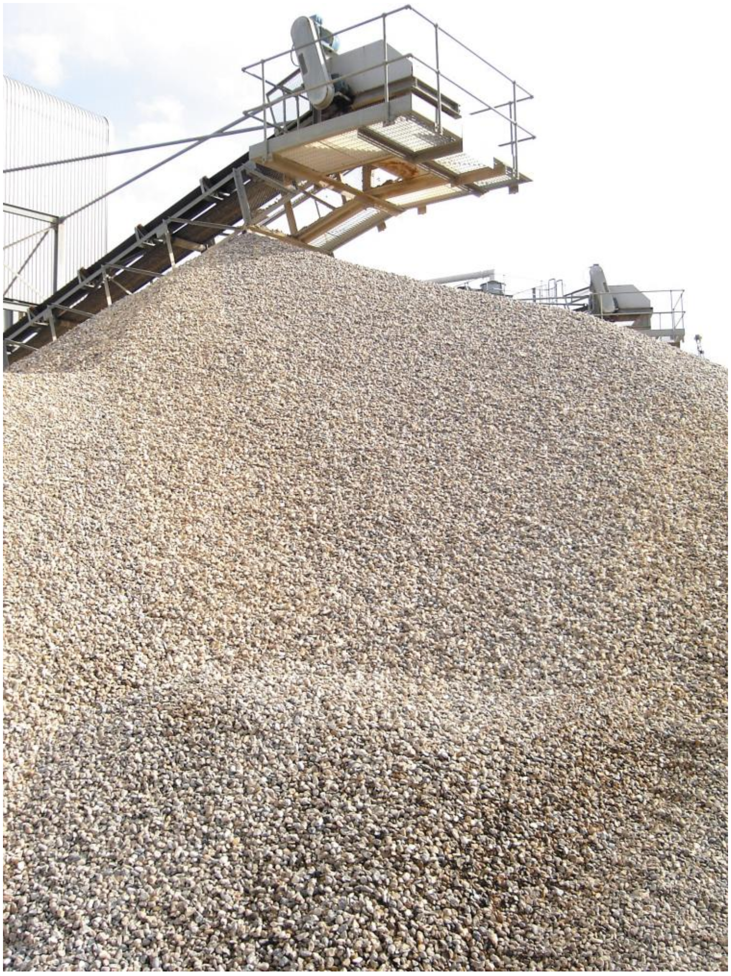
EVA025 –Final Report: Aggregates Industry Life Cycle Assessment Model: Modelling Tools and Case Studies

Life Cycle Assessment of Aggregates



Report Prepared by Dr Anna Korre & Professor Sevket Durucan – Imperial College London

Project code: EVA 025
Research start date: March 2007
ISBN: NB
Report Date: August 2009

Front cover photograph: Marine Dredged Aggregate Stockpile _ MIRO Photo Library

Published by
Waste & Resources
Action Programme

The Old Academy
21 Horse Fair
Banbury, Oxon
OX16 0AH

Tel: 01295 819 900
Fax: 01295 819 911
E-mail: info@wrap.org.uk

Helpline freephone
0808 100 2040

Executive summary

The objective of the work reported here was to develop a Life Cycle Inventory (LCI) and Assessment (LCA) Model for the aggregates industries. The work includes the extraction and processing of primary resources through to the point of their dispatch as aggregates (including overburden stripping, drilling and blasting, and restoration), and comparing with the processing of equivalent recycled aggregates for three grades (aggregates for unbound applications; aggregates for concrete; aggregates for asphalt) from:

- igneous rocks;
- sedimentary rocks;
- sand and gravel deposits (land and marine);
- recycled unbound inert waste;
- recycled concrete; and
- recycled asphalt

in particular to ascertain and quantify all the environmental impacts of each phase in the product life cycle.

As well as conventional crushing and screening, the aggregates processing component of the work also includes the Life Cycle impacts of excess production of fines, washing of recycled aggregates to enable further processing of fines and other aggregate sizes and the disposal options for inert construction and demolition wastes. The model includes impacts related to transport of primary and recycled aggregates from source to the market place, introducing a spatial dimension to the LCA process within the UK.

The project consortium comprises the Mineral Industry Research Organisation (MIRO), Imperial College London, the Quarry Products Association and the British Aggregates Association. Both MIRO and Imperial College have long-term experience and a track record of working with the aggregates industry. The team at Imperial College has previously developed a Life Cycle Inventory and Assessment system specifically tailored for the minerals industry (LICYMIN), in which the database structure enables dynamic and efficient abstraction of data. Furthermore, the sources and timing of environmental impacts are traceable throughout the system life cycle. The work on the Aggregates Industry LCA Model has drawn upon this experience and utilised some of the existing structure and algorithms of LICYMIN.

The project team has worked very closely with the Industry Trade Associations and the aggregates producers which provided access to data and ensured a seamless link between the team and the industry throughout the project. In summary, the project included the following key elements:

- A literature review of LCA work (or similar) for aggregates;
- Scoping and setting of the system boundaries for the Life Cycle Assessment;
- Development of a Life Cycle Inventory, with particular emphasis on CO_2 emissions and impacts at each phase of the product life cycle;
- Assessment of the relative Life Cycle environmental impacts of different options;
- A formal report of the methods used, results and conclusions; and
- Attending meetings and seminars as required.

This report addresses all tasks of the project and includes the literature review, the scoping and setting of the system boundaries for the Life Cycle Assessment of aggregates, and the final versions of the modelling tools designed to carry out Life Cycle Assessment of primary and recycled aggregates, as commissioned by WRAP. The modelling tools' features and limitations are discussed and a detailed analysis of the modelling tools' performance is provided. The tools developed were tested using a number of case studies, covering both recycled and primary aggregates systems.

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1.0 Introduction

1.1 Project background

WRAP is a not-for-profit private company backed by funding from DEFRA and the devolved administrations of Scotland, Wales and Northern Ireland. WRAP's aim is to accelerate resource efficiency within the UK by creating stable and efficient markets for recycled materials and products and removing barriers to waste minimisation, re-use and recycling. The WRAP Aggregates Programme, which is funded by DEFRA from the Aggregates Levy Sustainability Fund, was launched in 2002. Its aims are to promote sustainable aggregates use by reducing the demand for primary aggregates through encouraging greater use of recycled and secondary aggregates.

Approximately one quarter of the UK's annual use of aggregates as raw construction materials are derived from recycled or secondary sources (around 65 out of 275 million tonnes). According to a recent report issued on 'The sustainable use of resources for the production of aggregates in England' in October 2006 (WRAP Project code: AGG0059) the majority of this use has been for lower value applications and has influenced the market demand for low grade primary aggregates. This early project aimed at developing an economic model on aggregate demand and used information on materials, resource availability, production costs, haulage, waste disposal, and market prices to show how the supply of aggregates could change over a ten year period. However, besides the economics, it is also important to be able to assess which sources of aggregates represent the best environmental option, as well as comparing the environmental impacts of different disposal and recovery routes for wastes.

This project was designed to provide the necessary materials and a specifically designed tool that will both inform decisions on the development of future policy in this area and provide a more robust evidence base for WRAP's activities. The results of this work and the tool developed will be used by the WRAP aggregates team in reporting on the performance of related projects and when strategically engaging with construction and recycling companies. In addition, the tools may be used by the industry or any other nominated institution in comparisons of products or constructions with functional equivalence. It would also be possible to use the materials reported in this study and the output of the tools, when used by practitioners, towards Building Level comparisons as defined by ISO 21930:2007.

1.2 Life Cycle Assessment

Life Cycle Assessment is an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wastes released to the environment, and to evaluate and implement opportunities to affect environmental improvements. As such, it is an excellent tool that can be used to evaluate environmental performance and support decision-making in the whole value chain starting from raw materials extraction to processing, component fabrication, assembly, delivery, use, recycling and disposal. Figure 1 illustrates the four interrelated phases in an LCA study.

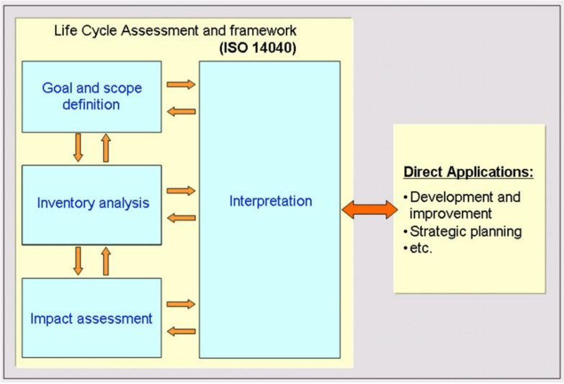

Figure 1. Stages of an LCA study

The environmental management standards relating to life cycle assessment used in this project are as follows:

- BS EN ISO 14040:2006 Environmental management. Life cycle assessment. Principles and framework.
- BS EN ISO 14044:2006 Environmental management. Life cycle assessment. Requirements and guidelines.
- PD ISO/TR 14047:2003 Environmental management. Life cycle impact assessment. Examples of application of ISO 14042.

- DD ISO/TS 14048:2002 Environmental management. Life cycle assessment. Data documentation format.
- PD ISO/TR 14049:2000 Environmental management. Life cycle assessment. Examples of application of ISO 14041 to goal and scope definition and inventory analysis.

1.3 Demand for aggregates

Aggregates are the most commonly used construction minerals in the UK and are essential for the sustainable development of a modern economy. The resources of material suitable for use as primary aggregates in England comprise land-won and marine sand and gravel, and crushed rock (limestone, sandstone, igneous and metamorphic rock). Reserves of land-won sand and gravel in England have declined from 907 million tonnes in 1995 to 650 million tonnes in 2004 and, according to a recent BGS report (Brown, 2006 242 /id), action is required if long-term supply is to be maintained.

In addition to primary aggregates there are already established large and successful markets for materials derived from recycled or secondary sources. Indeed, the UK is a leading user of such materials in Europe. However, WRAP and the industries involved in the business, recognise that there is more that can be - and is necessary - to be done.

By 2012, if UK demand for aggregates increases by an expected 1% per cent per annum, an extra 20 million tonnes of aggregates will be required each year. There is of course the choice to either satisfy this additional demand by extracting further primary aggregates, or follow a more sustainable route and continue to increase the use of recycled and secondary aggregates.

Scope for obtaining additional supplies already exists in the construction, demolition and excavation wastes that are currently sent to landfill, and through better utilisation of secondary resources. Equally, the suitability of using recycled and secondary aggregates for a wide range of applications has been well documented, including detailed project examples within the case studies section of WRAP's aggregates web site AggRegain (www.aggregain.org.uk).

1.4 Previous studies

The majority of earlier LCA work relating to aggregates production focused primarily on construction concrete and asphalt pavement production with the use of average data and offers limited information on recycling aspects. Some additional materials of similar nature and level of detail are available as part of the LCA systems for the environmental assessment of buildings. A review of the state of the art and capabilities of such tools (specifically on CO_2) is presented in the recent WRAP study 'The promotion of the benefits of recycled and secondary aggregates (RSA) use in the reduction of CO_2 emissions' - Project code: AGG079-007. As it was also confirmed by this study, there is little specific and marginal inventory data relevant for the LCA of aggregates and the models available are not designed, and therefore not entirely appropriate, for the purpose. In fact, these models often summarise and represent, at a coarse scale, many of the phases of the life cycle that are specifically important for aggregates production.

In recent years, the research team at Imperial College have developed a Life Cycle Inventory and Assessment system for the minerals industry (LICYMIN), including the extraction of raw materials, processing, waste disposal and recycling (Durucan *et al.*, 2006). The advantages of the LICYMIN LCA system, specifically developed for mining applications (including surface mining which includes all the operations involved in aggregates production) have been demonstrated through a comparison of its outputs with the outputs of a commercial LCA software using a bauxite surface mine example. The approach developed and implemented at Imperial College for the aggregates LCA database and tools, unlike the single fact sheet provided by the commercial software, enables dynamic and efficient abstraction of systems. Furthermore, the sources and timing of environmental impacts are traceable throughout the system life cycle.

It is common practice in LCA studies to use a predefined set of data to represent the minerals extraction processes, such as mining and quarrying. Besides this, few or nothing is added to improve the data quality. Furthermore, essential case specific or site specific information which affects the ultimate environmental impacts is not taken into account. To mention but a few omissions: exploration and development work, production method used, mineral losses and location. Therefore, the extraction/processing method dependent factors that govern the nature of discharges to the environment are not considered. The mining/quarrying system is represented as a crude black-box, not lending itself to the interpretation of different processes used in minerals production. This generic information is of little use to LCA studies for the minerals and aggregates industry, let alone using this information to account for the environmental burden contributing to more complex systems down-stream or for comparing alternative disposal and recovery routes. It is, therefore, essential that better quality and more representative LCI data on aggregates production, processing and recycling systems are obtained and used.

The LICYMIN LCA system developed for the mining industry at Imperial College (Durucan *et al.*, 2006) offers a relevant system definition for the extraction and processing of primary aggregates. The AggRegain Specifier tool also provides a complementary system structure for recycled and secondary aggregates. These materials and additional information collected during the literature review conducted in the early stages of the project have been used as the basis for the development of the Aggregates Industry Life Cycle Inventory and Assessment Model at the appropriate level of detail.

The most relevant publications identified during the literature review are listed in Table 1. As there were only a limited number of studies found specifically for the aggregates industry, it was decided to review the LCA studies for buildings and construction applications as in such cases the upstream processes, including the production of primary and recycled aggregates used and the transport to the construction site, should be considered. The studies reviewed in this context are listed in Table 2[1].

Table 1. Aggregates industry LCA specific literature

1.	Balazs S., Antonini E. and Tarantini M., 1998. Application of Life Cycle Assessment (LCA) methodology for valorization of building demolition materials and products.http://www.regione.emilia-romagna.it/vamp/testi_pdf/Q20_02.PDF
2.	Craighill A. and Powell J.C., 1999. A Life Cycle Assessment and evaluation of construction and demolition waste. WM 99-03.
3.	Di Maria F., Saetta S. and Leonardi D., 2003. Life cycle assessment of a PPV plant applied to an existing SUW management system. International Journal of Energy Research, 27(5): 481-494.
4.	Itoh Y. and Kitagawa T., 2003. Using CO_2 emission quantities in bridge lifecycle analysis. Engineering Structures, 25(5): 565-577.
5.	Koroneos C. and Dompros A., 2007. Environmental assessment of brick production in Greece. Building and Environment, 42(5): 2114-2123.
6.	Le Teno J.F. and Mareschal B., 1998. An interval version of PROMETHEE for the comparison of building products' design with ill-defined data on environmental quality. European Journal of Operational Research, 109(2): 522-529..
7.	Petersen A.K. and Solberg B., 2005. Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden. Forest Policy and Economics, 7(3): 249-259.
8.	Suh S., Lenzen M., Treloar G.J., Hondo H., Horvath A., Huppes G., Jolliet O., Klann U., Krewitt W., Moriguchi Y., Munksgaard J. and Norris G., 2004. System boundary selection in life-cycle inventories using hybrid approaches. Environmental Science & Technology, 38(3): 657-664.
9.	Yamada H., Daigo I., Matsuno Y., Adachi Y. and Kondo Y., 2006. Application of Markov chain model to calculate the average number of times of use of a material in society - An allocation methodology for open-loop recycling. International Journal of Life Cycle Assessment, 11(5): 354-360.

Table 2. LCA studies relevant to buildings and construction applications

10.	Arm M., 2001. Self-cementing properties of crushed demolished concrete in unbound layers: results from triaxial tests and field tests. Waste Management, 21(3): 235-239.
11.	Dong B., Kennedy C. and Pressnail K., 2005. Comparing life cycle implications of building retrofit and replacement options. Canadian Journal of Civil Engineering, 32(6): 1051-1063.
12.	Eikelboom R.T., Ruwiel E. and Goumans J.J.J.M., 2001. The building materials decree: an example of a Dutch regulation based on the potential impact of materials on the environment. Waste Management, 21(3): 295-302.
13.	Mroueh U.M., Eskola P. and Laine-Ylijoki J., 2001. Life-cycle impacts of the use of industrial by-products in road and earth construction. Waste Management, 21(3): 271-277.

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[1] *All references in each table are listed alphabetically.*

14.	Myer A., Bell K. and Chaffee C., 1997. Life-cycle analysis for design of the Sydney Olympic Stadium. Renewable Energy, 10(2-3): 169-172.
15.	Norman J., MacLean H.L. and Kennedy C.A., 2006. Comparing high and low residential density: Life-cycle analysis of energy use and greenhouse gas emissions. Journal of Urban Planning and Development-Asce, 132(1): 10-21.
16.	Park K., Hwang Y., Seo S. and Seo H., 2003. Quantitative assessment of environmental impacts on life cycle of highways. Journal of Construction Engineering and Management-Asce, 129(1): 25-31.
17.	Peuportier B.L.P., 2001. Life cycle assessment applied to the comparative evaluation of single family houses in the French context. Energy and Buildings, 33(5): 443-450.
18.	Scheuer C., Keoleian G.A. and Reppe P., 2003. Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy and Buildings, 35(10): 1049-1064.
19.	Zapata P. and Gambatese J.A., 2005. Energy consumption of asphalt and reinforced concrete pavement materials and construction. Journal of infrastructure systems, 11(1): 9.

The most important features and findings of the above studies can be summarised as follows:

In Italy, Balazs *et al.* (1998) applied the LCA methodology to evaluate building materials and products in a selected demolition site in Northern Italy. The authors showed that reuse of building components had a great advantage over landfilling.

In the UK, Craighill and Powell (1999) applied an LCA approach to evaluate the environmental, social and economic impacts of alternative methods of managing construction and demolition waste. They concluded that the reuse of such waste on site performed better than off site recycling, which in turn performed better than landfill disposal.

In Finland, Mroueh *et al.* (2000) used LCA to evaluate road construction comparing six different construction materials arising from natural, demolition and secondary (blast furnace and fly ash) sources. These authors developed an Excel-based life cycle inventory analysis program for road construction and used it to characterise the construction materials studied. They found that the production and transportation of materials produced the most significant environmental burdens, as these phases are highly energy consuming. The authors also characterised resource depletion and the leaching behaviour of secondary construction materials.

In the USA, Scheurer *et al.* (2003) carried out an LCA study on a 7,300 m^2 six-story building at the University of Michigan campus. Although the authors assumed recycling of materials such as concrete, masonry, mortar, brick and granite at the demolition phase, they did not consider any further reuse of the construction and demolition waste. This study focused on the operational phase of the building and the difficulties to characterise a dynamic system with a projected 75 year life span.

In Germany, Weil *et al.* (2006) applied materials flow analysis and LCA methods to evaluate the impact of change in the use of recycling, construction and demolition wastes. This change came as a result of the adoption of a new national regulation for soil and groundwater protection. The authors analysed a new closed loop recycling path and compared it with the current open loop recycling path used in earthworks and road construction. They concluded that the use of brick-enriched recycled aggregates was advantageous for the production of recycled concrete.

A recent study carried out in the UK (WRAP, 2006) reviewed the state-of-the-art literature published on LCA studies to evaluate the impact on the environment of managing key materials in different ways – through recycling, incineration or landfill. Recycled aggregates was one of the many materials included in this review. This review was wider than the current study in terms of the different materials covered, however, it was more limited in its depth with regards to aggregates. The WRAP (2006) findings for the UK and Italian cases listed above (Craighill and Powell, 1998; Balazs *et al.,* 1998) are consistent with the current study. The authors pointed out that the material replacement issues are not clearly defined in the studies identified and that generally there is a lack of detailed, quantitative and comparative studies on waste management options for aggregates.

2.0 Goal of the study

The objective of the current study was to develop a Life Cycle Inventory (LCI) and Assessment (LCA) Model for UK aggregates including the extraction and processing of primary resources through to the point of their dispatch as aggregates. The aggregates extraction subsystem developed includes overburden stripping, drilling and blasting, and restoration of the site, while the processing subsystem includes washing, classifying, crushing and screening of primary aggregates as well as the processing of equivalent recycled aggregates (conventional screening and crushing and washing processes that enable the further processing of fines and other aggregate sizes).

The grades of aggregate that the LCI encompasses include aggregates for unbound applications; aggregates for concrete and aggregates for asphalt from:

- igneous rocks;
- sedimentary rocks;
- sand and gravel deposits (land and marine);
- recycled unbound inert waste;
- recycled concrete; and
- recycled asphalt.

The Life Cycle Inventory (LCI) developed includes all resource inputs (materials, energy etc.), all waste (e.g. overburden waste, fines etc.) and emission streams (e.g. all gaseous emissions including CO_2, Particulate Matter etc.) throughout the system and enable the user of the LCA Model to ascertain and quantify the relevant environmental impacts at each phase in the product life cycle.

The LCI system developed also provides the facility to consider the relative proximity of sources of primary aggregates and recycled aggregates to the market place as well as disposal options for inert construction and demolition wastes.

3.0 Scope

The scope of the study is outlined in the following sections covering the product systems and system boundaries, the functional unit, the allocation procedures, the types of impacts considered in the LCIA methodology, some data requirements and assumptions, as well as the limitations of the study.

3.1 Product systems and system boundaries

The life cycle inventory and assessment tools for aggregates developed comprise four independent systems:

- the land won primary aggregates system including
    - the hard rock primary aggregates system;
    - the sand and gravel primary aggregates system;
- the marine aggregates system;
- the recycled aggregates system; and

an additional system that serves the land won and marine primary aggregates and the recycled aggregates:

- the product distribution system.

The details presented in the following sections provide a description of these product systems.

3.1.1 The land won primary aggregates system

The primary aggregates system comprises three life cycle phases: Extraction, Processing and Waste Management/Restoration. The extraction phase includes three sub-phases, namely overburden removal, primary fragmentation, loading and hauling. In the case of sand and gravel primary aggregates system, the second sub-phase is referred to as the excavation sub-phase. These operations are considered to include all the necessary elements representative of the primary aggregates extraction processes (Smith, 2001).

The Processing life cycle phase is composed of five sub-phases for the hard rock primary aggregates: primary crushing, scalping screening, secondary crushing, tertiary crushing, quaternary crushing and final screening. The processing phase of the land won sand and gravel primary aggregates includes nine sub-phases: preprocessing storage, scalping screening, crushing, sizing screening, washing-scrubbing, wet classification, dewatering, grinding and product storage. The specific processing operations vary greatly as they are influenced by a large number of parameters, such as the aggregate properties, potential waste products, operating criteria, methods of stockpiling, storage and shipping, space availability and safety (Barksdale, 1996). In addition, processing plants could be either fixed or mobile.

Restoration in most sand and gravel operations is progressive. On the other hand, restoration of crushed rock quarries is often carried out after a major production phase is completed. The soil/overburden is usually replaced in the disturbed areas of the operation surrounding the quarry to help restoring vegetation, making these areas ready for a previously agreed purpose. This may be for landfilling, agriculture, wildlife or as a new public amenity such as parkland or water sports. Four sub-phases have been identified for both the hard rock and for the sand and gravel primary aggregates systems: waste landfilling, site preparation for restoration, re-vegetation and re-instalment.

3.1.2 The marine aggregates system

The marine aggregates system comprises two life cycle phases: Extraction and Processing. The extraction phase is formed by two sub-phases, the marine aggregates loading followed by the marine aggregates discharge.

The processing life cycle phase has the same nine sub-phases as that of the land won sand and gravel primary aggregates system.

In LCA terms, the function of the primary aggregates system is to supply a given mass of aggregates produced from naturally occurring mineral sources extracted by physical means and for the sole purpose of being used as aggregates for the first time.

3.1.3 The recycled aggregates system

The recycled aggregates system comprises one main life cycle phase dealing with the processing of the recycled aggregates. Transportation to the recycling plant (if applicable) and distribution to the market are dealt with by the product distribution system, outside the recycled aggregates system. Demolition of buildings for the provision of recycled aggregates is excluded from the study on the basis that it is the same process for recycling and for destruction.

There are nine sub-phases in the recycled aggregates system, namely, waste reception, pre-screening, screening, crushing, conveying and magnetic separation, washing, secondary screening, secondary crushing, and material transport and storage.

The function of the recycled aggregates system is to supply a given mass of aggregates produced by recycling construction and demolition waste and asphalt. These sources were selected as they constitute the most important sources of recycled aggregates in Great Britain. For example, in 2003 84% of the recycled aggregates supplied at national level came from construction and demolition waste, 14 % raised from asphalt and 2% from spent rail ballast (ODPM BGS/NERC, 2005).

3.1.4 The product distribution system

The system which serves both the primary aggregates system and the recycled aggregates system is the product distribution system. In this study, three types of transport were considered: road transport by heavy goods vehicles, rail freight and shipping. It may be the case that two or even the three types of transport are combined for the distribution of a given aggregate in a particular market. Therefore, the option of combining different transportation scenarios is provided in the life cycle assessment tool for aggregates distribution.

At the start of the project WRAP already had a Carbon Dioxide (CO_2) Emissions Estimator Tool which is an Excel based calculation tool which estimates the carbon dioxide saved in selecting different construction techniques and supply alternatives, including the use of primary and recycled aggregates. The tools developed in this project include a much improved CO_2 emissions' estimation tool as well as the tools for estimating emissions that contribute to the other LCA impact categories.

3.2 Declared unit

The declared unit for the life cycle assessment of aggregates system is a unit mass of aggregate produced (one tonne of material). As the scope of the study does not extend to different uses or comparison of different aggregates in a particular use, the current study is based not on function but on a Declared Unit (ISO21930:2007). In order to represent realistic scenarios in downstream process LCA studies looking at specific contexts (for example compressed volume of aggregate for fill, or a given volume of concrete at a given strength), the LCA results reported per declared unit can be scaled to represent total mass or volume produced over a period of time. The LCA indicator results reported in this study are allocated per tonne of aggregate (declared unit) and per tonne of individual product size/type.

3.3 Spatial and temporal scope

The geographical boundary for the study is the UK.

In terms of temporal boundaries, the design of the system is not based on a fixed time period (e.g. the last five years). The system design allows the user to define the time period considered to complete the inventory for the particular case study. Regarding the energy source mix, the DEFRA environmental reporting conversion factors and the Scottish Energy scenario are being used for the calculation of indirect emissions (DEFRA, 2008; Scottish Energy 2005-2006). By modifying the indirect emissions specified in a dedicated worksheet inside each tool, it is possible to consider future scenarios or different energy source mixes.

3.4 Technological scope

The life cycle inventory developed is based on current technologies and looking into the future, rather than looking at operations that have been in use in the past but are not any more utilised in the UK.

3.5 Allocation

The allocation procedure for the environmental loads is based on physical/chemical causation per unit mass of aggregate produced. However, the environmental profile procedure has been adopted for the inputs of energy as explained above in Section 3.3. Since a unit mass of aggregate produced could include different size or type fractions, the LCA impact allocation to these fractions has also been included.

3.6 System expansion

System expansion is certainly relevant to the recycled aggregates. However, considering the resources dedicated to the current project, it was decided not to explore this option further.

3.7 Inclusions and exclusions

The manufacture of capital equipment required for the aggregates production operations is not included in the tools developed. The primary reason for this exclusion is that capital equipment manufacture was not within the scope of the project. However, this choice has been evaluated and justified based on previous life cycle studies (Landfield and Karra, 2000).

Human labour burdens were also excluded, due to difficulties in allocation, drawing boundaries, obtaining data and differentiating between labour and capital equipment. Furthermore, since primary and recycled aggregates production processes are similar, at least for the processing phase, it is reasonable to assume that human labour is of the same scale for each product system. It was confirmed with the sponsors and the peer review group that human labour can be considered outside of the scope and resources of this project.

The process of demolition is not considered as part of the recycled aggregates system.

3.8 Key assumptions and limitations

This study does not cover the impact categories addressing the issues of land use, waste generated or resource use. The land use impact calculation in LCA is still disputed amongst LCA practitioners (see examples of recent discussions in Bauer *et al.*, 2007; Dubreuil *et al.*, 2007; and Udo de Haes, 2006a). The authors agree with Udo de Haes that other approaches and tools provide more detailed information than LCA on effects of different land management practices. Similar issues exist with regards to resource use (Heinrich, 2006) and the water use in LCA (Koehler, 2008). Particularly with regards to resource use, prominent LCA practitioners and developers prefer substance flow analysis (SFA), and procedural approaches, such as certification of resource management with proximate labelling of the resources, instead of LCA (Udo de Haes, 2006b). Furthermore, most work on waste generation in an LCA framework is focused on biodegradable waste. With regards to the stratospheric ozone depletion impact, this occurs due to the upstream materials and energy use only (fuel and electricity), and not directly from the aggregates production. The authors have included the ozone layer depletion impact from fuel and electricity use in the indirect emissions spreadsheet, and since the amount of fuel/electricity per declared unit (1 tonne of aggregate) is also calculated, it is possible to provide a value for the stratospheric ozone depletion.

It should also be noted that there is some concern within the LCA community over the use of Marine aquatic ecotoxicity indicator (Huijbregts, 2000) and in particular for the HF and all other emissions' residence time in the oceans. For this reason, this particular indicator category results, although reported in the tools developed, should be considered with caution. This is reflected in the discussion of the results presented for the primary and recycled aggregates in the relevant sections of this report.

Where aggregate producers generate their own electricity, the tools developed use data from NAEI (2006) for auto-generation from natural gas. As there is no published method to estimate impacts from auto-generation using diesel, which is the commonly used fuel by aggregate producers, and the use of renewable sources for electricity generation is not widely implemented, the authors believe that it is appropriate to use the suggested method. Upstream emissions from the consumption of natural gas fuel for auto-generation are considered very small, below the 1% cut-off used in this study, and are not included.

In order to estimate the upstream emissions from electricity and fuel use (diesel and fuel oil), impact category indicator results were generated using the GaBi software. These impacts include the diesel production at refinery (EU-15 Diesel at refinery, ELCD/PE-GaBi) with transportation by truck for 100 km distance; the EU light fuel oil production at refinery (EU-15 Fuel oil light at refinery ELCD/PE-GaBi); and the UK power (GB: Power grid mix ELCD/PE-GaBi). Fuel oil produced at UK refineries is directly loaded to dredgers and ships for marine aggregates extraction and shipping, so no additional transport is considered.

The above key assumptions and limitations are also discussed in the relevant section of this report, in relation to the results of each primary and recycled aggregate case study carried out.

3.9 Data quality requirements

Besides the geographic, temporal and technology coverage already discussed; the following additional data quality requirements have been considered (ISO14041):

- precision
- completeness
- representativeness
- consistency
- reproducibility

MIRO and the industry representatives involved in this project, namely the Quarry Products Association and the British Aggregates Association, together with the steering committee and peer reviewers have assisted in defining and improving the data quality requirements.

When data are taken from the public domain literature, the sources have been referenced according to the ISO/TR 14049:2000(E) standard. Missing data and data gaps are reported and treated according to the same standard under each case study.

The interpretation of each LCA case study results includes data quality assessment and analyses of significant inputs, outputs and methodological choices in order to qualify the uncertainty of the results. However, it should be noted that the current project uses marginal data, which is case study specific and therefore entails a much lower level of uncertainty than studies based on averaged values drawn from the literature.

Since data collection involved several case study sites and publications, measures have been taken to reach uniform and consistent understanding of the systems modelled. The data provided by the site operators have been validated using mass balances for fuel and materials used, equipment manufacturers' specifications, and references from the literature.

It was decided to set the cut-off criteria at 1% for the inclusion of inputs and outputs in the LCA model on the assumption that the inclusion of such data has a very minor effect on the results. The effect of the cut-off criteria on the outcome of the study has been assessed, particularly for emissions relating to electricity and fuel use, and the chosen cut off is considered appropriate.

3.10 Inventory analysis

The life cycle inventory analysis has been an iterative process based on the definition of the goal and scope of the study, and executed through a set of iterative steps involving the development of the data collection forms and subsequently the data collection, validation and linking with the unit processes, accounting for allocation issues and recycling, relating the data to the declared unit, aggregation and finally refining the system boundary and possibly the addition of data and or unit processes until the set scope and objectives of the LCI analysis are fulfilled.

The LCA inventory data collection and analysis procedures are reported under section 8 of this report.

3.11 Impact assessment

The impact assessment methodology, aimed at evaluating environmental burdens for the primary and recycled aggregates systems, is based on the CML baseline categories (Guinée, 2001).

3.12 Sensitivity analysis

The interpretation of the case study results included a sensitivity analysis aiming at determining how changes in the data and methodological choices affect the results. The choice of emission factors for upstream emissions from electricity use has also been evaluated and is considered significant.

3.13 Peer review

In accordance with the ISO14040 standard, this study has been conducted under peer review by an external reviewer.

4.0 Inventory analysis

Inventory analysis involves the data collection and calculation procedures to quantify relevant inputs and outputs of the product systems. For each of the primary and recycled aggregates systems assessed, inventories of significant flows to and from the system and internal material and energy flows are produced. Significance is determined by threshold for mass (more than 1% of inputs), energy and environmental significance (potential for harm). The initial data sources for the inventory analysis were taken from the literature, as reported in ANNEX A.

This information was used to prepare the life cycle questionnaire/inventory which was filled in by the primary and recycled aggregates case study site operators.

5.0 Impact assessment

The Life Cycle Impact Assessment (LCIA) carried out for each case study includes the following mandatory elements:

- Selection of impact categories, category indicators and characterisation models;
- Assignment of LCI results to the selected impact categories (classification);
- Calculation of category indicator results (characterisation).

For each impact category the necessary components of the LCIA process are:

- Identification of category endpoints;
- Identification of appropriate LCI results that can be assigned to the impact category, taking into account the chosen category indicator and identified category endpoint(s); and
- Identification of the characterisation model and the characterisation factors.

Optional elements of LCIA (normalisation, grouping, weighting and data quality analysis) have also been included in the tools developed and the West Europe 1995 (Huijbregts, 1999) normalisation method was used in the primary and recycled aggregates LCA tools. These are the most recent set of normalisation factors available and they were used to illustrate the magnitude and the relative significance of the LCA impacts calculated for each case study.

6.0 Life cycle interpretation

The life cycle interpretation for each of the case studies comprises:

- Identification of significant issues based on the results of the LCI and LCIA phases;
- An evaluation that considers completeness, sensitivity and consistency checks;
- Conclusions, limitations and recommendations.

7.0 The Aggregates Industry Life Cycle Assessment Model

This section describes the Aggregates Industry Life Cycle Assessment Model (hereinafter referred to as the LCA Model) developed; its features, functions and limitations.

7.1 The Aggregates Industry Life Cycle Assessment Model

The LCA Model is a generic term used to describe five dedicated LCA tools that make up the complete LCA Model for primary and recycled aggregates production. These tools are:

1. The Crushed Rock Tool
2. The Land-won Sand and Gravel Tool
3. The Marine Aggregates Tool
4. The Recycled Aggregates Tool
5. The Product Distribution Tool

The LCA tools listed above share a considerable number of similar features; however, they also differ significantly with respect to the production processes they represent. These tools are constructed as Microsoft Excel workbooks with three objectives:

- to record information on inputs (materials and energy) and outputs (intermediate/final product flows and emissions).
- to calculate environmental interventions (emissions to the environment) using algorithms which utilise case specific data provided by the user and/or default values incorporated in each tool.
- to provide the functions to calculate the Life Cycle Impacts of the aggregates production system considered.

Each LCA Tool is divided in to four colour coded sections for ease of use:

- Life Cycle Inventory (LCI) Model
- Life Cycle Impact Characterisation Model
- Product Ecoprofiles

- Supporting information

The Life Cycle Inventory Model houses the data related to production phases/processes and stores the parameters relevant to the Life Cycle Analysis of each unit process. These parameters are either provided as hard data directly by the user or estimated using algorithms embedded in the system. The environmental interventions (emissions) calculated in the Life Cycle Inventory are pooled together and characterised in the subsequent section.

The Life Cycle Impact Characterisation Model is composed of eight spreadsheets. The first spreadsheet handles the classification of identified emissions into the appropriate baseline LCA impact categories (Guinée et al, 2001). The following six spreadsheets calculate and display these emissions' contribution to the Climate Change, Eutrophication, Acidification, Photo-oxidant Formation, Human Toxicity and Ecotoxicity indicators. The final spreadsheet calculates the normalised LCA impact category indicators using the West Europe 1995 factors (Huijbregts, 1999).

The product Ecoprofiles section is provided as a single spreadsheet accounting for the environmental interventions per individual product. The ecoprofiles are calculated using an allocation method (apportioning of the emissions) based on the mass fraction of each product in one tonne of aggregate (ISO14041, 1998) while accounting for each individual product chain separately. Different products (size fractions) that follow identical product chains naturally result to equal impact category indicators per tonne. For example, in sand and gravel production, the gravel and the sand flows separate after the scalping screening process. While gravel flows are screened into different size products, the sand flows go through a wet classification process. For this reason the emissions generated during the wet classification process contribute only to the sand products' ecoprofile.

The last section, common to all LCA Tools, is the supporting information part, where the formulae, default values and references used in the development of each tool are recorded.

Figure 2 illustrates the sub-phases included in each phase. The aggregates production phases that the model includes under each of the tools are shown in Table 3.

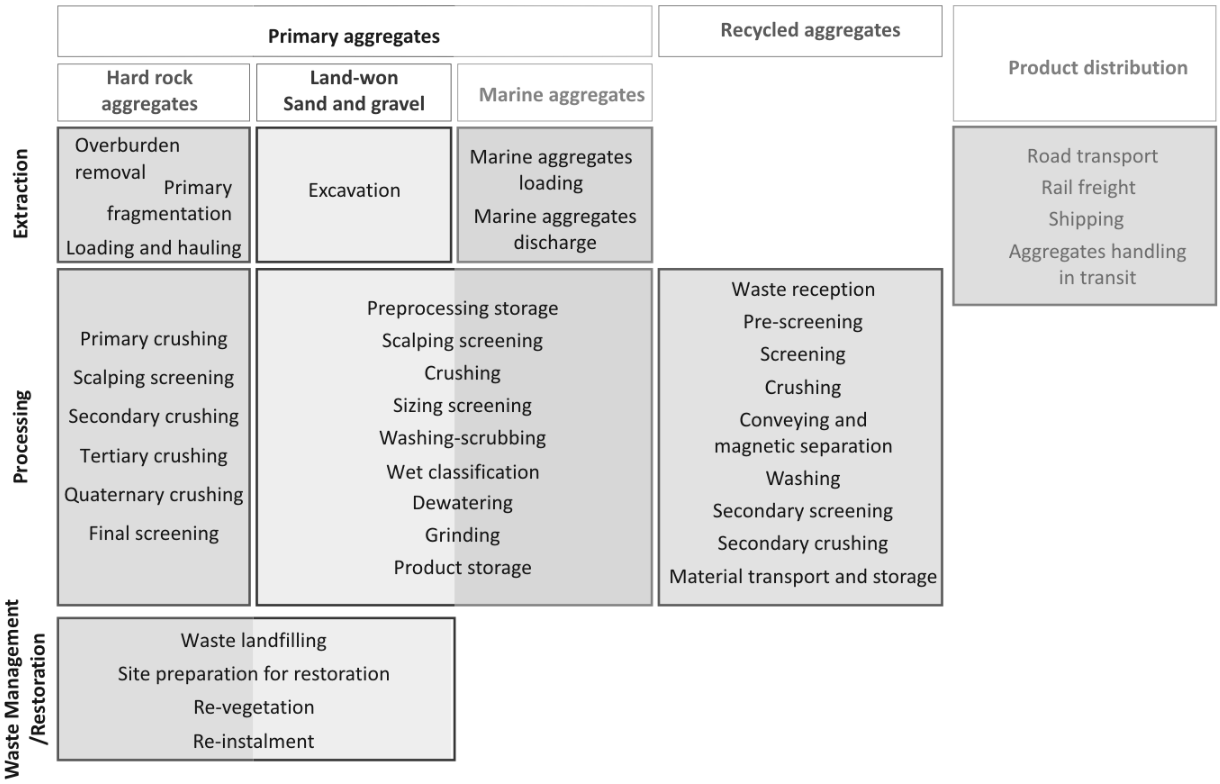


Figure 2. Aggregates LCA system, individual phases and corresponding unit processes.

The images of Figure 3 to Figure 7Figure 6 illustrate characteristic views of the spreadsheet tools developed for each primary and recycled aggregates production system studied and for the product distribution.

Table 3. Phases included in the Aggregates Industry LCA model and corresponding tools.

Aggregates Industry LCA Model	Life cycle phases				
	Extraction	Processing	Restoration	Materials Transfer	Off-site Transport
Crushed rock tool	✓	✓	✓		
Land-won sand and gravel tool	✓	✓	✓		
Marine sand and gravel tool	✓	✓			
Recycled Aggregates tool		✓			
Product Distribution Tool				✓	✓

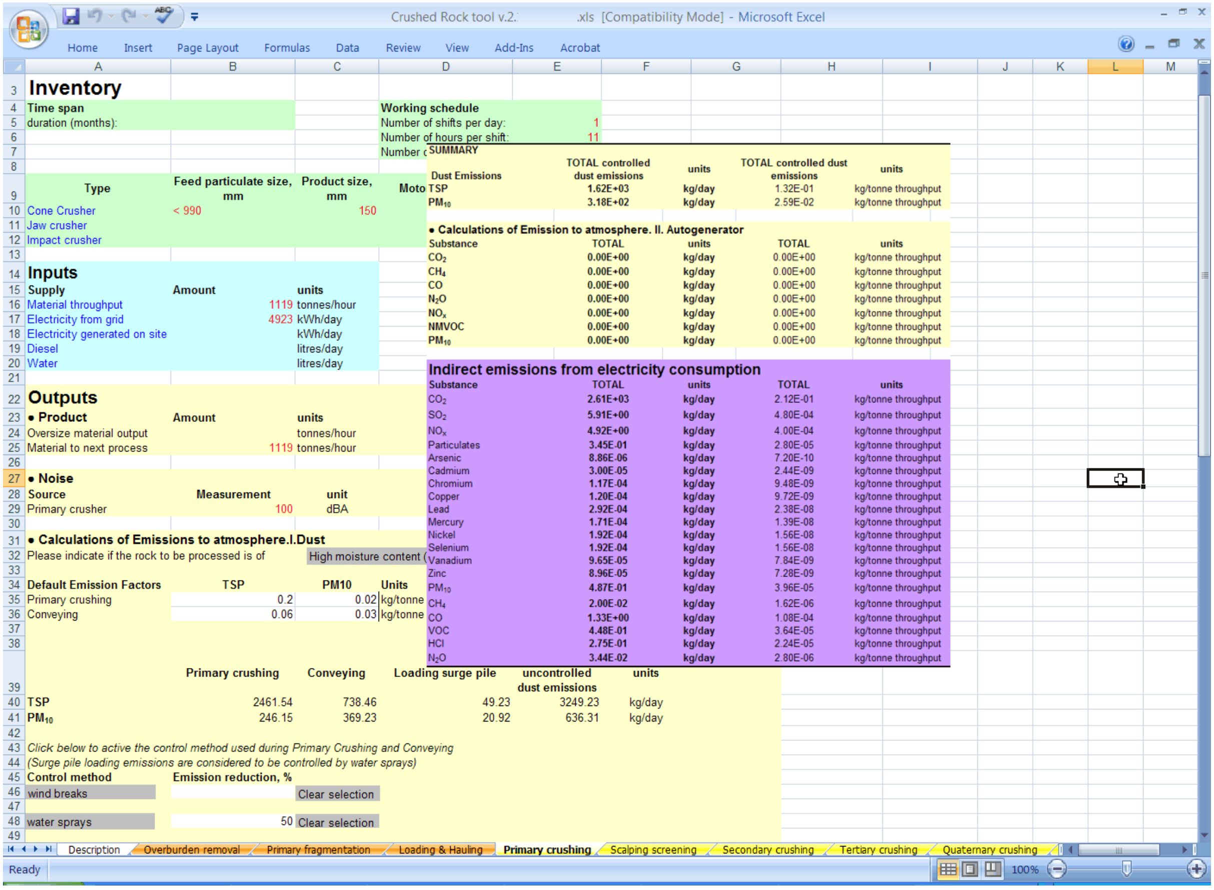
The main sources of emissions modelled in the tools are generated from the combustion of fuels used by production equipment, transport vehicles and on site electricity generators. The formulae used to estimate these emissions are taken from the National Atmospheric Emissions Inventory (NAEI, 2003; NAEI, 2000a). In addition, the marine sand and gravel tool includes equations to estimate emissions from shipping (NAEI, 2000b) while the product distribution tool also includes emissions due to rail freight (NAEI, 2000c).

As well as the fuel combustion related emissions, the atmospheric emissions include emissions from blasting operations. The dust emission calculations (TSP and PM10) account for multiple sources such as crushing, traffic on unpaved roads, blasting and drilling. Table 4 presents the atmospheric emission categories estimated in the tools and lists the specific substances considered.

Life cycle impacts due to water discharges are accounted for in the crushed rock and land-won sand and gravel tools using the data that can be provided for a given case study.

Table 4. Atmospheric emissions estimated by the aggregates tools

	Crushed rock tool	Land-won sand and gravel tool	Marine sand and gravel tool	Recycled Aggregates tool	Product distribution tool
Combustion gases:					
CO	✓	✓	✓	✓	✓
Benzene	✓	✓	✓	✓	✓
1,3-Butadiene	✓	✓	✓	✓	✓
CO_2	✓	✓	✓	✓	✓
NO_x	✓	✓	✓	✓	✓
PM_{10}	✓	✓	✓	✓	✓
CH_4	✓	✓	✓	✓	✓
N_2O	✓	✓	✓	✓	✓
NMVOC	✓	✓	✓	✓	✓
SO_2			✓		
Mercury			✓		
Lead			✓		
Benzo(a)pyrene			✓		
Blasting fumes:					
CO_2	✓				
CO	✓				
NO_2	✓				
NH_3	✓				
Dust:					
TSP	✓	✓	✓		✓
PM10	✓	✓	✓	✓	✓



Inventory

Time span
duration (months):

Working schedule
Number of shifts per day: 1
Number of hours per shift: 11

Type	Feed particulate size, mm	Product size, mm
Cone Crusher	< 990	150
Jaw crusher		
Impact crusher		

Inputs

Supply	Amount	units
Material throughput	1119	tonnes/hour
Electricity from grid	4923	kWh/day
Electricity generated on site		kWh/day
Diesel		litres/day
Water		litres/day

Outputs

• Product	Amount	units
Oversize material output		tonnes/hour
Material to next process	1119	tonnes/hour

• Noise Source	Measurement	unit
Primary crusher	100	dBA

• Calculations of Emissions to atmosphere.I.Dust
Please indicate if the rock to be processed is of High moisture content (

Default Emission Factors	TSP	PM10	Units
Primary crushing	0.2	0.02	kg/tonne
Conveying	0.06	0.03	kg/tonne

	Primary crushing	Conveying	Loading surge pile	uncontrolled dust emissions	units
TSP	2461.54	738.46	49.23	3249.23	kg/day
PM_{10}	246.15	369.23	20.92	636.31	kg/day

Click below to active the control method used during Primary Crushing and Conveying
(Surge pile loading emissions are considered to be controlled by water sprays)

Control method	Emission reduction, %	
wind breaks		Clear selection
water sprays	50	Clear selection

SUMMARY

Dust Emissions	TOTAL controlled dust emissions	units	TOTAL controlled dust emissions	units
TSP	1.62E+03	kg/day	1.32E-01	kg/tonne throughput
PM_{10}	3.18E+02	kg/day	2.59E-02	kg/tonne throughput

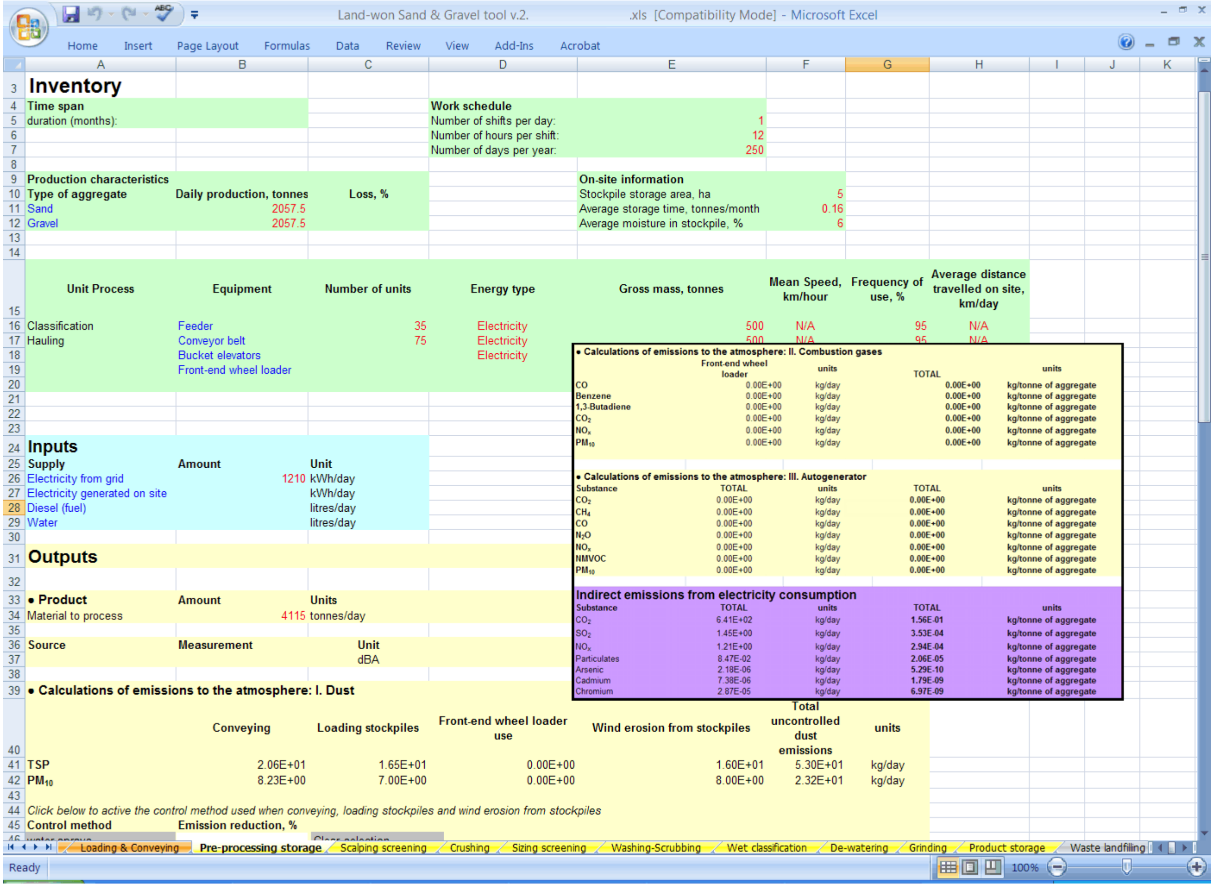
• Calculations of Emission to atmosphere. II. Autogenerator

Substance	TOTAL	units	TOTAL	units
CO_2	0.00E+00	kg/day	0.00E+00	kg/tonne throughput
CH_4	0.00E+00	kg/day	0.00E+00	kg/tonne throughput
CO	0.00E+00	kg/day	0.00E+00	kg/tonne throughput
N_2O	0.00E+00	kg/day	0.00E+00	kg/tonne throughput
NO_x	0.00E+00	kg/day	0.00E+00	kg/tonne throughput
NMVOC	0.00E+00	kg/day	0.00E+00	kg/tonne throughput
PM_{10}	0.00E+00	kg/day	0.00E+00	kg/tonne throughput

Indirect emissions from electricity consumption

Substance	TOTAL	units	TOTAL	units
CO_2	2.61E+03	kg/day	2.12E-01	kg/tonne throughput
SO_2	5.91E+00	kg/day	4.80E-04	kg/tonne throughput
NO_x	4.92E+00	kg/day	4.00E-04	kg/tonne throughput
Particulates	3.45E-01	kg/day	2.80E-05	kg/tonne throughput
Arsenic	8.86E-06	kg/day	7.20E-10	kg/tonne throughput
Cadmium	3.00E-05	kg/day	2.44E-09	kg/tonne throughput
Chromium	1.17E-04	kg/day	9.48E-09	kg/tonne throughput
Copper	1.20E-04	kg/day	9.72E-09	kg/tonne throughput
Lead	2.92E-04	kg/day	2.38E-08	kg/tonne throughput
Mercury	1.71E-04	kg/day	1.39E-08	kg/tonne throughput
Nickel	1.92E-04	kg/day	1.56E-08	kg/tonne throughput
Selenium	1.92E-04	kg/day	1.56E-08	kg/tonne throughput
Vanadium	9.65E-05	kg/day	7.84E-09	kg/tonne throughput
Zinc	8.96E-05	kg/day	7.28E-09	kg/tonne throughput
PM_{10}	4.87E-01	kg/day	3.96E-05	kg/tonne throughput
CH_4	2.00E-02	kg/day	1.62E-06	kg/tonne throughput
CO	1.33E+00	kg/day	1.08E-04	kg/tonne throughput
VOC	4.48E-01	kg/day	3.64E-05	kg/tonne throughput
HCl	2.75E-01	kg/day	2.24E-05	kg/tonne throughput
N_2O	3.44E-02	kg/day	2.80E-06	kg/tonne throughput

Figure 3. View of the crushed rock LCA tool.



Inventory

Time span
duration (months):

Work schedule
Number of shifts per day: 1
Number of hours per shift: 12
Number of days per year: 250

Production characteristics

Type of aggregate	Daily production, tonnes	Loss, %
Sand	2057.5	
Gravel	2057.5	

On-site information
Stockpile storage area, ha 5
Average storage time, tonnes/month 0.16
Average moisture in stockpile, % 6

Unit Process	Equipment	Number of units	Energy type	Gross mass, tonnes	Mean Speed, km/hour	Frequency of use, %	Average distance travelled on site, km/day
Classification	Feeder	35	Electricity	500	N/A	95	N/A
Hauling	Conveyor belt	75	Electricity	500	N/A	95	N/A
	Bucket elevators		Electricity				
	Front-end wheel loader						

Inputs

Supply	Amount	Unit
Electricity from grid	1210	kWh/day
Electricity generated on site		kWh/day
Diesel (fuel)		litres/day
Water		litres/day

Outputs

• Product	Amount	Units
Material to process	4115	tonnes/day

Source	Measurement	Unit
		dBA

• Calculations of emissions to the atmosphere: I. Dust

	Conveying	Loading stockpiles	Front-end wheel loader use	Wind erosion from stockpiles	Total uncontrolled dust emissions	units
TSP	2.06E+01	1.65E+01	0.00E+00	1.60E+01	5.30E+01	kg/day
PM_{10}	8.23E+00	7.00E+00	0.00E+00	8.00E+00	2.32E+01	kg/day

Click below to active the control method used when conveying, loading stockpiles and wind erosion from stockpiles

Control method	Emission reduction, %

• Calculations of emissions to the atmosphere: II. Combustion gases

	Front-end wheel loader	units	TOTAL	units
CO	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
Benzene	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
1,3-Butadiene	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
CO_2	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
NO_x	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
PM_{10}	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate

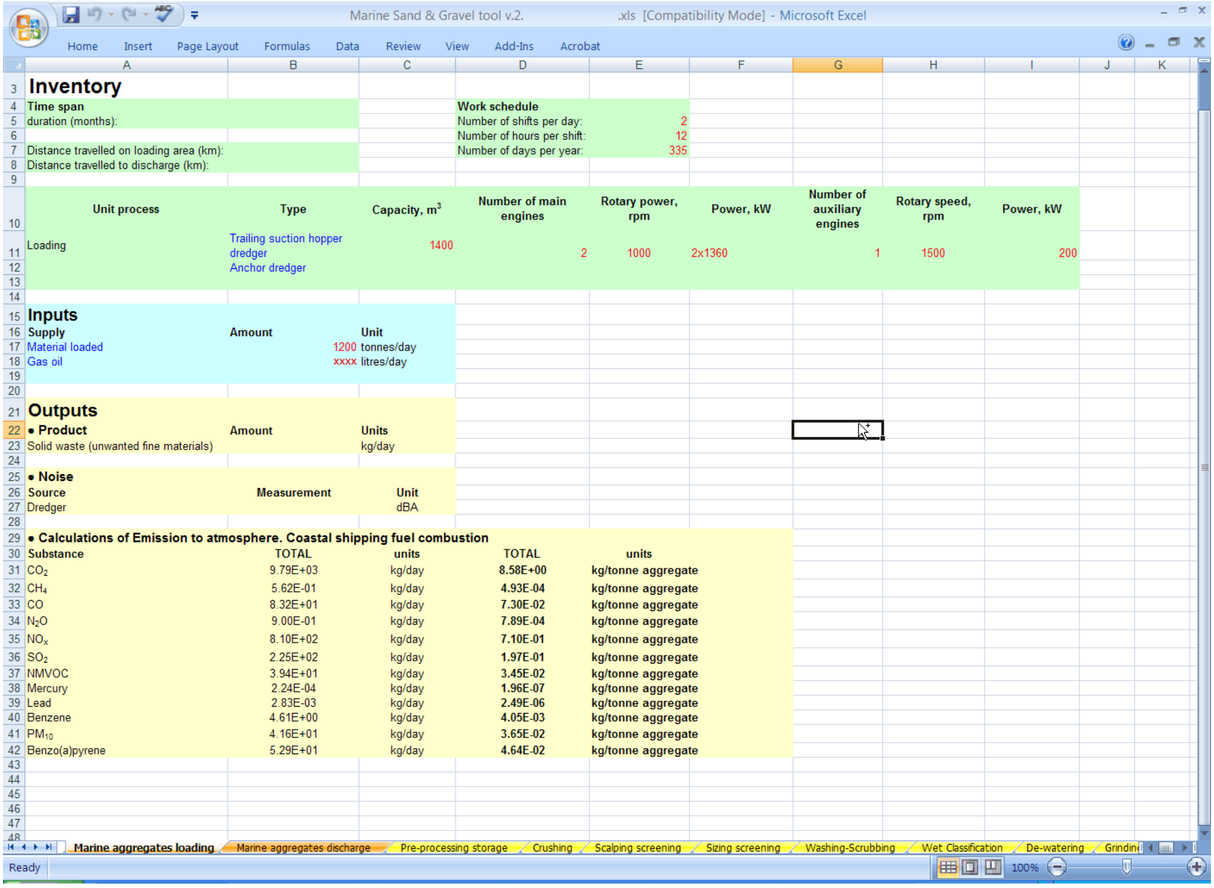
• Calculations of emissions to the atmosphere: III. Autogenerator

Substance	TOTAL	units	TOTAL	units
CO_2	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
CH_4	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
CO	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
N_2O	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
NO_x	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
NMVOC	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate
PM_{10}	0.00E+00	kg/day	0.00E+00	kg/tonne of aggregate

Indirect emissions from electricity consumption

Substance	TOTAL	units	TOTAL	units
CO_2	6.41E+02	kg/day	1.56E-01	kg/tonne of aggregate
SO_2	1.45E+00	kg/day	3.53E-04	kg/tonne of aggregate
NO_x	1.21E+00	kg/day	2.94E-04	kg/tonne of aggregate
Particulates	8.47E-02	kg/day	2.06E-05	kg/tonne of aggregate
Arsenic	2.18E-06	kg/day	5.29E-10	kg/tonne of aggregate
Cadmium	7.38E-06	kg/day	1.79E-09	kg/tonne of aggregate
Chromium	2.87E-05	kg/day	6.97E-09	kg/tonne of aggregate

Figure 4. View of the land won sand and gravel LCA tool.



Inventory

Time span
duration (months):

Distance travelled on loading area (km):
Distance travelled to discharge (km):

Work schedule
Number of shifts per day: 2
Number of hours per shift: 12
Number of days per year: 335

Unit process	Type	Capacity, m^3	Number of main engines	Rotary power, rpm	Power, kW	Number of auxiliary engines	Rotary speed, rpm	Power, kW
Loading	Trailing suction hopper dredger	1400	2	1000	2x1360	1	1500	200
	Anchor dredger							

Inputs

Supply	Amount	Unit
Material loaded	1200	tonnes/day
Gas oil	xxxx	litres/day

Outputs

• Product	Amount	Units
Solid waste (unwanted fine materials)		kg/day

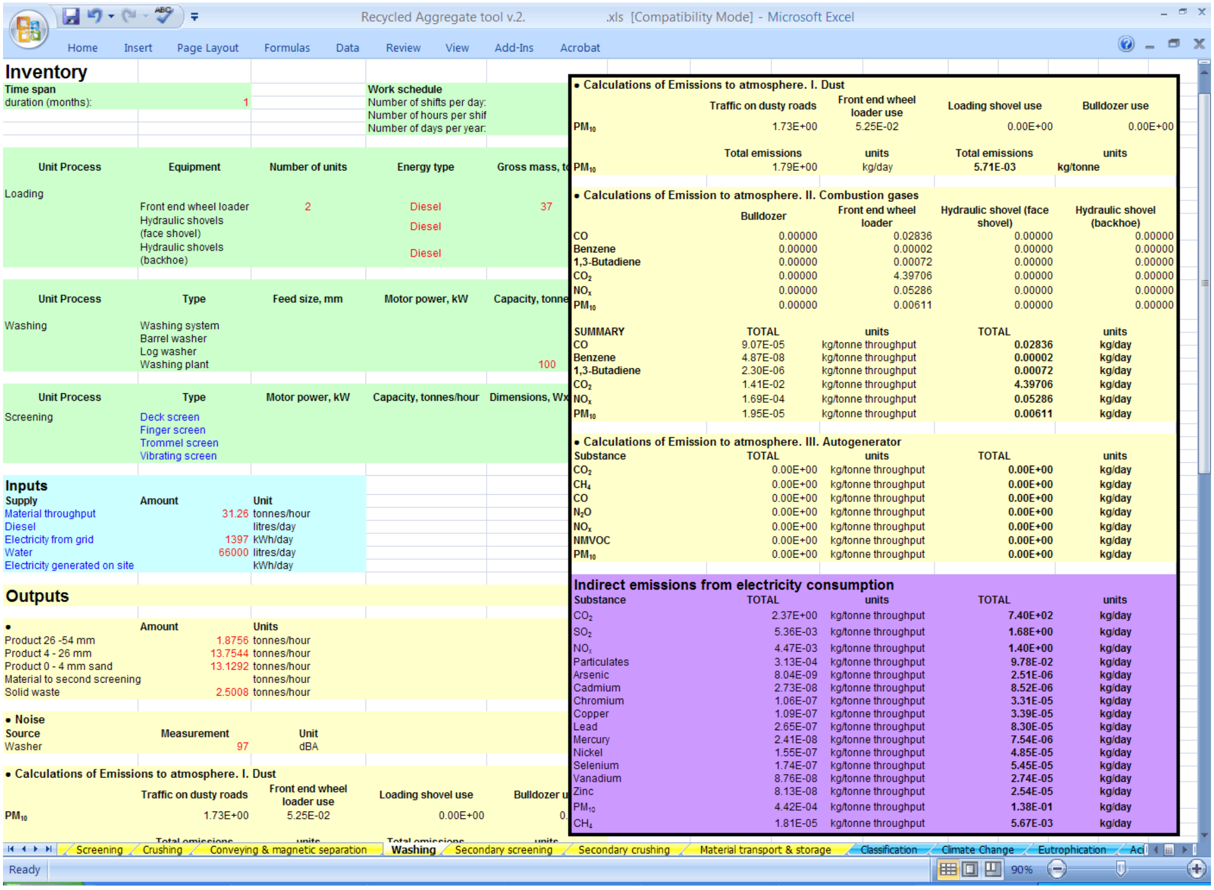
• Noise

Source	Measurement	Unit
Dredger		dBA

• Calculations of Emission to atmosphere. Coastal shipping fuel combustion

Substance	TOTAL	units	TOTAL	units
CO_2	9.79E+03	kg/day	8.58E+00	kg/tonne aggregate
CH_4	5.62E-01	kg/day	4.93E-04	kg/tonne aggregate
CO	8.32E+01	kg/day	7.30E-02	kg/tonne aggregate
N_2O	9.00E-01	kg/day	7.89E-04	kg/tonne aggregate
NO_x	8.10E+02	kg/day	7.10E-01	kg/tonne aggregate
SO_2	2.25E+02	kg/day	1.97E-01	kg/tonne aggregate
NMVOC	3.94E+01	kg/day	3.45E-02	kg/tonne aggregate
Mercury	2.24E-04	kg/day	1.96E-07	kg/tonne aggregate
Lead	2.83E-03	kg/day	2.49E-06	kg/tonne aggregate
Benzene	4.61E+00	kg/day	4.05E-03	kg/tonne aggregate
PM_{10}	4.16E+01	kg/day	3.65E-02	kg/tonne aggregate
Benzo(a)pyrene	5.29E+01	kg/day	4.64E-02	kg/tonne aggregate

Figure 5. View of the marine sand and gravel LCA tool.



Inventory

Time span
duration (months): 1

Work schedule
Number of shifts per day:
Number of hours per shif
Number of days per year:

Unit Process	Equipment	Number of units	Energy type	Gross mass, t
Loading				
	Front end wheel loader	2	Diesel	37
	Hydraulic shovels (face shovel)		Diesel	
	Hydraulic shovels (backhoe)		Diesel	

Unit Process	Type	Feed size, mm	Motor power, kW	Capacity, tonne
Washing	Washing system			
	Barrel washer			
	Log washer			
	Washing plant			100

Unit Process	Type	Motor power, kW	Capacity, tonnes/hour	Dimensions, Wx
Screening	Deck screen			
	Finger screen			
	Trommel screen			
	Vibrating screen			

Inputs

Supply	Amount	Unit
Material throughput	31.26	tonnes/hour
Diesel		litres/day
Electricity from grid	1397	kWh/day
Water	66000	litres/day
Electricity generated on site		kWh/day

Outputs

•	Amount	Units
Product 26 -54 mm	1.8756	tonnes/hour
Product 4 - 26 mm	13.7544	tonnes/hour
Product 0 - 4 mm sand	13.1292	tonnes/hour
Material to second screening		tonnes/hour
Solid waste	2.5008	tonnes/hour

• Noise

Source	Measurement	Unit
Washer	97	dBA

• Calculations of Emissions to atmosphere. I. Dust

	Traffic on dusty roads	Front end wheel loader use	Loading shovel use	Bulldozer u
PM_{10}	1.73E+00	5.25E-02	0.00E+00	0.

• Calculations of Emissions to atmosphere. I. Dust

	Traffic on dusty roads	Front end wheel loader use	Loading shovel use	Bulldozer use
PM_{10}	1.73E+00	5.25E-02	0.00E+00	0.00E+00

	Total emissions	units	Total emissions	units
PM_{10}	1.79E+00	kg/day	5.71E-03	kg/tonne

• Calculations of Emission to atmosphere. II. Combustion gases

	Bulldozer	Front end wheel loader	Hydraulic shovel (face shovel)	Hydraulic shovel (backhoe)
CO	0.00000	0.02836	0.00000	0.00000
Benzene	0.00000	0.00002	0.00000	0.00000
1,3-Butadiene	0.00000	0.00072	0.00000	0.00000
CO_2	0.00000	4.39706	0.00000	0.00000
NO_x	0.00000	0.05286	0.00000	0.00000
PM_{10}	0.00000	0.00611	0.00000	0.00000

SUMMARY	TOTAL	units	TOTAL	units
CO	9.07E-05	kg/tonne throughput	0.02836	kg/day
Benzene	4.87E-08	kg/tonne throughput	0.00002	kg/day
1,3-Butadiene	2.30E-06	kg/tonne throughput	0.00072	kg/day
CO_2	1.41E-02	kg/tonne throughput	4.39706	kg/day
NO_x	1.69E-04	kg/tonne throughput	0.05286	kg/day
PM_{10}	1.95E-05	kg/tonne throughput	0.00611	kg/day

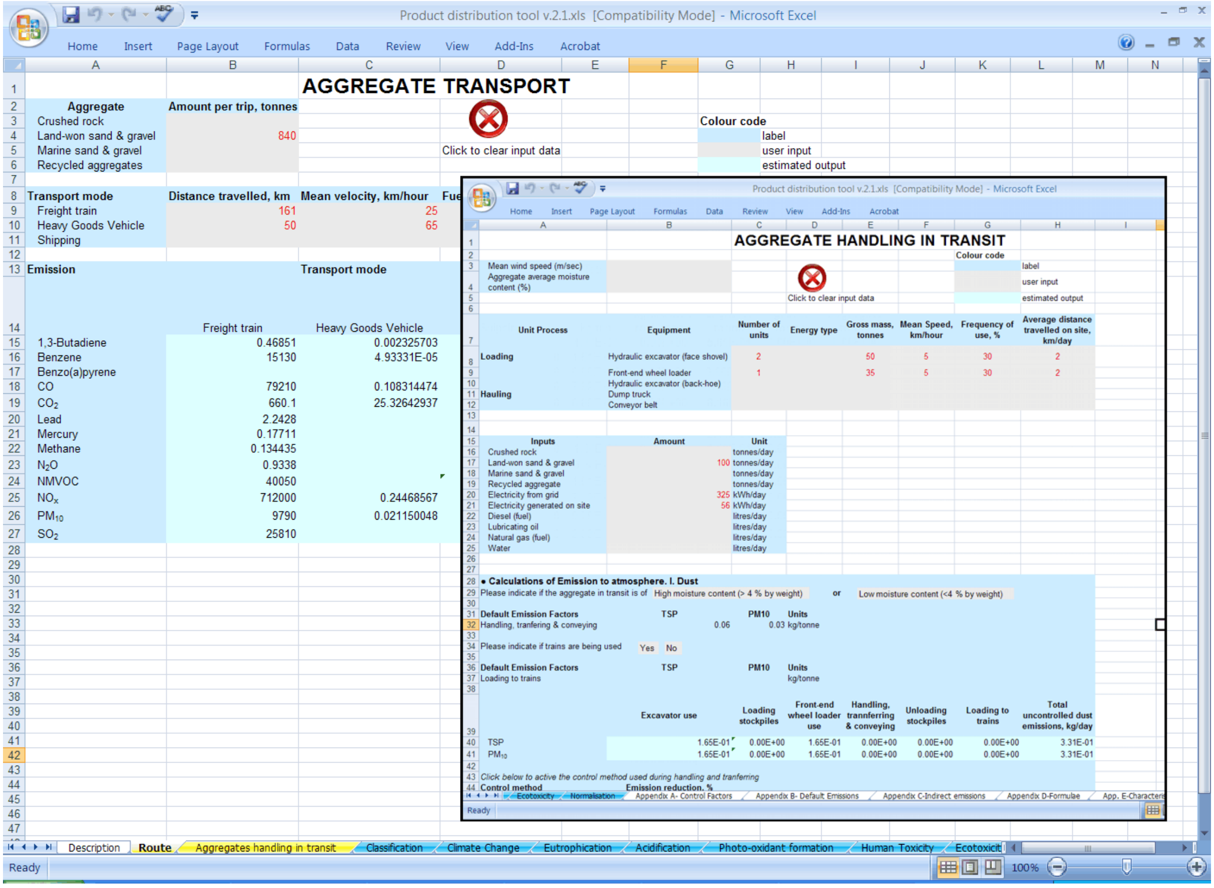
• Calculations of Emission to atmosphere. III. Autogenerator

Substance	TOTAL	units	TOTAL	units
CO_2	0.00E+00	kg/tonne throughput	0.00E+00	kg/day
CH_4	0.00E+00	kg/tonne throughput	0.00E+00	kg/day
CO	0.00E+00	kg/tonne throughput	0.00E+00	kg/day
N_2O	0.00E+00	kg/tonne throughput	0.00E+00	kg/day
NO_x	0.00E+00	kg/tonne throughput	0.00E+00	kg/day
NMVOC	0.00E+00	kg/tonne throughput	0.00E+00	kg/day
PM_{10}	0.00E+00	kg/tonne throughput	0.00E+00	kg/day

Indirect emissions from electricity consumption

Substance	TOTAL	units	TOTAL	units
CO_2	2.37E+00	kg/tonne throughput	7.40E+02	kg/day
SO_2	5.36E-03	kg/tonne throughput	1.68E+00	kg/day
NO_x	4.47E-03	kg/tonne throughput	1.40E+00	kg/day
Particulates	3.13E-04	kg/tonne throughput	9.78E-02	kg/day
Arsenic	8.04E-09	kg/tonne throughput	2.51E-06	kg/day
Cadmium	2.73E-08	kg/tonne throughput	8.52E-06	kg/day
Chromium	1.06E-07	kg/tonne throughput	3.31E-05	kg/day
Copper	1.09E-07	kg/tonne throughput	3.39E-05	kg/day
Lead	2.65E-07	kg/tonne throughput	8.30E-05	kg/day
Mercury	2.41E-08	kg/tonne throughput	7.54E-06	kg/day
Nickel	1.55E-07	kg/tonne throughput	4.85E-05	kg/day
Selenium	1.74E-07	kg/tonne throughput	5.45E-05	kg/day
Vanadium	8.76E-08	kg/tonne throughput	2.74E-05	kg/day
Zinc	8.13E-08	kg/tonne throughput	2.54E-05	kg/day
PM_{10}	4.42E-04	kg/tonne throughput	1.38E-01	kg/day
CH_4	1.81E-05	kg/tonne throughput	5.67E-03	kg/day

Figure 6. View of the recycled aggregate LCA tool.



AGGREGATE TRANSPORT

Aggregate	Amount per trip, tonnes
Crushed rock	
Land-won sand & gravel	840
Marine sand & gravel	
Recycled aggregates	

Click to clear input data

Colour code	
	label
	user input
	estimated output

Transport mode	Distance travelled, km	Mean velocity, km/hour	Fue
Freight train	161	25	
Heavy Goods Vehicle	50	65	
Shipping			

Emission	Transport mode	
	Freight train	Heavy Goods Vehicle
1,3-Butadiene	0.46851	0.002325703
Benzene	15130	4.93331E-05
Benzo(a)pyrene		
CO	79210	0.108314474
CO_2	660.1	25.32642937
Lead	2.2428	
Mercury	0.17711	
Methane	0.134435	
N_2O	0.9338	
NMVOC	40050	
NO_x	712000	0.24468567
PM_{10}	9790	0.021150048
SO_2	25810	

AGGREGATE HANDLING IN TRANSIT

Mean wind speed (m/sec)	
Aggregate average moisture content (%)	

Click to clear input data

Colour code	
	label
	user input
	estimated output

Unit Process	Equipment	Number of units	Energy type	Gross mass, tonnes	Mean Speed, km/hour	Frequency of use, %	Average distance travelled on site, km/day
Loading	Hydraulic excavator (face shovel)	2		50	5	30	2
	Front-end wheel loader	1		35	5	30	2
	Hydraulic excavator (back-hoe)						
Hauling	Dump truck						
	Conveyor belt						

Inputs	Amount	Unit
Crushed rock		tonnes/day
Land-won sand & gravel	100	tonnes/day
Marine sand & gravel		tonnes/day
Recycled aggregate		tonnes/day
Electricity from grid	325	kWh/day
Electricity generated on site	56	kWh/day
Diesel (fuel)		litres/day
Lubricating oil		litres/day
Natural gas (fuel)		litres/day
Water		litres/day

• Calculations of Emission to atmosphere. I. Dust

Please indicate if the aggregate in transit is of High moisture content (> 4 % by weight) or Low moisture content (<4 % by weight)

Default Emission Factors	TSP	PM10	Units
Handling, tranfering & conveying	0.06	0.03	kg/tonne

Please indicate if trains are being used Yes No

Default Emission Factors	TSP	PM10	Units
Loading to trains			kg/tonne

	Excavator use	Loading stockpiles	Front-end wheel loader use	Handling, trannferring & conveying	Unloading stockpiles	Loading to trains	Total uncontrolled dust emissions, kg/day
TSP	1.65E-01	0.00E+00	1.65E-01	0.00E+00	0.00E+00	0.00E+00	3.31E-01
PM_{10}	1.65E-01	0.00E+00	1.65E-01	0.00E+00	0.00E+00	0.00E+00	3.31E-01

Click below to active the control method used during handling and tranferring

Control method	Emission reduction, %

Figure 7. View of the product distribution LCA tool.

7.2 User friendly features

In order to assist the user during data input three special functions were coded in each LCA tool:

- This "sub-phase is not applicable" function is activated by clicking the ⊗ button located at the upper left hand corner in each spreadsheet. This function resets the cell values to blank, such that the information used to calculate the relevant environmental burdens are set to 'zero', resulting in the exclusion of the given operation in the LCA impact indicator calculations.
- The Error message function (**Error**) is activated when
    a. text is entered in a cell designated to a numerical value;
    b. a negative value is introduced;
    c. the numerical value is outside the ranges shown in Table 5.

  The error message is not shown in the cells assigned to earth moving machinery data for simplicity. However, ranges are also set for these as presented in Table 6. If the values entered are outside these ranges, they are set to zero. .
- The **Check Mass Balance** message in the Processing life cycle phase spreadsheets is displayed when the values entered as outputs ('Product', 'Material to next process', etc) are higher than the values entered as inputs ('Material throughput', etc). This comparison is made on the same spreadsheet for batch mode production and between sequential spreadsheets for production in continuous mode.

Table 5. Ranges set for the parameters used in the aggregates LCA tools

Parameter	Range	Comment
Time span		
Duration (months)	1 - 60	The maximum value was set to 5 years as this value is considered to be representative of LCA systems under the ISO 14041-98 framework.
Work schedule		
Number of shifts per day	1-4	
Number of hours per shift	1-24	
Number of days per year	1-365	
Overburden		
Average distance to bunds (km)	1-1000	
Average moisture content (%)	1-50	
% used for onsite restoration	1-100	
Other conditions		
Mean wind speed (m/sec)	1-10	
Average silt content (%)	1-50	
Product loss (%):	1-50	
After-use (%)		
Nature reserve	1-100	
Agriculture	1-100	
Grassland	1-100	
Recreational	1-100	

Table 6. Ranges set for the parameters used in combustion related emission calculations

Parameter	Range
Number of units	Up to 50
Mean Speed, km/hr	5-130
Frequency of use (%)	1-100
Average distance travelled on site (km)	Up to 5000
Vehicle	Gross mass range, tonne
Hydraulic excavator	1-100
Scraper	1-80
Truck	1-350
Wheel loader	1-200
Compactor	1-70
Bulldozer	1-100

8.0 Case study results

The development of the LCA tools has benefited greatly from the contributions made by the aggregates industry. Visits were arranged to quarries, recycling sites and wharves to hold discussions with the operators and collect data. Nine field sites have been visited and provided the data required to implement the LCA case studies. The selection of sites was such that large as well as small operations are covered. For the primary aggregates igneous as well as sedimentary deposits were considered for crushed rock primary aggregates. On-shore and off-shore sedimentary deposits were considered for sand and gravel primary aggregates. In the case of marine aggregates significantly different dredger capacities were selected. For the recycled aggregates, the transport of material from the demolition site to the recycling facility has also been accounted for in the results presented. Finally, the recycling site used included the full range of production from unbound to washed and graded aggregate.

In this report, the relevant life cycle impact assessment results are presented without direct reference to the site which has made their data available, instead, the range of results obtained throughout the case studies are summarised and listed in order to provide general guidance.

8.1 Crushed rock aggregates

The case studies used to develop and implement the inventory forms covered soft and hard rock crushed aggregates production sites (limestone and granite quarries respectively) and operations of varied annual production to represent the full range of operations in the UK. In all cases, inventory data representing one year of operation were used to estimate emissions and the corresponding LCA impact category results.

The results presented in Table 7 illustrate the range of LCA impact category indicator results that were found for the production of one tonne of material that is ready for transport to customers at the studied crushed rock aggregates production site. The Overburden removal, Waste landfilling, Site preparation and Re-vegetation processes are not reported in Table 7 as they did not form part of the production system for the case studies. This is not considered to affect significantly (more than 1% of the corresponding impact indicator scores). Figure 8 illustrates an example of the GWP indicator scores allocated to individual sub-phases for one of the crushed rock primary aggregate sites studied. Figure 9 illustrates a view of the Eutrophication worksheet in the crushed rock LCA tool with the emissions and impact category indicator results for one of the sites studied.

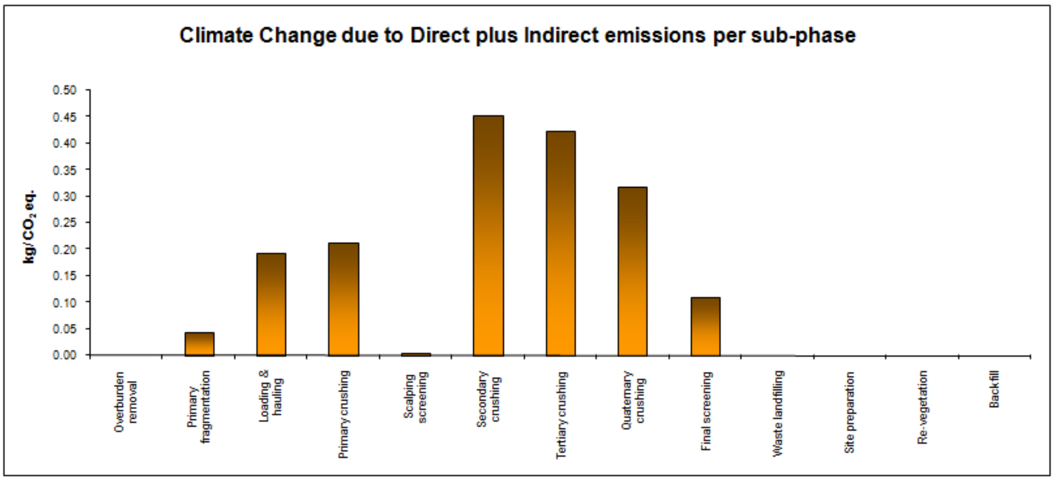


Figure 8. GWP indicator scores for a crushed rock aggregate site per tonne of aggregate produced.

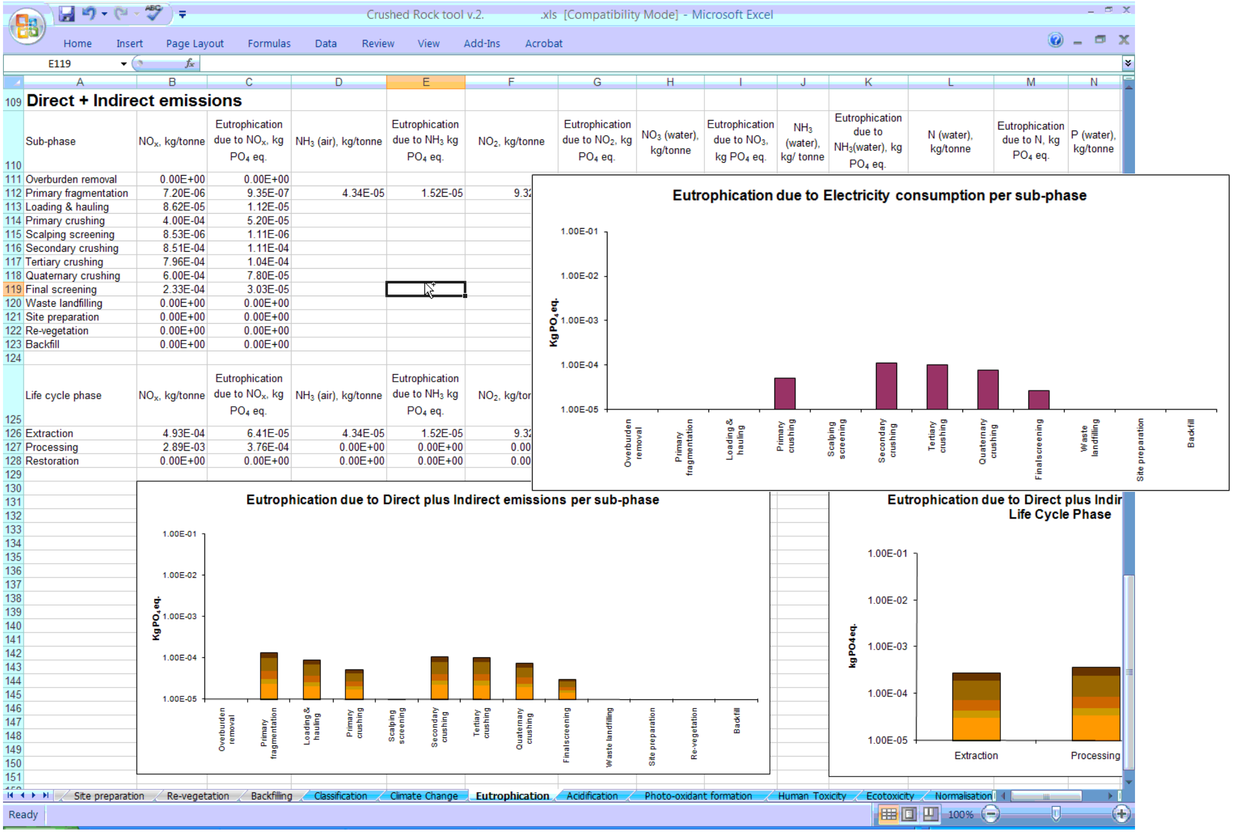
In addition to the impacts corresponding to one tonne of aggregate (reference unit), the product eco-profiles module of the crushed rock LCA tool developed was used to calculate the impacts corresponding to the production of one tonne of each individual product (size fraction) that may follow only part of the crushed rock aggregate production process (Table 8). In order to achieve an unbiased allocation of impacts to each individual product, the LCA indicator scores calculated for each process have been allocated proportionally to the relevant product streams that pass through each.

Table 7. Crushed rock aggregates system example: Impact assessment results per unit process per one tonne of aggregate produced.

Impact Category Units	**Unit process**									**Total impact**
	Primary fragmentation	Loading & hauling	Primary crushing	Scalping screening	Secondary crushing	Tertiary crushing	Quaternary crushing	Final screening	Backfill	
Global Warming kg CO_2 eq	$4.47X10^{-2}$- $1.11X10^{-1}$	$7.83X10^{-2}$- $1.94X10^{-1}$	$2.66X10^{-1}$- $9.52X10^{-1}$	$5.68X10^{-3}$- $1.63X10^{-1}$	$7.94X10^{-2}$- $7.50X10^{-1}$	$1.86X10^{-2}$- $5.31X10^{-1}$	$3.99X10^{-1}$	$1.38X10^{-1}$- $1.87X10^{-1}$	$1.05X10^{-2}$	1.48- 2.52
Eutrophication kg PO_4 eq	$1.35X10^{-4}$- $1.38X10^{-4}$	$4.21X10^{-5}$- $9.31X10^{-5}$	$7.14X10^{-5}$- $2.55X10^{-4}$	$2.77X10^{-6}$- $7.97X10^{-5}$	$2.13X10^{-5}$- $2.01X10^{-4}$	$4.98X10^{-6}$- $1.42X10^{-4}$	$1.07X10^{-4}$	$4.02X10^{-5}$- $7.25X10^{-5}$	$3.83X10^{-7}$	$5.51X10^{-4}$- $8.78X10^{-4}$
Acidification kg SO_2 eq	$5.45X10^{-4}$- $8.87X10^{-4}$	$4.90X10^{-4}$- $1.22X10^{-3}$	$1.47X10^{-3}$- $5.24X10^{-3}$	$4.93X10^{-5}$- $1.42X10^{-3}$	$4.37X10^{-4}$- $4.13X10^{-3}$	$1.02X10^{-4}$- $2.92X10^{-3}$	2.20X10-^{3}	$7.60X10^{-4}$- $1.06X10^{-3}$	$5.49X10^{-6}$	$8.58X10^{-3}$- $1.48X10^{-2}$
Photo-oxidant formation kg ethylene eq	$2.70X10^{-5}$- $9.07X10^{-5}$	$6.71X10^{-5}$- $1.73X10^{-4}$	$8.40X10^{-5}$- $3.00X10^{-4}$	$4.41X10^{-6}$- $1.27X10^{-5}$	$2.50X10^{-5}$- $2.37X10^{-4}$	$5.87X10^{-6}$- $1.67X10^{-4}$	$1.26X10^{-4}$	$4.34X10^{-5}$- $7.57X10^{-5}$	$8.15X10^{-5}$	$6.78X10^{-4}$- $9.94X10^{-4}$
Human toxicity kg 1,4-DB eq	$1.00X10^{-1}$- $1.72X10^{-1}$	$5.79X10^{-2}$- $6.18X10^{-02}$	$3.97X10^{-2}$- $8.59X10^{-2}$	$2.13X10^{-2}$- $2.71X10^{-2}$	$5.92X10^{-3}$- $5.59X10^{-2}$	4.71X10-^{3} - $7.46X10^{-2}$	$2.77X10^{-2}$	$1.30X10^{-2}$- $3.77X10^{-2}$	$1.15X10^{-3}$	$3.37X10^{-1}$- $4.08X10^{-1}$
Freshwater Aquatic Ecotoxicity kg 1,4-DB eq.	$1.97X10^{-5}$- $1.62X10^{-3}$	$1.47X10^{-3}$- $3.87X10^{-3}$	$3.99X10^{-4}$- $1.43X10^{-3}$	$6.76X10^{-5}$- $1.94X10^{-3}$	$1.19X10^{-4}$- $1.12X10^{-3}$	$2.78X10^{-5}$- $7.94X10^{-4}$	$5.98X10^{-4}$	$2.03X10^{-4}$- $8.07X10^{-4}$	$1.81X10^{-5}$	$5.98X10^{-3}$- $9.00X10^{-3}$
Marine Aquatic Ecotoxicity kg 1,4-DB eq.	$3.07X10^{-1}$- 25.27	22.97-60.27	13.01-46.42	$1.20x10^{-3}$- 34.45	3.88- 36.63	$9.08x10^{-1}$- 25.90	19.51	6.61-16.27	$2.82\ X10^{-1}$	124.74-198.40
Terrestrial Ecotoxicity kg 1,4-DB eq.	$8.69X10^{-6}$- $7.16X10^{-4}$	$6.51X10^{-4}$- $1.71X10^{-3}$	$1.91X10^{-4}$- $6.82X10^{-4}$	$3.02X10^{-5}$- $8.67X10^{-4}$	$5.69X10^{-5}$- $5.37X10^{-4}$	$1.33X10^{-5}$- $3.80X10^{-4}$	$2.86X10^{-4}$	$9.69X10^{-5}$- $3.64X10^{-4}$	$7.98X10^{-6}$	$2.71X10^{-3}$- $4.10X10^{-3}$
Ozone layer depletion kg R11 eq.	$1.65X10^{-11}$- $1.36X10^{-9}$	$1.23X10^{-9}$- $3.23X10^{-9}$	$3.90X10^{-8}$- $1.39X10^{-7}$	$8.82X10^{-10}$- $2.54X10^{-8}$	$1.16X10^{-8}$- $1.10X10^{-7}$	$2.73X10^{-9}$- $7.77X10^{-8}$	$5.86X10^{-8}$	$1.98X10^{-8}$- $2.39X10^{-8}$	$1.51X10^{-11}$	$1.85X10^{-7}$- $3.39X10^{-7}$

Table 8. Crushed rock aggregates system example: Range of impact assessment results for different crushed rock aggregate products per one tonne of aggregate produced.

Impact Category Units	**Product category A** Subbase, capping layers, crusher runs, agricultural lime, scalping, 80-40 mm, 150 mm, 125 mm, 40 mm, dust 6mm, dust 3mm	**Product category B** 28 mm, 20 mm, 14 mm, 10 mm
Global Warming kg CO_2 eq	0.51-1.35	2.43-4.14
Eutrophication kg PO_4 eq	$3.05X10^{-4}$-$5.65X10^{-4}$	$8.24X10^{-4}$-$1.31X10^{-3}$
Acidification kg SO_2 eq	$3.28X10^{-3}$-$8.41X10^{-3}$	$1.39X10^{-2}$-$2.38X10^{-2}$
Photo-oxidant formation kg ethylene eq	$2.89X10^{-4}$-$6.27X10^{-4}$	$8.95X10^{-4}$-$1.51X10^{-3}$
Human toxicity kg 1,4-DB eq	0.22-0.35	0.44-0.63
Freshwater Aquatic Ecotoxicity kg 1,4-DB eq.	$4.35X10^{-3}$-$7.26X10^{-3}$	$7.23X10^{-3}$-$1.14X10^{-2}$
Marine Aquatic Ecotoxicity kg 1,4-DB eq.	74.79-141.46	$1.81x10^3$-$3.20x10^3$
Terrestrial Ecotoxicity kg 1,4-DB eq.	$1.94X10^{-3}$-$3.26X10^{-3}$	$3.31X10^{-3}$-$5.26X10^{-3}$
Ozone layer depletion kg R11 eq.	$4.32X10^{-8}$-$1.68X10^{-7}$	$3.24X10^{-7}$-$5.76X10^{-7}$



Direct + Indirect emissions

	Sub-phase	NO_x, kg/tonne	Eutrophication due to NO_x, kg PO_4 eq.	NH_3 (air), kg/tonne	Eutrophication due to NH_3 kg PO_4 eq.	NO_2, kg/tonne	Eutrophication due to NO_2, kg PO_4 eq.	NO_3 (water), kg/tonne	Eutrophication due to NO_3, kg PO_4 eq.	NH_3 (water), kg/ tonne	Eutrophication due to NH_3(water), kg PO_4 eq.	N (water), kg/tonne	Eutrophication due to N, kg PO_4 eq.	P (water), kg/tonne
111	Overburden removal	0.00E+00	0.00E+00											
112	Primary fragmentation	7.20E-06	9.35E-07	4.34E-05	1.52E-05	9.32								
113	Loading & hauling	8.62E-05	1.12E-05											
114	Primary crushing	4.00E-04	5.20E-05											
115	Scalping screening	8.53E-06	1.11E-06											
116	Secondary crushing	8.51E-04	1.11E-04											
117	Tertiary crushing	7.96E-04	1.04E-04											
118	Quaternary crushing	6.00E-04	7.80E-05											
119	Final screening	2.33E-04	3.03E-05											
120	Waste landfilling	0.00E+00	0.00E+00											
121	Site preparation	0.00E+00	0.00E+00											
122	Re-vegetation	0.00E+00	0.00E+00											
123	Backfill	0.00E+00	0.00E+00											

	Life cycle phase	NO_x, kg/tonne	Eutrophication due to NO_x, kg PO_4 eq.	NH_3 (air), kg/tonne	Eutrophication due to NH_3 kg PO_4 eq.	NO_2, kg/tor
126	Extraction	4.93E-04	6.41E-05	4.34E-05	1.52E-05	9.32
127	Processing	2.89E-03	3.76E-04	0.00E+00	0.00E+00	0.00
128	Restoration	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00

Figure 9. View of the crushed rock tool Eutrophication impact category results page populated with emission calculations per tonne of product and impact category scores. The histogram in the foreground presents indirect emissions due to electricity consumption.

The information presented in Table 7 and the detailed results that the authors have reviewed illustrate that in terms of GWP the various crushing unit processes result in the highest impacts in this category. This is due to the high energy demand of these processes. It was also observed that for the soft crushed rock primary aggregates these impacts were lower than for hard rock aggregates. However, which of the primary, secondary, tertiary or quaternary crushing process resulted in the highest GWP impacts depends on the proportion of aggregates production that passes through each crushing processes, the specific material hardness and the size fraction required. The unit processes relating to the extraction phase consistently contribute only a small proportion of the overall GWP indicator in relation to the processing phase. In those cases where restoration phase processes were reported they had an even smaller, nearly negligible contribution to the GWP indicator scores for one tonne of quarry product and for one tonne of individual aggregate size fraction.

Eutrophication, Acidification and Photo-oxidant formation impacts are in all cases dominated by indirect emissions and very much depend on the source of electricity supply used, namely the national grid or electricity that is generated on site. For these impact categories the extraction and processing phases make similar contributions to these indicator scores. The Human toxicity is influenced to a greater extend by the extraction sub-phases than processing, while the three Ecotoxicity impact categories are dominated by the effects of processing sub-phases with similar contributions from each.

It is also important to note that the larger crushed rock aggregate operations consistently illustrate lower impact category indicator scores in comparison to smaller operations, proving that the relationship between emissions and annual production is not linear.

The ranges of LCA impact category indicator scores reported in Table 8 for different products were based on mass fraction based allocation per unit process. Table 9 provides one example of the mass fraction based impacts allocation for one of the sites. The ranges of indicator score results confirm that it is very important to consider product category specific results when carrying out comparative assessments and that there are significant differences between these even for one aggregates production site. Finally, it is important to note that the case results reported here do not include the impacts from the transport of aggregate from the production site to the market place or customer. However, the product distribution LCA tool provides the facility to calculate these additional impacts on a case by case basis.

8.2 Land won sand and gravel aggregates

The land won sand and gravel aggregates case studies covered operations of significantly varied annual production and operational practices, representing the full range of such activities in the UK. In all cases, inventory data representing one year of operation were used to estimate emissions and the corresponding LCA impact category results.

Table 10 illustrates the range of LCA impact category indicator results that were found for the production of one tonne of material that is ready for transport to customers at the studied sand and gravel production site. The Grinding, Waste landfilling and Backfilling processes are not reported in Table 10 as they did not form part of the production system for the case studies. Crushing was necessary for one of the sites only, which explains why a single value is reported in Table 10. It is also important to consider that for land won sand and gravel operations which extract material that is very similar to the product specifications required the need for processing is minimal and therefore the corresponding LCA impact category impacts would have low scores. The higher impacts recorded in this category of primary aggregates production are for cases where crushing and long distance transport of the product on site (loading and conveying) is required. Figure 10 illustrates an example of the GWP indicator scores allocated to individual sub-phases for one of the land won sand and gravel primary aggregate sites studied. Figure 11 illustrates a view of the Acidification worksheet in the sand and gravel LCA tool with the emissions and impact category indicator results for one of the case studies.

Sand and gravel primary aggregate sites are ideal locations for waste disposal since they are often underlain by impermeable sediments that form part of the sequence that is extracted and are of no economic value. As a result, land won sand and gravel production operations often include restoration activities. In order to allocate the impacts corresponding to restoration correctly these are allocated on the basis of overall expected production over the life time of the quarry. Table 13 illustrates that the restoration activities make a very small contribution to the overall category indicator impacts recorded per tonne of aggregate product produced.

Table 9. Example product eco-profile allocation method carried out on a mass fraction basis.

1 tonne of aggregate product consists of:		Fractional allocation per unit process is as follows:												
Product	Fraction	Overburden removal	Primary fragmentation	Loading & hauling	Primary crushing	Scalping screening	Secondary crushing	Tertiary crushing	Quaternary crushing	Final screening	Waste landfilling	Pit preparation	Re-vegetation	Backfill
Subbase	-	-	-	-	-	-					-	-	-	-
Capping layers	-	-	-	-	-	-					-	-	-	-
Crusher runs	0.03	0.03	0.03	0.03	0.03	0.03					0.03	0.03	0.03	0.03
Agricultural lime	-	-	-	-	-	-					-	-	-	-
Scalpings	-	-	-	-	-	-					-	-	-	-
Product 80-40 mm	-	-	-	-	-	-					-	-	-	-
Product 150 mm	0.09	0.09	0.09	0.09	0.09	0.09					0.09	0.09	0.09	0.09
Product 125 mm	-	-	-	-	-	-					-	-	-	-
Product 40 mm	-	-	-	-	-	-					-	-	-	-
Product 28 mm	0.17	0.17	0.17	0.17	0.17	0.17	0.20	0.20	0.20	0.20	0.17	0.17	0.17	0.17
Product 20 mm	0.27	0.27	0.27	0.27	0.27	0.27	0.32	0.32	0.32	0.32	0.27	0.27	0.27	0.27
Product 14 mm	0.20	0.20	0.20	0.20	0.20	0.20	0.24	0.24	0.24	0.24	0.20	0.20	0.20	0.20
Product 10 mm	0.20	0.20	0.20	0.20	0.20	0.20	0.24	0.24	0.24	0.24	0.20	0.20	0.20	0.20
Dust 6mm	0.03	0.03	0.03	0.03	0.03	0.03					0.03	0.03	0.03	0.03
Dust 3mm	-	-	-	-	-	-					-	-	-	-

*All columns add up to 1

Table 10. Land won sand and gravel aggregates system example: Impact assessment results per unit process per one tonne of aggregate produced.

Impact Category Units	**Unit process**													**Total impact**
	Overburden removal	Excavation	Loading and Conveying	Pre-processing storage	Scalping screening	Crushing	Sizing screening	Washing-scrubbing	Wet classification	De-watering	Product storage	Pit preparation	Re-vegetation	
Global Warming kg CO$_2$ eq	4.91x10^{-3}-0.36	7.66x10^{-2}	1.55x10^{-1}-9.19x10^{-1}	1.14x10^{-1}-1.96x10^{-1}	1.97x10^{-2}-1.68x10^{-1}	4.19x10^{-1}	1.97x10^{-2}-5.88x10^{-1}	2.22x10^{-2}-5.71x10^{-1}	1.97x10^{-2}-4.19x10^{-1}	4.92x10^{-3}-2.91x10^{-1}	2.09x10^{-3}-6.48x10^{-1}	1.53x10^{-5}-3.31x10^{-4}	3.99x10^{-7}-3.13x10^{-4}	0.27-2.39
Eutrophication kg PO$_4$ eq	7.75 x10^{-6}-1.96 x10^{-4}	3.58 x10^{-5}	8.93x10^{-5}-2.54x10^{-4}	3.06x10^{-5}-8.67 x10^{-5}	1.49x10^{-5}-4.49x10^{-5}	1.12x10^{-4}	1.49x10^{-5}-1.57x10^{-4}	1.67x10^{-5}-1.53x10^{-4}	1.49x10^{-5}-1.12x10^{-4}	3.72 x10^{-6}-7.80x10^{-5}	3.27 x10^{-6}-1.73x10^{-4}	2.17x10^{-8}-5.25x10^{-7}	6.35 x10^{-10}	1.66 x10^{-4}-7.43x10^{-4}
Acidification kg SO$_2$ eq	2.98 x10^{-5}-2.25 x10^{-3}	4.80 x10^{-4}	9.67x10^{-4}-5.09x10^{-3}	6.29x10^{-4}-1.08x10^{-3}	5.72x10^{-5}-9.23x10^{-4}	2.31x10^{-3}	5.72x10^{-5}-3.24x10^{-3}	6.43x10^{-5}-3.14x10^{-3}	5.72x10^{-5}-2.31x10^{-3}	1.43x10^{-5}-1.60x10^{-3}	1.26x10^{-5}-3.57x10^{-3}	9.35x10^{-8}-2.02x10^{-6}	2.44x10^{-9}-1.91x10^{-6}	1.34X10^{-3}-1.35X10^{-2}
Photo-oxidant formation kg ethylene eq	1.42x10^{-6}-3.07x10^{-4}	6.87x10^{-5}	1.29x10^{-4}-3.16x10^{-4}	3.60x10^{-5}-1.45x10^{-4}	3.82x10^{-6}-5.28x10^{-5}	1.32x10^{-4}	3.82x10^{-6}-3.49x10^{-4}	8.95x10^{-7}-7.69x10^{-3}	3.82x10^{-6}-3.47x10^{-4}	9.56x10^{-7}-9.19x10^{-5}	5.48x10^{-7}-2.04x10^{-4}	5.57x10^{-9}-9.01x10^{-8}	1.09x10^{-10}-8.52x10^{-8}	1.61x10^{-4}-8.47x10^{-3}
Human toxicity kg 1,4-DB eq	1.71x10^{-3}-7.98x10^{-1}	8.61x10^{-3}	2.58x10^{-2}-6.67x10^{-2}	1.32x10^{-2}-2.01x10^{-2}	8.80x10^{-3}-6.08x10^{-2}	7.14x10^{-2}	4.93x10^{-2}-6.17x10^{-2}	1.56x10^{-4}-3.96x10^{-2}	1.41x10^{-4}-2.90x10^{-2}	3.51x10^{-5}-2.02x10^{-2}	4.26x10^{-3}-4.79x10^{-2}	4.40x10^{-6}-1.78x10^{-4}	3.77x10^{-10}-2.95x10^{-7}	1.25x10^{-1}-3.49x10^{-1}
Freshwater Aquatic Ecotoxicity kg 1,4-DB eq.	6.76x10^{-13}-3.37x10^{-3}	7.69x10^{-4}	1.40x10^{-3}-1.76x10^{-3}	1.71x10^{-4}-1.58x10^{-3}	4.32x10^{-17}-2.51x10^{-4}	6.27x10^{-4}	4.32x10^{-17}-8.80x10^{-4}	5.33x10^{-4}-8.55x10^{-4}	4.32x10^{-17}-6.27x10^{-4}	1.08x10^{-17}-5.34x10^{-4}	6.77x10^{-13}-9.70x10^{-4}	9.57x10^{-14}-2.27x10^{-8}		1.58x10^{-3}-6.50x10^{-3}
Marine Aquatic Ecotoxicity kg 1,4-DB eq.	1.67x10^{-11}-52.48	11.98	21.85-49.78	5.58-24.68										2. 74x10^{1}-152.92
Terrestrial Ecotoxicity kg 1,4-DB eq.	9.88x10^{-14}-1.49x10^{-3}	3.39x10^{-4}	6.19x10^{-4}-8.27x10^{-4}	8.18x10^{-5}-6.99x10^{-4}	4.08x10^{-18}-1.20x10^{-4}	3.00x10^{-4}	4.08x10^{-18}-4.21x10^{-4}	2.55x10^{-4}-4.09x10^{-4}	4.08x10^{-18}-6.78x10^{-4}	1.02x10^{-18}-2.40x10^{-4}	1.18x10^{-13}-4.64x10^{-3}	1.61x10^{-14}-1.00x10^{-8}		6.99x10^{-4}-2.98x10^{-3}
Ozone layer depletion kg R11 eq.	1.49x10^{-9}-5.63x10^{-9}	1.29x10^{-0}	2.35x10^{-9}-1.29x10^{-7}	2.65x10^{-9}-2.87x10^{-8}	9.49x10^{-9}-2.45x10^{-8}	6.14x10^{-8}	3.68x10^{-8}-8.92x10^{-8}	5.22x10^{-8}-2.26x10^{-7}	5.16x10^{-8}-6.14x10^{-8}	1.26x10^{-8}-4.27x10^{-8}	9.49x10^{-8}	3.80x10^{-14}-3.80x10^{-14}		2.65x10^{-9}-4.44x10^{-7}

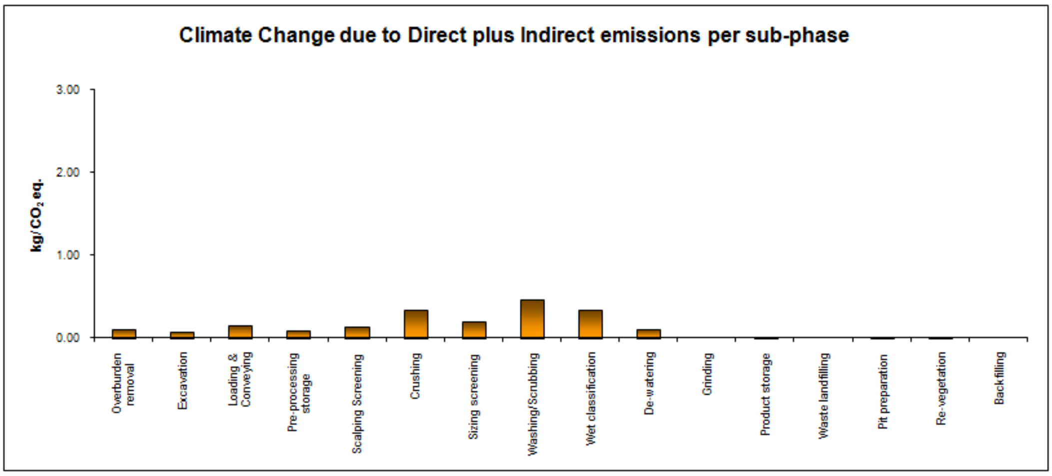
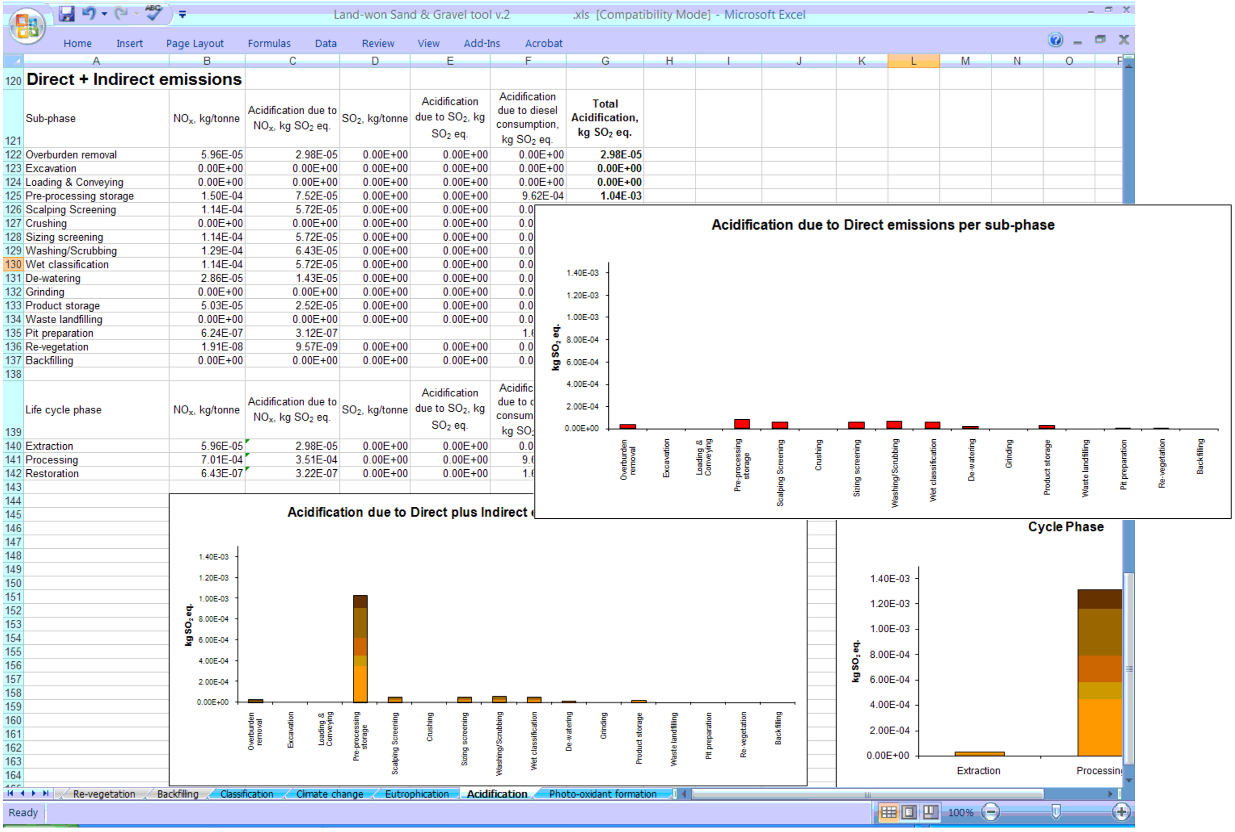


Figure 10. GWP indicator scores for a land won sand and gravel aggregate site per tonne of aggregate produced.



Direct + Indirect emissions

Sub-phase	NO_x, kg/tonne	Acidification due to NO_x, kg SO_2 eq.	SO_2, kg/tonne	Acidification due to SO_2, kg SO_2 eq.	Acidification due to diesel consumption, kg SO_2 eq.	**Total Acidification, kg SO_2 eq.**
Overburden removal	5.96E-05	2.98E-05	0.00E+00	0.00E+00	0.00E+00	**2.98E-05**
Excavation	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Loading & Conveying	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
Pre-processing storage	1.50E-04	7.52E-05	0.00E+00	0.00E+00	9.62E-04	**1.04E-03**
Scalping Screening	1.14E-04	5.72E-05	0.00E+00	0.00E+00	0.0	
Crushing	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0	
Sizing screening	1.14E-04	5.72E-05	0.00E+00	0.00E+00	0.0	
Washing/Scrubbing	1.29E-04	6.43E-05	0.00E+00	0.00E+00	0.0	
Wet classification	1.14E-04	5.72E-05	0.00E+00	0.00E+00	0.0	
De-watering	2.86E-05	1.43E-05	0.00E+00	0.00E+00	0.0	
Grinding	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0	
Product storage	5.03E-05	2.52E-05	0.00E+00	0.00E+00	0.0	
Waste landfilling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0	
Pit preparation	6.24E-07	3.12E-07			1.	
Re-vegetation	1.91E-08	9.57E-09	0.00E+00	0.00E+00	0.0	
Backfilling	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0	

Life cycle phase	NO_x, kg/tonne	Acidification due to NO_x, kg SO_2 eq.	SO_2, kg/tonne	Acidification due to SO_2, kg SO_2 eq.	Acidific due to c consum kg SO
Extraction	5.96E-05	2.98E-05	0.00E+00	0.00E+00	0.0
Processing	7.01E-04	3.51E-04	0.00E+00	0.00E+00	9.
Restoration	6.43E-07	3.22E-07	0.00E+00	0.00E+00	1.

Figure 11. View of the sand and gravel tool Acidification impact category results page populated with emission calculations per tonne of product and impact category scores. The histogram in the foreground presents indirect emissions due to electricity consumption.

In addition to the impacts corresponding to one tonne of aggregate (reference unit), the product eco-profiles module of the land won sand and gravel LCA tool developed was used to calculate the impacts corresponding to the production of one tonne of each individual product (size fraction) that may follow only part of the sand and gravel production process (Table 11). In order to achieve an unbiased allocation of impacts to each individual product, the LCA indicator scores calculated for each unit process have been allocated proportionally to the relevant product streams that pass through each unit process.

The information presented in Table 10 and the detailed results that the authors have reviewed illustrate that in terms of GWP the loading and conveying, washing and scrubbing, product storage and crushing sub-phases (where crushing is present) result in the highest impacts in this category. This is due to the comparatively higher energy demand of these processes and it is dominated by the upstream indirect emissions from electricity used for these processes. In all cases the processing phase GWP impacts was significantly higher than that for the extraction and restoration phase impacts.

Eutrophication, Acidification and Photo-oxidant formation impacts are in all cases dominated by the processing phase and indirect emissions, which very much depend on the source of electricity supply used, namely the national grid or electricity that is generated on site. The process configuration at the sand and gravel production site, i.e. sub-phase and equipment used, influences the relative scale of these impacts per sub-phase. The Human toxicity is influenced to a greater extend by the extraction sub-phases than processing, while the three Ecotoxicity impact categories are dominated by the effects of processing sub-phases.

The ranges of LCA impact category indicator scores reported in Table 8 for different products were based on mass fraction based allocation per unit process. Table 9 provides one example of the mass fraction based impacts allocation for one of the sites. The ranges of indicator score results confirm that it is important to consider product category specific results when carrying out comparative assessments and that there are significant differences between these even for one aggregates production site. Since the proportion of sand versus gravel product is not very varied, the importance of product specific allocation is not as pronounced as for crushed rock aggregates. Similar to the crushed rock aggregates results reported in Section 8.1, the case study results presented here do not include the impacts from the transport of aggregates from the production site to the market. The product distribution LCA tool provides the facility to calculate these additional impacts.

Table 11. Land won sand and gravel aggregates system example: Range of impact assessment results for different size products per one tonne of aggregate produced.

Impact Category Units	**Gravel Products** 40-20 mm, 20-10 mm, 5-10 mm, 3-5 mm, oversize	**Sand Products** Coarse sand, building sand, fine sand
Global Warming kg CO_2 eq	0.29-4.02	0.25-3.45
Eutrophication kg PO_4 eq	1.84×10^{-4}-1.19×10^{-3}	1.50×10^{-4}-1.03×10^{-3}
Acidification kg SO_2 eq	1.41×10^{-3}-2.25×10^{-2}	1.28×10^{-3}-1.93×10^{-2}
Photo-oxidant formation kg ethylene eq	1.62×10^{-4}-1.47×10^{-2}	1.60×10^{-4}-1.81×10^{-3}
Human toxicity kg 1,4-DB eq	1.82×10^{-1}-1.12	7.57×10^{-2}-1.03
Freshwater Aquatic Ecotoxicity kg 1,4-DB eq.	1.58×10^{-3}-9.24×10^{-3}	1.58×10^{-3}-8.38×10^{-3}
Marine Aquatic Ecotoxicity kg 1,4-DB eq.	24.68-204.67	24.68-176.48
Terrestrial Ecotoxicity kg 1,4-DB eq.	6.99×10^{-4}-4.28×10^{-3}	6.99×10^{-4}-3.87×10^{-3}
Ozone layer depletion kg R11 eq.	2.65×10^{-9}-6.35×10^{-7}	2.65×10^{-9}-4.26×10^{-7}

Table 12. Example product eco-profile allocation method for land won sand and gravel aggregates carried out on a mass fraction basis.

Product	Fraction	Overburden removal	Excavation	Loading and Conveying	Pre-processing storage	Scalping screening	Crushing	Sizing screening	Washing-scrubbing	Wet classification	De-watering	Grinding	Product storage	Waste landfilling	Pit preparation	Re-vegetation	Backfilling
Gravel products	0.55	0.55	0.55	0.55	0.55	0.55	1.00	1.00	1.00			1.00	0.55	0.55	0.55	0.55	0.55
Sand products	0.45	0.45	0.45	0.45	0.45	0.45				1.00	1.00		0.45	0.45	0.45	0.45	0.45

8.3 Marine sand and gravel aggregates

The marine sand and gravel aggregates case studies were based on two dredgers of significantly different capacity operating from the same wharf facility in order to provide comparable results for the marine extraction phase. The inventory data analysed covered one year of each dredger and on-shore processing operation and were used to estimate emissions and the corresponding LCA impact category results.

The LCA impact category indicator results shown in Table 13 illustrate the range of LCIA results for the production of one tonne of material that is ready for transport to customers at the wharf. All on-shore processing sub-phases are aggregated under wharf processes since they only contribute a small fraction of the overall impacts in comparison to the marine extraction sub-phases. Figure 12 illustrates an example of the GWP indicator scores allocated to individual sub-phases and Figure 13 illustrates a view of the Photo-oxidant formation worksheet showing upstream indirect emissions from fuel consumption and the direct plus indirect Photo-oxidant formation impact category results for one of the case studies.

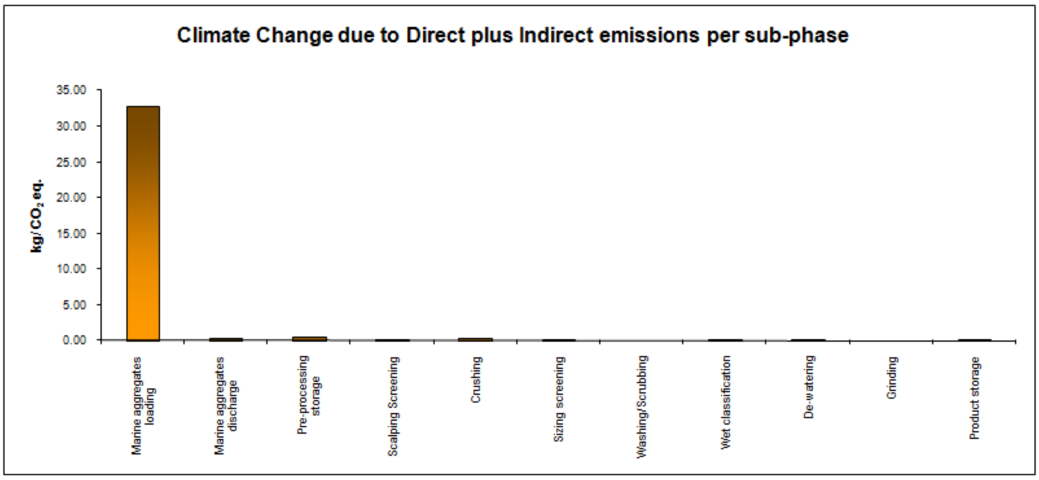
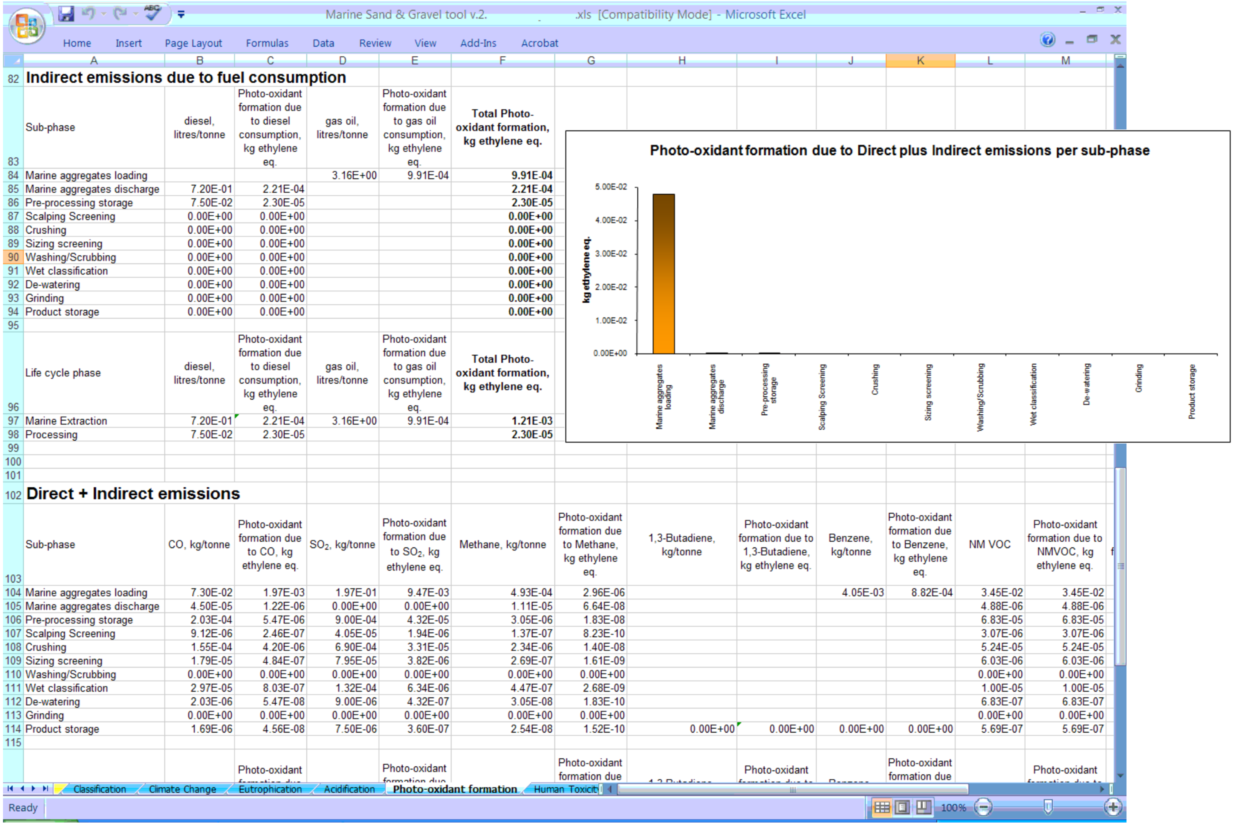


Figure 12. GWP indicator scores for a marine sand and gravel aggregate operation per tonne of aggregate produced.



Indirect emissions due to fuel consumption

Sub-phase	diesel, litres/tonne	Photo-oxidant formation due to diesel consumption, kg ethylene eq.	gas oil, litres/tonne	Photo-oxidant formation due to gas oil consumption, kg ethylene eq.	**Total Photo-oxidant formation, kg ethylene eq.**
Marine aggregates loading			3.16E+00	9.91E-04	**9.91E-04**
Marine aggregates discharge	7.20E-01	2.21E-04			**2.21E-04**
Pre-processing storage	7.50E-02	2.30E-05			**2.30E-05**
Scalping Screening	0.00E+00	0.00E+00			**0.00E+00**
Crushing	0.00E+00	0.00E+00			**0.00E+00**
Sizing screening	0.00E+00	0.00E+00			**0.00E+00**
Washing/Scrubbing	0.00E+00	0.00E+00			**0.00E+00**
Wet classification	0.00E+00	0.00E+00			**0.00E+00**
De-watering	0.00E+00	0.00E+00			**0.00E+00**
Grinding	0.00E+00	0.00E+00			**0.00E+00**
Product storage	0.00E+00	0.00E+00			**0.00E+00**

Life cycle phase	diesel, litres/tonne	Photo-oxidant formation due to diesel consumption, kg ethylene eq.	gas oil, litres/tonne	Photo-oxidant formation due to gas oil consumption, kg ethylene eq.	**Total Photo-oxidant formation, kg ethylene eq.**
Marine Extraction	7.20E-01	2.21E-04	3.16E+00	9.91E-04	**1.21E-03**
Processing	7.50E-02	2.30E-05			**2.30E-05**

Direct + Indirect emissions

Sub-phase	CO, kg/tonne	Photo-oxidant formation due to CO, kg ethylene eq.	SO$_2$, kg/tonne	Photo-oxidant formation due to SO$_2$, kg ethylene eq.	Methane, kg/tonne	Photo-oxidant formation due to Methane, kg ethylene eq.	1,3-Butadiene, kg/tonne	Photo-oxidant formation due to 1,3-Butadiene, kg ethylene eq.	Benzene, kg/tonne	Photo-oxidant formation due to Benzene, kg ethylene eq.	NM VOC	Photo-oxidant formation due to NMVOC, kg ethylene eq.
Marine aggregates loading	7.30E-02	1.97E-03	1.97E-01	9.47E-03	4.93E-04	2.96E-06			4.05E-03	8.82E-04	3.45E-02	3.45E-02
Marine aggregates discharge	4.50E-05	1.22E-06	0.00E+00	0.00E+00	1.11E-05	6.64E-08					4.88E-06	4.88E-06
Pre-processing storage	2.03E-04	5.47E-06	9.00E-04	4.32E-05	3.05E-06	1.83E-08					6.83E-05	6.83E-05
Scalping Screening	9.12E-06	2.46E-07	4.05E-05	1.94E-06	1.37E-07	8.23E-10					3.07E-06	3.07E-06
Crushing	1.55E-04	4.20E-06	6.90E-04	3.31E-05	2.34E-06	1.40E-08					5.24E-05	5.24E-05
Sizing screening	1.79E-05	4.84E-07	7.95E-05	3.82E-06	2.69E-07	1.61E-09					6.03E-06	6.03E-06
Washing/Scrubbing	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00					0.00E+00	0.00E+00
Wet classification	2.97E-05	8.03E-07	1.32E-04	6.34E-06	4.47E-07	2.68E-09					1.00E-05	1.00E-05
De-watering	2.03E-06	5.47E-08	9.00E-06	4.32E-07	3.05E-08	1.83E-10					6.83E-07	6.83E-07
Grinding	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00					0.00E+00	0.00E+00
Product storage	1.69E-06	4.56E-08	7.50E-06	3.60E-07	2.54E-08	1.52E-10	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.69E-07	5.69E-07

Figure 13. View of the marine sand and gravel tool Photo-oxidant formation impact category results page populated with emission calculations per tonne of product and impact category scores. The histogram in the foreground presents direct and indirect emissions.

The results reported in Table 13 and the detailed information for the two case studies suggest that all LCIA impact categories are dominated by the impacts of the marine sand and gravel loading sub-phase. The gas oil consumption for the dredger and the corresponding upstream indirect emissions overshadow all other impacts. Table 14 presents the range of impact assessment indicator results allocated to the different aggregate products. These results are not significantly different since the proportion of sand versus that of gravel in the primary resource is equal. There are few sub-phases that are not part of both sand and gravel production streams (Table 15) and these make a small contribution to the overall indicator scores.

Table 13. Marine sand and gravel aggregates system example: Impact assessment results per unit process per one tonne of aggregate produced.

Impact Category Units	**Unit process**			**Total impact**
	Marine aggregates loading	Marine aggregates discharge	Wharf processes	
Global Warming kg CO_2 eq	32.79–40.30	0.255–0.357	1.06	34.10–41.61
Eutrophication kg PO_4 eq	9.28×10^{-2}–0.115	8.76×10^{-5} – 1.30×10^{-4}	2.87×10^{-4}	9.32×10^{-2}–0.115
Acidification kg SO_2 eq	0.599–0.740	1.03×10^{-3}–1.61×10^{-3}	5.84×10^{-3}	0.606-0.747
Photo-oxidant formation kg ethylene eq	4.79×10^{-2}–5.90×10^{-2}	1.44×10^{-4}–2.27×10^{-4}	3.49×10^{-4}	4.83×10^{-2}–5.95×10^{-2}
Human toxicity kg 1,4-DB eq	8.72–10.78	1.56×10^{-2}–2.48×10^{-2}	9.01×10^{-2}	8.83–10.89
Freshwater Aquatic Ecotoxicity kg 1,4-DB eq.	4.08–5.06	1.56×10^{-3}–2.50×10^{-3}	1.81×10^{-3}	4.09–5.06
Marine Aquatic Ecotoxicity kg 1,4-DB eq.	236.83–241.24	24.30–38.89	54.46	315.60–334.60
Terrestrial Ecotoxicity kg 1,4-DB eq.	2.18×10^{-2}–2.53×10^{-2}	6.88×10^{-4}–1.10×10^{-3}	8.54×10^{-4}	2.34×10^{-2}–2.68×10^{-2}
Ozone Layer Depletion kg D11 eq.	1.70×10^{-8}–1.91×10^{-8}	2.61×10^{-9}–4.17×10^{-9}	1.52×10^{-7}	3.30×10^{-9}–1.75×10^{-7}

Table 14. Marine sand and gravel aggregates system example: Range of impact assessment results for different aggregate products per one tonne of aggregate produced.

Impact Category Units	**Gravel Products** 40-20 mm, 20-10 mm, 5-10 mm, 3-5 mm, oversize	**Sand Products** Coarse sand, building sand, fine sand
Global Warming kg CO_2 eq	34.17-41.58	34.24-41.65
Eutrophication kg PO_4 eq	0.093-0.115	0.093-0.115
Acidification kg SO_2 eq	0.606-0.747	0.606-0.747
Photo-oxidant formation kg ethylene eq	4.84×10^{-2}-5.95×10^{-2}	4.84×10^{-2}-5.95×10^{-2}
Human toxicity kg 1,4-DB eq	8.84-10.89	8.84-10.89
Freshwater Aquatic Ecotoxicity kg 1,4-DB eq.	4.09-5.06	4.09-5.06
Marine Aquatic Ecotoxicity kg 1,4-DB eq.	313.93-332.92	317.27-336.26
Terrestrial Ecotoxicity kg 1,4-DB eq.	2.37×10^{-2}-2.68×10^{-2}	2.38×10^{-2}-2.69×10^{-2}
Ozone layer depletion kg R11 eq.	1.66×10^{-7}-1.70×10^{-2}	1.76×10^{-7}-1.80×10^{-7}

Table 15. Example product eco-profile allocation method for marine sand and gravel aggregates carried out on a mass fraction basis.

Product	Fraction	Marine aggregates loading	Marine aggregates discharge	Pre-processing storage	Crushing	Scalping screening	Sizing screening
Gravel products	0.50	0.50	0.50	0.50	0.50	0.50	1.00
Sand products	0.50	0.50	0.50	0.50	0.50	0.50	

		Washing-scrubbing	Wet classification	De-watering	Grinding	Product storage
Gravel products	0.50	1.00			1.00	0.50
Sand products	0.50		1.00	1.00		0.50

8.4 Recycled aggregates

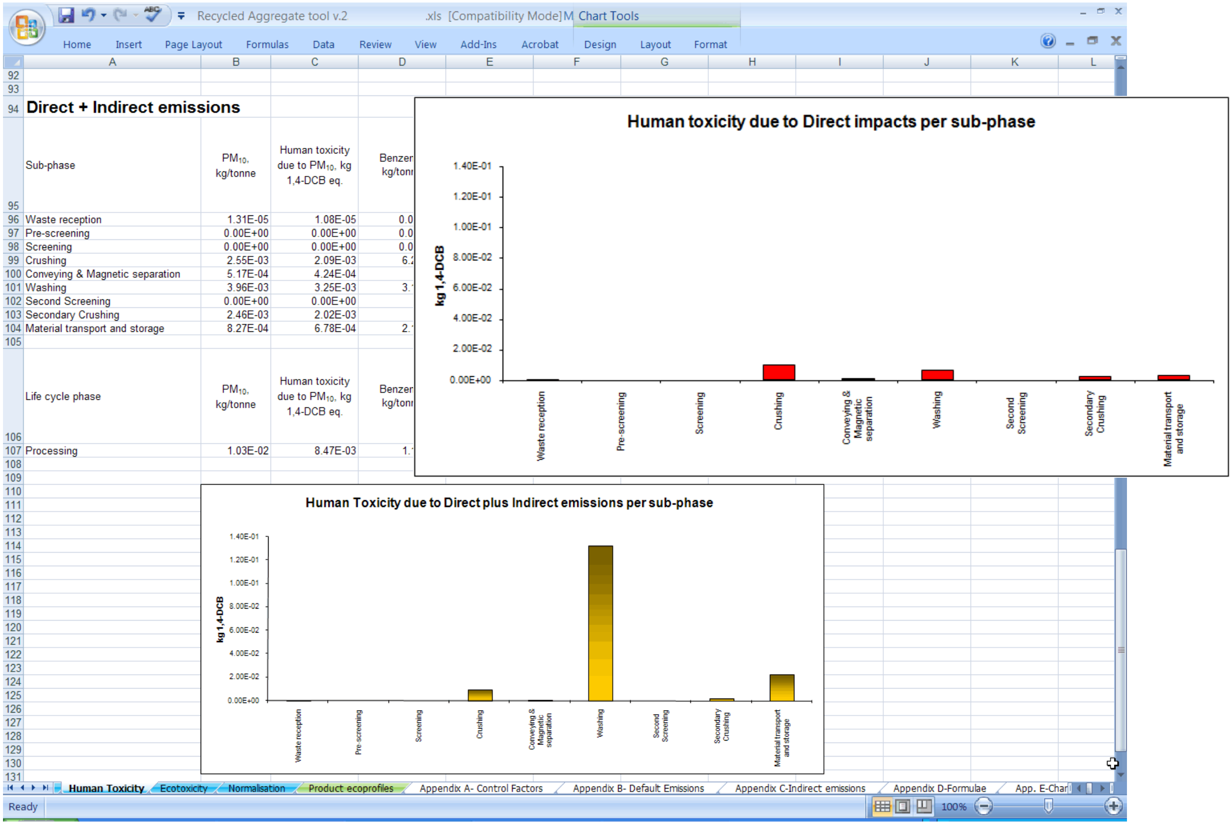
The information reported in Table 16 and Table 18 present the impact assessment results calculated for the production of one tonne of recycled aggregate material at an example recycling site. The recycled aggregates LCA tool has been used to calculate the impacts of one tonne of recycled aggregate production as well as one tonne of each product that follows a different production process stream.

The impact allocation to specific products was based on attributing the impacts of each unit process to the relevant product stream only. The product distribution tool was used to calculate the impacts relating to material transport to the recycling site. For the particular case reported here, the distance of source to recycling site was set at 10 km and it was assumed that the material is transported using 20 tonne trucks consuming diesel at 0.4 litres/tonne.km. The individual impact ranges reported in Table 16 do not include the impacts generated during product delivery to a potential customer.

Table 16 presents the average on-site impacts that are incurred when producing one tonne of recycled aggregate. The original inventory input data used reflect one year of site operation, material and energy inputs and aggregate production. The impacts reported for waste reception only reflect the unloading operation, which explains the human toxicity impacts due to particulate material emissions, while the on-site transport and storage unit process, including all diesel consumed on site and the corresponding upstream emissions, is reported separately.

Table 16. Recycled aggregates system example: Impact assessment results per unit process per one tonne of recycled aggregate produced.

Impact Category Units	**Unit process** Waste reception	Crushing	Conveying & Magnetic separation	Washing	Secondary Crushing	Material transport & Storage	Total Impact
Global Warming kg CO_2 eq		0.2304	$7.72x10^{-3}$	1.92	0.0659	0.1957	2.42
Eutrophication kg PO_4 eq		$7.22x10^{-5}$	$1.6x10^{-6}$	$5.25x10^{-04}$	$1.37x10^{-05}$	$9.27x10^{-05}$	$7.06x10^{-04}$
Acidification kg SO_2 eq		$2.78x10^{-4}$	$6.16x10^{-6}$	$10.56x10^{-3}$	$5.26x10^{-5}$	$1.22x10^{-3}$	$12.13x10^{-3}$
Photo-oxidant formation kg ethylene eq		$1.70x10^{-5}$	$4.12x10^{-7}$	$6.05\ x10^{-4}$	$3.52x10^{-6}$	$1.74x10^{-4}$	$8.00x10^{-4}$
Human toxicity kg 1,4-DB eq	$1.08x10^{-05}$	0.0943	$4.39x10^{-4}$	0.1389	0.0214	$22.37x10^{-3}$	0.1733
Freshwater Aquatic Ecotoxicity kg 1,4-DB eq.		$6.19x10^{-12}$	$4.65x10^{-18}$	$28.59\ x10^{-4}$	$3.97x10^{-17}$	$19.55x10^{-4}$	$19.55\ x10^{-4}$
Marine Aquatic Ecotoxicity kg 1,4-DB eq		$1.83x10^{-10}$	$2.59x10^{-17}$	93.23	$2.21x10^{-16}$	30.45	30.45
Terrestrial Ecotoxicity kg 1,4-DB eq		$1.04x10^{-12}$	$4.40x10^{-19}$	$13.68x10^{-4}$	$3.76x10^{-18}$	$8.62x10^{-4}$	$8.62x10^{-4}$
Ozone layer depletion kg R11 eq.				$2.80x10^{-7}$		$3.27x10^{-9}$	$2.83x10^{-7}$



Direct + Indirect emissions

Sub-phase	PM_{10}, kg/tonne	Human toxicity due to PM_{10}, kg 1,4-DCB eq.	Benzen kg/tonn
Waste reception	1.31E-05	1.08E-05	0.0
Pre-screening	0.00E+00	0.00E+00	0.0
Screening	0.00E+00	0.00E+00	0.0
Crushing	2.55E-03	2.09E-03	6.
Conveying & Magnetic separation	5.17E-04	4.24E-04	
Washing	3.96E-03	3.25E-03	3.
Second Screening	0.00E+00	0.00E+00	
Secondary Crushing	2.46E-03	2.02E-03	
Material transport and storage	8.27E-04	6.78E-04	2.

Life cycle phase	PM_{10}, kg/tonne	Human toxicity due to PM_{10}, kg 1,4-DCB eq.	Benzen kg/tonn
Processing	1.03E-02	8.47E-03	1.

Figure 14. View of the recycled aggregate tool Human toxicity impact category results page populated with emission calculations per tonne of product and impact category scores. The histogram in the foreground presents direct emissions.

The case study has shown that washing is the most intensive sub-phase in all impact categories, exhibiting two to several orders of magnitude higher impacts. Considering that not all materials handled at the aggregates recycling site pass through this process, the impacts allocated to different products may be significantly different as shown in the last column of Table 18. Figure 14 illustrates a view of the Human toxicity impact worksheet showing the direct plus indirect and, in the foreground, the same indicator scores due to direct emissions for one case study. The contribution of the energy intensive sub-phases and particularly the upstream impacts is clearly visible when comparing the Figure 14 inset of direct Human toxicity impacts with the direct plus indirect impacts shown.

Table 17. Example product eco-profile allocation method for recycled aggregates carried out on a mass fraction basis.

Product	Fraction	Waste reception	Pre-screening	Screening	Crushing
Unbound materials	0.19	0.19	0.19	0.19	0.19
Other bound materials	0.44	0.44	0.44	0.44	0.44
Washed and graded aggregate	0.37	0.37	0.37	0.37	0.37

		Conveying & magnetic separation	Washing	Secondary screening	Secondary crushing	Material transport & storage
Unbound materials	0.19					0.19
Other bound materials	0.44	0.54		1.00	1.00	0.44
Washed and graded aggregate	0.37	0.46	1.00			0.37

Table 18. Recycled aggregates system example: Percentage contribution of impacts due to transport and on site processes for the production of one tonne of different recycled aggregate products and the range of actual impact values in kg equivalent.

Impact Category Units		Unbound materials	Other bound materials	Washed & graded aggregate	Impact range
Global Warming	P[1] (%)	76.3	81.6	97.7	0.5581 – 5.7384
kg CO_2 eq	T[2] (%)	23.7	18.4	2.3	
Eutrophication	P (%)	3.9	4.7	28.2	0.0042 – 0.0056
kg PO_4 eq	T (%)	96.1	95.3	71.8	
Acidification	P (%)	3.9	4.2	44.5	0.0389 – 0.0674
kg SO_2 eq	T (%)	96.1	95.8	55.5	
Photo-oxidant formation	P (%)	3.4	3.6	25.4	0.0056 – 0.0072
kg ethylene eq	T (%)	96.6	96.4	74.6	
Human toxicity	P (%)	4.8	5.6	39.3	0.6606– 1.0356
kg 1,4-DB eq	T (%)	95.2	94.4	60.7	
Freshwater Aquatic Ecotoxicity	P (%)	3.1	3.1	13.8	0.0622 – 0.0700
kg 1,4-DB eq.	T (%)	96.9	94.9	86.2	
Marine Aquatic Ecotoxicity	P (%)	3.1	3.1	23.1	969.9210 – 1221.2508
kg 1,4-DB eq.	T (%)	96.9	96.9	76.9	
Terrestrial Ecotoxicity	P (%)	3.1	3.1	14.6	0.0275 – 0.0311
kg 1,4-DB eq.	T (%)	96.9	96.9	85.4	
Ozone layer depletion	P (%)	3.1	3.1	88.3	1.04×10^{-7} – 8.58×10^{-7}
kg R11 eq.	T (%)	96.9	96.9	11.7	

[1] P : % contribution from the processing of materials on site

[2] T : % contribution from transport of materials to the recycling site

Another process that is often associated with a high level of impact contribution is the transport of materials to the recycling site, which is considered as an additional burden. Table 18 illustrates the percentage contribution of impacts due to transport and on site processes for different product streams identified in this example. It is clear that for the products that go through the washing unit process transport represents a much smaller proportion of the overall impact. The slight differences observed in the share of transport related impacts between the bound and unbound products relate to the impacts of the individual unit processes involved in their production streams. Table 17 illustrates an example allocation of impacts to each individual product on the basis of individual process and allocated proportionally to the relevant product streams that pass through this process.

9.0 Conclusions

The LCA Model developed for the UK aggregates industry and its implementation at various case study sites have demonstrated that the model helps to identify clearly the unit processes and specific emissions that may be targeted to reduce the impacts for a given aggregates production site. The design and the structure of the LCI model developed ensure that the product ecoprofiles produced by the model are based on the evaluation of actual operational site data and are representative of the processes considered. Due to its flexible structure, changes in operational design or unit processes of an aggregates production site can easily be implemented in the model calculations.

The most significant finding of this study was that impacts quoted as averages for the whole primary or recycled aggregates site (per tonne of aggregate produced, which is the LCA declared unit) are not representative of the impacts associated with the individual products and should not be used to assess individual product eco-profiles.

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ANNEX A Inventory analysis: initial sources of data

Input data sources and processes

As a first step to the study the EVA025-MIRO consortium identified the data sources available for the production and processing of primary and recycled aggregates (input data for the LCI to be developed) from the literature. At the start of the project, the consortium had a good knowledge of the necessary data sources for the LCI model of the primary aggregates in general (Barksdale, 1996; Smith and Collis, 2001). Therefore, the focus of the review conducted at the start of the project was to identify specific data from the literature for the UK aggregates (ODPM, 2003, 2004, 2005; Barritt, 2004; BRE, 2005; McEvoy *et al.* 2004; Winter and Henderson, 2003; etc.) and materials necessary for the recycled aggregates LCI model development in particular (ODPM, 2000; Smith *et al.*, 2003, Wainwright *et al.*, 2002; WRAP, 2006a, b; etc.). This information was used to prepare the questionnaire/inventory which was filled in by the primary aggregates production and recycling case study site operators. A list of the relevant studies and data sources used is given in Table 19.

Table 19. Aggregates LCI input data sources

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18.	Hsiao T.Y., Huang Y.T., Yu Y.H. and Wernick I.K., 2002. Modeling materials flow of waste concrete from construction and demolition wastes in Taiwan. Resources Policy, 28(1-2): 39-47.
19.	Huang W.L., Lin D.H., Chang N.B. and Lin K.S., 2002. Recycling of construction and demolition waste via a mechanical sorting process. Resources Conservation and Recycling, 37(1): 23-37.
20.	Kartam N., Al-Mutairi N., Al-Ghusain I. and Al-Humoud J., 2004. Environmental management of construction and demolition waste in Kuwait. Waste Management, 24(10): 1049-1059.
21.	Khalaf F.M. and DeVenny A.S., 2004. Recycling of demolished masonry rubble as coarse aggregate in concrete: Review. Journal of Materials in Civil Engineering, 16(4): 331-340.
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One of the few studies relevant to this project's objectives was carried out by Schuurman *et al.* (2005) on the use of finer instead of coarse sand in concrete in the Netherlands. This work has two main findings that were used to formulate recommendations to the Dutch national policy on fine sand in concrete. First, that hardly any negative environmental effect was anticipated when finer sand was used. Second, that the type of transportation used and distance travelled to reach the aggregates market significantly affect the overall environmental impacts of the system. Schuurman *et al.* (2005) also pointed out that the collection of data proved to be challenging as extraction of raw materials is often a dynamic process in time.

Emission data sources - release rates

Through Imperial College's earlier work and development of the Mining LCA model (LICYMIN), the EVA025-MIRO consortium already had sufficient data on the types and rates of environmental interventions for the primary aggregates production processes. In order to prepare for the requirements of the LCI emissions inventory (output data), the consortium collected and reviewed a number of studies that relate to the emissions from recycled aggregates production and use. Special emphasis was given to emissions that are classified into LCA impact categories and their rates of release. The studies identified are listed in Table 20.

Table 20. Aggregates LCI emission data sources and methods to estimate release rates

61.	Jang Y.C. and Townsend T., 2001a. Sulfate leaching from recovered construction and demolition debris fines. Advances in Environmental Research, 5(3): 203-217.
62.	Jang Y.C. and Townsend T.G., 2001b. Occurrence of organic pollutants in recovered soil fines from construction and demolition waste. Waste Management, 21(8): 703-715.
63.	Karius V., Hamer K. and Lager T., 2002. Reaction fronts in brick-sand layers: Column experiments and modeling. Environmental Science & Technology, 36(13): 2875-2883.
64.	Kohler M. and Kunniger T., 2003. Emissions of polycyclic aromatic hydrocarbons (PAH) from creosoted railroad ties and their relevance for life cycle assessment (LCA). Holz Als Roh-und Werkstoff, 61(2): 117-124.
65.	Kosson D.S., Van der Sloot H.A., Sanchez F. and Garrabrants A.C., 2002. An integrated framework for evaluating leaching in waste management and utilization of secondary materials. Environmental Engineering Science, 19(3): 159-204.
66.	Ohara S. and Wojtanowicz A.K., 1995. A drilling mud management strategy using computer-aided life-cycle analysis. Oil Gas-European Magazine, 21(4): 30-&.
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69.	Treloar G.J., Love P.E.D. and Crawford R.H., 2004. Hybrid life-cycle inventory for road construction and use. Journal of Construction Engineering and Management-Asce, 130(1): 43-49.

70.	Meeussen J.C.L., Dijkstra J.J., Van der Sloot H.A. and Comans R.N.J., 2004. The relevance of geochemical fronts in leaching behaviour of cement-based materials. Geochimica et Cosmochimica Acta, 68(11): A183-A183.
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The two studies carried out by Jang and Townsend (2001a, b) concluded that when considering the beneficial reuse of C&D debris fines as a substitute for soil, site-specific hydrogeology and appropriate state and local regulations for allowable sulphate concentrations in groundwater should be considered. This is in agreement with a later study by Townsend *et al.* (2004). The results of the second study indicated that the organic chemicals in recovered soil fines from C&D debris recycling facilities were not of major concern in terms of human risk and leaching risk to groundwater under reuse and contact scenarios.

A number of studies listed above by van der Sloot focus on the evaluation of the leaching behaviour of recycled aggregate materials and products. The study by Delay *et al.* (2007) provides an assessment of the test procedures necessary to examine waste materials before they can be reused. The results show a good agreement between the leaching behaviour determined with the lysimeter unit and the column units used in the laboratory, also supporting the opinion that the laboratory studies reviewed can be used as the basis for setting the ranges and rates of emissions that need to be coded in the LCI model for aggregates.

Report Prepared by Dr Anna Korre & Professor Sevket Durucan – Imperial College London

Published by
Waste & Resources
Action Programme

The Old Academy
21 Horse Fair
Banbury, Oxon
OX16 0AH

Tel: 01295 819 900
Fax: 01295 819 911
E-mail: info@wrap.org.uk

Helpline freephone
0808 100 2040

www.wrap.org.uk