-5 Process and Machinery Parameters

Process		Make& Model	Operating capacity	Engine power	Work load (AI proposal)
Lorry transport	Bitumen to asphalt plant	Volvo FM12	28t*(56mph)	_340-460hp_	293.1Km*118.7t
	Asphalt to road site	_Volvo A25D_	20t*(53Km/hr)	_300hp_	60.7Km*2423t
	Waste to disposal	Hino FY420	20t*(58mph)	420hp	14.5Km*2423t
Materials production	Excavating	Volvo EC460B	400t/hr	_306hp_	2304.3t
	Loading	Volvo L220E	400t/hr	_352hp_	2304.3t
		Volvo L330E		_502hp_	
		Cat 980G		_311hp_	
	Conveying	Volvo A40	300t/hr	_426hp_	2304.3t
		~~Cat D250~~			
	Crushing	Metso LT125	_800t/hr_	_430hp_	2304.3t
		~~Mesto HP300~~		300hp	
		~~Mesto HP500~~		500hp	
	Screening	~~Mesto ST356~~		148hp	2304.3t
		HRI	250t/hr	45kw	
	Asphalt mixing	Benninghoven	16t/76kw		2423t
Road laying	Planing	Wirtgen2.2	_2.2m*(5Km/hr)_	_800hp_	10,150m^2
	Paving	ABG Titan273	_(40m/min)*7.5m_	_152hp_	2 pass*10,150m^2
	Rolling	Bomag BW161 AC-4 (8-10t)	1.68m*4.96Km/hr	_99hp_	6 pass*10,150m^2
		Hamm HW90B (8.8-11t)	79in*4.96Km/hr	_74hp_	6 pass*10,150m^2

Notes:

1. Aggregates for this project were quarried and processed from the same plant.

2. In the case that 'project specific' data are not available, data on 'operating capacity' and 'engine power' were obtained, based on the knowledge of 'make& model', from the manufacturers' (e.g. Volvo, Wirtgen) product brochures, and shown in italic in the table. If a machine's operating parameters were not available from any sources, it was excluded from this LCA study (crossed out in the table). The average figure was used

for a process if machines of multiple make and/or model were used in that process (shaded in the table).

(Assumptions made in the table):

3. The original WCC proposal was not put into practice. The transport distance and vehicles in that proposal were assumed identical to those in the AI proposal, had the materials supply been won by AI for that proposal.

4. Transport vehicles were run at ‘maximum load’, ‘full legal speed’ and ‘empty on return’. Road planer, paver and roller were run at ‘full speed’ and ‘full working width’.

4.1.3.4. Calculation and Establishment of the Life Cycle Inventory

This study used EAPA’s LCI data on bitumen production in which the environmental loadings were allocated among the refinery products: 40% to bitumen and 60% to lighter products (Eurobitume 1999).

Table 4-6 Eco-profile of PG50/70 Bitumen Production

Inventory for straight run PG50/70 bitumen production	Energy (MJ/kg)			Air emissions (g/kg)				
	Diesel	Gas	Electricity	CO_2	NO_x	SO_2	CO	PM_{10}
	1.008	3.252	0.173	280	2.10	1.80	0.14	0.22

Energy use (fuel consumption) was then calculated based on the operating capacity, the engine power, the work load, and assumptions made in the tables above. Other environmental inputs and outputs were also calculated. The scope of this inventory was determined by the available data from Wolverhampton contractors and the BRE’s database.

Table 4-7 Summary of Energy Consumption and Solid Waste

		WCC proposal			AI proposal		
Process		Energy use(GJ)	Percent	Solid waste	Energy use(GJ)	Percent	Solid waste
Manufacture	Aggregates	36.28	2.49%	N/A	24.33	2.73%	N/A
	Bitumen	899.90	61.89%		526.33	58.99%	
	Mixing	62.21	4.28%		41.43	4.64%	
Transport	Bitumen to asphalt plant	50.71	3.49%	N/A	29.66	3.32%	N/A
	Asphalt to road site	335.78	23.09%		222.64	24.95%	
	Waste to storage	63.87	4.39%		42.54	4.77%	
Placement	Planing	1.98	0.14%	3638t	1.98	0.22%	2423t
	Paving	0.13	0.01%	N/A	0.13	0.01%	N/A
	Rolling	3.16	0.22%		3.16	0.35%	
Total		1454.00	100%	3638t	892.19	100%	2423t

Table 4-8 Inventory Data of Wolverhampton Project

		WCC proposal		**AI proposal**		**Saving**	
Life expectancy (yr)		12		15		-25%	
		1	**2***	**1**	**2^***	**1**	**2**
INPUT							
Mineral (t)	Stone	2091.90	174.33	1562.84	104.19	25.3%	40.2%
	Sand	1033.15	86.10	574.25	38.28	44.4%	55.5%
	Filler	309.96	25.83	184.15	12.28	40.6%	52.5%
	Total	3435.00	286.25	2321.23	154.75	32.4%	45.9%
Bitumen (t)		203.00	16.92	118.73	7.92	41.5%	53.2%
Energy (GJ)	Diesel	696.53	58.04	444.12	29.61	36.2%	49.0%
	Gas	660.14	55.01	386.10	25.74	41.5%	53.2%
	Electricity	97.33	8.11	61.97	4.13	36.3%	49.1%
	Total	1454.00	121.16	892.19	59.48	38.6%	50.9%
OUTPUT							
Emissions to air (kg)	CO_2	103.63E+03	8.64E+03	64.19E+03	4.28E+03	38.0%	50.4%
	CH_4	127.88	10.66	77.61	5.17	39.3%	51.4%
	NO_x	165.85	13.82	102.47	6.83	38.2%	50.6%
	SO_2	195.95	16.33	124.76	8.32	36.3%	49.0%
	N_2O	1.02	0.09	0.65	0.04	36.6%	49.3%
	VOC	56.54	4.71	35.74	2.38	36.8%	49.4%
	CO	26.14	2.18	16.56	1.10	36.7%	49.3%
	PM_{10}	8.79	0.73	5.57	0.37	36.7%	49.4%
Solid waste (t)	Pavement materials	3638	303.167	2423	161.533	33.4%	46.7%

Note:

Figure in Column **2** is the result of dividing Column **1** figure by life expectancy.

4.1.4. Life Cycle Impact Assessment (LCIA)

4.1.4.1. LCIA methodology

A summary of the impact categories and characterisation methods is shown in Table4-9. It takes into account the selections by ISO standard (ISO 14047 2003), BRE (Howard, Edwards et al. 1999), and review of LCIA by Nordic countries (Pennington, Potting et al. 2004).

Table 4-9 Methodology for Life Cycle Impact Assessment

Impact Category	Characterization Model	Category Indicator	Characterization Factor
Depletion of mineral resources		Quantity of minerals consumed	Inventory of Depletion Potential (DP) for extraction: DP/kg extraction
Fossil fuel depletion		Quantity of energy consumed	Tonnes of oil equivalent (TOE)
Global warming (climate change)	IPCC (Intergovernmental Panel on Climate Change) Model	Increase of infrared radiative forcing (IRF) (W/m^2)	GWP_{100} (Global Warming Potential for time horizon of 100 years) for each GHG (greenhouse gas) emission: kg CO_2-eq./kg emission
Acidification	IIASA (International Institute of Applied System Analysis) Model: RAINS (Regional Air Information and Simulation)	Hydrogen ion (H^+) release	Acidification Potential (AP) for each acidifying emission to air and water: kg SO_2-eq./kg emission
Stratospheric ozone depletion	WMO (World Meteorological Organization) Model	Increase of stratospheric ozone breakdown	Ozone Depletion Potential (ODP) for each emission: kg Chlorofluorocarbons (CFC)-11-eq./kg emission
Photo-oxidant (-chemical) formation (low level ozone creation)	UNECE (United Nations Economic Commission for Europe) Trajectory Model	Increase of tropospheric ozone formation	Photochemical Ozone Creation Potential (POCP) for each toxic emission to air: kg ethylene (C_2H_4)-eq./kg emission
Aquatic eutrophication	Stoichiometric procedure	Deposition of N/P equivalent in biomass	Relative carbon/nitrogen/phosphorous ratio (the Redfield C/N/P = 106:16:1)
Terrestrial eutrophication			Eutrophication Potential (EP) for each eutrophicating emission: kg nitrogen oxide (NO_x)-eq./kg emission
Human toxic effect	RIVM (National Institute for Public Health and the Environment, the Netherlands) Model: USES2.0 (Uniform System for the Evaluation of Substances)	Predicted daily intake	Disability-Affected Life Years (DALYs) for each toxic emission: DALYs/kg emission
Eco-toxic effect		Predicted environmental concentration	Ecotoxicity Potential (ETP) for each toxic emission: kg 1,4 dichlorobenzene-eq./kg emission
Land use		Land occupation or transformation	Units of area multiplied by time (m^2*yr) for land occupation; units of area (m^2) for land transformation
Others (odour, noise, etc)			DALYs per unit
Solid waste		Quantity of solid waste generated	

Characterised results are shown in the table below.

Table 4-10 Characterisation Results

Impact category	Environmental loading			Characterisation factor (CF)	Characterised results	
	Loading (kg)	Inventory figure				
		WCC	AI		WCC	AI
Climate change				**kg CO_2-eq. (100yrs)**		
Source: IPCC2001	CO_2	8.64E+03	4.28E+03	1	8.91E+03	4.41E+03
	CH_4	10.65	5.17	23		
	N_2O	0.09	0.04	296		
Acidification				**kg SO_2-eq.**		
Source: CML2002	SO_2	16.33	8.32	1	26.00	13.10
	NO_x	13.82	6.83	0.7[1]		
Low-level ozone creation				**kg C_2H_4-eq.**		
Source: CML2002	SO_2	16.33	8.32	0.048	5.66	2.86
	CO	2.18	1.10	0.04		
	VOC	4.71	2.38	1.0		
	CH_4	10.65	5.17	0.007		
Eutrophication				**kg PO_4-eq.**		
Source: CML2002	NO_x	13.63	6.74	0.13[2]	1.84	0.91
Human toxicity				**kg 1,4-dichlorobenzene-eq**		
Source: CML2002	PM_{10}	0.73	0.37	0.82	21.76	10.82
	NO_x	13.82	6.83	1.2		
	SO_2	16.33	8.32	0.096		
	VOC	4.71	2.38	0.64		

Notes:

1. Acidification CF for NO and NO_2 is 1.07 and 0.7, respectively.
2. Eutrophication CF for NO and NO_2 is 0.2 and 0.13, respectively.

Research is carried out by BRE to provide a consistent weighting for those impact categories addressed in LCIA, based on the broad agreement between expert panels within the construction industry. The results of environmental assessment of different activities and impacts might by this means, be compared to one another, and presented by a single score named ‘Ecopoints’ (Dickie and Howard 2000).

4.1.4.2. Calculating and Presenting LCIA Results

The selection of categories for impact assessment in this study was limited by the inventory data (Table4-8). In the ‘emissions to air’ inventory, some pollutants (e.g. SO_2) contribute to more than one impact category in LCIA (parallel processes). The substance in that case was allocated in its full amount to these categories as if it goes through the serial processes (ISO 14047 2003). Similarly, the characterised result of an impact category (e.g. global warming) may come from two or more pollutants.

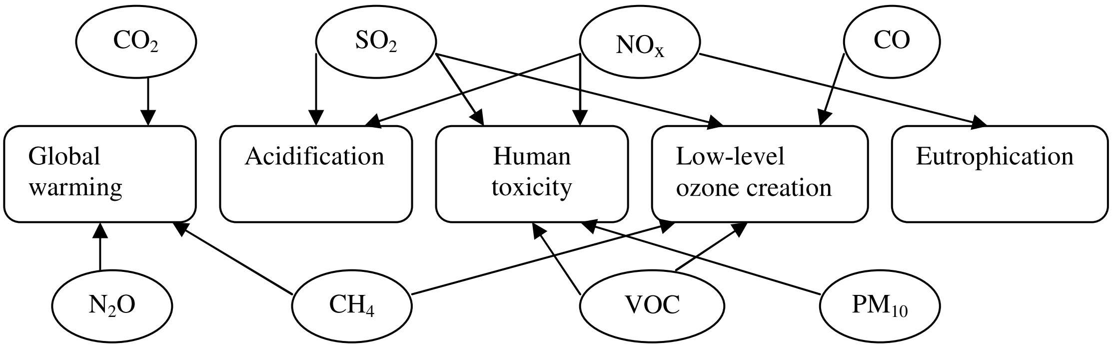

Figure 4-3 Assignment of LCI Results

Table 4-11 LCIA Results of Wolverhampton Project

Impact category		**Units**	**WCC proposal**	**AI proposal**	**Saving**
Depletion of minerals	Quarrying products	Tonne	286.25	154.75	45.9%
	Bitumen	Tonne	16.92	7.92	53.2%
Energy consumption		GJ	121.16	59.48	50.9%
Global warming		kg CO_2-eq. (100yrs)	8.91E+03	4.41E+03	50.5%
Acidification		kg SO_2-eq.	26.00	13.10	49.6%
Low-level ozone creation		kg C_2H_4-eq.	5.66	2.86	49.4%
Eutrophication		kg PO_4-eq.	1.84	0.91	50.6%
Human toxicity		kg 1,4-dichlorobenzene-eq	21.76	10.82	50.3%
Solid waste generation		Tonne	303.17	161.53	46.7%

4.1.5. Discussion

The use of Bardon Superflex14 in Wolverhampton inlay project reduced the asphalt input by 1/3, and the energy use by nearly 40%. (Table4-8) ‘Bitumen production’ and ‘transport asphalt to site’ stood as the energy intensive processes in the project, representing about 59% and 25%, respectively, of the total energy required (Table4-7). As a number of key emissions are correlated with energy consumption (Table4-3), asphalt of low bitumen content and in-situ recycling seem therefore more beneficial by environmental means. From a technical point of view however, the surface quality (e.g. skid resistance) and durability of the asphalt shall not be compromised as a result.

A number of process parameters in the two proposals were assumed to be the same in this study, making the two proposals differ basically in the quantity of materials in use. This is reflected in the LCI and LCIA results (Table4-8 and Table4-11). This study did not deal with non-energy related environmental burdens. Rather, it identified mainly the energy use through the project processes, and calculated the associated emissions using BRE's Emissions Factors database (Table4-3). Availability of data inhibited the otherwise more comprehensive and accurate LCA study. A detailed environmental profile for the asphalt associated products is therefore needed. This study showed the benefits of liaising with contracting partners to identify the environmental issues involved in the project processes, and to obtain relevant data in support of a more robust analysis in the future.

For the same product or process, substantial difference can be expected in the data from different sources, which has been illustrated by other LCA studies (Zapata and Gambatese 2005). This also highlights the importance of two elements in LCA: 1) the source and quality of data and, 2) a sensitivity check for evaluation. Three issues were mentioned in the Journal Editorial as the 'classical methodological problems in LCA' (Editorial 2005). These problems were indeed encountered in this study, and highlight the need for more research to increase environment knowledge of the asphalt products and processes, and to implement the developing LCA in the road building industry.

- How to allocate environmental burdens among the products in a process;
- How and how far to interpret the LCI results; and
- How to proceed with the analysis in absence of required data.

As defined in the 'functional unit' (Table4-2), environmental loadings in this study were divided by service life (in years) of the asphalt layers. This made the difference between the two proposals more distinctive by another 11-15% in the final LCI results (Table4-8). This confirms the TRL's advice that 'design for more durable roads' represents one of the asphalt industry's best strategies towards sustainable construction (TRL 2005). It also confirms the suggestion made by SETAC that further research is needed to study the relations between service life and life time environmental effects for the building and construction sector (SETAC 2003).

4.1.6. Review

A review note was submitted by the author on 12 January 2006 to Aggregate Industries UK Ltd., in which the data source and quality, calculation techniques and assumptions made in the LCA of Wolverhampton project were reviewed (Huang and Bird 2006). The summary table (see Table4-12) is presented below. Some reasonable estimates are also made in the LCA of LHR T5 project; while flaws are learned and avoided, which include:

- Fuel consumption, measured in litre/hr or litre/km, rather than the engine power, should be used to measure the energy consumption of transport vehicles and construction equipment;
- For a process, data from different sources need to be compared, and the most appropriate one selected for use in the model, rather than relying on data from one source;
- The computing tool needs to be ready at the time of case study for data revision and sensitivity check, for efficiency and quality reasons;
- More knowledge is needed of how the processes and machinery are arranged on site in asphalt pavement projects;
- Improve the presentation of LCA results, and review afterwards.

Table 4-12 Review of Data and LCA Model in Wolverhampton Project

	Data Source and Quality	**Assumption**	**Calculation Technique**
Bitumen Production	1. Business annual data is unsuitable for scientific analysis. 2. Inconsistency of data source. 3. Unit processes are not defined the same way as LCA requires. 4. Life time boundary is not stated.	Energy use and emissions allocated by mass to oil refinery products (40% to bitumen, 60% to lighter products).	
Pavement and Materials	1. Materials composition in WCC proposal refers to BS average figure. 2. Technical data are needed to replace arbitrary speculation on pavement life expectancy.	1. Same bulk density for surface and binder course materials. 2. Same weight of planed and inlay materials. 3. Same life time for surface and binder course.	
Vehicle and Equipment	A number of data on 'working capacity', 'engine power' and 'fuel type' are sourced from manufacturers' website.	1. Fuel type is diesel unless stated otherwise. 2. Same transport distance and vehicles for a process in both proposals. 3. Transport vehicles run at 'maximum load', 'full legal speed' and 'empty on return'. 4. Road planer, paver and roller run at 'full speed' and 'full working width'.	1. Average figure is used for calculation where machines of different parameters were used. 2. Only machines of known parameters are counted in calculation. 3. Transport distance is assumed proportional to work days.
Energy-related Emissions	NAEI 1999 data for total emissions; DTI 1997 data for 'upstream' emissions.		Total emissions from database OR 'upstream' emissions from database + combustion data from manufacturer.
Energy Use of Transport Vehicles			Diesel consumption under 'full-load' and 'empty-load' was not differentiated.

4.2. Asphalt Paving at London Heathrow (LHR) Terminal 5

4.2.1. Project Background, Goal and Scope Definition

Previous LCA study has questioned the environmental benefits of using waste glass for construction aggregates in terms of carbon footprint (Grant Thornton and Oakdene Hollins 2006), especially when the recycling involves a transportation of waste glass of more than 30-40km (Hopkins and Foster 2003). This case study is to investigate, by using the LCA model, the environmental impacts of asphalt paving at LHR Terminal-5 in which natural aggregates were partially replaced with waste glass, incinerator bottom ash (IBA) and reclaimed asphalt pavement (RAP), and compare to those had the pavement of the same size and function been laid using virgin aggregates only. This is followed by a discussion and data analysis (completeness check, sensitivity check and consistency check) referring to the most significant variables in the project. This case study is to test and calibrate the LCA model described in Chapter3. The findings, presented as inventory (LCI) and characterisation results (LCIA), can be beneficial to road engineers or researchers dealing with recycling in roads. The LCA report was submitted on 09 February 2007 to Aggregate Industries UK Ltd (Huang and Bird 2007).

4.2.1.1. Data Source and Quality

The same as in the first case study, data needed in this LCA study are obtained firstly, and as much as possible, from material suppliers and contractors of the project. The missing data come from those justified for use in the model described in Chapter3, which are a combination of literatures and other European LCA databases. Analysis of data quality for this case study is seen in the 'interpretation' phase below.

4.2.1.2. System Boundary

Product systems are defined as the asphalt layers (surface course, binder course and base) in the LHR Terminal-5 project constructed partially using glass, IBA and RAP (referred as 'AI proposal'), compared to the asphalt layers of the same size and function but containing virgin aggregates and binder only (referred as 'conventional proposal'): this is a comparative LCA study. It is assumed that using those recycled materials has no measurable effects on the asphalt layers' life expectancy or technical constraints on reuse or recycling when theses layers are replaced. Asphalt layers in future maintenance will be recycled as the RAP into new pavement structures, same as was the practice in this project.[8]

The upstream boundary for recycled materials is set at the collection point: bottle banks for glass, incinerators for IBA and road site of the old asphalt pavement for RAP. Alternative ways of disposal of these materials include the transport to landfill. Boundaries, assumptions and options made for conventional materials and processes are described above in the model. The transport of bitumen and emulsifier to emulsion plant is not included in this study (dashed arrow in the figure), for 1) data are not available and, 2) tonnage of those materials are low (indicates the significance of the omission would be low to the final results). This study also refers to the agreement made in 05-06/2005 between Aggregate Industries and the author (see Appendix1).

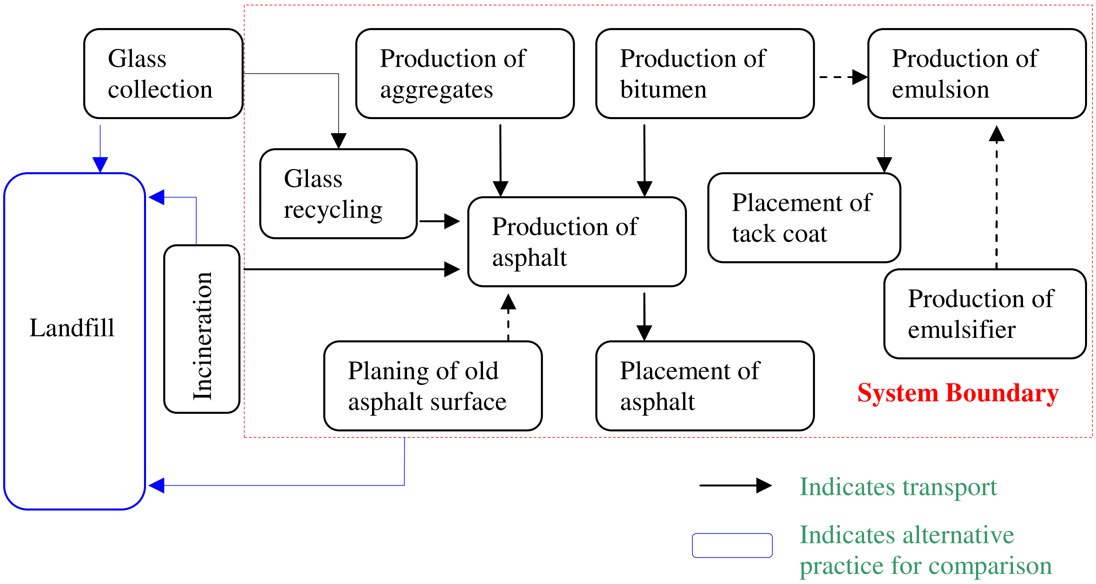

Figure 4-4 System Boundary of LHR T-5 Project

4.2.1.3. Functional Unit

The function of asphalt surface is to provide a safe, durable, comfortable and economical driving. Functional unit is defined as the 30,000m^2 of the asphalt surface. Unlike the first case study in which a difference in pavement life is expected (15yrs

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[8] The underlined text indicates the assumptions made in this LCA study, which needs to be agreed by the users of the LCA results.

rather than 12yrs), this case study assumes the same durability of asphalt layers. This is reflected in the definition of functional unit that it includes factors in only the construction stage. The pavement layers included for study consist of 35mm SMA surface course, 77mm HMB binder course and 205mm HMB base. This involves the use of quarry aggregates, bitumen and emulsion, waste glass, IBA and RAP (see Figure4-5).

4.2.1.4. Allocation

Allocation of environmental burdens between products, where data are inherently integrated and not possible to separate, can be done by either physical property (e.g. weight, volume) or economic value of the product (ISO 14044 2006). In bitumen production, the system boundary is expanded to account for the oil refining process collectively. Similarly in aggregates production, the boundary is expanded to include the production of all sizes of aggregates. Then the inventory loading or energy use is allocated between quarry products based on the tonnage.

For recycled materials (glass for example), allocation has two approaches: 1) LCI burdens of producing glass are partitioned by the residual value of waste glass, and included in the LCA study. 2) As the inherent properties of glass have not been changed, waste glass is counted in the LCA study as raw materials input the same way as stone aggregates. Embedded energy in glass manufacturing is therefore not included in the LCA study. This case study takes the second approach.

4.2.1.5. Method of Impact Assessment

The two-step (Classification, Characterization) 'Environmental Problems' approach developed by CML and SETAC in the early 1990s is adopted by the later international standard on LCA as the mandatory elements for impact assessment, and is followed in this model development.

4.2.2. Inventory Analysis

4.2.2.1. Pavement Parameters

Data on asphalt tonnage and recipe are provided by Aggregate Industries UK Ltd upon data request (see Appendix2). Calculation methods and assumptions made are the same as in the model above.

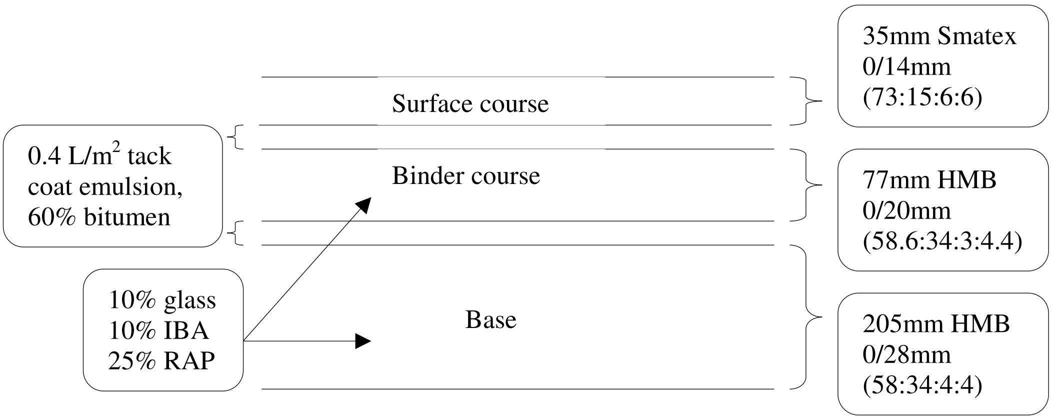

Figure 4-5 Pavement Structure in LHR T5 Project

Table 4-13 Pavement Parameters

	Pavement Parameter	**Conventional Proposal**	**AI Proposal**
	Pavement area	30,000m^2	30,000m^2
Surface course	Life expectancy	*12 yrs*	12 yrs
	Layer thickness	35mm	35mm
	Mixture weight	*1890t*	1890t
	Asphalt recipe (coarse:fine:filler:bitumen)	*0/14mm SMA (73:15:6:6)*	Bardon Smatex 0/14mm (73:15:6:6)[1]
Tack coat	Emulsion usage	*0.4 L/m^2*	0.4 L/m^2
	Bitumen content	*60%*	60%
Binder course	Life expectancy	*15 yrs*	15 yrs
	Layer thickness	65mm	77mm
	Mixture weight	*4100t*	4100t
	Asphalt recipe (coarse:fine:filler:bitumen)	*0/20mm HMB (58.6:34:3:4.4)*	HMB 0/20mm (58.6:34:3:4.4)[2]
Tack coat	Emulsion usage	*0.4 L/m^2*	0.4 L/m^2
	Bitumen content	*60%*	60%
Base	Life expectancy	*15 yrs*	15 yrs
	Layer thickness	205mm	205mm
	Mixture weight	*12,915t*	12,915t
	Asphalt recipe (coarse:fine:filler:bitumen)	*0/28mm HMB (58:34:4:4)*	HMB 0/28mm (58:34:4:4)[2]

Notes:

1. The SMA used PG-50 (40/60) bitumen with 0.4%, of total mix, of (cellulose) fibre. The mixing-paving temperature window for unmodified PG-50 is 180~190°C.

Detailed technical assessment is seen in TRL report (TRL 2000). HMB in binder course and base used PG-35 (30/45) bitumen.

2. 10% IBA and 10% glass was used to replace coarse and fine aggregates, respectively, in both binder course and base. In addition, 25% RAP (48% coarse, 47% fine, 5% binder) was used in both layers.

3. Figures in Italic are assumed the same as those in the project, for conventional proposal.

A breakdown of materials usage in this project can be calculated accordingly:

Table 4-14 Materials in LHR T-5 Project (unit: tonne)

		Natural aggregates				Glass	IBA	RAP	Primary bitumen	Emulsifier	Fibre
		Coarse	Fine	Filler	Total						
AI proposal	Surface course	1379.7	283.5	113.4 (105.8)	1776.6 (1769.0)	N/A	N/A	N/A	113.4	N/A	7.6[1]
	Tack coat	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.2[2]	0.036[3]	N/A
	Binder course	2402.6	1394	123	2530.2	139.4	240.3	1025[4]	165.2	N/A	N/A
	Tack coat	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.2[2]	0.036[3]	N/A
	Base	7490.7	4391.1	516.6	8021.8	439.1	749.1	3228.8[4]	476.2	N/A	N/A
	Total				**12328.6**	**578.5**	**989.3**	**4253.8**	**769.2**	**0.072**	**7.6**
Conventional proposal	Total[5]				18094.6	N/A	N/A	N/A	824.8	0.072	7.6

Notes:

1. Fibre used in SMA surface is counted as filler.
2. Specific density of bitumen and emulsion is assumed to be 1kg/litre.
3. Emulsifier usage is assumed to be 3kg per tonne emulsion.
4. NCHRP research indicated that residue binder in the RAP might need to be counted as ‘active’ binder when the replacement rate of RAP exceeds 20% (NCHRP 2001). TRL suggested a 50% recovery rate of the binder in porous asphalt that is recycled into thin surfacing accounting for up to 30% of the new mixture (TRL 2005). In this case study, 50% residue binder in the RAP is assumed to be recovered in the new asphalt mixture. The rest 50% is counted as hardened ‘black rock’, the aggregates portion of the new mixture.
5. Materials usage for asphalt layers made using virgin aggregates only.

4.2.2.2. Process Parameters

Data on transport distance and energy consumption of construction vehicles are provided by Aggregate Industries UK Ltd. upon data request (see Appendix2).

Table 4-15 Transport Parameters

Freight	Origin	Destination	Mileage	Vehicle type	Fuel consumption	Payload	Fuel efficiency
Aggregates	Bardon Hill quarry	West Drayton	120mi (193.1km)	Train	8-9 L/mi (5.0-5.6 L/km)	1729t	0.85 L/t[1]
Bitumen	Southampton	West Drayton	80mi (128.7km)	Truck	**Data Missing, data on 14t truck from IVL are used for calculation**		
Emulsion[2]	York (to Crawley first)	LHR T5	230mi (370.1km)	Truck			
Asphalt	West Drayton	LHR T5	4mi (6.4km)	Truck			
Glass[2]	Brentford	West Drayton	11mi (17.7km)	Truck			
IBA[2]	Edmonton	West Drayton	20mi (32.2km)	Truck			

Notes:

1. Fuel consumption in empty journey is counted in the calculation of fuel efficiency.
2. The suppliers of emulsion, glass and IBA are Colas, Day Group Ltd. and Ballast Phoenix Ltd, respectively.
3. The transport of bitumen and emulsifier to emulsion plant is not included in the study, for data are not available.
4. Fuel consumption for collection of waste glass is 0.4MJ/t (see in the model). The processes (crushing, screening, etc) and energy for making glass aggregates are assumed the same as for making natural aggregates in a quarry.

Table 4-16 Machinery Parameters

	Width of screed/roller (m)	Working speed (m/hr)	Fuel consumption (L/hr)
Emulsion applier	2	220	6.0
Paver	4.9	300[1]	16.87
Roller	1.7	6000[2]	12.5

Notes:

1. The paver runs at a speed of 10-12m/min for surface and binder course, and 8-10m/min for the base.
2. The roller will pass up and down over the freshly laid material for a certain number of passes as specified for that material. It must roll before the temperature drops too

much, so it can never get too far behind the paver, or too close where the material is still too soft.[9]

3. Paving and rolling is finished in 2 passes on the base with a total thickness of 205mm.

4.2.2.3. LCI Calculation

Environmental inputs (raw materials, energy) and outputs (emissions to air and water, solid waste) are calculated for the T-5 project, as well as the hypothetical proposal in which only virgin aggregates were used. Individual processes are grouped into ‘materials production’, ‘transport’ and ‘asphalt placement’, based on the features of road projects. Grouped LCI results can be presented in either amount or percent of the total, or both. Results of key processes and LCI loadings for both proposals are presented for comparison. Complete inventory results are shown in the spreadsheet.

Table 4-17 Life Cycle Inventory of LHR T-5 Project (selected environmental loadings)

Process		LCI of pavement object where recycled materials are used							
		Aggregates(t)	Bitumen(t)	Energy		CO_2(kg)	SO_2(kg)	NOx(kg)	Solid waste(t)
				GJ	%				
Production	Aggregates	12328.6		807	6.05	43800	84.4	318	2.3
	Glass aggr.	**Data Missing**							-578.5
	IBA aggr.								-989.3
	RAP aggr.			212	1.59	15100	5.31	152	-4253.8
	Bitumen		754.8	3460	26.0	215000	1380	1610	6.1
	Emulsion[1]		14.4	8.6	0.06	253	0.5	0.5	
	Asphalt[2]			7950	59.5	412000	615	756	9.9
Transport	Aggregates			447	3.35	44200	44.3	957	
	Glass aggr.			10.6	0.08	754	0.3	3.9	
	IBA aggr.			33	0.25	2350	0.8	12	
	Bitumen			101	0.75	7160	2.53	36.5	
	Emulsion			9.2	0.07	654	0.2	3.3	
	Asphalt			126	0.95	8960	3.16	45.7	
Placement	Tack coat			34.9	0.26	2480	0.9	25	
	Paving			85	0.64	5810	1.8	51	
	Rolling			53.1	0.40	3780	1.33	38	
Total		12328.6	769.2	13300	100	763000	2150	4010	-5803.3

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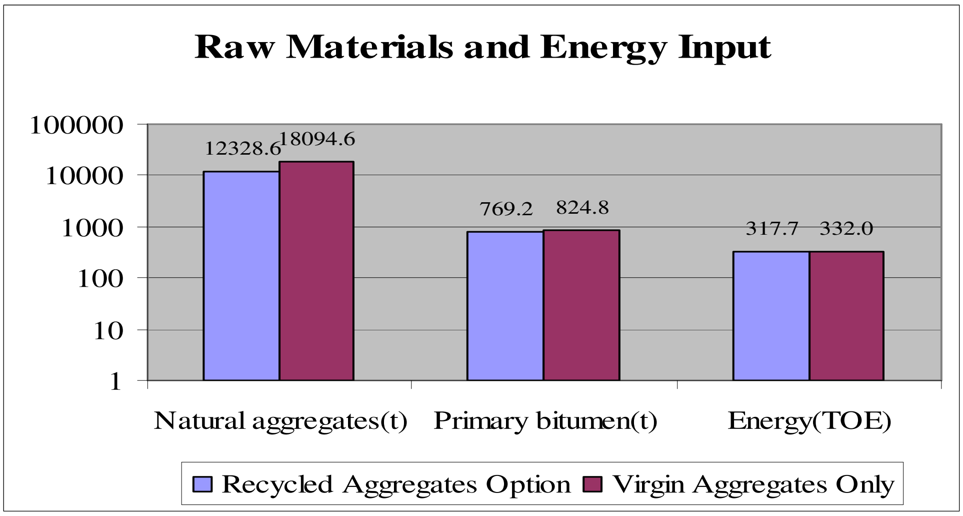
[9] Personal communication with Roger Bird on 09 February 2007.

Table 4-17 Life Cycle Inventory of LHR T-5 Project (selected environmental loadings) - continued

Process		LCI of pavement object where only virgin materials are used							
		Aggregates(t)	Bitumen(t)	Energy		CO_2(kg)	SO_2(kg)	NOx(kg)	Solid waste(t)
				GJ	%				
Production	Aggregates	18094.6		1180	8.5	64300	124	466	3.3
	Bitumen		810.4	3710	26.7	230000	1480	1730	6.6
	Emulsion[1]		14.4	8.6	0.06	253	0.5	0.5	
	Asphalt[2]			7950	57.0	615	756	412000	9.9
Transport	Aggregates			656	4.7	64800	65.1	1400	
	Bitumen			108	0.8	7690	2.71	39.2	
	Emulsion			9.2	0.07	654	0.2	3.3	
	Asphalt			126	0.9	8960	3.16	45.7	
Placement	Tack coat			34.9	0.3	2480	0.9	25	
	Paving			85	0.6	5810	1.8	51	
	Rolling			1180	0.4	83900	29.6	845	
Total		18094.6	824.8	13900	100	802000	2300	4560	19.8

Notes:

1. LCI includes the loadings from production of the emulsifier.
2. LCI does not include the loadings from production of the aggregates and bitumen.



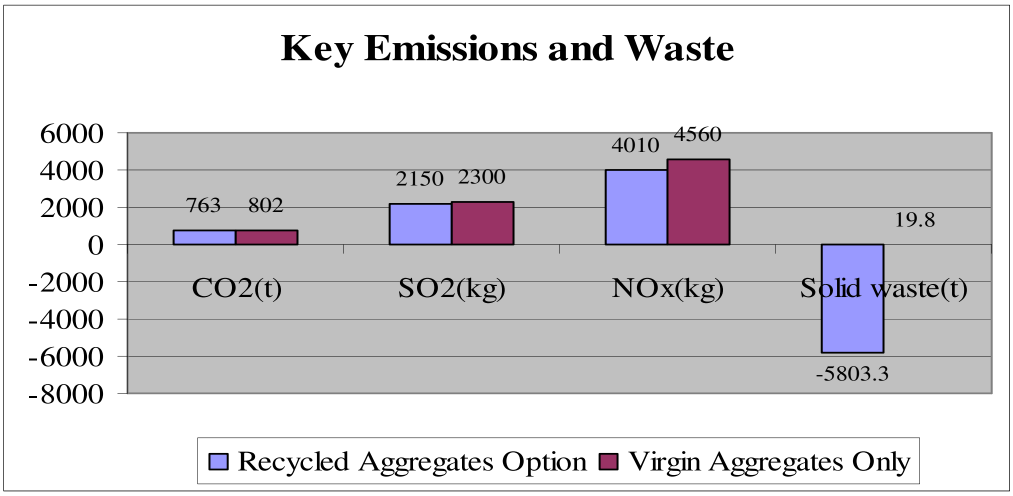


Figure 4-6 Comparison of Key Environmental Loadings

As for comparison, the tonnage of glass, IBA and RAP in the asphalt is in turn set to zero, hypothetically, to see how the LCI loadings change as a result. It can be seen from the table and figure below that RAP replacement has the greatest effects, compared with glass and IBA, for: 1) its tonnage, and 2) its dual effects of replacing aggregates and reducing the input of primary bitumen, an energy hungry product.

Table 4-18 Effects of Glass, IBA and RAP Replacement on LCI Results

Scenario of Using Recycled Materials	Selected Environmental Loadings in LCI of Pavement Object						
	Aggregates(t)	Bitumen(t)	Energy (TOE)	CO_2(t)	SO_2(kg)	NOx(kg)	Solid waste(t)
Glass, IBA, RAP as in T5	12328.6	769.2	317	763	2150	4010	-5803.3
IBA, RAP as in T5, no glass	12907.1	769.2	320	766	2150	4070	-5224.8
Glass, RAP as in T5, no IBA	13317.9	769.2	320	767	2150	4100	-4813.8
Glass, IBA as in T5, no RAP	16526.8	824.8	330	794	2280	4220	-1548.3
Virgin materials only	18094.6	824.8	332	802	2300	4560	19.8

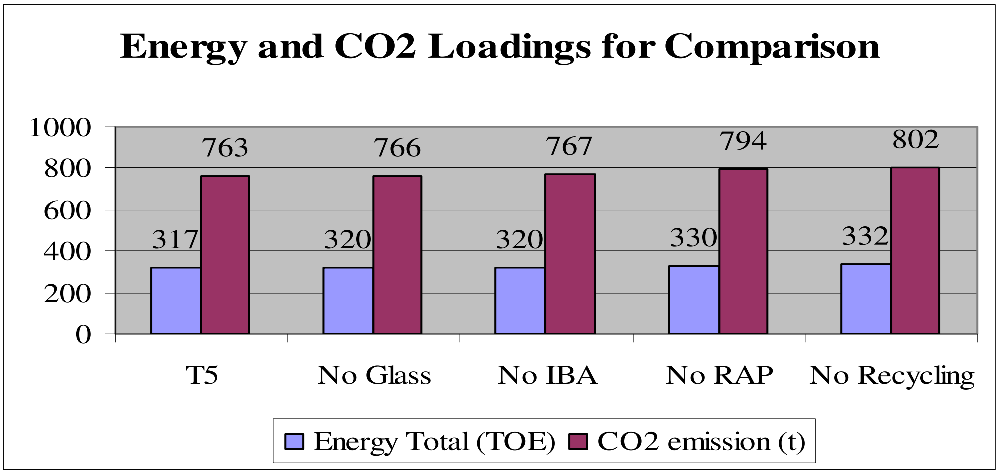


Figure 4-7 Comparison of Energy and CO_2 between Recycling Scenarios

4.2.3. Impact Assessment

Life cycle impact assessment is not carried out in this case study, for: 1) it would be purely an environmental assessment process which does not rely on any inputs from road engineers once the inventory is complete and, 2) most of the procedures would repeat those in the LCA study of Wolverhampton project.

4.2.4. Interpretation

4.2.4.1. Identification of Significant Areas

In the LHR T-5 project, asphalt mixing, bitumen and aggregates production consumed approximately 60%, 26% and 6%, respectively, of all the energy and as a result, released more pollutants than other processes. The introduction of recycled materials did not have an effect on the environmental burdens of asphalt production or placement, yet it reduced, by about 7%, the input of primary bitumen. Another significant benefit of using recycled materials (glass, IBF and RAP) in LHR T-5 was the saving of more than 5,700 tonnes of natural aggregates, and diverting 579t and 989t of waste glass and IBA, respectively, from landfill.

Transport of aggregates accounted for over 61% of all diesel use in transport. This is due to the long haulage distance (120miles) and materials tonnage. Railway locomotive with a higher fuel efficiency (0.17MJ/t*km) than trucks (0.46-0.94MJ/t*km) was used for aggregates transport. RAP, glass and IBA were obtained from local sources; the haulage of RAP which was applied on site was not included in the analysis. Given the tonnage of glass and IBA, an increase of transport distance will not be significant in affecting the total energy use or emissions. On the contrary, hot mix asphalt was transported for a short distance of 4miles in this project, which explains why it represented only 17% of diesel use in transport. The energy consumed in main phases of the construction process is illustrated in the figure below (refer to Table4-17).

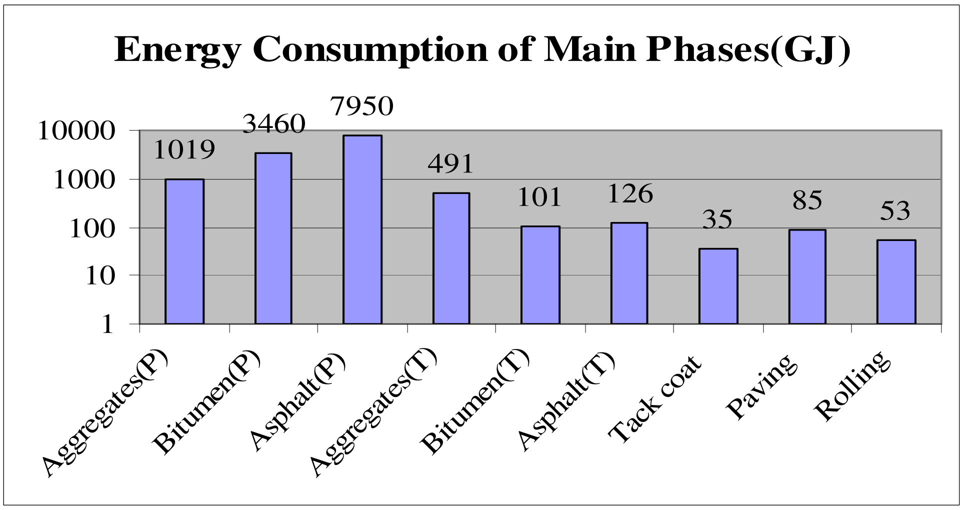


Figure 4-8 Energy Consumption of Main Processes in LHR T-5 Project

4.2.4.2. Completeness Check

The completeness check attempts to ensure that data on all products and processes required for LCA study of the project have been obtained, and any data gap or the need for further data acquisition is identified.

Table 4-19 Completeness Check on Data Source and Quality

Unit process group		Data source	Complete?	Limitation/Action required
Materials production	Aggregates	AI	√	No
	Glass aggregates	Day Group Ltd.	X	Energy data on recycling glass for aggregates use are needed
	IBA aggregates	Ballast Phoenix Ltd.	X	Energy data on recycling IBA for aggregates use are needed
	RAP aggregates	IVL	√	No
	Bitumen	Eurobitume	√	LCI data on straight run 50/70 bitumen only
	Emulsion	IVL	√	No
	Asphalt	AI	√	No
Transport	Aggregates	AI	√	No
	Glass aggregates	AI, IVL	X	Mileage is known from AI, but fuel efficiency has to use that for 14t truck from IVL
	IBA aggregates	AI, IVL	X	
	Bitumen	AI, IVL	X	
	Emulsion	AI, IVL	X	
	Asphalt	AI, IVL	X	
Asphalt placement	Tack coat	AI	√	No
	Paving	AI	√	No
	Rolling	AI	√	No

4.2.4.3. Sensitivity Check

The sensitivity check aims to determine the influence of variations in data source, methodology and assumptions on the inventory results. Normally it is carried out after the identification of significant areas, on the most significant variables in the project.

Materials production accounted for in the LHR T-5 project the largest proportion of energy use and emissions, particularly the production of aggregates, bitumen and asphalt. It can be seen in the Model (see in Chapter3) that this is also the area in which many alternative data exist. Therefore, sensitivity check is carried out, on the effect of data source on the key environmental impacts (energy, CO_2, etc). A variation of 10% is considered significant.

Table 4-20 Sensitivity Check on Data Source and Mixing Method for Asphalt Production

Total energy use in the project (103GJ)	Hot mix production	Cold mix production	Deviation (103GJ, %)	Sensitivity
AI data	14.5	7.5	-7, -48.3%	Significant
EAPA data	15.9			
IVL data		6.5	-9.4, -59.1%	Significant
Deviation (103GJ, %)	+1.4, +9.7%	-1, -13.3%		
Sensitivity	Insignificant	Significant		

Table 4-21 Sensitivity Check on Data Source for Bitumen and Aggregates Production

	Total CO2 emissions in the project (tonne)		Deviation (tonne, %)	Sensitivity
Data on production of bitumen	Eurobitume data	VTT data		
	843	881	+38, 4.5%	Insignificant
Data on production of aggregates	AI data	VTT data		
	843	824	-19, -2.3%	Insignificant

Sensitivity checks above indicate that the source of data on production of asphalt, bitumen or aggregates does not have significant effects on the total of energy use or carbon footprint of the project. The only exception is the energy total when data on cold mix production come from IVL compared with AI. However, the project’s energy total can be almost halved had the aggregates and bitumen (emulsion) been mixed by the ‘cold’ method. The reduction can be greater at nearly 60% if data on the ‘hot mix production’ and ‘cold mix production’ come from EAPA and IVL, respectively. This is of course, based on the assumption that aggregates grading and bitumen content of the cold mix asphalt equal those of its hot mix counterparts.

Apart from data source and mixing method, according to ISO14044, sensitivity check may also be carried out on other alternatives in the scope definition, such as the allocation rule, system boundary, assumptions, and methodology for impact assessment (e.g. selection of impact categories and characterisation factors).

4.2.4.4. Consistency Check

Different to the completeness check, the consistency check is to find out whether and how far the data used for the LCA study share comparable characteristics or the same level of details. These may include: age, accuracy, temporal, spatial and technical coverage of the data.

Table 4-22 Consistency Check on Data Source and Quality

Unit process group		Data source	Age	Accuracy	Time-, geography-, and technology-related coverage
Materials production[2]	Aggregates	AI	1998-2006	√	Mean value of AI's HMA plant at Greenwich and Durham, weekly average[1]
	Glass aggregates	Day Group Ltd.		X	Data unavailable, glass recycling plant (for aggregates use) at Brentford
	IBA aggregates	Ballast Phoenix Ltd.		X	Data unavailable, IBA aggregates production plant at Edmonton
	RAP aggregates	IVL	2000	√	A diesel driven mobile plant
	Bitumen	Eurobitume	1997-1999	√	Partial LCI study on straight run PG50/70 bitumen
	Emulsion	IVL	2000	√	An emulsion plant, LCI for emulsifier: Akzo Nobel
	Asphalt	AI	1998-2006	√	Mean value of AI's HMA plant at Greenwich and Durham, weekly average[1]
Transport	Aggregates	AI	2006	√	Diesel locomotive for 120mi
	Glass aggr.	AI, IVL		X	Data unavailable, use fuel consumption of 14t truck from IVL, empty return assumed; mileage from AI
	IBA aggr.	AI, IVL		X	
	Bitumen	AI, IVL		X	
	Emulsion	AI, IVL		X	
	Asphalt	AI, IVL		X	
Asphalt placement	Tack coat	AI	2006	√	
	Paving	AI	2006	√	Effective working time: 50min/hr, laying speed does not differentiate between base and surface layers
	Rolling	AI	2006	√	Effective rolling width: 85% roller width; effective working time: 50min/hr; 6 passes assumed

Notes:

1. Data come from 'plant weekly operating report'.

2. Alternative LCI data are available from VTT on production of crushed aggregates, gravel, limestone filler and bitumen.

4.2.5. Discussion

Production of bitumen and hot mix asphalt together consumed more than 78% of all the energy in LHR T-5 project. Transport in total accounted for only about 5%. This is because the transport process was either of short distance, or of long haulage but done by fuel efficient mode. Alternative data to those used in this case study are available, on materials production including aggregates, bitumen and hot/cold mix asphalt, etc.

Sensitivity analysis indicated that it was the asphalt mixing method, rather than the data source, that had significant effects on the energy or CO_2 total.

Not all required data for the LCA study of LHR T-5 project was available from contractors. Some (e.g. transport) can be obtained from industry average not specific to this project, other data deficiency (e.g. glass/IBA aggregates) may affect the definition of system boundary for this LCA study. Data used in this case study were of mixed age, accuracy and applicability. A full life cycle inventory of the products or processes in constructing the asphalt pavements is ideally welcome for LCA use; very often however, only energy data are available.

Old asphalt planings is the most desirable type of recycled aggregates, taking into consideration the quantity, transport, resource efficiency and recyclability of the asphalt layers. Compared with such industrial waste like glass, whose secondary use in roads is relatively new, far more research has been done on the RAP (FHWA and Ohio DOT 2002). The results from on-going laboratory work and trials can expect to predict the pavement life on a more scientific basis (TRL 2005).

Chapter 5 : Model Extension

The cost of road maintenance works has two aspects. One is the direct cost incurred by contractors (agency's cost) in carrying out the work, the other is the cost borne by road users during the roadwork. Similar principles apply to the environment footprint of road maintenance works. The computer program QUADRO (QUeues And Delays at ROadworks) is introduced in DMRB Volume14 to compare the full cost of alternative maintenance options including the agency's and users' cost (DMRB 2002). Through a case study of a rehabilitation project on a 2-lanes dual carriageway, this thesis introduces the concept of using LCA and EnvPro (packed with VISSIM), respectively, to measure the environmental impacts of roadwork and the traffic on it. These impacts will be assessed for their significance to the total emissions from the road. This thesis therefore makes an equivalent environmental assessment to the QUADRO.

5.1. Environmental Impacts from the Traffic

A number of energy and LCA studies of roads have indicated that the construction of pavement structures contributes to only a light fraction (e.g. less than 10%) of the energy or emissions total. The majority of environmental loadings come from the trafficking vehicles during the pavement life time (Hakkinen and Makela 1996; Inamura 1999; The Highways Agency 2003). Although the study of energy and emissions from traffic is not in the scope of this PhD study, the speed of delivery of road maintenance works certainly has an effect on the fuel use and emissions by the traffic, and therefore needs to be addressed in the LCA study of roadwork.

5.2. Introduction of VISSIM and EnvPro

Micro-simulation model, VISSIM (Visual Simulation), is able to analyse urban traffic and transit operations in given context of lane configuration, traffic volume and composition, traffic signals and transit stops, etc. Among the main applications is to evaluate and compare the many design alternatives such as signalised or stop-sign-controlled intersection, traffic diversion or traffic sign setting, etc. The aim is to optimise traffic operations in a combined network of coordinated and actuated traffic signals (PTV 2005). When used for assessment of the environment footprint of road works, micro-simulation results may help to evaluate the traffic management options such as the time of roadwork, lane closure and traffic diversion, with an aim to reduce disruption to traffic and as a result, the overall fuel use and associated emissions.

Statistical data such as travel time and queue length are gathered and presented as the simulation results. In order to make the results ready for LCI analysis, traffic emissions model is needed to convert the results into emissions inventory. EnvPro (Environmental Program), developed jointly by PTV AG and Newcastle University (Transport Operations Research Group, TORG), is able to estimate pollutions from the traffic using the simulation results of VISSIM. VISSIM4.1 and EnvPro1.6 are responsible for traffic simulation and emissions modelling, respectively in this study.

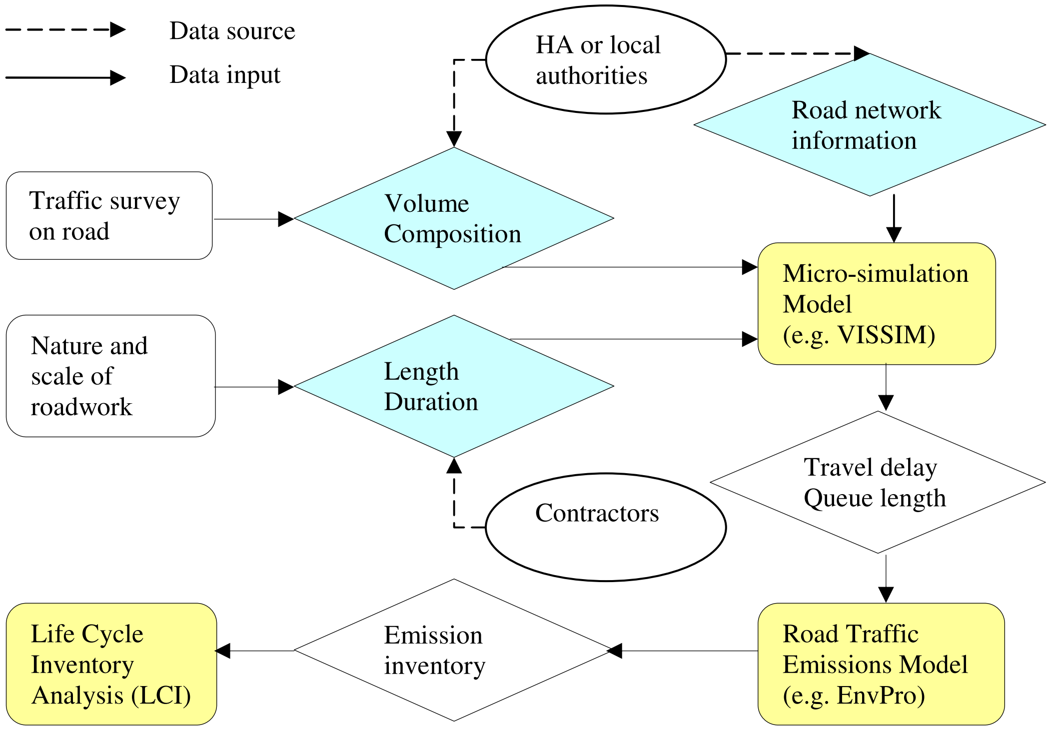


Figure 5-1 Consideration of Disturbance to Traffic by Roadwork

5.3. Case Study – Rehabilitation of Pavement between Hanford Roundabout on A34 to City of Stoke-on-Trent Boundary

5.3.1. Background

A full reconstruction was proposed, and materials options reviewed, for pavement between Hanford Roundabout on A34 to City of Stoke-on-Trent Boundary. The pavement construction involved HDM base and DBM binder course, with HRA forming the surface layer. The primary aim was to evaluate the recent changes to pavement design in DMRB (HD26/06), to see how alternative asphalt mixture (EME2) can affect the layer thickness (TRL 2005).

Table 5-1 Materials Options for Pavement Rehabilitation at Stoke-on-Trent

Pavement Layer	Option1		Option2		Option3		Option4	
	Materials Type	Thickness	Materials Type	Thickness	Materials Type	Thickness	Materials Type	Thickness
Surface Course	HRA	50mm	HRA	50mm	HRA	50mm	HRA	50mm
Binder Course	EME2, 14mm	70mm	EME2, 14mm	70mm	Bardon Superbase14	70mm	Bardon Superbase14	70mm
Base	EME2, 20mm	120mm	EME2, 14mm	120mm	Bardon Superbase20	140mm	Bardon Superbase14	140mm
Foundation	Surface stiffness modulus 120MPa required				Standard unbound Type I sub-base permitted			

This case study however, deals with what effect the speed of delivery of the roadwork had on the traffic and, as a result, the fuel use and emissions. The roadwork was 2.6km long and carried out on a 2-lane dual carriageway. Rather than 8 day as originally proposed, the project was finished in 5 days. This case study uses VISSIM to simulate the traffic flow in normal time and during the roadwork, and was based on the knowledge of traffic data and road configuration. The outputs from the traffic model are the inputs to EnvPro, and then the difference can be seen by comparing the fuel use and emissions inventory. Energy and relevant emissions from the roadwork itself is addressed by LCA (with assumptions made on the asphalt products and processes).

5.3.2. LCA of Roadwork

Majority of the roadwork deal with surface course only, the rest have binder course and/or the base involved. The mileage divide is summarised in the table below. Also presented are the pavement parameters.

Table 5-2 Mileage Divide of Roadwork in Stoke-on-Trent Rehabilitation Project

	Asphalt type	Asphalt recipe[1]	Layer thickness	Accumulated mileage[3]
Surface course type I	0/14mm HRA, 50pen	64.5:23:7.6:4.9	50mm	4014m
Surface course type II	Super Hitex	64.5:23:7.6:4.9	40mm	491m
Binder course	0/20mm DBM	64.5:23:7.6:4.9	60mm	491m
Base	0/28mm HDM	64.5:23:7.6:4.9	200mm	440m

Notes:

1. Asphalt recipe is presented as ‘coarse: fine: filler: bitumen’. The asphalt recipe in Superflex™ (data come from Wolverhampton project, see Chapter4: Case Study) is assumed the recipe for all layers of this roadwork. Emulsion recipe and usage for tack coat between asphalt layers come from LHR T5 project. No recycled materials are assumed to be used.

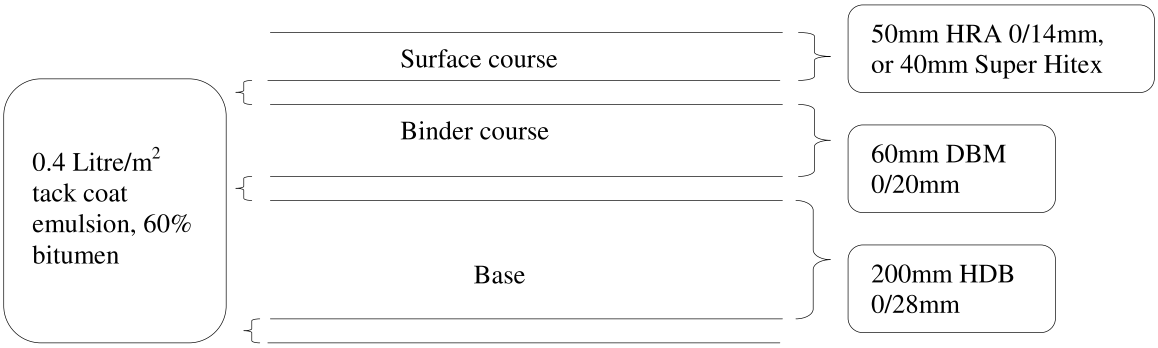


Figure 5-2 Pavement Structure in Stoke-on-Trent Rehabilitation Project

2. Roadwork to the base has binder course and surface course placed on top of it; roadwork to binder course has surface course placed on top of it.
3. Pavement width is assumed 2*3.5m = 7m for the 2.6km long, 2-lanes dual carriageway. Mileage of different depths of roadwork read from the AutoCAD drawings by courtesy of Stoke-on-Trent City Council.

- The base: 440m;
- Binder course (only): 87+25+86+18+27*2+50+38+133 = 491m;
- Type II surface course (only): 72+50+54+48+43*2+61+60+60 = 491m;
- Type I surface course (only): (1962-87-50-25-48-27-43-50-60) + (1970-72-86-54-18-27-43-38-61-60) = 1572+1511 = 3083m;
- Total length of roadwork: 1962+1970+133+440 = 4505m.

Assume the transport mode (a combination of 14t truck and rail locomotive) and workload (aggregates: 120mi; bitumen: 80mi; emulsion: 230mi; asphalt: 4mi) equal to those in LHR T5 project. Run these process and pavement data through the LCA model. The estimated figures of energy and emissions from the roadwork can be worked out by this simplified LCA process.

Table 5-3 Energy Use and Key Emissions from Stoke-on-Trent Rehabilitation Project

Process		CO	NOx	HC	CO_2	PM	Energy
	Unit	gram	gram	gram	gram	gram	GJ
Production	Aggregates	72.2E+03	159E+03	22.8E+03	21.3E+06	13.9E+03	386
	Bitumen	41.6E+03	625E+03	386E+03	83.2E+06	65.4E+03	1340
	Emulsion	28.4	202	152	0.1E+06	82.2	3
	Asphalt	77.4E+03	268E+03	68.3E+03	152E+06	52.5E+03	2900
Transport	Aggregates	53.1E+03	433E+03	7.2	20.1E+06	1.8	226
	Bitumen	6.8E+03	16.1E+03	2.1E+03	3.2E+06	89.8	44.3
	Emulsion	1.1E+03	2.6E+03	328	0.5E+06	14.3	7.1
	Asphalt	6.7E+03	15.8E+03	2.0E+03	3.1E+06	88.6	43.7
Placement	Tack coat	1.4E+03	2.7E+03	0.12	0.27E+06	77.2	3.8
	Paving	1.5E+03	3.0E+03	0.16	0.34E+06	92.8	4.9
	Rolling	1.1E+03	2.2E+03	0.10	0.22E+06	63.1	3.1
Total		263E+03	1530E+03	482E+03	284E+06	132E+03	4970

5.3.3. Micro-simulation (VISSIM)

The roadwork was carried out on a 2.6km long, 2-lanes dual carriageway between A34 Strongford (Hanford roundabout) to City of Stoke-on-Trent boundary. The northbound traffic is 12,410 vehicles per day and the southbound 14,083.[10] Distribution of traffic by time of day is described by DfT in Transport Statistics Bulletin (DfT 2006). This thesis uses the profile for all vehicles during weekdays (Monday to Friday). The traffic on north- and south-bound carriageway is allocated to each hour period.

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[10] Traffic data is the daily average in June. During simulation, a 60%:40% ratio between car traffic (60km/hr) and HGV traffic (50km/hr) is assumed.

Table 5-4 Traffic Distribution by Time of Day

Time of Day	DfT's Traffic Profile (all vehicles, workday)	Northbound	Southbound
0--1	17	82	93
1--2	12	58	66
2--3	10	48	55
3--4	11	53	60
4--5	17	82	93
5--6	39	188	214
6--7	95	459	521
7--8	178	860	976
8--9	193	933	1058
9--10	158	764	866
10--11	147	710	806
11--12	149	720	817
12--13	152	735	834
13--14	156	754	856
14--15	163	788	894
15--16	176	851	965
16--17	199	962	1091
17--18	204	986	1119
18--19	163	788	894
19--20	114	551	625
20--21	80	387	439
21--22	60	290	329
22--23	45	217	247
23--24	30	145	165
Total	**2568**	**12410**	**14083**

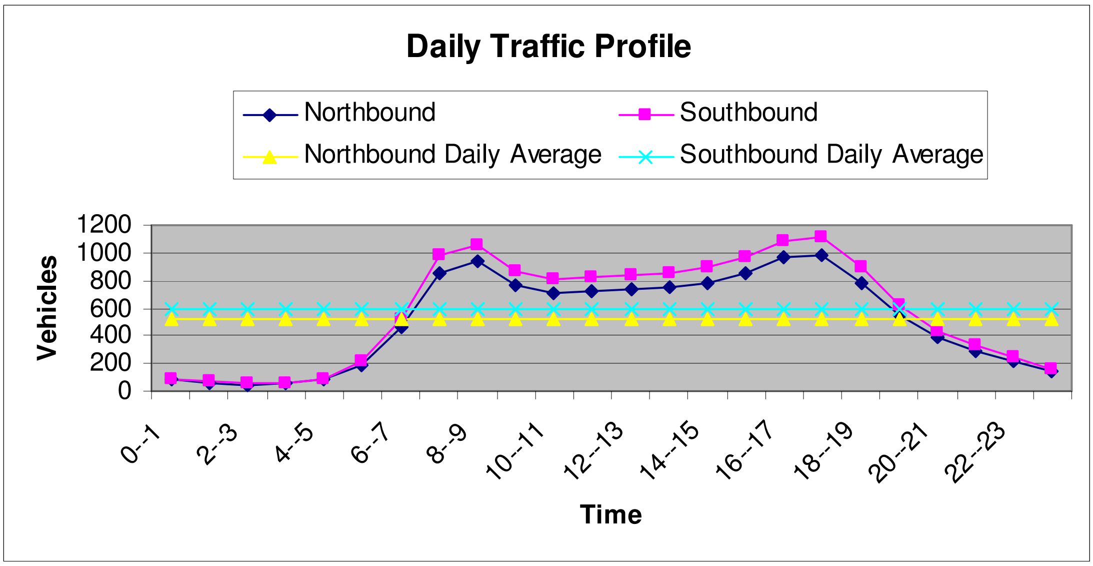


Figure 5-3 Daily Traffic Profile

The procedures of running VISSIM to simulate the traffic movements on a road include the following steps:

1) Load the AutoCAD drawings in VISSIM as background (convert the map to VISSIM supported format if needed) and scale it;
2) Draw the links on top of, and in line with, the road alignment;
3) Assign the lane number and traffic data to those links;
4) Generate the links for traffic in the opposite direction, use the function that VISSIM provides for this step but make amends to the road alignment on the map;
5) Repeat 3) for the links;
6) Run the simulation.

5.3.4. Emissions Modelling (EnvPro)

The .fzp file (Vehicle Record) produced by VISSIM is brought into EnvPro as input. The output of EnvPro (the .em file) opens with Notepad or WordPad. It includes an emissions inventory of CO, NO_x, CO_2, HC, PM and FC (fuel consumption), presented in g or g/km (litre or litre/km for FC). This inventory refers to the fuel use and emissions by the traffic on that length of road during the simulation period. EnvPro estimates the pollutions based on two models developed under EU project in the early 1990s: QUARTET and MODEM (PTV and TORG 2004).

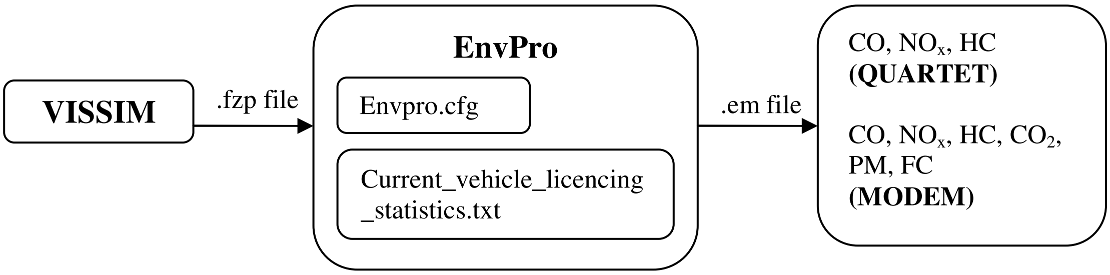


Figure 5-4 Inputs and Outputs of EnvPro (PTV and TORG 2004)

5.3.5. Inventory from the Traffic

Firstly, run the data for traffic in normal time through VISSIM and EnvPro in turn, and get the fuel consumption and emissions by the traffic in one day.

Table 5-5 Fuel Use and Emissions by Traffic per day during Normal Time

	CO	NOx	HC	CO_2	PM	FC
Unit	gram	gram	gram	gram	gram	litre
QUARTET model	5.98E+05	3.87E+05	2.33E+05			
MODEM model	4.70E+05	7.01E+04	4.54E+04	1.40E+07	1.23E+06	4.68E+03
Variation	21.4%	81.9%	80.5%			

The principles and measures of lane closure for roadwork on dual carriageways are described in DfT's Traffic Sign's Manual (DfT 2006). This case study assumes that the two lanes are closed on an alternate basis over the entire length of the roadwork. This means during the time of the roadwork, only one lane is effectively carrying the traffic, in both directions of the dual carriageway. Close one lane in both directions of the traffic in VISSIM, run the model and then input to the EnvPro, to simulate emissions during the period of the road works.

Table 5-6 Fuel Use and Emissions by Traffic per day during Roadwork

	CO	NOx	HC	CO_2	PM	FC
Unit	gram	gram	gram	gram	gram	litre
QUARTET model	5.98E+05	3.91E+05	2.37E+05			
MODEM model	4.85E+05	7.01E+04	4.79E+04	1.44E+07	1.26E+06	4.82E+03
Variation	18.9%	82.1%	79.8%			

5.4. Discussion

Obviously the difference in results from the two models is substantial. The QUARTET (Quadrilateral Advanced Research on Telematics for Environment and Transport) model estimates traffic emissions based on an average speed/flow. On the other hand, MODEM is an instantaneous and continuous emissions model, providing estimates of fuel consumption and emissions in presence of accelerations, decelerations, stop and go phenomena, typically seen in urban and congested traffic. Therefore, the MODEM model is better able to compute on a micro-scale (second by second) emissions. An interesting result from this modelling exercise is that the QUARTET estimates are systematically higher than the MODEM estimates for all pollutants. The reason for this is not clear and should be a subject of future research.

This case study uses the results from the MODEM model for discussion. Compare the inventories in Table5-5 and Table5-6. It can be seen from Table5-7 that the traffic during roadwork consumes 3% more fuels, and the emissions increase from 0.1% for NOx to 5.5% for HC.

Table 5-7 Comparison of Fuel Use and Emissions by Traffic per day

	CO	NOx	HC	CO_2	PM	FC
Unit	gram	gram	gram	gram	gram	litre
Traffic in Normal Time	4.70E+05	7.01E+04	4.54E+04	1.40E+07	1.23E+06	4.68E+03
Traffic in Roadwork Time	4.85E+05	7.01E+04	4.79E+04	1.44E+07	1.26E+06	4.82E+03
Increase	0.15E+05	0.7E+02	0.25E+04	0.04E+07	0.03E+06	0.14E+03
Increase (%)	3.2%	0.1%	5.5%	2.9%	2.4%	3.0%

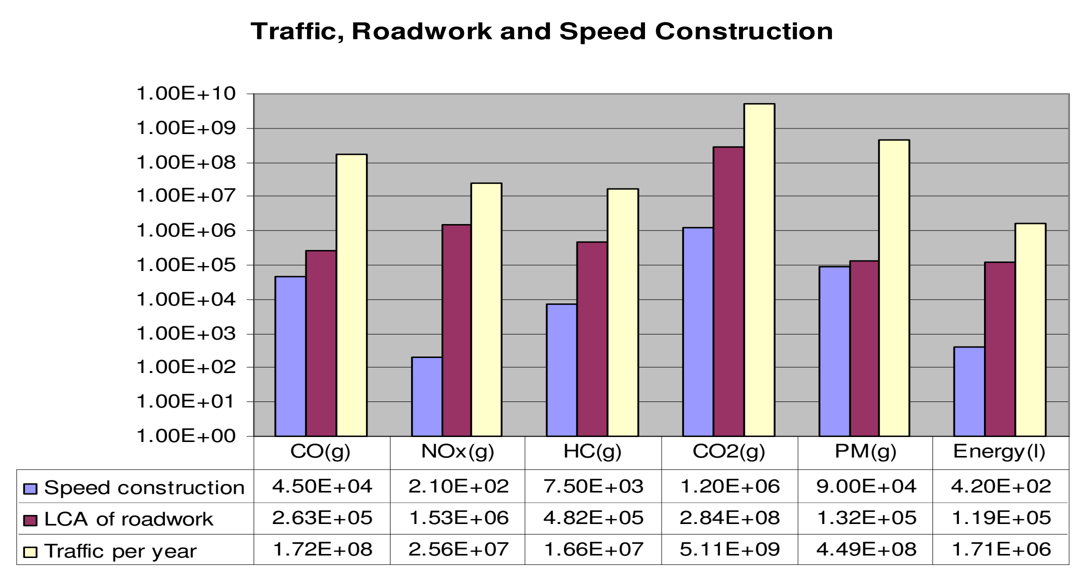
The reduction of the duration of roadwork from 8 days to 5 days in this project saved fuels and emissions by the traffic. Figures can be estimated by multiplying the ‘increase’ in Table5-7 by 3 (8-5). The fuel use and emissions by the traffic in normal time for one year can be estimated by multiplying the inventory figures in Table5-5 by 365. These results are compared with the LCA results of the roadwork (Table5-3).

Table 5-8 Comparison of Fuel Use and Emissions by Traffic, Roadwork and Speed Construction

	CO	NOx	HC	CO_2	PM	Energy
Unit	gram	gram	gram	gram	gram	litre
Traffic per year in normal time	1.72E+08	2.56E+07	1.66E+07	5.11E+09	4.49E+08	1.71E+06
Roadwork (LCA results)	2.63E+05	1.53E+06	4.82E+05	2.84E+08	1.32E+05	1.19E+05[1]
Savings due to speed construction (3 days)	4.50E+04	2.10E+02	7.50E+03	1.20E+06	9.00E+04	4.20E+02

Note:

1. Density of the fuel is assumed to be 1.0E+03 litre/tonne.



	CO(g)	NOx(g)	HC(g)	CO2(g)	PM(g)	Energy(l)
Speed construction	4.50E+04	2.10E+02	7.50E+03	1.20E+06	9.00E+04	4.20E+02
LCA of roadwork	2.63E+05	1.53E+06	4.82E+05	2.84E+08	1.32E+05	1.19E+05
Traffic per year	1.72E+08	2.56E+07	1.66E+07	5.11E+09	4.49E+08	1.71E+06

Figure 5-5 Comparison of Fuel Use and Emissions by Traffic, Roadwork and Speed Construction

It can be seen from Figure5-6 that savings of CO and PM due to speed delivery of the roadwork are comparable to those coming from the roadwork itself. This indicates the significance of reducing the disturbance to traffic during roadwork. The speed construction does not have significant effect on the HC, CO_2 and energy loadings. The saving of NO_x is minimal.

It can be seen from Figure5-6 that NOx, CO_2 and energy figures between roadwork and traffic per year are comparable; while the difference in CO and PM is of 3 orders of magnitude. Although approximations were made in the calculation, it can be safely argued that the majority of fuel use and CO_2 comes from the trafficking vehicles on the road.

There are a couple of previous LCA studies of roads that have similar conclusion: 1) CO_2 from construction stage accounts for about 5% of the total including construction, maintenance and operation period (Inamura 1999) and, 2) the energy used for constructing the road equals that consumed by traffic on that road for about one year (The Highways Agency 2003). Moreover, this case study builds up the framework of applying LCA and VISSIM, two of the most influential tools in the transport area, to measure and compare the energy and key emissions on a road during its lifetime.

5.5. Limitations of Case Study

A number of pavement and process parameters for LCA of the roadwork are assumed the same as in Wolverhampton or London Heathrow T-5 project. The only traffic data available in this case study are daily average. It was distributed to each hour period, based on the UK profile (for all vehicles and for weekdays). For VISSIM simulation, data for peak hours may need to be detailed to every quarter hour, because vehicles on road during that time are affected more by one another which will change the overall travel delay and queue length.[11] One limitation of the EnvPro1.6 is that the speed of traffic for simulation must be lower than 70-80km/hr (43-50mi/hr) for most of the time (PTV and TORG 2004); on dual carriageways in the UK however, the speed limit is 50-70mi/hr (DSA 2004). In practice, when a roadwork is carried out that seriously brings down the traffic flow, vehicles on the affected road are normally

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[11] Personal communication with Sergio Grosso on 19 June 2007.

looking for diversion which will reduce the actual number of vehicles. This is more pronounced in urban areas.

It is not necessary to run the VISSIM and EnvPro for assessment of environmental impacts in every road project, notably where the roadwork has no significant effects on the traffic. For example, where the roadwork is carried out at night time (see traffic profile in Figure5-3), or a reasonable diversionary route within the area is available, there will be little disturbance to the traffic. Knowledge of the road network and traffic management by the contractor is needed to make a more accurate simulation.

Chapter 6 : Discussion

6.1. Waste Arisings and Use in Asphalt Pavements

The level of recycling in roads varies in the UK, due to the difference in, access to suitable natural aggregates and the capacity of local landfills. Other than technical barriers exist, for example, lack of infrastructure to collect the material, alternative use of the recycled material, and additional cost may inhibit the waste from being recycled into road structure. The government encourages recycling through legislation, purchasing power and grants that are offered to companies to help initiate recycling locally (QPA 2004). The use of recycled materials in asphalt pavements must have a value-added prospect; and is likely to be practical where there is a surplus that is otherwise destined for landfills.

From a technical perspective, asphalt in which well crushed glass (e.g. ≤4.75mm) replacing a few percent (e.g. 10-15%) of fine aggregates should not be excluded from use in asphalt surface layers, as glass particles are ground too finely to present any safety risks, and the PSV, AAV and affinity requirements apply only to coarse aggregates in the mixtures. However, this may pose a non-technical barrier as fine aggregates are only used in moderate amount in SMA and OGFC, where recycled SWM that can be used in larger size (e.g. steel slag) makes a better choice because of less processing requirements and a higher replacement rate. It is recognised that the replacement rate should be allowed to vary to the size of glass particles in use, and vice versa.

Steel slag should be used in place of coarse aggregates in surface asphalt, to make best use of its mechanical strength and skid resistance. Large particle size and high replacement rate are recommended by laboratory and trial results. The drawback is the high specific gravity of steel slag (3.2-3.6), if used in stone-dominated mixtures like SMA or OGFC, will drive up the overall mix density, implying an increase of transport cost. Volumetric stability (un-weathered slag particles tend to absorb moisture and expand) and leaching (of heavy metals) behaviour caused the most concerns. Precautionary treatment, e.g. natural weathering, is practised to reduce the free CaO/MgO content of steel slag prior to use as aggregates; and regular (e.g. twice a year) leaching test is recommended for use in roads and hydraulic structures.

In general, tyre rubber is used in asphalt mixtures to reduce cracking, improve durability and mitigate noise. Depending on the application, different variables need to be considered when assessing the technical performance of asphalt containing tyre rubber: binder properties in the wet process, and asphalt properties in the dry process. So far, most laboratory and field work has been focused on the 'wet' trial. It is generally agreed that asphalt rubber mixtures improves durability and low-temperature performance. On high-temperature performance, there are mixed views in the States ranging from better, equal or comparable, to worse. Results from the 'dry' trial so far are of limited number, and are far from conclusive. The wet process is more tolerant, whilst the dry process requires extra care in materials selection, mix design and asphalt manufacture. The economic break-even point in both applications is whether the increased cost (e.g. waste processing, higher binder usage) can be warranted by a return through longer pavement life. Life cycle cost analysis can be helpful to find out when and where the use of tyre rubber in asphalt is cost effective.

Recycled LDPE can substitute a portion of 15-30% of aggregates depending on its particle size and if properly designed, the rutting, cracking and aging performance of asphalt mixture may improve. Recycled PE accounting for 8% of the binder as a bitumen modifier, may also increase the mixture's mechanical stability. Similar to tyre rubber in the 'dry process', a number of asphalt properties when using recycled plastics are yet to be reported. In addition, the cost and environmental implications are unclear due to the limited practice to date.

Table 6-1 Waste Arisings in the UK and Application in Asphalt Pavements

	Waste arisings	Recycling rate	Use as aggregates	Use in asphalt pavements			
	Mt/yr	%	%	Aggregates	Replace rate (%)	Binder	Replace rate (%)
Glass	3.4	33	4.1	√	10-30	X	
Steel slag	0.75	100	98	√	30-62	X	
Scrap tyre	0.44	21	N/A	√	1-3	√	18-22
Plastics	2.8	5	0.29	√	15-30	√	8

√ indicates an option; X indicates not an option.

6.2. Introducing LCA to Asphalt Industry – Risks and Benefits

To date, the use of LCA in the Construction and Building Materials industry is mainly practised by the cement/concrete sector and in 'vertical' construction. Results and findings so far are of mixed value to the road building industry. Asphalt and concrete have been competing for use in road building for decades. There are some threats to the asphalt industry, or a company in their asphalt business, from not adopting LCA, especially when recycled materials are involved and alleviation of Company's environment footprint is on their business agenda. The risks include (Bird, Clarke et al. 2004):

- Lack of reliable and objective measures of Company's sustainability level in business development;
- 'Green-pursuit' actions or claims dwarfed by competitors whose efforts are backed by industry-accredited techniques;
- Loss of market share under client pressures (e.g. green procurement requirement); and
- Wrongly made 'green' claims can lead to bad publicity and even criminal liability.

In contrast, the benefits of initiating LCA studies can be as follows (Bird, Clarke et al. 2004):

- Provide an assessment tool to review and improve Company's supply chain management, and back their environmental declaration and labelling;
- Support Company's reporting on their products with a tool that can impartially and completely measure the environmental performance and compare against competing materials, rather than relying on existing models or databases that quite often are developed by commercial rivals with built-in bias or lack of transparency. Particular benefits of image arise if the Company's LCA tool becomes globally accepted as the industry standard;
- Increase market share by providing stakeholders with in-depth knowledge of the products and Company's sustainability objectives; and
- Provide a complementary dimension to the technical and economic studies, all

contributing to Company's life cycle management (LCM).

6.3. Summary of LCA Model and Key Points

Relations between worksheets in this model are described in Figure6-1. It can be seen that they are not parallel. Data in 'Energy and Emissions Inventory' need the input from 'Process Parameters'. Then the 'Inventory Results' are calculated into the unit of pavement object based on the input from 'Pavement Parameters' and 'Transport Distance'. The serial relations between data are also found within the same worksheet, such as the 'Energy and Emissions Inventory', in which the inventory of engines contributes to the inventory of transport vehicles and construction equipments.

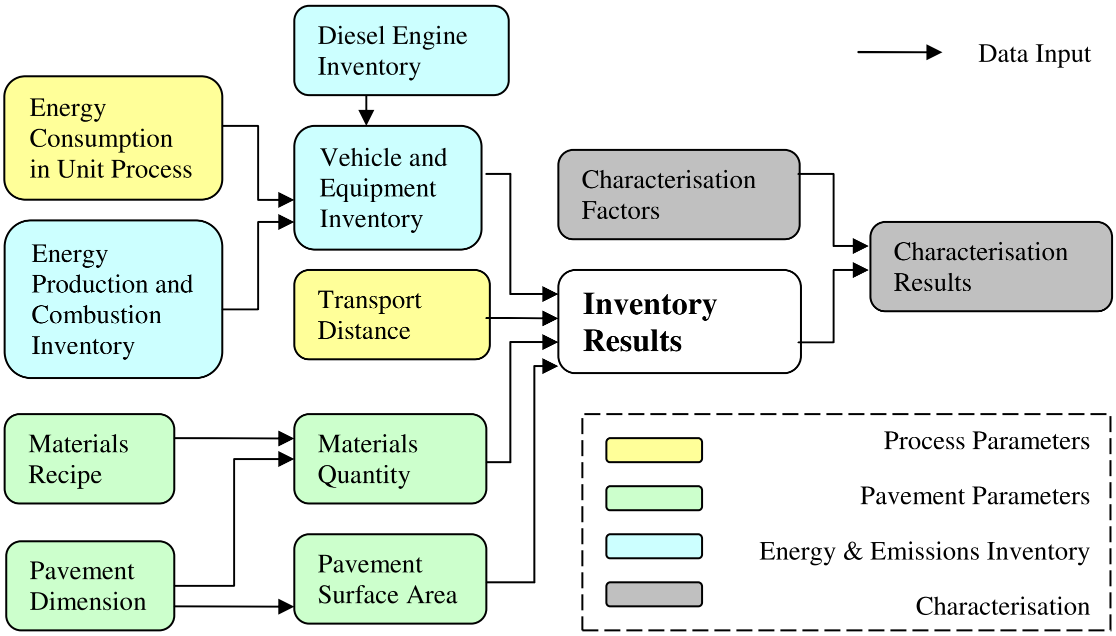


Figure 6-1 Relations between Worksheets in LCA Model

Fuel consumption in this model is presented in the unit of litre/km for trucks, and litre/hr for construction vehicles (e.g. roller). Relevant data normally are not found in manufacturer's manual or product brochure, but have to come from contractors on site, which makes the data acquisition in real case studies subject to commercial restriction. It is important to get the primary data correct (e.g. fossil fuel combustion, diesel engine emissions), as these data are used in a number of later calculations therefore a minor deviation at the beginning may lead to cumulative difference in the inventory results. The data quality fortunately, can be tested by the sensitivity check afterwards, like the LHR T-5 case study in Chapter 4.

Generally, Energy consumption in production of materials per tonne is in the descending order of: emulsifier (58.7GJ) > cement (5.1GJ) > bitumen (4.5GJ) > hot mix asphalt (0.42GJ) > emulsion (0.18GJ) > concrete (0.12GJ) > aggregates (0.07GJ) > cold mix asphalt (0.052GJ) > RAP (0.050GJ). 14t truck has the lowest fuel efficiency in terms of litres of diesel per tonne kilometre (0.94MJ/t*km), followed by the heavier 32t truck (0.46MJ/t*km), railway locomotive (0.17MJ/t*km) and cargo ship (0.13MJ/t*km). The data illustrated below refer to Table3-3 and Table3-5.

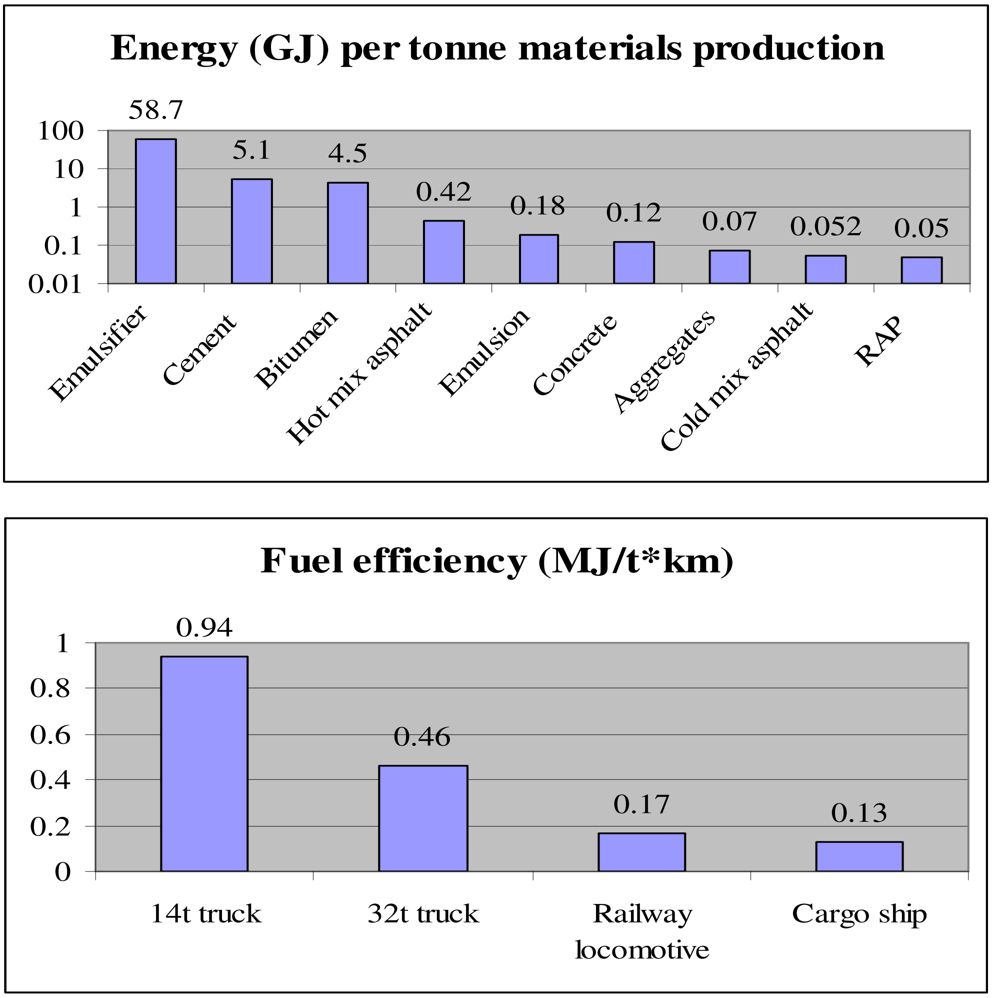


Figure 6-2 Energy Consumption in Production and Transport

It is useful to have the above knowledge in mind when design and deliver the project, as this will be the 'pro-active' approach to sustainable construction. There are certain trade-offs to consider when selecting the materials for a project. For example, cold mix asphalt saves gas oil for heating aggregates, while it consumes emulsifier which comes from energy hungry processes. More importantly, the selection of mixing method and bitumen content has to consider such issues like the durability of the asphalt product. Selection of transport mode and vehicles are often restrained by availability and the economics. Apart from the unit figures above, the energy input to a component material also depends on the tonnage of that material in the project. In transport process, the mileage might be a dictating factor.

A flowchart of the main phases in an asphalt pavements project is illustrated below:

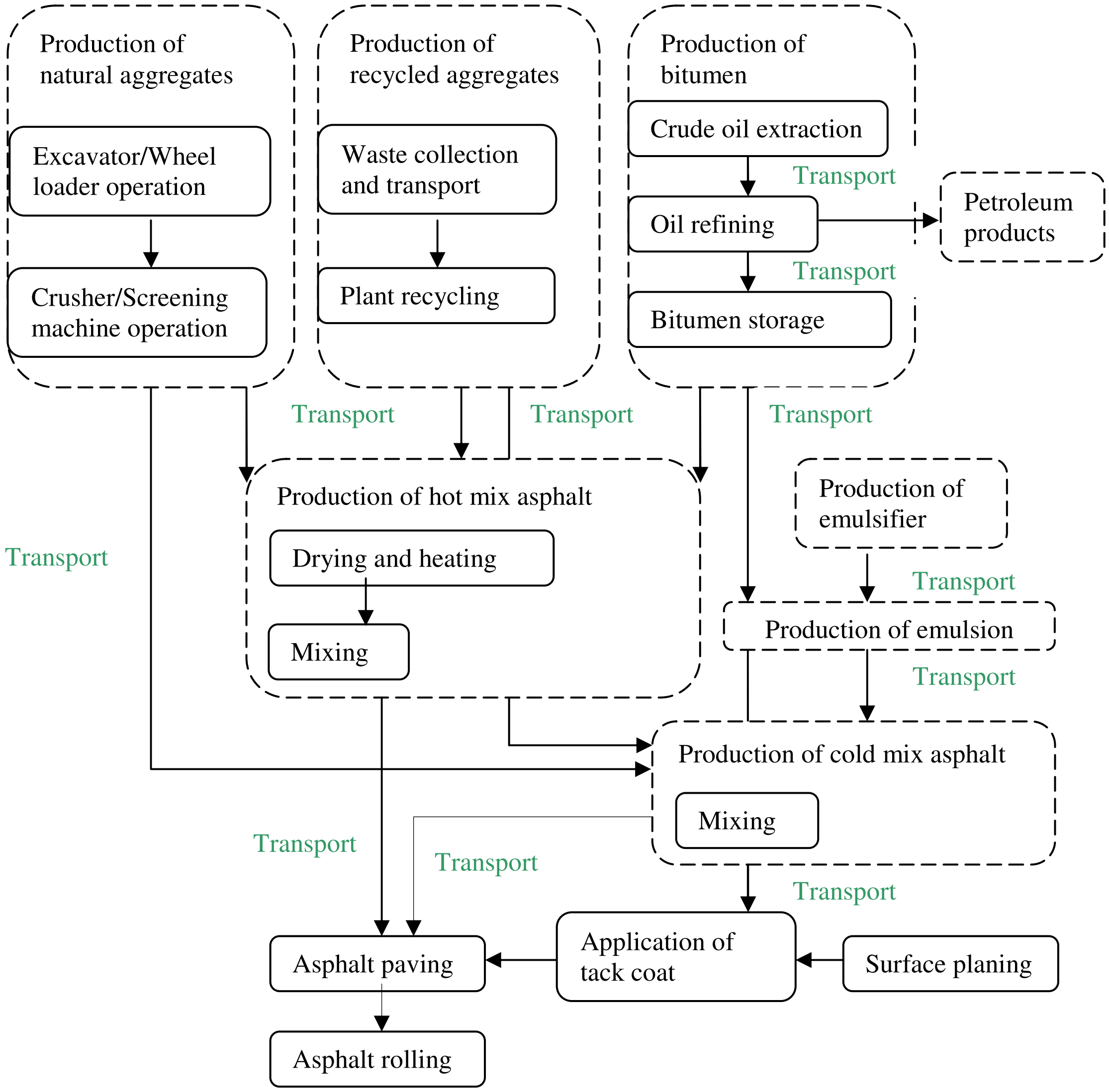
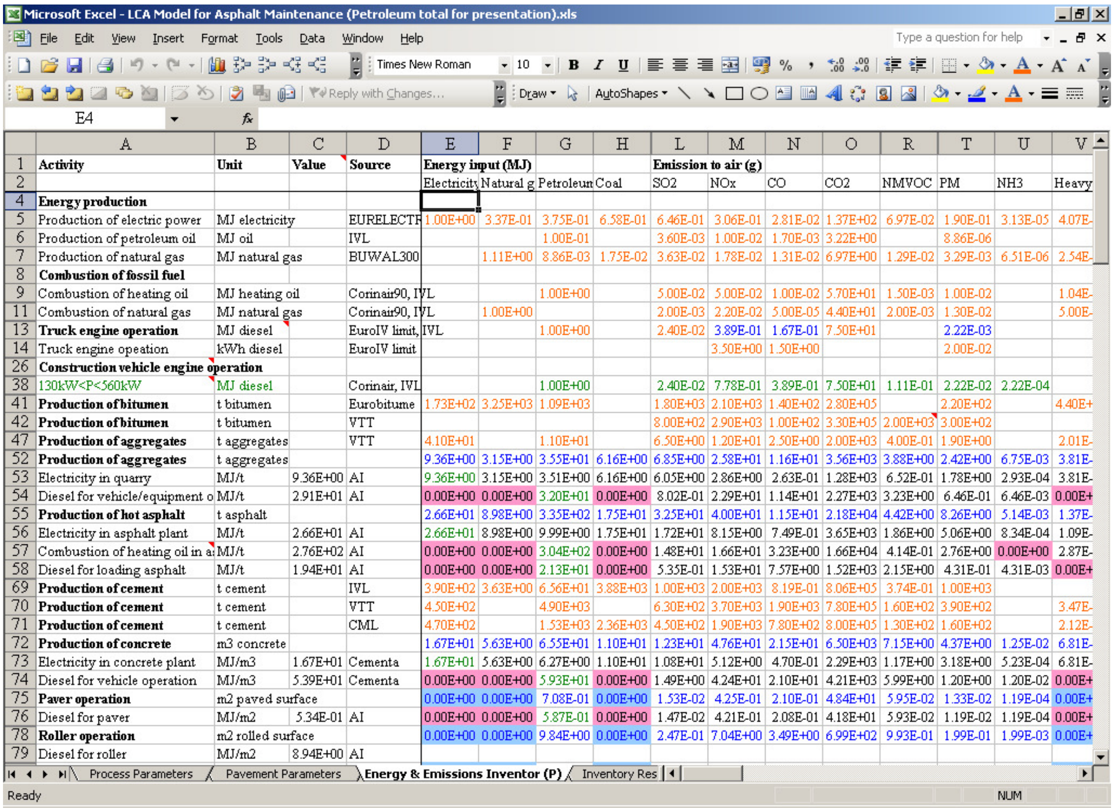


Figure 6-3 Unit Processes in Asphalt Pavement Project

It can be seen from the data acquisition above that, the key points in obtaining data for a LCA study include:

- ➢ Identify the appropriate data source; data should be up-to-date, recognised and the reference accessible;
- ➢ The boundary of data and any assumptions made should be unambiguously stated. Pay extra attention when data required in a process come from more than one place, as the data boundary and underlying assumptions in there may be different;
- ➢ In the case the required data are available from more than one source, state which one was selected for use in the model, and justify the selection. It is advisable to keep the rest active in the model (linked with other data by formulas), in addition to those selected, for sensitivity check and future data review;
- ➢ State the source of data wherever there is a data input.

One feature of this LCA model is that it breaks down the construction process to units on a level that data can be: 1) specific to a pavement object therefore the hypothesis is minimal and, 2) easy to collect and aggregate. Another advantage is that this model, during its development, is applied to, and tested by, real case studies that in return build up the scope of the model. Methodology and data sources in this model are not meant to be complete, but they provide a useful starting point.



	A	B	C	D	E	F	G	H	L	M	N	O	R	T	U	V
1	**Activity**	**Unit**	**Value**	**Source**	**Energy input (MJ)**				**Emission to air (g)**							
2					Electricity	Natural g	Petroleum	Coal	SO2	NOx	CO	CO2	NMVOC	PM	NH3	Heavy
4	**Energy production**															
5	Production of electric power	MJ electricity		EURELECTR	1.00E+00	3.37E-01	3.75E-01	6.58E-01	6.46E-01	3.06E-01	2.81E-02	1.37E+02	6.97E-02	1.90E-01	3.13E-05	4.07E-
6	Production of petroleum oil	MJ oil		IVL			1.00E-01		3.60E-03	1.00E-02	1.70E-03	3.22E+00		8.86E-06		
7	Production of natural gas	MJ natural gas		BUWAL300		1.11E+00	8.86E-03	1.75E-02	3.63E-02	1.78E-02	1.31E-02	6.97E+00	1.29E-02	3.29E-03	6.51E-06	2.54E-
8	**Combustion of fossil fuel**															
9	Combustion of heating oil	MJ heating oil		Corinair90, IVL			1.00E+00		5.00E-02	5.00E-02	1.00E-02	5.70E+01	1.50E-03	1.00E-02		1.04E-
11	Combustion of natural gas	MJ natural gas		Corinair90, IVL		1.00E+00			2.00E-03	2.20E-02	5.00E-05	4.40E+01	2.00E-03	1.30E-02		5.00E-
13	**Truck engine operation**	MJ diesel		EuroIV limit, IVL			1.00E+00		2.40E-02	3.89E-01	1.67E-01	7.50E+01		2.22E-03		
14	Truck engine opeation	kWh diesel		EuroIV limit						3.50E+00	1.50E+00			2.00E-02		
26	**Construction vehicle engine operation**															
38	130kW<P<560kW	MJ diesel		Corinair, IVL			1.00E+00		2.40E-02	7.78E-01	3.89E-01	7.50E+01	1.11E-01	2.22E-02	2.22E-04	
41	**Production of bitumen**	t bitumen		Eurobitume	1.73E+02	3.25E+03	1.09E+03		1.80E+03	2.10E+03	1.40E+02	2.80E+05		2.20E+02		4.40E+
42	**Production of bitumen**	t bitumen		VTT					8.00E+02	2.90E+03	1.00E+02	3.30E+05	2.00E+03	3.00E+02		
47	**Production of aggregates**	t aggregates		VTT	4.10E+01		1.10E+01		6.50E+00	1.20E+01	2.50E+00	2.00E+03	4.00E-01	1.90E+00		2.01E-
52	**Production of aggregates**	t aggregates			9.36E+00	3.15E+00	3.55E+01	6.16E+00	6.85E+00	2.58E+01	1.16E+01	3.56E+03	3.88E+00	2.42E+00	6.75E-03	3.81E-
53	Electricity in quarry	MJ/t	9.36E+00	AI	9.36E+00	3.15E+00	3.51E+00	6.16E+00	6.05E+00	2.86E+00	2.63E-01	1.28E+03	6.52E-01	1.78E+00	2.93E-04	3.81E-
54	Diesel for vehicle/equipment o	MJ/t	2.91E+01	AI	0.00E+00	0.00E+00	3.20E+01	0.00E+00	8.02E-01	2.29E+01	1.14E+01	2.27E+03	3.23E+00	6.46E-01	6.46E-03	0.00E+
55	**Production of hot asphalt**	t asphalt			2.66E+01	8.98E+00	3.35E+02	1.75E+01	3.25E+01	4.00E+01	1.15E+01	2.18E+04	4.42E+00	8.26E+00	5.14E-03	1.37E-
56	Electricity in asphalt plant	MJ/t	2.66E+01	AI	2.66E+01	8.98E+00	9.99E+00	1.75E+01	1.72E+01	8.15E+00	7.49E-01	3.65E+03	1.86E+00	5.06E+00	8.34E-04	1.09E-
57	Combustion of heating oil in a	MJ/t	2.76E+02	AI	0.00E+00	0.00E+00	3.04E+02	0.00E+00	1.48E+01	1.66E+01	3.23E+00	1.66E+04	4.14E-01	2.76E+00	0.00E+00	2.87E-
58	Diesel for loading asphalt	MJ/t	1.94E+01	AI	0.00E+00	0.00E+00	2.13E+01	0.00E+00	5.35E-01	1.53E+01	7.57E+00	1.52E+03	2.15E+00	4.31E-01	4.31E-03	0.00E+
69	**Production of cement**	t cement		IVL	3.90E+02	3.63E+00	6.56E+01	3.88E+03	1.00E+03	2.00E+03	8.19E-01	8.06E+05	3.74E-01	1.00E+03		
70	**Production of cement**	t cement		VTT	4.50E+02		4.90E+03		6.30E+02	3.70E+03	1.90E+03	7.80E+05	1.60E+02	3.90E+02		3.47E-
71	**Production of cement**	t cement		CML	4.70E+02		1.53E+03	2.36E+03	4.50E+02	1.90E+03	7.80E+02	8.00E+05	1.30E+02	1.60E+02		2.12E-
72	**Production of concrete**	m3 concrete			1.67E+01	5.63E+00	6.55E+01	1.10E+01	1.23E+01	4.76E+01	2.15E+01	6.50E+03	7.15E+00	4.37E+00	1.25E-02	6.81E-
73	Electricity in concrete plant	MJ/m3	1.67E+01	Cementa	1.67E+01	5.63E+00	6.27E+00	1.10E+01	1.08E+01	5.12E+00	4.70E-01	2.29E+03	1.17E+00	3.18E+00	5.23E-04	6.81E-
74	Diesel for vehicle operation	MJ/m3	5.39E+01	Cementa	0.00E+00	0.00E+00	5.93E+01	0.00E+00	1.49E+00	4.24E+01	2.10E+01	4.21E+03	5.99E+00	1.20E+00	1.20E-02	0.00E+
75	**Paver operation**	m2 paved surface			0.00E+00	0.00E+00	7.08E-01	0.00E+00	1.53E-02	4.25E-01	2.10E-01	4.84E+01	5.95E-02	1.33E-02	1.19E-04	0.00E+
76	Diesel for paver	MJ/m2	5.34E-01	AI	0.00E+00	0.00E+00	5.87E-01	0.00E+00	1.47E-02	4.21E-01	2.08E-01	4.18E+01	5.93E-02	1.19E-02	1.19E-04	0.00E+
78	**Roller operation**	m2 rolled surface			0.00E+00	0.00E+00	9.84E+00	0.00E+00	2.47E-01	7.04E+00	3.49E+00	6.99E+02	9.93E-01	1.99E-01	1.99E-03	0.00E+
79	Diesel for roller	MJ/m2	8.94E+00	AI												

Figure 6-4 Snapshot of the LCA Spreadsheet in Microsoft Excel

6.4. Improvement through Case Studies

It can be seen from the two case studies in Chapter4 the improvement of this LCA model during the development, what other details were considered in the asphalt pavement project, how the second case study learned from the first one and applied the findings, and how the LCA model and case studies will benefit from each other's advancement. The main improvements include:

- While the first case study built up the framework of LCA model and the mechanism for data collection; the second one focused on the technical details of the project, the accuracy of analysis, and improvement of the model;
- The communication skills with contractors, make concise and to-the-point questionnaire (see Appendix1 and Appendix2);
- The level of details and sophistication of the model, when the calculation process becomes swift and more adaptive at the same time;
- The incorporation of up-to-date and alternative data sources, rather than rely on a low number of references which is prone to limit the scope and accuracy of any LCA study;
- The presentation of results, featured by graphic illustration and data quality analysis (check for completeness, sensitivity and consistency);
- The development of LCIA phase, provide both the mandatory and optional elements addressed in the ISO 14040 series.

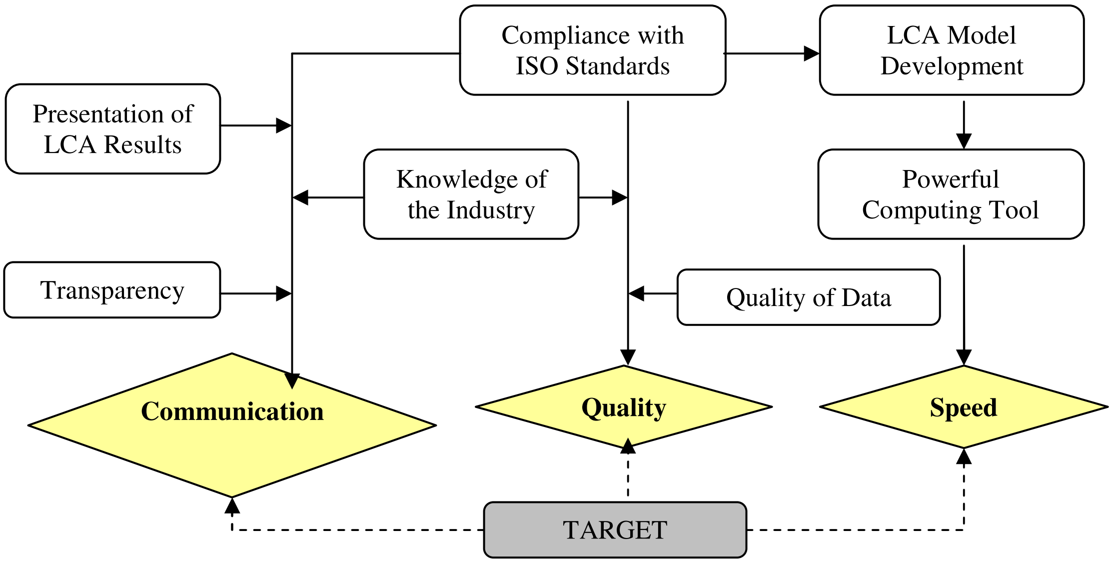


Figure 6-5 Elements for a Successful LCA Study of Asphalt Pavements

6.5. Challenges and Further Work

In general, energy related emissions can be calculated with relatively high accuracy, by tracing the energy consumption through the process. Non-energy related emissions (e.g. emissions from hot asphalt) however, are difficult to measure and quantify. For instance, emissions and dust are the major concerns in environmental regulation of an asphalt plant (Read and Whiteoak 2003), yet the life cycle inventory of production of hot mix asphalt in this model did not include those loadings, for relevant data are not available.

One of the essences of LCA is transparency. That is, a user or future developer of the model will be able to tell where data in the model came from, and what assumptions were made. This is achieved in this model by providing the data alongside a description of the source of that data, assumptions made, and data quality check at the end of the case study (see Chapter4).

More processes in road works need to be studied, and relevant data included in the model. Continue to collect data, on both the new processes (e.g. cold in-situ recycling) or materials (e.g. Sasobit), and those already represented in the model but being outdated. As for secondary aggregates, materials associations are potential sources of data on the manufacturing and recycling process. A method is needed to allocate (energy and emissions) data to the waste recycled for use as aggregates, as 1) it is an open-loop recycling, and 2) the collection and recycling process normally deals with more than one type of solid waste.

This study mainly quantified the energy use through the construction processes, and calculated the associated environmental loadings. The main scope is that it did not include many inventory data on non-energy related impacts, for instance, the emissions from freshly paved hot asphalt when it cools down from 180ºC to 20ºC. Fortunately, the asphalt industry (roofing, road paving) has begun to quantify those impacts with a concern over the effects they have on occupational health (BG Academy 2007). Research results and publications are likely to shed a light on the improvement of inventory data on such non-energy related impacts in the future. Company's IPPC (Integrated Pollution Prevention and Control) application documents for their sites or plants also could be potential sources of data on those 'process related' emissions.[12] The EU IPPC Directive of 1996 is based on several principles, namely: 1) an integrated approach, 2) best available techniques (BAT), 3) flexibility, and 4) public participation. The progress that each individual industry is complying with this Directive can be found at the EU IPPC Bureau's website (EU IPPC Bureau 2007).

The reasons for focusing on the structural aspects of asphalt pavements are 1) to give the prediction of pavement life time on scientific basis, and 2) to reduce subjective factors related to locality (e.g. noise) or value choices (e.g. anti-skid requirement). Earthworks (site clearance, drainage system, etc.) are not included in the model. This model deals mainly with asphalt materials and down to the base layer in pavement structure. It is recognised that new construction and some deep recycling may involve foundation and concrete materials laid before.

The use of recycled materials in asphalt pavements is relatively new in practice, with limited information on the materials behaviour over time and at what frequency the pavement needs to be repaired. This explains the difficulty in predicting pavement life, a key factor affecting the workloads in a road LCA study. Although fuel consumption

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[12] Personal communication with Professor Tom Donnelly on 30 May 2006.

by traffic on the finished roads was included in VTT's study, it was noted to vary with too many factors, such as mixture type, surface unevenness (roughness), season in a year, pavement age, tyre type and travel speed, to name only a few. Therefore it is advisable to assume it equal in comparative LCA studies.

Some engineering performance (e.g. the rolling resistance) of the pavement has the effect not only on riding quality or fuel efficiency, but durability of the pavement itself, as it changes the impact from traffic tyres on the pavement surface (Cebon 1999). Maintenance during service life normally causes traffic delay due to lane closure or route diversion, and subsequently additional fuel use and tailpipe pollution. To include this factor in the LCA model needs the inputs from micro-simulation model and traffic emissions model. Little information so far is available on the recyclability of pavement containing secondary materials. These variables might be included in the road LCA model in the future, provided the relevant information required for a LCA study becomes conclusive.

Chapter 7 : Conclusion and Recommendations

7.1. Conclusion

The scale of resources used, and waste generated has placed the construction industry in the position where it can either greatly contribute to, or considerably impede, society's progress towards sustainable development. Recycling in roads is an important means by which the asphalt industry could play a role in sustainable construction. Simply taking recycled materials does not guarantee a sustainable or 'green' outcome, but it is commonly perceived as a means to that end. Approval for use in pavement structure is given by road authorities to an expanding list of recycled materials, although the cost of recycling, in both financial and environmental terms, calls for high-end uses of those recycled materials. For any attempted application, both the specification and technical properties of the material need to be studied, to ensure the physical integrity of pavement structure will not be compromised as a result of the recycling.

Replacing natural aggregates with recycled and secondary in asphalt pavements reduces landfill pressures and quarrying demands, complements other solid waste management efforts providing an alternative outlet for the waste otherwise destined for landfill (e.g. the excess of colour mixed glass when supply exceeds the capacity of colour sorting facilities). Waste materials from local sources or even on-site (e.g. the RAP) can reduce the transport required for virgin aggregates; some components (e.g. revitalised bitumen in the RAP) reduce the input of materials whose production is made of energy intensive processes. These environmental benefits however, need to be quantified and compared against those 'penalties' that must be paid by the recycling if it requires additional transport and processing efforts. Procurement documents for pavement construction regarding the laying techniques, materials and maintenance options ask for prescriptive environmental assessment. Comparative studies are needed to investigate the many impacts that arise from alternative practices, to ensure that the pavement project is carried out with the least environmental impacts in terms of energy use, emissions and leaching, etc.

Life cycle assessment makes an important part of the 'life cycle thinking' as a tool to support decision making. To duly reflect the current practice in road construction, the LCA model should encapsulate maintenance and recycling scenarios, with data specific to the UK road industry. The ideal model should be flexible enough to add, delete, combine and divide component units to adapt to a particular pavement object, with minimum repetitive work. To achieve that, the model should represent as many variables in a pavement object as possible, whilst remaining flexible for data update and formula revision in the future. A practical model must be populated with good quality data. The key environmental loadings specific to a pavement object should be present in the inventory. A practical model must also be tested and calibrated through real road projects. Data in this LCA model come from a mixed source of UK plants, EU standards and relevant LCA results and databases. Methodology follows the ISO14040 series and BRE's 'Environmental Profiles'. LCA practice in road construction by Nordic institutions (IVL, VTT, DTU, etc) is referred by this thesis.

It is the case studies that built up the scope and capacity of this LCA model during its development. This LCA model is applied, during its development, to 3 case studies of asphalt paving in the UK. The first case study (the Wolverhampton) established the framework of the LCA model and the mechanism for data collection. The second one (the LHR Terminal-5) focused on the technical details of the project, the accuracy of analysis, and the calibration of the model. The third one (Stoke-on-Trent) compared the energy and emissions of the roadwork measured by LCA, with those coming from the disturbed traffic due to the roadwork. The scope of the model is built up, and the accuracy of modelling and computing capacity enhanced, as a result.

LCA has its limitations. Firstly, it displays no sensitivity to location. PM_{10} emissions for example, the health and environmental impacts can be quite different if it comes from an asphalt plant where it is normally retained and treated, other than released from tail pipe in an unleashed state. The receiving media and its bearing capacity therefore need to be considered. Secondly, it has no sensitivity to time. High level of emissions for a short period will have the same LCA results as low level of emissions for a long period as long as the total amount equates. Complementary tools (e.g. risk assessment) might be welcome to the particular needs in a project through a 'hybrid' approach. Thirdly, the methodology for some stages of LCIA is yet to be developed and agreed. Finally, aiming to provide an objective assessment tool, subjectivity literally exists in every phase of LCA; and being more comprehensive goes easily to greater potential of bias. Based on these limitations, LCA is likely to be better received within a company or trade union, where there is shared agreement on methodology, assumptions and value choice.

The aim of applying LCA to the road industry is not necessarily to argue for the use of recycled materials in whatever possible circumstances. Rather, it provides an objective and complete review of the many environmental impacts of asphalt pavements from materials quarrying and transport, to asphalt manufacture, placement and disposal. The aim is to reduce the environmental impacts by identifying the 'critical' stages and aspects that make the priority areas upon which to act. Besides, the case studies indicate that LCA can play a role in a much wider context in the road industry, through other comparative studies. It is recognised however, that the LCA result alone does not make the final decision, that environmental assessment must be placed alongside the outcome of technical and economic studies.

There are a couple of similarities between the economic and environmental implications of road maintenance works. One is that the majority of both impacts are borne by road users; the other is the reiterative nature of the assessment that requires the maintenance implications be taken into account when assessing alternative maintenance options for a particular maintenance task or a profile of tasks over the road's lifetime. From this point of view, life cycle assessment (LCA) and whole life costing (WLC) or life cycle cost analysis (LCCA) share the same methodology. The measures that highway authorities could take to reduce the impacts from maintenance works on road users include effective traffic management (lane closure, traffic diversion) and phasing of maintenance works into off-peak hours (night work), etc.

7.2. Recommendations for Further Work

The use of recycled materials in road structures is relatively new in practice. The lack of sufficient historical data on pavement life using recycled materials calls for a method of prediction or estimation, on a scientific basis. Similarly, arguments exist over the type, rate and position of the pavement structure that recycled materials should be applied. The findings for some recycled materials are yet to be conclusive. Again, to solve these disputes needs more laboratory and trial works, and long-term observation afterwards. Innovative pavement design method (e.g. the EME2) or revision of specification of highway materials might as a result, inspire some research and practice on the use, where appropriate, of other recycled materials in the asphalt pavements.

The selection of data sources for the developing LCA model is a compromise between accuracy and simplicity. Still there is room for improving both the wealth and quality of data fed to a LCA study. LCA in road practice is relatively new, inventory data on some materials and processes are yet to be available. On the other hand, innovative materials (e.g. Sasobit) and techniques (e.g. 'hot on hot' - dual layer asphalt paving[13]) emerge in response to the industry improvement, which requires an expanding database for LCA practitioners that can accommodate these novelties. Often the required data for a unit process come from more than one source, in which case the compatibility (date, boundary, underlying assumptions, etc.) of the data needs to be studied. Data acquisition for LCA is further hurdled by the fact that some proprietary data (e.g. fuel consumption of trucks) are not available due to commercial restriction. In summary, the main challenges of LCA in road practice include:

- Include non-energy (process) related emissions in the model;
- Look for energy/inventory data on more recycled materials, pay particular attention to the most significant variables, such as the transport (distance, fuel efficiency, etc);
- Predict the life expectancy, and the way of disposal, of pavement layers made using recycled materials;
- Include the environmental impacts of road works (maintenance, repair, etc) in the model and, if possible, the effect of road works on traffic and subsequently the fuel consumption and emissions, using micro-simulation model (e.g. VISSIM).

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[13] The 4 biggest advantages of dual layer asphalt paving is thinner surface course, better bonding between surface and binder course, allow for cold weather work, and speed construction.

Despite the challenges above, the LCA is being accepted by the road industry to measure and compare the life time environmental impacts of its product or process, and use the results for internal review or environmental labelling. Recommended applications of LCA in road paving include the comparison of:

- Different asphalt composition and materials usage (like the Wolverhampton case study);
- Recycled materials with virgin aggregates (like the LHR T5 case study);
- Different recycled materials (glass, RAP, etc.);
- Different laying/recycling techniques (hot ex-situ, cold in-situ, etc.) and maintenance options (depth, interval, etc.);
- Asphalt with concrete (standard recipe for both, same function in the pavement layer.

Selections as above are normally restrained by the availability and economics. The LCA should aim to provide an environmental perspective to the decision making, where applicable, the multi-criteria analysis can be carried out considering the outcomes of technical, environmental and economic studies, all on a life cycle basis.

Despite the ‘iterative’ nature of LCA that findings from a later phase may prompt some revision of earlier elements, and the difficulties in collecting data and making comparison between candidate proposals in a road project at the design stage, it is advisable to study by LCA the potential impacts of these alternatives prior to the practice. For example, how long is the maximum distance of waste haulage that can justify the recycling cost in a project? To do this requires the support from reliable technical data, as well as a sound analysis to enhance the level of acceptance of the results. The aim is to further test and calibrate the model, in an improvement context, as a decision supporting tool for the UK road industry.

Despite that previous LCA studies have questioned the environmental benefits of recycling some waste (e.g. glass) for use as aggregates based on such impacts as carbon footprint, it is advisable to study by LCA the environmental effects of recycling in pavement projects, due to the ‘site specific’ characteristics of road works including materials selection and transport scenario. More importantly, these two types of LCA studies normally do not share the same functional unit or system boundary. For instance, in LCA of glass, the functional unit is packaging a certain volume of liquid, while the functional unit in LCA of roads is the provision of a certain area of asphalt surface on the carriageway. Therefore, the LCA results of such ‘close-loop’ recycling do not negate the environmental benefits of ‘open-loop’ recycling that could be identified by LCA using different functional unit.

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Appendix 1: Data Request and Assumptions in the LCA Study of Wolverhampton Inlay Project Questionnaire

To proceed with the research, some strategic as well as detailed information of the project is needed. Please refer to the document submitted on 27/04/2005 for context, and provide answers to following questions in greatest details at your best knowledge. Any comments and suggestions are welcome. In case the information to a particular question is not available, please give the name and number/email of the person who may possess the answer.

1. What type of data is to be used in the project?

A. Industry typical

B. Project specific

C. Both, but industry typical preferably

D. Both, but project specific preferably

Name and phone/email: ___________________________

2. What is the end-point boundary of this LCA study?

A. End of inlay work (finish rolling)

B. End of proposed pavement service life (15 years ahead)

C. Other, please specify _B above is almost correct but the proposed solution is intended to give a sound asphalt base/binder course so that future surfacing is limited to the top 35mm rather than repeating the 100mm plane out and replace maintenance cycle that existed previously

Name and phone/email: ___________________________

3. On what basis shall the environmental loadings of crude oil distillation be allocated among the many co-products? (This is to calculate the environmental costs of bitumen production)

A. By volume of product

B. By value per litre of product

C. By volume times value/litre

D. Other, please specify ______not sure I fully understand this one

Name and phone/email: ___________________________

4. What is the treatment scenario of old pavement surface? (This is to define the type of vehicle used in that process)

A. Repave, please provide details _________________________

B. Remix, please provide details _________________________

C. Tack coat before paving fresh asphalt, please provide details – K-140 at 0.2 kg / m2 of residual binder on bottom layer and 0.15 kg / m2 for upper layer

D. Other, please specify _I will need to speak with you on scenarios A & B these were not proposed by WMBC to my knowledge

N*ame and phone/email:* ___________________________

5. Do the environmental loadings specified (in Part 4 of the 27/04/2005 document) represent the most common and significant of those in the project?

A. Yes, but reference behind should be detailed and justified

B. Yes, but some additional need to be added in (please specify _______________) and some irrelevant to be deleted (please specify ________________) from the list

C. No, we have our own list of the significant, please provide the detail ___________

D. No, we need to establish our own list of the significant

Name and phone/email: ___________________________

6. Are the assumptions made (in Part 6 of the 27/04/2005 document) appropriate?

A. Transport distance and machinery used in both proposals are identical: Yes ☐ No ☐ Only Yes if supply was won by AI for both proposals

B. Transport machinery is used at 'maximum load', 'full speed' and 'empty return': Yes ☐ No☐

C. Road paver and roller are used at 'full speed' and 'full width': Yes ☐ No ☐

(Please specify your requirement if you give 'No' to an assumption ____________)

Name and phone/email: ___________________________

7. What is the composition of the asphalt?

Surface course (coarse: fine: filler: binder): 64.5; 23; 7.6; 4.9

Binder course (coarse: fine: filler: binder): as above

Name and phone/email: ___________________________

8. Please provide the information of vehicles used in the inlay sequence:

		Make & Model	Working Capacity	Engine Power	Agree with the assumptions in 6?	
Equipment				MJ	Yes, calculated work hours*	No, actual work hours
Excavator			t/hr			
Loader (dumper truck, hopper)			t/hr			
Conveyor			t/hr			
Crusher			t/hr			
Screening machine			t/hr			
Oil refinery			litre/hr			
Lorry			t * (Km/hr)			
Dryer and heater		BENNINGHOVEN	240 t/hr			
Mixer		AS ABOVE	240 t/hr			
Paver			(Km/hr) * m			
Roller	Initial		(Km/hr) * m			
	Main		(Km/hr) * m			
	Finish		(Km/hr) * m			
Others						

* indicates items to be completed by the author

Name and phone/email: _try Dean Floyd[14] *at Kennedy's for site information – I will inform you of most appropriate plant person*

9. In project where secondary aggregates (e.g. plastics, scrap tyres) are involved, to what stage in the life cycle shall the environmental loadings of the recycled material be traced?

A. Raw material acquisition

B. Waste collection

C. Recycled product ready for aggregates use

D. Other, please specify ________________________

Name and phone/email: __________________________

10. Is a commercial database/model considered for purchase and use in future work?

A. Yes, Boustead Model 5.0 (£1,500)

---

[14] Surfacing Estimator, Tel: 0121 568 7918.

B. Yes, but consider alternative product, please specify ______________

C. Yes, but talk about it later

[✓ D. No, try to establish our own database]

Name and phone/email: __________________________

11. Comments and suggestions for future work:

____

____

____

Questionnaire made By Yue Huang Yue.Huang@ncl.ac.uk
At 19/05/2005

Completed by Bob Allen[15] on 01/06/2005

The author also appreciates the time the following people took to provide data and advice for this case study: Dean Floyd, Doug Ross from Aggregated Industries UK Ltd., Ian Chattington from Power Plane Ltd., Danny Taylor from H&D Haulage, and Mr G. Pratt from HR International Crushing& Screening Ltd.

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[15] Research Manager, Aggregate Industries, Tel: 0133 537 2242.

Appendix 2: Data Request for LCA Study of London Heathrow (LHR) Terminal 5 Project to Aggregate Industries UK Ltd

Data from materials supply side are needed for Life Cycle Assessment (LCA) study of London Heathrow Terminal 5 Project. Please provide data in following tables at your best knowledge. Any comments and suggestions are welcome. In the case a particular data is not available, please give the name and contact of the person who may have the answer.

Table1. Pavement Parameters

	Pavement Parameter	**Figure**	**Unit**
Surface Course	Life expectancy	12	yrs
	Area	30,000	m^2
	Layer thickness	35	mm
	Mixture type	14mm smatex	(e.g. 0/14mm SMA)
	Mixture weight	1890	tonne
	Materials breakdown	73:15:6:6	(e.g. coarse:fine:filler:binder)
Tack Coat I	Area	30.000	m^2
	Emulsion usage	0.4 lts m2	kg/m^2
	Bitumen content	60	%
Binder Course	Life expectancy	15	yrs
	Area	30000	m^2
	Layer thickness	65	mm
	Mixture type	20mm hmb	(e.g. 0/20mm HDM)
	Mixture weight	4100	tonne
	Materials breakdown	58.6:34:3:4.4	(e.g. coarse:fine:filler:binder). Glass used in fines 10%, Incinerator bottom Ash used in coarse 10%
Tack Coat II	Area	30000	m^2
	Emulsion usage	.0.4 lt m2	kg/m^2
	Bitumen content	60	%
Base	Life expectancy	15	yrs
	Area	30000	m^2
	Layer thickness	205	mm
	Mixture type	28mm hmb	(e.g. 0/20mm DBM)
	Mixture weight	12915	tonne
	Materials breakdown	58:34:3:4	(e.g. coarse:fine:filler:binder) Glass used in fines 10%, Incinerator bottom Ash used in coarse 10%

Note:

1. Please specify here if recycled materials (e.g. glass) were used including the type, grading, position in the pavement and replacement rate (percent of aggregates), etc.

Note above for Glass and IBA inclusion. In addition 25% of RAP would have been used. This is 48 % coarse, 47% fine and 5% binder

2. Please specify here any particular nature of the binder (e.g. PMB) in use.

Binder course and Base would have used 35 pen straight run binder. The SMA would be 50 pen straight binder with 0.4%, of total mix, of fibre.

Table2. Transport Distance (unit: km)

Materials	From	To	Figure	Application
Coarse aggregates	Quarry	Asphalt plant		HMA
Coarse aggregates	Quarry	Road site		Unbound
Fine aggregates	Quarry	Asphalt plant		HMA
Fine aggregates	Quarry	Road site		Unbound
Filler	Quarry	Asphalt plant		HMA
Filler	Quarry	Road site		Unbound
Bitumen	Refinery	Asphalt plant		HMA
Asphalt	Asphalt plant	Road site		HMA
Bitumen emulsion	Emulsion plant	Road site		Tack coat

Note:

3. Please make changes in the Table if the origin/destination was different from indicated, or add in new items if additional materials (e.g. recycled, PMB) were involved.

Distance by rail Bardon Hill quarry to West Drayton is 120 miles each way. Fuel consumption of mainline locomotives is 8-9 litres/mile. Payload of train to West Drayton is 1729t therefore 0.85 litres were used to transport a tonne of aggregate between BHQ and WD.[16]

Table3. Vehicle/Plant Parameters

Process		**Make&Model**	**Capacity**	**Fuel consumption**		**Unit**
				F-load	E-load	
Truck transport	Aggregates		tonne			litre/km
	Bitumen		tonne			litre/km
	Asphalt		tonne			litre/km
	Bitumen emulsion		tonne			litre/km
Aggregates production		Quarry plant				tonne/kWh
						tonne/litre
Asphalt mixing		Asphalt plant		Drying cost £2.65		tonne/kWh
						tonne/litre
Applying tack coat			Note5	6.0		litre/hr
Paving			Note5	16.87		litre/hr
Rolling			Note5	12.5		litre/hr

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[16] Email communication on 10/10/2006 with Simon Blake, National Rail Manager, Bardon Aggregates, Tel: 0145 528 8204, Mobile: 0777 028 3533.

Note:

4. Transport trucks are assumed to be used at ‘full load’ and ‘empty on return’.

5. Working capacity for emulsion applier, paver and roller includes the following parameters:

	Unit	Emulsion applier	Paver	Roller
Width of screed/roller	m	Width 2m	4.9 m	1.7m
Working speed	km/hr	20	3.0	6.0

6. Please provide other relevant information on materials and process of this project:

____

____

____

Data requested by Yue Huang on 19/09/2006

Mobile: 07877379249, Email: Yue.Huang@ncl.ac.uk

Completed by Mark Kirby[17] and Phil Coupland[18] on 21/12/2006

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[17] Contracts Manager, Associated Asphalt, Mobile: 0787 644 0758.

[18] Area Technical Manager, Bardon Aggregates, Mobile: 0774 093 4019, Tel: 0189 544 2852.

Appendix 3: Users' Manual of LCA Model and Description of Formulas

In Chapter 3, the structure of the LCA model is described together with the relations between worksheets in it. This manual will explain in greater detail how data in those worksheets are linked by formulas, and give advice on how to run the model, interpret and present the outputs. This manual mainly refers to contents in Chapter 3 and the LCA spreadsheet in Microsoft Excel.

Table1. Worksheets in LCA Model

Worksheet	Description	Sub-worksheet
Process Parameters	Data on transport distance and fuel efficiency, energy consumption of unit processes in a pavement project	'Energy in transport' 'Energy in materials production' 'Energy in pavement construction'
Pavement Parameters	Data on pavement dimension and materials recipe, determine the materials tonnage in a pavement project	'Pavement dimension' 'Materials recipe' 'Pavement life time'
Energy and Emissions Inventory	Inventory data available for 'primary' processes are presented. LCI figures for unit operation of transport, materials production and pavement construction are calculated with formulas	'Energy production' 'Combustion of fossil fuel' 'Transport vehicle operation' 'Construction vehicle operation'
Inventory Results	LCI data on 'energy and emissions' are aggregated into the unit of the pavement project	'Production process' 'Transport process' 'Construction process'
Characterisation Results	LCI results assigned to defined impact categories, characterised by selected model and presented by category indicators	'Global warming' 'Acidification' 'Photo-oxidant formation' 'Human toxicity' 'Eco-toxicity' 'Eutrophication'

1. General Principles in Worksheets

1. In the spreadsheet, data in orange indicate raw data inputs. Data in green are specific to a project. Data in blue are either the total of a process, or the figure for calculation in following worksheets. Data in red are for checking purpose.
2. Each raw data is manually put in the spreadsheet only once, and referred by formulas to all following calculations. Should the data be changed in the future, for example due to industry improvement or for sensitivity check purpose, it can be done by altering a single number in the spreadsheet.
3. Calculated results are presented (not rounded) to the same decimal places as raw data in that process.

4. Data from contractors of a project (Aggregate Industries UK Ltd in both case studies) are preferred to alternatives for use in case study of that project. Raw data are presented alongside its source.
5. Be aware of the comments attached to a cell for additional information.

2. Process Parameters

2.1. Calorific Value of Different Types of Energy

'Mega Joules' (MJ) is the universal unit in this model for energy input including electric power, petroleum fuel (diesel, heating oil, LPG), natural gas and coal. These types of energy are normally measured in kWh, litre (or kg), m^3 and kg, respectively. Conversion factors are given in DTI's DUKE (Digest of UK Energy Statistics). The density of petroleum fuel (diesel, heating oil, etc) is assumed, as litre is prevailingly used for measurement of their consumption. (Table3-2 in Chapter 3)

2.2. Energy in Materials Production

In materials production, raw energy data (electric power, diesel, heating oil) presented other than in MJ/tonne are converted using the calorific value described above. (Table3-3 in Chapter 3) These types of energy have different environmental loadings in their production (see in 'Energy and Emissions' worksheet). This worksheet gives both the sum and individual type of energy consumed in a process.

2.3. Energy in Transport

Transport scenarios in a pavement project are illustrated in Figure3-11 in Chapter 3. The mode and length of transport vary between different projects. Distance measured in mile will be converted to km (conversion factor: 1.61). Fuel consumption is normally measured in litre/km. The difference is noted when the vehicle is full-loaded or on empty return and, if available, the average data should be used.

2.4. Energy in Pavement Construction

2.4.1. Applying Tack Coat

Some parameters (e.g. ramp width, emulsion usage, applying speed) of an emulsion applier from IVL are presented in the worksheet for reference use. The applying speed is tired up with the emulsion usage.

$$EnergyForSpreader(l/m^2) = \frac{FuelConsumption(l/hr)}{RampWidth(m) \times ApplyingSpeed(m/hr)}$$

2.4.2. Asphalt Paving and Rolling

The range of data is mentioned in the comment attached to a cell where a figure is selected to represent that process. Fuel consumption of paver and roller is calculated the same way as the emulsion applier above. Effective working time is assumed to be 50min/hr. There is LPG consumption in the paving process, for heating the screed. The number of passes is a parameter for the rolling process.

$$EnergyForPaver(l/m^2) = \frac{DieselConsumption(l/hr)}{ScreedWidth(m) \times PavingSpeed(m/hr)} + LPG(l/m^2)$$

$$EnergyForRoller(l/m^2) = \frac{FuelConsumption(l/hr)}{RollerWidth(m) \times RollingSpeed(m/hr) \times NumberOfPasses}$$

2.4.3. Other Processes

Diesel and LPG are consumed in asphalt remixer (hot in-situ recycling) for engine operation and heating, respectively. Data on some other pavement processes (applying chippings, cold milling, slip form paving, etc.) are also available from IVL's database. Make and model of the machinery in use however, are not stated.

3. Pavement Parameters

3.1. Pavement Life Time

The pavement life expectancy in neither case study is definitive. In Wolverhampton project, the life time of surface and binder course is defined on an arbitrary basis. The scope of LCA of London Heathrow T5 project is constrained to the construction phase. An ideal functional unit for LCA of road construction is the total environmental loadings from construction and maintenance of the pavement in 40-50 years' time, divided by pavement area or road mileage. Reliable data are needed to predict the life expectancy of pavement layers containing recycled materials, as well as the nature and amount of maintenance work in specified time period.

$$FunctionalUnit = \frac{TotalEnviornmentalLoadingsInSpecifiedTimePeriod}{PavementSurfaceArea}$$

3.2. Pavement Dimension

Knowing the dimension of pavement layers can help estimate the asphalt tonnage, although the tonnage is known in both case studies. Some thick layers (e.g. base) may be paved and compacted in more than one pass. This will affect the energy figures for paving and rolling these layers.

3.3. Materials Tonnage

Aggregates in asphalt layers come from two sources: natural aggregates and those secondary (glass, IBA, etc.) and recycled (RAP). Bitumen is made of primary bitumen and that recovered from revitalised binder in the RAP. For asphalt layers that have a number of types of materials input, a check of the total tonnage at the end is carried out, like in the LHR T5 case study. Again there is no conclusion on what percent of original binder in the RAP is counted as 'active' in the new asphalt mixture.

Having the data on emulsion usage and emulsion recipe, the amount of bitumen and emulsifier in tack coat can be calculated. Also provided in the worksheet are data from alternative sources and data on other pavement processes (chip seal, cold mix asphalt, etc).

$$Bitumen(Emulsifier) = EmulsionUsage \times PavementArea \times Bitumen(Emulsifier)Content$$

4. Energy and Emissions Inventory

4.1. Energy Production

Life cycle inventory of production of electric power, petroleum fuel (refer to diesel, heating oil and LPG) and natural gas are available, from different sources although. These data are very important in the LCA, for 1) they will be used in all following unit calculations and, 2) the scope of the data will determine the scope of the final inventory, as very few non-energy related emissions are included in the study.

4.2. Combustion of Fossil Fuels

Consumption of fossil fuels takes the following forms:

- Combustion of heating oil and LPG for heating purpose;
- Diesel engine operation for transport vehicles;
- Diesel engine operation for construction vehicles.

Emission limits on different combustion processes are specified in EMEP/CORINAIR Emission Inventory Guidebook. Below are the categories in it. Those relevant to this LCA study are shown in the table.

- Group 1 Combustion in energy and transformation industries
- Group 2 Non-industrial combustion plants
- Group 3 Combustion in manufacturing industry
- Group 4 Production processes
- Group 5 Extraction & distribution of fossil fuels and geothermal energy
- Group 6 Solvent and other product use
- Group 7 Road transport
- Group 8 Other mobile sources and machinery
- Group 9 Waste treatment and disposal
- Group 10 Agriculture
- Group 11 Other sources and sinks

Table2. Emission Standards for LCI of Consumption of Fossil Fuels

Machinery in pavement project	Reporting detail	Name of SNAP/CORINAIR Activity	Chapter
Transport vehicles	Heavy-duty (>3.5t) diesel engines	Road transport	Group 7: B710
Materials production plant	Combustion of LPG/heating oil for asphalt/cement production	Cement/Asphalt concrete plant	Group 3: B331
Construction vehicles and equipment	Diesel engines in crushing equipment, paver, roller, etc.	Other mobile sources and machinery	Group 8: B810

Different emission limits apply for the above processes in the Guidebook, and are used in this worksheet as the emissions inventory for the energy consumption stage. Missing data are supplemented by IVL, who has separate inventory data for cargo ship and rail locomotive. An efficiency of 40% is assumed for diesel engines in both transport and construction vehicles. Required data for LCI of combustion in materials production are not available from Group3 B331 (see Table above). Those data on combustion in energy and transformation industries (Chapter1 B111) are used instead.

4.3. Transport Vehicles Operation

Data on diesel consumption come from the ‘Process Parameters’ worksheet. Loadings in the ‘Energy and Emissions Inventory’ consist of two parts: the diesel engine operation and the production of diesel.

$$TransportInventory = DieselConsumption \times (DieselEngineI + Diesel\,\mathrm{Pr}\,oduction)Inventory$$

4.4. Construction Vehicles Operation

Similar to transport vehicles, inventory loadings for construction vehicles (paver, roller, etc.) come from diesel engine operation and production of diesel, except that different emissions data for diesel engine operation apply. For convenience use, inventory data for engine operation of a power between 130-560kW are used for all calculation. A more precise way to do it is to know the engine power of each machine, and use the inventory data for that range accordingly. Some plants or construction vehicles burn LPG for heating, inventory loadings in this case will include those from production and combustion of LPG. Inventory loadings of production of electric power will be included in processes where electricity is consumed.

$$\begin{aligned}&ConstructionInventory = DieselConsumption \times (DieselEngineII + Diesel\,\mathrm{Pr}\,oduction)Inventory\\&+ LPGConsumption \times (LPG\,\mathrm{Pr}\,oduction + LPGCombustion)Inventory + ElectricityConsumption\\&\times Electricity\,\mathrm{Pr}\,oductionInventory\end{aligned}$$

The inventory data for production of some materials (bitumen, cement, emulsifier, etc.) are available. These data are indicated in this worksheet by the orange colour, and will be brought into ‘Inventory Results’ worksheet for calculation.

5. Inventory Results

The inventory results for a pavement project are worked out by multiplying the unit (Energy and Emissions) inventory by the relevant workload in that pavement project. The workload can be measured in materials tonnage, transport distance, or pavement area, based on the nature of the process.

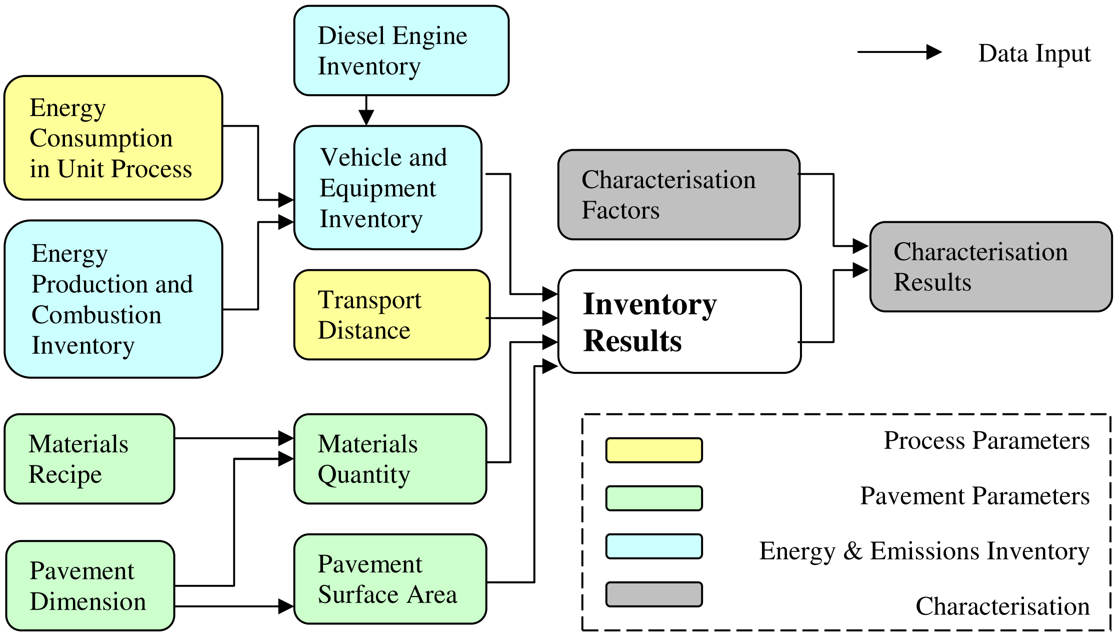

Figure1. Relations between Worksheets in LCA Model

5.1. Production Process

The unit inventory of materials production comes from ‘Energy and Emissions’ worksheet; the tonnage of materials comes from ‘Pavement Parameters’ worksheet.

$$InventoryForProduction = UnitInventoryForProduction \times MaterialsTonnage(t)$$

5.2. Transport Process

The unit inventory of materials transport comes from ‘Energy and Emissions’ worksheet; the tonnage of materials comes from ‘Pavement Parameters’ worksheet; the distance of transport comes from ‘Process Parameters’ worksheet.

$$InventoryForTransport = UnitInventoryForTransport \times MaterialsTonnage(t) \times TransportDistance(km)$$

5.3. Construction Process

The unit inventory of construction (materials placement) comes from ‘Energy and Emissions’ worksheet; the area of pavement surface comes from ‘Pavement Parameters’ worksheet.

$$InventoryForConstruction = UnitInventoryForConstruction \times PavementArea(m^2)$$

6. Characterisation Results

When inventory loadings are assigned to the appropriate impact category, the loadings are converted into equivalents of that category indicator. The selection of indicator and conversion factor depends on what characterisation model is used for that impact category. For example, loadings in the Global Warming category are characterised as below. Depending on the scope of the LCA study, the characterised results can go further into the normalisation and weighting phases (see in Chapter 3).

$$CharacterisationResults = \sum_i InventoryLoading_i \times CharacterisationFactor_i (GWP_i)$$

7. Summary and Further Work

The methodology and data sources for this LCA model are explained in Chapter 3. Calculation process including the formulas described above is found in the Microsoft Excel spreadsheet. Chapter 4 gives a couple of examples applying this model for assessment of real road projects.

This model is developed using asphalt materials for example. In practice, recycled and secondary aggregates are also seen in concrete pavements. Energy and emissions data (or the LCI) are needed for products and processes in cement production and concrete laying. A couple of publications are available as a starting point for researching such databases. One is the WBCSD's Cement Initiatives that publish reports on LCA tools for the cement industry (WBCSD 2002), the other is the WRAP's LCA of recycling key materials in the UK that summarise results from case studies on environmental preference of waste management options based on the CO_2 footprint (WRAP 2006).