WHOLE-LIFE PERFORMANCE OF CLAY BRICKWORK MASONRY

ADRIAN ROBERT BOWN

A thesis submitted in partial fulfilment of the requirements of
Leeds Metropolitan University for the degree of Doctor of Philosophy

This research was carried out in collaboration with
the Brick Development Association Ltd. who jointly funded the project
with the Engineering and Physical Sciences Research Council

January 2007

CONTENTS

Page

CHAPTER 1 INTRODUCTION

CHAPTER 2 SUSTAINABILITY OF CLAY BRICKWORK MASONRY

CHAPTER 3 GENERAL REVIEW OF THE FRAMEWORK FOR LIFE-CYCLE ASSESSMENT AND THE WORK OF THE U.K. BUILDING RESEARCH ESTABLISHMENT ON L.C.A.

CHAPTER 4 METHODOLOGY OF RESEARCH

APPENDIX A CONVERSION OF INITIAL INVENTORY DATA TO CHARACTERISED AND NORMALISED DATA

APPENDIX B METHODOLOGIES FOR CONVERTING INSTALLED ENVIRONMENTAL PROFILE DATA TO WHOLE-LIFE DATA

APPENDIX C METHODOLOGY FOR CONVERTING CHARACTERISED ENVIRONMENTAL IMPACT DATA TO AN ECO-POINT

APPENDIX D EXTRACT FROM MAINTENANCE DATABASE

APPENDIX E CALCULATION OF THE *U*-VALUES AND OPERATIONAL ENERGY REQUIREMENTS FOR USE IN THE LIFE-CYCLE ANALYSES

APPENDIX F METHODOLOGY USED TO DEVELOP LIFE-CYCLE COSTINGS

APPENDIX G CALCULATION FOR COMPARISONS WITH BUILDING RESEARCH ESTABLISHMENT DATA

APPENDIX H COMPARISON OF ESTIMATES FOR THE CONTRIBUTION OF BUILDING ELEMENTS TO IMPACT OF A TYPICAL BUILDING

APPENDIX I COMPARISON OF ENVIRONMENTAL PERFORMANCE OF AN EXISTING BUILDING AND A REPLACEMENT BUILDING

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

ABSTRACT

This thesis presents the findings of a program of research to investigate the whole-life performance of clay brickwork masonry.

Although brickwork is employed in a variety of structures, the research was restricted to its use for domestic housing and low-rise commercial properties as this is the principal market for clay bricks in the U.K.

Whilst the environmental impacts from the manufacture of clay bricks and mortars are reasonably well defined, very little hard data was found to exist for the post-factory gate environment situation. This latter information is required to develop better estimates of the whole-life performance of brickwork walling.

Overall, it was shown that brickwork in domestic housing is an extremely durable and robust material with very low post-factory gate environmental impacts. The research found that clay bricks have the potential to last up to 650 years in solid walls before they would all have been replaced; for clay bricks in cavity walls this reduced to 197 years. The time to first repointing was also found to vary between the two types of walls. This was between 74 and 162 years for solid walls and 52 and 81 years for cavity walls, depending upon the maintenance regime adopted.

Post-factory gate environmental profiles and costings for different forms of brickwork walling construction were developed. These showed that, over a 500 year lifespan, the walling with the lowest overall environmental impact was a 215 mm solid brickwork wall. This form of walling does not, however, comply with the current statutory requirements for the thermal performance of external walls and, as such, it cannot be used for modern domestic construction. Based on this research, the most sustainable form of clay brickwork masonry walling that complies with the current U.K. thermal requirements was found to be a 215 mm solid wall with external insulation finished with a protective of cement render.

Published data on the whole-life environmental performance of brickwork walling were found to be very conservative and over-estimated both the environmental impacts and whole-life costs by up to 117 %.

Overall, the evaluation of the environmental impacts from brickwork walling was found to be very problematic due to the commercial nature of life-cycle assessment studies and the inability to access much of the existing pre-factory gate data.

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to his supervisors, Dr P. R. Bingel and Mr J. Sturges for their continual encouragement, support, and guidance throughout the duration of this research project.

He would also like to thank all of the people who have contributed towards this project and is greatly indebted to the B.D.A. and the E.P.S.R.C. for providing the necessary funding to complete it.

CHAPTER 1: BACKGROUND TO THE RESEARCH PROJECT

1.1 INTRODUCTION

This project is concerned with the whole-life environmental impact of clay brickwork masonry with particular reference to the post-factory gate situation. Issues such as this, form part of the wider agenda associated with *sustainability* and the synonymous term, *sustainable development*. It is therefore considered useful to begin with a review of the overall concept of sustainable development and the driving forces behind its implementation. This is followed by a description of the background to the research.

1.2 SUSTAINABLE DEVELOPMENT

Sustainable development is a relatively new concept that has arisen over the past two decades out of international concerns for climate change caused by global warming, increased pollution, the loss of flora, fauna, wildlife, etc. It has been recognised that there is an urgent need for all countries and industries to adopt more sustainable patterns of consumption, both in terms of primary energy consumption and raw material usage.

A main aim of sustainable development is to base future development on patterns of production and consumption that can be pursued in the long-term without further degradation of the natural environment or human society. In essence, this refers to doing something with the long-term in mind, with several hundred years currently being considered sufficient. Alternatively, *'today's decisions should therefore be made with a consideration of sustaining our activities into the long term future'* [http://ag.arizona.edu/futures/home/glossary.html].

Significant steps have been taken over the past two decades to place sustainable development on the agenda of governments and businesses across the world. Landmark events in the development of a global strategy for sustainability and sustainable development include the *Brundtland Report: Our Common Future* originating from the World Commission on Environment and Development Conference in 1987, the *Rio Earth Summit* in 1992, the *Kyoto Climate Change Summit* in 1997 and, more recently, the *Johannesburg Rio + 10 Conference* in 2002.

These events have been widely reported in the media and the need to become more environmentally friendly and less wasteful in terms of energy and raw materials usage has been recognised internationally. For example, at the Kyoto Climate Change Summit, most industrialised countries agreed to stabilise their greenhouse gas emissions at 1990 levels by the year 2000 and to reduce them by a further 5 % to 8 % between 2008 and

2012. There is a weakness with these international agreements, however, as the U.S.A., a major contributor of greenhouse gas emissions, is not a signatory to any of them and, consequently, is not bound to these reductions.

Initially, sustainability and sustainable development were only applied to natural resource situations, where the long-term was the focus. This has since been broadened, however, to incorporate more wide-ranging issues such as economic development, the environment, food production, and energy as well as numerous social issues such as lifestyle, fairness and quality of life. Many of these issues interact with, and consequently influence, each other. This complex multi-facetted nature of sustainability, or sustainable development, is often illustrated through the use of the simple Venn diagram shown in Figure 1.1.

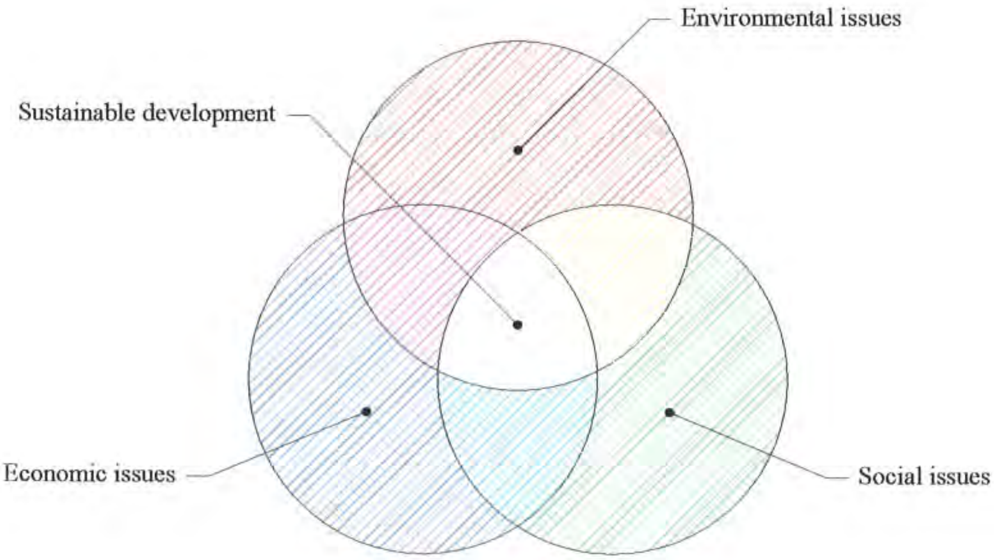


Figure 1.1: The Three Facets of Sustainable Development

In recognition of the many issues involved with sustainable development, the United Nations prefers to express it in terms of a few, very broad, simple objectives which relate to both the industrialised and developing nations of the world [http://www.maple-leafweb.com/features/development/understanding.html], namely:

i. the alleviation of poverty
ii. improving the ability of all countries, particularly in the Southern hemisphere, to meet globalisation's challenges

iii. promoting responsible production and consumption
iv. ensuring that all people have access to energy sources
v. reducing environmentally-related health problems
vi. improving access to clean water.

In this respect the global picture is striking as the most recent figures from the World Bank show that in 2001 over one-fifth of the world's population had to survive on an income of less than US $1.00 a day and that one-fifth did not have any access to even the most basic level of health care [http://www.worldbank.org/research/povmonitor/index].

1.3 DEFINITIONS OF SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT

A large number of definitions have been suggested to describe the broad scope of sustainability and sustainable development. The most widely adopted appears to be *'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'* [World Commission on Environment and Development Conference, 1987]. Another is *'the use of resources in a manner that allows the resources to be replenished by natural systems, as well avoidance of pollution that damages biological systems'* [American Heritage Electronic Dictionary, 2004] whilst a third is *'the ability of a community or society to develop a strategy of economic growth and development that continues to function indefinitely within the limits set by ecology and is beneficial to all stakeholders and the environment'* [The Corporate Library, 2004].

Further definitions include *'economic development that can continue indefinitely because it is based on exploitation of the renewable resources and causes insufficient environmental damage for this to pose an eventual limit'* [Allaby, 1988] and *'to find the optimal level of interaction between three systems; the biological and natural resource system, the economic system and the social system'* [Barbier, 1989].

The most all-encompassing definition, however, is probably *'achieving a quality of life (or standard of living) that can be maintained for generations because it is; socially desirable, fulfilling people's cultural, material, and spiritual needs in equitable ways; economically viable, paying for itself, with costs not exceeding income; economically sustainable, maintaining the long-term viability of supporting eco-systems'* [I.U.C.N. – World Conservation Union, 1993].

The broad range of definitions used to describe sustainable development reflect the difficulties that are often associated with evaluating what is, and what is not, *sustainable* in absolute terms. In practice this is extremely difficult to answer, as trade-offs between competing environmental, social and economic issues are often required in any study or evaluation. In addition, whilst some decisions relating to sustainability can be made on the basis of quantitative scientific data, others are essentially subjective, being based upon value-choice judgements only.

At present, probably the most perceptive advice that can be given about the sustainability of buildings is that of the Architect Simon Allford. During a discussion on his winning design for a sustainable school, he noted '*All the way through* [the design process] *we never said what we thought we meant by sustainability...sustainability is like plumbing or air-conditioning - it's a general attitude you apply to a building. It doesn't create its own architecture but it informs the way the architecture is produced*' [quoted in Slavid, 1998].

1.4 EXTERNAL DRIVERS FOR SUSTAINABLE DEVELOPMENT WITHIN THE U.K. CONSTRUCTION INDUSTRY

Whilst sustainable development is concerned with all aspects of contemporary lifestyle and, consequently, with all of the sectors in a modern economy, there has been especial intense political and social pressures on the Construction Industry for it to become more environmentally aware and to start to consider the long-term effects of its activities. The Construction Industry is currently seen to be a major contributor to the problems predicted to arise as a result of global warming. This is due to its consumption of vast quantities of natural resources in the forms of energy, water, materials and land, all of which have a significant effect on the environment. In the U.K. alone, the Construction Industry annually consumes over 350 million tonnes of raw material and generates over 70 million tonnes of waste (most of which is disposed of in landfill sites). In addition, the energy used in constructing, occupying and operating buildings in the U.K. represents approximately 50 % of the country's emissions of the main greenhouse gas, carbon dioxide (CO_2) – see Figure 1.2.

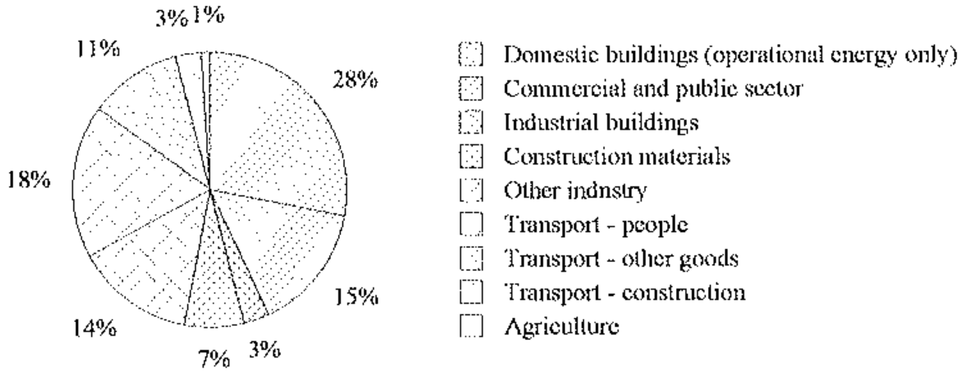


Figure 1.2: Emissions of Carbon Dioxide in the U.K.
[Thistlethwaite, 2004]

The U.K. Government has therefore produced a series of official publications as part of its commitment to encourage the Construction Industry to adopt more sustainable practices. The aim of these is to make construction professionals more aware of the environmental, economic and social factors that underpin the broad concept of sustainable development and include:

- *Better Buildings Better Lives: Sustainable Buildings Task Group Report* [Department of Trade and Industry, 2004]
- *Building A Better Quality Of Life: A Strategy For More Sustainable Construction* [Department of the Environment, Transport and the Regions, 2000]
- *A Better Quality Of Life: A Strategy For Sustainable Development In The U.K.* [*U.K. Government Publication*, 1999]
- *Sustainable Development :Opportunities For Change* [Department of the Environment, Transport and the Regions, 1998^{a}]
- *Opportunities For Change: Sustainable Construction* [Department of the Environment, Transport and the Regions, 1998^{b}]
- *Toward Sustainability- A Strategy For The Construction Industry (2000)* [The Sustainable Construction Focus Group, 2000]
- *The U.K. Construction Industry: Progress Towards More Sustainable Construction (2000-2003)* [The Sustainable Construction Task Group, 2003]

Whilst the U.K. Government has primarily sought to encourage (rather than coerce) the Construction Industry to embrace the principles of sustainable development, it has, where necessary, introduced legislation to enforce its adoption. Examples of this include *The Landfill Tax Regulations 1996* and the *Environmental Protection Act 1990*, whilst fiscal measures such as the *Climate Change Levy* which was contained in *Part II* of the *Finance Act 2000* and the *Aggregates Levy* in *Part II* of the *Finance Act 2001* are also having a significant impact on organisations within the Construction Sector.

Further examples of national and international legislation and initiatives to encourage or enforce the take up of sustainable development include:

- Agenda for 21st Century (Agenda 21). This was a comprehensive plan of action which was to be implemented globally, nationally and locally by governments and major groups and covered every area in which human behaviour impacts on the environment. This agreement was reached at the 1992 U.N. Global Conference on Environment and Development in Rio de Janeiro. The principles of Agenda 21 are recognised by 120 countries.
- The U.K. Energy White Paper: This was published in February 2003 and was entitled *Our Energy Future – Creating a Low Carbon Economy*. The paper presented a long term strategy for the U.K.'s energy policy.
- The Energy Performance of Buildings Directive. This was produced by the E.U. in December 2000 and addressed the increasing use of energy in buildings. The directives was implemented in the U.K. via *Part L* of the *Building Regulations*.
- The Kyoto Agreement. This resulted from an intergovernmental conference on global warming which was staged in 1997. The agreement, or more correctly the Kyoto Protocol, binds signatories to reducing their carbon emissions by a minimum of 5 % below 1990 levels by 2012.
- Sustainable Community: This was a plan launched by the Office of the Deputy Prime Minister (O.D.P.M.) in 2003. It set out a long-term program of action for tackling housing shortages in the U.K. especially the high demand for housing in the South East of England and the low demand elsewhere in the country.

The challenge for the Construction Industry is therefore for it to move towards socially and environmentally responsible policies whilst, at the same time, maintaining their economic viability. They are being encouraged to pursue this by; increasing top-line growth through innovation; generating new markets; and by improving cost efficiencies. There is further pressure on companies to adopt sustainable practices from the increasing use of socially responsible investment. To this end, the annual reporting of companies' performance, including many of those associated with the Construction Industry, is now commonly expressed in terms of *triple bottom line accounting*, with progress on social and environmental issues being presented alongside the financial results.

1.5 LEGISLATION ON ENVIRONMENTAL AUDITING

The Sustainable Buildings Task Group's report *Better Buildings - Better Lives* [Department of Trade and Industry, 2004] advocates expanding the Building Regulations to include sustainability. The report suggests establishing a national Code for Sustainable Building (C.S.B.) which would be founded on the existing frameworks and methodologies of the B.R.E.'s *BREEAM* and *EcoHomes* packages. This would specify minimum standards for resource efficiency in three main areas; energy and water efficiency; waste; and use of materials. The group recommend requiring a minimum 10 % (by economic value) for re-used, reclaimed or recycled materials on all new building projects and, because they are already covered by existing statutes such as the planning system and the Building Regulations, any major refurbishment works.

Although the Sustainable Buildings Task Group do not recommend applying the national code retrospectively to the bulk of the existing housing stock (unless it is undergoing a major refurbishment), they do discuss encouraging more sustainable building practices when the stock undergoes routine maintenance and improvements that are outside the scope of the current regulatory system. They suggest that this could be achieved by extending the scope of *Schedule 1* in a future edition of the Building Regulations to cover a wider range of sustainability issues.

The U.K. Parliament is also increasingly proposing and enacting legislation which is concerned with improving the sustainability of new and existing buildings. For example, it has passed a Private Member's Bill, *The Sustainable and Secure Buildings Bill (2004)*, that requires an energy audit to be carried out for all new multi-occupancy buildings. Similarly, the O.D.P.M. published the *Possible Future Performance Standards for Part L* paper in 2003 [Office of the Deputy Prime Minister, 2003^{a}] which proposed substantial changes to the Buildings Regulations over the next decade. The document discusses a plan to introduce *carbon pricing* for all non-renewable fuels containing carbon in an attempt to penalise consumers for the social costs of carbon use. It suggests that it will be possible to analyse (and presumably tax) the energy and carbon burden of embodied energy within the next decade and suggests a figure of £70.00 per tonne of carbon emitted (in 2000 price levels) which would increase annually by £1.00 before inflation.

1.6 MASONRY INDUSTRY RESPONSE TO DRIVERS FOR SUSTAINABILITY

As a result of these Government initiatives, most of the manufacturing sectors within the U.K. Construction Industry have developed their own sustainability strategies to comply with the various targets that have been identified. These sustainability strategies are published annually and describe the progress achieved in the preceding year across a range of Key Performance Indicators (K.P.I.'s). Although the range of issues considered are very diverse they all conform to the Government's requirements for sustainable development, as outlined in its 1999 publication *A Better Quality Of Life: A Strategy For Sustainable Development For The U.K.*, namely:

- social progress which recognises the needs of everyone
- effective protection of the environment
- prudent use of natural resources
- maintenance of high but stable levels of economic growth and employment.

The U.K. Clay Brick Industry has identified its own range of K.P.I.'s which are listed in the Brick Development Association's (B.D.A.) *Sustainability Strategy for the U.K. Clay Brick Industry* [Brick Development Association, 2003^a]. The aim of these are to:

- improve the occupational health and safety of the industry's employees
- extend the application of environmental management systems to the industry's operations and reduce the impact of atmospheric emissions from the production process
- minimise industry waste disposed to landfill
- reduce energy consumed through improved energy efficiency
- reduce the volume of treated water used in the production process
- maintain and increase value through the development of new products.

A relevant part of the B.D.A. publication [*ibid*, 2003^a] is Section 2.3 – *The Prudent Use of Natural Resources*. This states that '*the* [brick] *industry recognises the importance of measuring and reducing the natural resources it consumes and that, equally, it is* *appropriate that the significance of resources consumed is evaluated over the whole life of the product. To this end, the industry is involved in a life-cycle analysis for brick with the Building Research Establishment'.* This refers to a joint project between the B.D.A. and the Building Research Establishment (B.R.E.) which aimed to develop a series of *environmental profiles* for different forms of clay brickwork masonry construction. The B.R.E. developed three types of profile for the project, namely

i. cradle to installation for building elements (e.g., walls, floors, roofs, etc.) - from manufacture through to them being installed into / onto a building
ii. cradle to grave for building elements - from manufacture, through installation to eventual demolition and disposal. They are all based on an assumed lifespan of 60 years
iii. individual pre-factory gate profiles for building materials (e.g., steel, aluminium, concrete, brick etc) – they are presented on a per tonne basis.

The joint B.D.A. / B.R.E. project was concerned with buildings rather than civil engineering structures such as bridges, culverts, tunnels etc. The lifespan for buildings were limited to a maximum of 60 years, after which the building was assumed to be demolished and the component materials either recycled, re-used or considered as waste. In view of the fact that clay brickwork can, and frequently does, last for centuries the U.K. Clay Brick Industry were concerned that the B.R.E. approach did not accurately reflect the true whole life environmental performance of clay brickwork masonry. To provide a better understanding of this aspect of clay brickwork masonry performance, the Industry initiated the project described here to evaluate the post-factory gate environmental performance of clay brickwork masonry.

1.7 THE RESEARCH PROJECT

The starting point for this project was the recent work by the B.R.E. into environmental profiling which led to the publication of environmental profiles for all of the major construction materials used in the U.K. These enable designers and specifiers to understand the environmental impacts of using different construction materials for building elements, and allow the overall environmental impact of a building design to be optimised. To date, much of the data used to develop these profiles relate to the pre-factory gate (production) situation. This was supplied to the B.R.E. by U.K. materials manufacturers including the Clay Brick Industry, via the B.D.A.

In view of the fact that clay brickwork masonry has an established reputation for durability, low maintenance and a long service life, the Clay Brick Industry was keen to develop its own detailed post-factory gate environmental profiles for clay brickwork within the U.K. rather than being limited to the B.R.E.'s 60 year lifespan. This involved investigating a range of issues including:

i. The notional design life of brickwork buildings and other types of brickwork structures and its relevance to the choice of masonry materials and types of masonry construction.
ii. The potential service life of brickwork masonry structures.
iii. The maintenance issues associated with different forms of brickwork masonry construction.
iv. Overall life cycle assessment (L.C.A.) and life-cycle costings (L.C.C) of brick-built structures.
v. The demolition and potential for recycling of brickwork masonry structures.

The intention at the start of this project was, therefore, to examine each of the above issues in detail. Because of time limitations and the range and complexity of the issues, it was quickly decided to concentrate on items i. to iv. with respect to traditional brickwork masonry used in low-rise residential housing and smaller commercial buildings only. It was considered that this would provide realistic data on the potential post factory gate environmental performance of brickwork in its major role – as a walling material. It would also demonstrate how other social and economic factors (many of which are qualitative and less tangible in nature) actually influence the post-factory gate environmental performance of clay brickwork. Typically these include consideration of why brick buildings are demolished, the value of recycling brickwork, future-proofing the design of buildings and demographic effects on building usage.

From initial discussions with the industrial partners it was recognised that in view of the wide ranging nature of sustainable development and the complexity of the quantitative and qualitative issues associated with life cycle analysis in particular, it would take ten years or more to fully investigate all aspects of the whole life environmental performance of clay brickwork masonry. As such, this project forms a first step.

CHAPTER 2: SUSTAINABILITY OF CLAY BRICKWORK MASONRY

2.1 INTRODUCTION

This research is primarily concerned with investigating and quantifying the whole life environmental impacts and costs arising from the use of clay brickwork masonry in buildings. It is therefore thought useful to initially highlight the various factors that should be considered in order to make a building *sustainable*. The U.K. Government's Department of the Environment, Fisheries and Rural Affairs (2003) defines these in the following broad terms:

- *A building that leaves as small an environmental footprint as possible, is economic to run over its whole life cycle, and fits well with the needs of the local community.*
- *A building that is energy and carbon efficient, designed to minimise energy consumption, with effective insulation and the most efficient heating or cooling systems and appliances*
- *A building built with good access to public transport in mind.*
- *A building built with a minimum of waste in its construction and looks to maximise re-use of on-site materials such as waste soil.*
- *A building designed and constructed to enable its occupants to use less water, through, for example, the installation of more efficient fittings and appliances.*
- *A building designed to make recycling and composting easy for the occupants.*

It can be seen that the issues involved in the development of sustainable buildings are complex and involve consideration of economic and social factors as well as environmental impacts. As such, this is the overall context within which the *sustainability* of clay brickwork masonry used in buildings has to be evaluated.

To date, the majority of research in the field of sustainable construction has been concerned with developing low energy buildings. Whilst this approach has undoubtedly provided a better understanding of how to achieve reductions in operational energy, it has been usefully questioned by Sayce (2002) who found that decisions about whether commercial buildings, in particular, should be demolished or refurbished are complex and that energy efficiency, whilst desirable, is not the key to the sustainability of a particular building. In practice, Sayce found that the quest for sustainable commercial buildings in particular, is more complicated and is driven by a combination of economic, social and environmental issues. These include:

- Loose-fit, or the ability to adapt to meet occupier needs.
- Low energy, as this is beginning to affect the economics of both building use and construction.
- Location and integration of buildings, to support a range of urban activities.
- *Likeability* and *lovability*, or the ability of a building to provide an environment that is liked by the occupants, and to which external stakeholders respond emotionally.

One fact to emerge from Sayce's (2002) work is that, in a survey of stakeholder groups, the durability of an existing building's fabric was considered to be the most important issue in promoting its longevity. Whilst longevity may not necessarily be the answer to producing sustainable buildings, Sayce noted that, *'on energy grounds alone, demolition is difficult to justify and the case for green refurbishments or retrofits is convincing, even if not well taken up in the U.K.'*. This is of interest in relation to brickwork generally as *'a brick structure, subject to minimal maintenance, will last almost indefinitely. Its longevity is an even greater advantage since its appearance is enhanced with age'* [Brick Development Association Ltd., 2003[b]]. Sayce also noted that, *'in the final analysis, sustainability is a subjective concept which is incapable of being measured meaningfully ... rather it is a product of today's value sets, which change with time'*.

In the light of these introductory comments, a number of basic issues relating to the sustainability of clay brickwork masonry are reviewed below, as they are particularly relevant to the aims of this project. These include:

- embodied energy and pre-factory gate environmental impacts of clay brickwork
- life span of clay brickwork walling
- maintenance of clay brickwork walling
- post factory gate environmental impact of brickwork walling
- whole-life costing of brickwork

2.2 EMBODIED ENERGY AND PRE-FACTORY GATE ENVIRONMENTAL IMPACT OF BRICK

The U.K. Heavy Clay Industry annually consumes approximately 5.4 Terawatt hours of energy [Brick Development Association Ltd., 2003^{a}]. This figure is based on data for the whole industry which includes the manufacture of roofing tiles, flooring blocks and clay pipes as well as bricks. In economic terms, however, clay bricks account for 82 % of the total value of the Heavy Clay Industry. Whilst the industry is energy intensive, it consumes less than 1.5 % of the total energy used by U.K. manufacturers in 2000 (408.8 Terawatt hours) [*ibid,* 2003^{a}].

By comparison, the European Directive on the Energy Performance of Buildings [http://www.esru.str] estimates that residential and tertiary sector buildings currently account for more than 40 % of the total energy consumed annually within the E.U. In the year 2000, U.K. buildings contributed slightly less than half (approximately 43 %) of the country's carbon dioxide emissions, with homes alone contributing nearly 65 % of this total.

From the above data, it can be seen that a significant proportion of the annual energy usage within the U.K., and Europe generally, is associated with the operational use of buildings over their lifetime, i.e. heating / ventilation, and lighting. This is significantly higher than the embodied energy values of the materials used in the actual construction of buildings themselves. In this respect, Edwards and Hyett (2002) estimate that a typical value for the ratio of *in-use* energy to embodied energy is 10 : 1 and in the particular case of brickwork, De Vekey (1999) states *'if a minimum average of 100 years life for all existing (brick) buildings is assumed, the annual energy consumption of brick production and transportation is 1 GJ/year for older stock and about half that for more recent stock, assuming that no energy-consuming maintenance is necessary. To put this into context, the annual average energy cost for heating in the UK is about 25-50 GJ per dwelling, so that the long term energy cost of the brick masonry is one to two percent of the heating costs or less'.*

Sayce and Ellison (2003) suggest that in the quest for sustainable buildings, the Construction Industry should take action to reduce carbon dioxide emissions (a by-product from the burning of fossil fuels for energy) in the following order, ranked on the basis of quantity of emissions:

i. energy use during building occupation
ii. embodied energy in materials
iii. energy use during the construction process.

With respect to the first item, the U.K. Government has set a target of reducing fossil fuel emissions by 60 % by the year 2050 [cited by Boardman, 2005]. Oxford University and Heriot Watt Universities [Broadman *et al,* 2005] have recently completed a three-year project entitled *Low Carbon Futures: The 40 % House Project* which investigated this particular issue. They concluded that 3.2 million of the least energy-efficient homes in the U.K. should be demolished and replaced to meet this target; this equates to approximately 15 % of the current total number of homes in the U.K. They based their criteria for demolition on homes for which it would be too expensive to upgrade to meet the necessary standards for thermal performance. They also suggest introducing new legislation to re-classify these homes as being unfit for habitation as it would be too expensive to heat them and they should therefore be considered as being unhealthy.

Although the Broadman *et al* report and its recommendation to demolish three million homes were widely reported in the media, it is thought unlikely that such a policy would ever be adopted. There are a number of reasons for this including the cost and logistics of rebuilding an extra three million homes on top of the estimated ten million new homes that experts predict will be needed over the same period [Broadman *et al,* 2005]. Because it is already experiencing severe skill shortages, it is also unlikely that the U.K. construction industry could increase its present level of production without a significant investment of both time and money, which is unlikely in the current business climate. Similarly, it would probably be impossible to increase the demolition rate from the current level of 20,000 homes a year to 80,000, if three million homes are to be demolished before 2050. The vast amount of demolition waste produced from such a process would itself create a major environmental problem as this would probably have to be disposed of at landfill sites. Finally, there have been significant changes in the political landscape since the post-Second World War slum clearance initiatives; for example, nearly 70 % of homes in England were owner occupied in 2003 compared to only 30 % in 1951, the earliest date that the relevant figures are available [Office of the Deputy Prime Minister, 2003^b]. The Government would have to either develop a strategy for financially compensating the owners of the affected buildings (which would be financially devastating for the country as a whole) or make them responsible for the cost of demolishing and rebuilding the properties and accept the political consequences of this at the next election. It is therefore thought unlikely that any mainstream political party would ever seriously consider adopting such a policy.

At a recent conference on designing sustainable buildings [cited by Clover, 2005], the architect Quinlan Terry voiced his concerns about this recommendation to demolish vast numbers of homes. He suggested that the proposal missed the *bigger picture* of sustainable development, i.e. that *'the fossil fuel emissions that are produced during the* *construction of the existing homes were already in the atmosphere'* and that *'additional emissions would be created from the demolition and the subsequent rebuilding works of these properties'*. He also questioned how long the new buildings themselves would last.

It is worth noting that the above issues show the multi-faceted nature of sustainable development. The idea of demolishing a significant section of the existing housing stock, as proposed by Broardman *et al*, was based on environmental considerations; there are, however, accompanying financial and social impacts arising from such activities which cannot be ignored.

2.3 LIFESPAN OF CLAY BRICKWORK WALLING

As already noted, this research project is primarily concerned with the whole-life performance of clay brickwork masonry in traditional low-rise residential housing and smaller commercial brick built properties. For this, detailed information relating to the life span of the clay brickwork is required. Whilst the work by the B.R.E., described in Paragraph 1.6, assumes that buildings only last for 60 years, this is clearly unrealistic in the case of the U.K. residential housing stock, where brick has been used for many centuries. It is, therefore, useful to firstly outline the historic development of brickwork in the U.K. as this provides relevant background information on its earliest use and the changes that have taken place over the years.

Lynch (2003) notes that brickwork was rarely used in Britain until the close of the Middle-Ages although it was extensively used in Europe before that time. Lynch divides the development of brickwork in the U.K. into three historical phases:

- Tudor brickwork (1485 -1603) – this phase is characterised by patterned brickwork with extravagant and elaborate shapes, and thick (15-25mm) mortar joints due to the irregular size and shape of the bricks
- The Georgian Period (1714 – 1830) – this phase is considered a high point in the use of brick with blended clays, better moulding and a more-even firing giving a more uniform shape and size. This period saw the introduction of new colours including grey stocks and the production of yellow marl London stocks. It also saw the introduction of expensive gauged brickwork with thin lime putty joints and fine *tuck* pointing
- Victorian brickwork (1830 – 1914) – this phase saw much elaborate brickwork, including the use of specials and garish polychromatic brickwork. A greater number of bricks were made in this period than during all the previous periods,

with the process becoming mechanised. A variety of face bonds were used, although the *Flemish bond* was used predominately in domestic housing.

In the light of the above information, a breakdown showing the precise age of the U.K. brick housing stock would be useful; such data, however, are not available. Rather *The 2002 Housing Statistics* [Office of the Deputy Prime Minister, 2003[b]] simply show that in 1861, the earliest year for which statistics are available, there were approximately 4.2 million households in the England and by 2001 this had risen to over 21 million homes - see Table 2.1.

	Total number of houses
1861	4,206,000
1871	4,736,000
1881	5,291,000
1891	5,761,000
1901	6,612,000
1911	7,493,000
1921	8,161,000
1931	9,595,000
1941	11,050,000
1951	12,500,000
1961	13,9150,00
1971	15,951,000
1981	17,306,000
1991	19,213,000
2001	21,134,000

Table 2.1: Age Distribution of Domestic Properties in England (Office of the Deputy Prime Minister, 2003[b])

There is no indication in the official statistics of how many of these properties are constructed with brick. It is, however, worth noting that after the Great Fire of London in 1666, Parliament enacted *The London Rebuilding Act 1667* which introduced the first ever fire safety regulations for buildings and ever since, the vast majority of U.K. housing have been built with brickwork walls [Howell, 2003[a]]. It is also self evident from a trip around the towns and countryside of the U.K. that many brick properties from the 16th and 17th centuries and earlier are still in existence, with their brickwork intact and continuing to fulfil its purpose. Such properties are a testament to the potential long service life of brick and brickwork. This is indirectly reflected in the U.K. housing statistics, which state that only 20,000 properties were demolished in the year 2000. Using a very simple analysis, this means that unless this rate is increased substantially, it will take over 1000 years to demolish the current housing stock.

In The Green Guide to Specification, Howard *et al* (1998) state *'The average life for all the standing stock of masonry dwellings is 58 years but a significant proportion is over 125 years - however, this form of masonry construction (brick cavity wall) is likely to provide an effective life (typically over 100 years) far exceeding the scope of consideration of this project (60 years)'*. In addition the Green Guide notes that *'Brick construction may indeed last many hundreds of years, having impressive recycling attributes, particularly if used with easily removable mortars; the relatively high energy and emissions* [during the manufacture] *are therefore compensated for by the benefits of longevity and low maintenance'*.

Whilst many early brick built dwellings still function well in the 21st century, it is recognised that many brickwork houses and commercial buildings have also been demolished, particularly in the 20th century as part of slum clearance initiatives and the general quest for improved standards of living as well as redevelopment generally. It is considered unlikely, however, that the majority of the properties were demolished because the brickwork was defective.

The long service lives associated with Tudor, Georgian and Victorian brickwork contrasts sharply with the present day situation where, for example, the National Housebuilding Council (N.H.B.C.) considers the design life of a modern house to be 60 years [N.H.B.C., 2004]. What precisely this means in reality is difficult to determine particularly as the N.H.B.C. also acknowledge that the life span of brickwork is *'in excess of 60 years'*. This 60 year period appears to have arisen out of financial considerations for loans imposed by the banks rather than anything to do with the longevity of a property itself and its relation to the actual life expected of a house is, therefore, somewhat misleading.

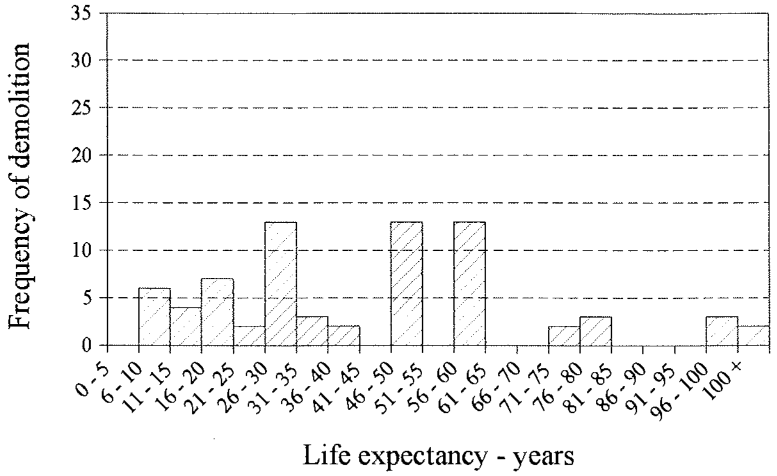
When commenting on the U.K. Government's enthusiasm for trying to replace older buildings with newer, more energy-efficient ones, the Chairman of the R.I.C.S. Building Conservation Forum recently stated *'Just because a house is old, it does not necessarily mean it is inferior. Victorian and Edwardian houses were generally built with better-*

quality materials and using superior methods. That is why they have lasted for 100 years or more. We will be lucky if some of the houses being built today last for 30 years' [Howell, 2003[a]].

It is of interest to note that, in a discussion of the paper *Engineering Buildings for a Small Planet: Towards Construction Without Depletion* published in *The Structural Engineer* (2001), Dr Jonathon Wood highlighted the fact that very durable and very adaptable buildings would actually be required for the long term. Wood also proposed that all new buildings should have a minimum design life of 300 years. The author of the original paper agreed with Dr Wood's proposals and suggested that one way of achieving this would be for the Government to reduce the level of V.A.T. on materials used for refurbishment work. As V.A.T. is not currently imposed on construction materials that are used for new build properties, the present system actually discourages people from refurbishing and redeveloping existing buildings.

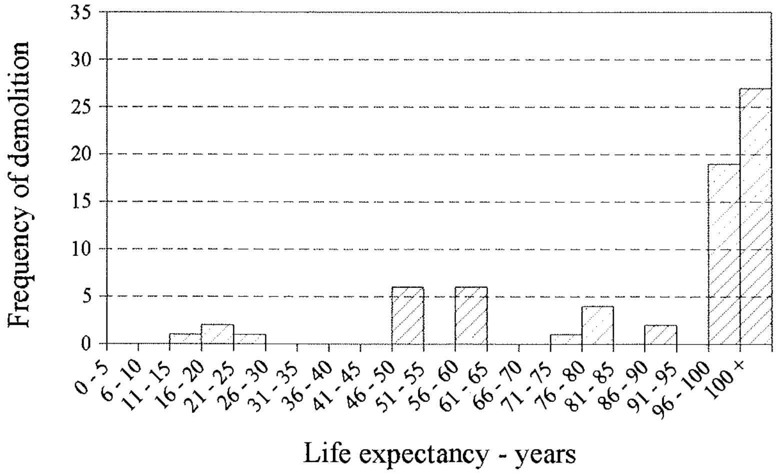
Figure 2.1 shows an extract from *The B.M.I.'s Life Expectancy of Building Components* [Harvey, 2001]. This gives three *average* life expectancies for brickwork; a typical, a minimum and maximum value. These are based on the opinions of some 80 building surveyors who regularly inspect and report on buildings in use, and form part of a larger survey of building components. There is a considerable variation between the minimum and maximum values for brickwork, i.e. 45 and 125 years, respectively. The aim of the B.M.I.'s survey was not to identify the actual causes of failure, but merely report the life expectancies. The survey did, nevertheless, raise some general conjectural issues relating to brickwork including:

- Many failures of brickwork result from the interaction of components.
- The early failure of components with long life expectancies often results from the impact of failures in other materials.
- The expected life of a component does not relate solely to its physical life.
- The failure of a composite component will be determined by the weakest link.



Minimum Life Expectancy

Typical Life Expectancy



Maximum Life Expectancy

Figure 2.1: Life expectancy of Fair-Faced Brickwork

(Harvey, 2001)

In developing these life expectancies, the B.M.I. noted that the nature of the exercise did not lend itself to accurate predictions, as it was based entirely on the views of 80 surveyors. In addition, it was noted that the life expectancy of components is intrinsically linked to the life expectancy of the buildings and that commercial buildings will often have relatively short economic test lives e.g. most Private Finance Initiative contracts are costed over 25 year lifespans. The B.M.I. also note *'historically, 60 years was taken as the standard test life for buildings and that it is therefore reasonable to assume that components with an average life expectancy of over 60 years could be regarded as lasting indefinitely'*. Within the context of a long life material such as brickwork this phrase is considered to be somewhat unhelpful, as it is effectively saying that buildings will already have become obsolete due to a variety of other factors before failure of the brickwork occurs. These other factors include:

- Economic - life to when the use of the building ceases to be the least cost alternative for fulfilling its function.
- Functional - life to when the building ceases to function for the same purpose as that for which it was built.
- Technological - life to when the building is no longer technologically superior to alternatives.
- Social - life to when human desire dictates replacement for reasons other than economic considerations.
- Legal - life to when legal requirements dictate replacement for reasons other than economic considerations.
- Physical - life to when physical failure is possible.

These factors, which are similar to those listed by Sayce (2002), appear to relate more to commercial property, as many older buildings often cannot be adapted to meet the needs of newer industries. On the other hand, the principal function of residential properties has essentially remained the same over the centuries.

Some indication of the typical lifespan and replacement rates for brickwork can also be obtained from BS 7543 [British Standards Institution, 2003]. This shows that when certain types of facing bricks are either saturated or subjected to freeze / thaw action they may spall. The lifespan of these bricks is, consequently, quoted at between 5 and 20 years, although the lifespan of the building remains at 60+ years. Further sources of information on typical life spans of clay brickwork include *A Decent Home: The revised definition and guidance for implementation* [Department for Transport, Local

Government and the Regions, 2002] which gives a figure of 80 years for the component lifetimes for all types of wall structures and housing. The B.M.I. [Harvey, 2001], described above, quote a figure of 85 years for the typical average life expectancy of fair-faced brickwork. With the exception of the B.M.I. guide, none of the documents explain how they determined these values.

2.4 MAINTENANCE OF CLAY BRICKWORK WALLING

Lynch (2003) describes the general problems and defects that occur in brickwork. These include manufacturing defects in bricks, which are caused by impurities in the clay used for the bricks, and under firing of the bricks. Affected bricks decay more rapidly than properly burnt bricks and they are especially susceptible to frost action, which can act as a point of entry for moisture. This can affect the whole wall leaving it vulnerable to damage from further frost and chemical actions. Poor detailing can also contribute to failure of brickwork through construction defects such as:

- decayed timbers that are bonded into the brickwork and / or joists, timber lintels, plates or bearers which have been embedded or built in to the masonry
- the expansion of rust on corroding iron and steel structural members, wall ties or reinforcement embedded in the brickwork
- failure of arches and lintels from inadequate bearings or abutments
- poor bonding and inadequate or even non-existent tying-in of brickwork. This can be due to a habit in the 18th and 19th centuries of *snapping* headers, leading to a wall of two skins instead of one mass. Alternatively, failure can occur at the junctions between walls, particularly where front and rear walls are insufficiently tied to the cross walls.
- *corbelling* (over projecting brickwork) and over-sailing, are especially prone to being inadequately bonded to the main wall. They are also susceptible to water penetration from inadequate, or non-existent, protective weathering.
- sulphate attack may also occur when water is present with cement-based mortars. This leads to a slow, steady expansion of sulphate crystals within the mortar or the bricks as the water evaporates. It can then result in damage and even failure of the masonry. This is particularly common in unlined chimney stacks, where sulphates have been introduced by the burning of sulphur-rich fossil fuels. Where chimneys have been designed without bends, allowing rain to penetrate straight down the flue, damp may appear on the chimney breast with a possible resultant

salt problem. This can especially occur when the air is humid, or where the fireplace has been sealed without proper ventilation.

- poorly designed parapet copings without damp proof courses, inadequate overhangs, or poor jointing techniques, can all encourage damp penetration.

Lynch notes that induced decay and the effects from vegetation and birds are also a problem. For example:

- The introduction of hard cements mortars is one of the most common causes of failure in historic brickwork. It can lead to the failure of the mortar and / or the brickwork itself.
- Vegetation - although it is often attractive, it is generally harmful to older brick walls of traditional construction. Many types of ivy can cause serious damage to brickwork particularly if it is in poor state of repair, or constructed of soft, possibly spalling bricks bedded in soft lime mortar where the pointing is defective. If the ivy cannot be carefully removed, it should, at the least, be heavily controlled and never allowed to reach eaves level where it might block gutters and downpipes. In a strong wind, vegetation can also transfer additional wind-load into the brickwork. This can cause the gutter to pull out and can damage the parapets or even the chimney-stacks.
- Pigeons can also present problems. This is especially true in city centres. Not only can they force up loose roof coverings, but they will block gutters and downpipes with their feathers, detritus and excrement, causing water penetration and consequent decay. The faeces rapidly defaces the external (and internal) fabric of buildings, and may damage porous brickwork. Its removal is both difficult and expensive. Their control is therefore imperative, and can involve bird nets, repellent gels, poisons, traps or even shooting.

All the above maintenance issues are consequently of interest when attempting to evaluate the whole-life performance of clay brickwork.

In spite of the above problems, much anecdotal evidence on the longevity of brickwork exists. An example of this is an extract from *Brick. Made for Generations: A Sustainability Strategy for the Brick Industry* [Brick Development Association Ltd., 2003^{a}], which notes simply that brick will last almost indefinitely. Similarly, Howell (2003^{a}) suggests that, even when they are neglected, traditional solid brick walls built using lime mortar are capable of lasting for centuries. Like Lynch above, Howell also considers that unnecessary repointing with cement mortars actually hastens their decay and observes, from his experience as a bricklayer, that solid walls should only need repointing *'every 100 years or more'* [Howell, 2003^{a}].

2.5 POST-FACTORY GATE ENVIRONMENTAL IMPACT OF BRICKWORK WALLING

To date very little research has been undertaken into the post-factory gate environmental performance of clay brickwork masonry. As a consequence, there is very little data available on this aspect of the material's behaviour.

Within the U.K., the majority of work into the sustainability of construction materials has been undertaken by the B.R.E. As part of this process, the B.R.E. have developed whole life environmental profiles for a range of different building elements, including clay brickwork walling. All of these whole-life profiles are based on the same 60 year life. These *cradle to grave* profiles include consideration of the maintenance issues that would be associated with different forms of masonry wall construction over the 60 year period. These data relating to maintenance were obtained from the B.R.E.'s Centre for Whole Life Performance. The B.R.E.'s work on the sustainability of construction materials is reviewed in greater detail in Chapter 3.

The only other work in the U.K. to evaluate the whole life environmental performance of clay brickwork appears to be that of Steele [Steele *et al,* 2003], who carried out a life-cycle assessment (L.C.A.) exercise on a very limited number of masonry arch bridges in Surrey. This involved a detail analysis of the historical maintenance records for arch bridges as well as L.C.A. comparisons of different methods of strengthening such bridges. The work showed that, whilst the initial pre-factory gate environmental impacts for masonry arch bridges were relatively high, the long life and low maintenance requirements meant that, overall, they were good value in environmental terms, with relatively low environmental impacts over their (long) lives. It was of interest to note from informal discussions with Steele that the environmental impacts of diverting existing road traffic in order to repair/strengthen a masonry arch bridge were highly significant. In one particular case, it was found that if a relatively short road diversion lasted more than three weeks it was, environmentally speaking, better to build a new, and stronger, arch bridge adjacent to the existing bridge rather than divert the traffic. The old bridge would then be demolished. In relation to the financial budget available to the local highways authority, the cost of this option is considered, however, to be prohibitive.

In the U.S.A. the Brick Industry Association (B.I.A.) has carried out a life cycle analysis for brick and block masonry similar to that of the B.R.E., except that, rather than using a 60 year life, they based their calculations on the *warranted life* of the product, which is 100 years for brickwork – see Figure 2.2.

Figure 2.2 provides a cradle-to-grave assessment for the energy consumption and pollution generated during the manufacture of a unit area (square foot) of *brick masonry* over its warranted life. The B.I.A. considers that the warranted life, when available, is the best indicator of the potential performance of the product and, as such, this is consistent with the general approach adopted in this thesis and previously by Steele [*ibid,* 2003]. The exact relevance of the American term *warranted life* in relation to U.K. clay brickwork is not clear, however, as U.K. brick manufacturers do not provide a 100 year warranty, i.e. they do not guarantee their products for a 100 year period.

CLADDING LIFE-CYCLE ANALYSIS

Basic Data	Brick Masonry	Block Masonry	Fiber *[sic.]* Cement	Vinyl Siding	Exterior Insulation and Finish Systems (EIFS)
Warranty	100 years	50 years	50 years	50 years	50 years
Weight / ft ^{2}	35.5 lb.	42.8 lb.	2.3 lb.	0.5 lb.	1.24 lb.
Energy: Mining & Manufacturing Recycling & Energy kWh /ft ^{2} / yr	Recycling: Brick 100 % Mortar 40 % Energy: 0.252	Recycling: 80 % Energy: 0.228	Recycling: 0 % Energy: 0.328	Recycling: 80 % Energy: 0.210	Recycling: 0 % Energy: 5.48
Pollution: Water & air emissions lb / ft ^{2} / yr	0.011	0.005	0.026	0.001	0.023
Distribution Energy Avg. / Distance, Miles & Net Energy kWh / ft ^{2} / yr	175 miles 0.004	100 miles 0.004	365 Miles 0.146	310 miles 0.001	300 miles 0.189
Waste & Depletion lb / ft ^{2} / yr	0.108	0.203	0.048	0.460	0.828
TOTALS					
Energy	0.256	0.232	0.474	0.211	5.669
Pollution	0.011	0.005	0.026	0.001	0.023
Waste & Depletion	0.108	0.203	0.048	0.460	0.828

Figure 2.2: Brick Industry Association Life Cycle Analysis of Construction Materials (Brick Industry Association *[of America]*, 2003)

Detailed comparisons between the B.I.A. values for the environmental impacts of brick masonry shown in Figure 2.2 and those quoted by the B.R.E. for U.K. masonry are difficult as the B.I.A. do not state the type of brick wall construction they have based their calculations on. They weight of the brickwork given in Figure 2.2, however, suggests that it is probably a single, half brick thick wall, i.e. 102.5 mm. In addition, the figures for recycling of the brickwork quoted by the B.I.A. appear to be very high in comparison with the U.K. where it has been estimated that only 140 million out of the 2,500 million bricks that are demolished annually in the U.K., are reclaimed in the U.K.; this equates to less than 6 % compared to the total number of demolished bricks. A further 600 million to 1,200 million bricks are crushed and used as hardcore fill material each year [Gregory and Hughes, 2005]. This latter figure is low in relation to the U.K.'s current annual production of approximately 3,000 million new bricks [http://www.dti.gov.uk/construction/stats/].

The B.I.A. do, nevertheless, point out that *'brick has a life cycle, conservatively estimated at one hundred years'* and that *'critics, who understandably may attempt to divert your attention elsewhere, tend to focus on the amount of heat energy used to make brick without putting it in the context of its long life.'*

The B.I.A. also quotes other less tangible benefits of using brick such as:

- it has virtually no emissions
- it is fireproof and water and insect resistant
- it is virtually impervious to the ravages of time and weather
- it is a natural insulator
- it is able to absorb and release thermal energy over an extended period, making it an ideal choice for reducing peak energy loads – this thermal-lag makes brickwork a particularly appealing material for use in conjunction with passive solar construction.

In practice, very little useful information is publicly available for either the pre- or post-factory gate environmental performance, or the cradle-to-grave performance of clay brickwork masonry. This reflects the commercial nature of most of the software relating to life-cycle assessment (L.C.A.), where access to the software is conditional upon the purchase of a licence. In addition, most of the L.C.A. computer packages that are currently available do not show the data used in the actual assessment or the assumptions made by the program during the assessment; instead they simply produce a final *answer* which cannot be independently verified. This is a fundamental problem with much of the software for life cycle assessment generally and, as such, is discussed in more detail in Chapter 3.

2.6 WHOLE LIFE COST OF BRICKWORK

As part of the overall drive towards sustainable buildings and sustainable construction in general, the technique of life-cycle costing (L.C.C.), which is also known as whole life costing (W.L.C.), is being actively promoted, particularly when used in conjunction with life cycle assessment (L.C.A.). B.R.E. Digest 452 [Edwards, Bartlett and Dickie, 2000] considers that *'this combination of economic and environmental assessment tools has the potential to make a significant contribution to sustainable building design by obtaining 'best value' solutions in both financial and economic terms'*. This is also the approach recommended by the Institution of Structural Engineers in order to obtain the most sustainable solutions for building design [The Institution of Structural Engineers, 1999].

The definition of L.C.C given in Part 1 of ISO 15686 [British Standards Institution, 2000^c] is *'a tool to assist in assessing the cost performance of construction work, aimed at facilitating choices where there are alternative means of achieving the client's objectives and where those alternatives differ, not only in their initial costs but also in their subsequent operational costs.'*

Whilst there are many publications dealing with L.C.C., it is not the intention of this thesis to consider the technique in detail. Rather it is considered sufficient to simply state that, in practical terms, L.C.C. includes consideration of a product's initial cost plus all future costs (operating, maintenance, repair and replacement costs, and functional-use costs) minus the salvage value of the product, i.e. the value of an asset at the end of its economic life or study period. L.C.C. is also usually discounted to the present value over time using different financial accounting techniques such as Net Present Value (N.P.V.) or Discounted Cash Flow (D.C.F.).

For this thesis, the life-cycle costs of several forms of clay brickwork walling will be developed and used in conjunction with the results from a life-cycle assessment to select the most *sustainable* form of masonry construction.

In relation to brickwork generally, it is of interest to note that *Spon's Architects' and Builders' Price Book* (Davis, Langdon and Everest, 2003) estimates that the cost of cladding a new office building in brickwork will be considerably lower than cladding it in a *high-tech* curtain walling system. For instance, the price of cladding an office building with brickwork / timber studwork external walling ranges from £78 / m^2 to £87 / m^2. A brickwork / blockwork external wall ranges from £74 / m^2 to £87 / m^2; and a double-glazed curtain walling system from £279 / m^2 to £334 / m^2. From a simple economic viewpoint, it is difficult to understand why the latter has, therefore, become so popular in recent decades, especially as brickwork requires only minimal maintenance and is probably capable of lasting centuries.

Figure 2.3 taken from BRE Digest 452 [Edwards, Bartlett and Dickie, 2000] shows how the results from life-cycle costing and assessment analyses may be combined to determine the best *solution* for a sustainable building. The figure is based on the results of a L.C.A study on different forms of internal wall construction for a new hospital building. These are expressed in terms of eco-points, a notional unit of environmental impact developed by the B.R.E. In this example, the second option (yellow) has both the lowest cost and the lowest environmental impact and is consequently the best and most sustainable solution overall. It is easy to identify which is the most suitable option in Figure 2.3 but it would be more problematic if, for instance, Option 1 was cheaper than Option 2 but Option 2 had the lowest environmental impacts. In such circumstances, where there is not a clear winner, the final decision would have to be based on a *value-choice judgement.*

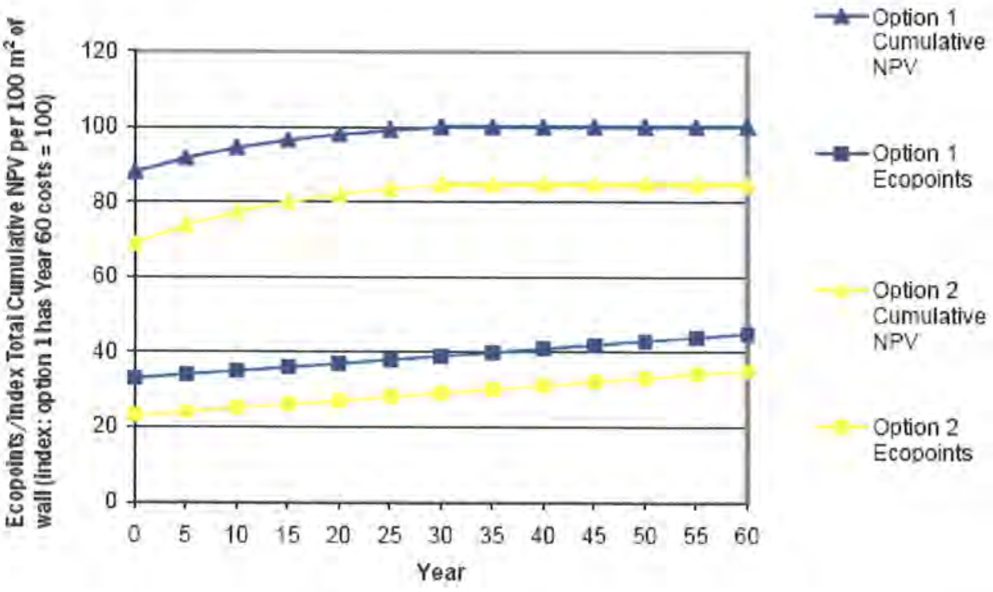


Figure 2.3: Financial and Environmental Performance of Internal Walls (Edwards, Bartlett and Dickie, 2000)

2.7 CONCLUSIONS

The review of the factors influencing the sustainability of clay brickwork masonry has revealed the following conclusions:

1. To date, the majority of research into sustainable buildings has concentrated on reducing their operational energy. Although this is an important issue, it is not necessarily central to sustainable development, however, and other matters such as the adaptability of the building to meet the needs of the future user and their geographical location may be equally, and in certain circumstances more, important.

2. The longevity of buildings has also been identified as being an important issue with respect to their sustainability

3. The published lifespans of clay bricks and brickwork masonry range from 30 years to 125 years. These are considered low particularly when 40 % of the existing housing stock in the U.K. was built before 1861 and, consequently, is already over 140 years old.

4. There are many defects and problems that can affect clay bricks and brickwork such as spalling, the failure of other components, poor bonding and sulphate attack, which can reduce its potential lifespan

5. In the U.K., the only work into the sustainability of clay brickwork masonry concentrated on the whole-life environmental performance of clay masonry brickwork arch bridges whole-life in Surrey, England. It found that masonry was very good value.

6. The majority of the work in the U.K. is produced by the Building Research Establishment (B.R.E.). They produce a series of packages which allow construction professionals to assess the whole-life environmental impacts of various construction materials used in the U.K. All of the impacts are based on a single 60 year lifespan, however.

7. The American Brick Industry Association (B.I.A.) conducted a life-cycle assessment (L.C.A.) on the five common construction materials that are used as

walling in America. Their work concluded that brickwork was the most sustainable of the five.

8. The B.I.A. used a 100 year lifespan for brickwork in their calculations which was based on the warranted lifespan of new bricks in America which compares to the single 60 year lifespan that the B.R.E. use for their work on construction materials in the U.K.

9. The B.I.A. also noted other less tangible benefits of brickwork including that it is fireproof and insect and water resistant, it is a natural insulator and its capacity to store and release thermal energy over extended periods of time.

CHAPTER 3: GENERAL REVIEW OF THE FRAMEWORK FOR LIFE-CYCLE ASSESSMENT AND THE WORK OF THE U.K. BUILDING RESEARCH ESTABLISHMENT ON L.C.A.

3.1 INTRODUCTION

The aim of this chapter is to critically review the framework for carrying out a life-cycle assessment (L.C.A.) of products or product systems / processes, as currently recommended by British and ISO Standards. This will include a detailed review of all of the available methodologies for life-cycle impact assessment (L.C.I.A.) and the accuracy and limitations of L.C.A. generally. It will also review the U.K.'s Building Research Establishment (B.R.E.) work on sustainability and environmental profiling of construction materials and forms of construction. Wherever possible, the discussion is directed towards the production and use of clay bricks and clay brickwork masonry.

3.2 LIFE-CYCLE ASSESSMENT

Life-cycle assessment (L.C.A.) is a generic technique for studying the environmental impact of any product or product system / process over its whole life in order to determine their impact on the environment. The Society of Environmental Toxicology and Chemistry (S.E.T.A.C.) describes life cycle assessment as '*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 effect environmental improvements*' [S.E.T.A.C., 1991] - this is best illustrated by Figure 3.1.

Figure 3.1: A System Approach to Life-Cycle Assessment
(Steele *et al*, 2003)

L.C.A. is a process that attempts to model a range of complex environmental processes involving both quantitative and qualitative issues associated with the natural sciences. Whilst parts of these modelling processes may involve scientific procedures, other aspects may be primarily based upon subjective *value-choice* decisions / judgements which cannot be quantified in scientific terms. Interpretation of the results from an L.C.A. study should, therefore, ideally involve a decision-analytic framework which systematically integrates scientific and value judgements [Hertwich and Pease, 1998]. In reality, this can, however, be very difficult to achieve. The results from L.C.A. analyses are usually expressed in terms of resource use, pollution, effects on human health and ecological consequences. To do this, different life cycle impact assessment (L.C.I.A.) procedures and methodologies are used.

L.C.A. was originally intended for the comparison of clearly defined end-product alternatives such as different forms of milk packaging or babies' nappies, and many industrialists thought that the results from such assessments could be used as marketing tools to support environmental claims [Goedkoop and Oele, 2004]. This is now not considered to be the best application of L.C.A. as the results are invariably difficult to communicate to the general public or, indeed, even to professionals in other disciplines. A recent survey by Goedkoop and Oele (2004) has shown that life-cycle assessments are now more often carried out for internal purposes (such as product improvement, support for strategic choices, benchmarking and external communication) within a company.

The results from a L.C.A. can also be used to:

i. identify opportunities to improve the environmental performance of products
ii. assist decision-making in industry, government and non-governmental organisations
iii. aid the selection of relevant indicators of environmental performance, including measurement techniques
iv. support marketing with environmental claims and eco-labelling

A life-cycle assessment is, however, not the only technique available to assess the environmental performance of a product or product system. Alternatives to L.C.A. include; risk assessment; environmental auditing; and environmental impact assessment. In some situations one or more of these alternatives may be more appropriate than L.C.A. [British Standards Institution, 1997].

As L.C.A. is still a relatively new technique, considerable work remains to be done and practical experience gained on its application so that it can be seen to be technically credible. In addition, the limitations associated with its use need to be recognised

[Goedkoop and Oele, 2004]. In particular it needs to be appreciated that the accuracy and validity of any whole-life assessment may be limited due to the lack of appropriate data relating to the manufacture and in-service performance of the product being investigated, and any assumptions that were made during the development or analysis of the data.

This is potentially of major concern for materials and product systems with inherently long life spans such as clay bricks and clay brickwork masonry where, for example, data on its post-factory gate environmental performance are very limited. This can lead to erroneous conclusions about the whole life environmental performance of such products. Inconsistencies may also arise when L.C.A. comparisons are made, for example, between traditional brickwork / blockwork walling and more modern brickwork / timber cavity walls used for housing. Whereas data relating to the post-factory gate environmental performance of the former can be derived from condition surveys of the existing building stock and analyses of historical maintenance records, no equivalent historical data are available for modern forms of timber frame construction. Future maintenance requirements of the latter are, therefore, only estimates.

3.3 STANDARDS FOR LIFE-CYCLE ASSESSMENTS

A series of ISO standards have been designed specifically for life-cycle assessments, as shown below. As L.C.A. is a relatively new concept, the standards have all been developed within the last decade and are a *first-attempt* to rationalise the process of L.C.A. generally. As such they are consensus-based and voluntary, and are not legally enforceable or binding. It is therefore considered likely that they will undergo further development and / or refinement as the concept and practical operation of L.C.A. develops [British Standards Institution, 2004].

ISO 14040 – Environmental Management – Life-Cycle Assessment: Principles and Framework [British Standards Institution, 1997] - specifies the general framework, principles, and requirements for conducting and reporting life cycle assessment studies, but does not describe the methodology in detail

ISO 14041 – Environmental Management – Life-Cycle Assessment: Goal Scope and Definition and Inventory Analysis [British Standards Institution, 1998^{a}] - specifies the requirements and procedures for the compilation and preparation of the definition of a goal and scope for an L.C.A. and for performing, interpreting, and reporting a life-cycle inventory (L.C.I.) analysis

ISO 14042 – Environmental Management – Life-Cycle Assessment: Life-Cycle Impact Assessment [British Standards Institution, 2000^a] - Describes and gives guidance on the general framework for the L.C.I.A. phase of a L.C.A. and the key features and inherent limitations of L.C.I.A. It also specifies the requirements for conducting the L.C.I.A. phase and the relationship of L.C.I.A. to other L.C.A. phases

ISO 14043 – Environmental Management – Life-Cycle Assessment: Life-Cycle Interpretation [British Standards Institution, 2000^b] - provides requirements and recommendations for conducting the life-cycle interpretation in L.C.A. or L.C.I. studies. It does not, however, describe specific methodologies for the life-cycle interpretation phase of L.C.A. and L.C.I. studies

ISO 14048 – Environmental Management – Life-Cycle Assessment [British Standards Institution, 2002] - describes the data documentation format

ISO 14049 – Environmental Management – Life-Cycle Assessment [British Standards Institution, 2000^c] - provides examples of the application of ISO 14041 to goal and scope definition and inventory analysis

ISO 14050 – Environmental Management: Vocabulary [British Standards Institution, 1998^b] - provides definitions of the different terms used in environmental management

Each of the above ISO standards has the status of a British Standard and form part of a wider series of ISO standards associated with environmental management systems, namely the ISO 14000 Environmental Management System Standards.

A particular problem for the non-expert with little experience of environmental management is that most of the language and terminology used in this area is highly specialised and, consequently, the topic can appear to be very confusing. This is understandable given that L.C.A. is a relatively new technique which has been developed for application across a vast range of different materials, products and product systems / processes. One of the standards - ISO 14050 [British Standards Institution, 1998^b] - is, therefore, concerned solely with the vocabulary of Environmental Management and contains explanations and definitions of the various phrases and terminology that are frequently used in this type of work. A limited number of these are shown below in order to facilitate the reading and understanding of this thesis.

3.4 TERMS RELATING TO LIFE-CYCLE ASSESSMENT

The following descriptions are based on the definitions given in ISO 14050 [British Standards Institution, 1998^b].

- **Product (or Product System)** – any goods or services, e.g. a brick, a block, or a concrete lintel, or the generation of electricity
- **Functional unit** – quantified performance of a product system for use as a reference unit in a L.C.A. study – e.g. 1 m^2 of clay brickwork masonry walling for housing with a specified thermal performance sufficient to meet the requirements of the local legislation, e.g. the Building Regulations in the U.K.
- **Input** – all material and energy which enter a unit process, e.g. the raw materials used to manufacture a clay brick, the process fuels which are used during the manufacturing process, the transport fuels to bring the raw materials to the manufacturing site, the water required, etc.
- **Output** - the materials and / or energy which leave a unit process, e.g. the product and the emissions to air, discharges to water, and the emissions to land, for instance the solid wastes associated with the production processes
- **Life-cycle assessment (L.C.A.)** – the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life
- **Life-cycle inventory (L.C.I.) analysis** – the phase of a L.C.A. involving the compilation and quantification of inputs and outputs for a given product system, e.g. 1 m^2 of clay brickwork masonry walling for housing with a specified thermal performance over its complete life, i.e. on a *cradle* to *grave* basis.
- **Life-cycle impact assessment (L.C.I.A.)** – the phase of the L.C.A. aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product or product system
- **Impact category** – the class representing the environmental issues of concern into which the L.C.I.A. results can be assigned, e.g. global warming, acidification, heavy metals, ozone depletion, eutrophication, pollution to air, waste disposal, etc.
- **Life-cycle impact category indicator** – the quantifiable representation of an impact category
- **Characterisation factor** – a factor developed from modelling which is applied to L.C.I.A. results to convert them to the common unit of the life cycle impact

category indicator

- **Category endpoint** – an attribute or aspect identifying an environmental issue of concern, i.e. the natural environment, human health or resources
- **Life cycle interpretation** – the phase in a L.C.A. in which the findings of the inventory analysis and / or the impact assessment are combined with respect to the defined goal and scope of the study in order to reach the conclusions and recommendations
- **Weighting** - a deliberate attempt to rank the various environmental impacts
- **System boundary** – the interface between a product system and the environment or other product systems
- **Allocation** – the partition of the input or the output flows of a unit process to the product system

As previously explained, the purpose of a L.C.A. is to study the potential environmental impacts of a product, or form of construction, throughout its life starting from the extraction of the raw materials, through production and use and ending with disposal. This is often expressed in terms of *cradle-to-grave* performance although this can then be divided further into *pre-factory gate* and *post-factory gate* performance.

Pre-factory gate performance includes the excavation of the raw material, all aspects of the manufacturing process, and any packaging prior to leaving the factory. Post-factory gate situation includes the transport of the material to site, the construction of the product, system maintenance and eventual demolition and disposal. This thesis is primarily concerned with an investigation of the latter, i.e. the *post-factory gate* performance of clay brickwork masonry walling.

3.5 KEY FEATURES OF A LIFE-CYCLE ASSESSMENT

ISO 14040 [British Standards Institution, 1998] lists a number of attributes that should be considered in life-cycle assessments to ensure that the results are meaningful and valid. These include:

- Ensuring that the whole process is transparent. This includes clearly identifying the initial scope of the study and the methodologies and cataloguing any assumptions that are made during the LC.A. There should also be a description of the data quality and the data sources should be documented.
- Depending on the intended application of the study, a requirement to respect

confidentiality and proprietary matters; there is, however, a potential conflict with the first issue regarding the transparency of L.C.A. studies.

- There is no scientific basis for reducing L.C.A. results to a single *score* or number (i.e. a scoring system), because there will be trade-offs, value-judgements and complexities within the various systems that are included and analysed at different stages of their life cycles.

ISO 14040 [British Standards Institution, 1997] also details a number of requirements which are necessary if the results from an L.C.A. are to be used for comparative assertions that are disclosed to the public. These include:

- clearly identifying the source of the data used in the study
- an assessment of the precision, completeness and representation of the data
- disclosing any uncertainties in the data
- a critical review of the whole process including a comparison of the systems used to determine the outputs from the L.C.A.

3.6 PHASES OF A LIFE-CYCLE ASSESSMENT

ISO 14040 [*Ibid,* 1997] recommends that L.C.A. studies be divided into four stages:

i. The definition of a *goal* and *scope* for the study.
ii. The construction of a model for the product's life-cycle which includes all of the environmental inputs (i.e. raw material, energy, etc.) and outputs (i.e. emissions, waste, etc.) – the *Life Cycle Inventory* (L.C.I.) stage.
iii. The development of an understanding of the environmental relevance of all the inputs and outputs through the use of an appropriate impact assessment model – the *Life Cycle Impact Assessment* (L.C.I.A.) phase
iv. The *interpretation* of the results from the study

This process is shown diagrammatically in Figure 3.2.

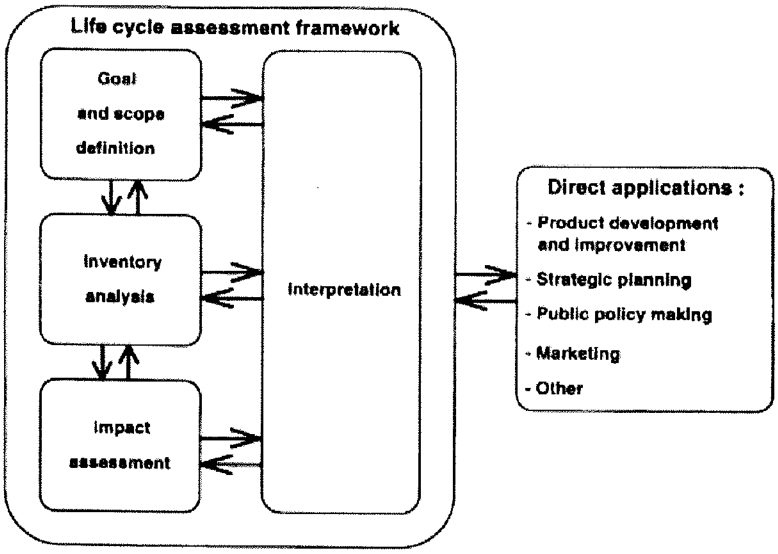


Figure 3.2: Phases of a Life-Cycle Assessment
(British Standards Institution, 2000^a)

The results from the study can then be used for product development and improvement, strategic planning, etc. or circulated to a wider audience as appropriate.

3.7 METHODOLOGICAL FRAMEWORK FOR A L.C.A. STUDY

The phases of a life-cycle assessment shown in Figure 3.2 are reviewed in greater detail below.

3.7.1 DEFINING THE GOAL AND SCOPE OF A L.C.A. STUDY

Both *SimaPro 5.1 User Manual* [Goedkoop and Oele, 2002] and ISO 14040 [British Standards Institution, 1998] emphasise the need to carefully define the initial goal and scope of a L.C.A. study. This is because it is at this stage that the most important and subjective choices are described. The factors that should be considered at this initial stage include:

- the intended purpose of the L.C.A.
- an accurate definition of the product, its life cycle and its function
- a precise definition of the functional unit, so that sensible comparisons can be made between alternative products
- a description of the system boundaries for the analysis (e.g. the exclusion or

inclusion of capital goods such as lorries and factories from the analysis) and the manner in which allocation problems will be dealt with, i.e. the rules by which the environmental impacts related to the same manufacturing process are either assigned to the output products or the by-products / recyclable wastes

- the data and data quality requirements
- any assumptions and limitations
- the requirements of the life cycle impact assessment (L.C.I.A.) procedure and the subsequent interpretation of the results
- the intended audience and the process for disseminating the results
- If applicable, the method for conducting a peer review of the whole process.

3.7.2 THE GOAL OF A L.C.A. STUDY

It is important to confirm the intended application and audience of the L.C.A. during the initial stage of the study because of the wide variety of choices that are available in the presentation of the final results. For example, a study that provides data for an internal company study is likely to be very different from one that aims at making public comparisons between two products [Goedkoop and Oele, 2002]. In the latter case, *weighting* - a deliberate attempt to rank the various environmental impacts - may not be used in the impact assessment because the process involves making subjective choices which could be used to conceal specific environmental impacts [British Standards Institution, 2000^{a}]. When making L.C.A. comparisons between alternative products, a peer review process is also necessary to ensure that the assessments are valid.

3.7.3 THE SCOPE OF A L.C.A. STUDY

The scope of a life-cycle assessment study defines and describes the important methodological choices, assumptions and limitations that will be considered and used in the subsequent study. The scope can be separated into four areas as listed below.

3.7.3.1 FUNCTION AND FUNCTIONAL UNIT

Because they can be used in comparisons of alternative products, it is important to clearly define the functional units of the L.C.A. technique; a construction-related example of this would be 1 m^2 of floor slab in a multi-storey building. A comparison could then be made between different types of floor construction, e.g. a traditional reinforced concrete slab cast in-situ using (re-useable) ply formwork or a reinforced concrete slab cast onto a permanent formwork shuttering. Such an assessment would need to consider the number of times that the ply formwork could be re-used whilst the permanent formwork could only be used once.

The normal functional unit for the external walls of buildings is $1m^2$ of walling that additionally achieves the minimum level of thermal performance specified in the Building Regulations [Office of the Deputy Prime Minister, 2002] for buildings in the U.K., for example. This enables alternative forms of wall construction, including those with different materials such as brickwork / blockwork and PVC-u weatherboarding / blockwork, to be compared.

3.7.3.2 SYSTEM BOUNDARIES

Because product systems are often interrelated in complex ways, the limitations, assumptions and system boundaries associated with the product or product system being studied should be clearly described. For example, the L.C.A. for a concrete floor slab might include the environmental impacts from a lorry that would be needed to transport the necessary materials to site. However, the lorry would have originally been built in a factory, but in order for that factory to be built, another lorry must have transported those materials to that site. This is a fundamental issue with life-cycle assessments and requires system boundaries to be drawn that clearly describe the boundaries of the intended study. The usual procedure for the case described above, would be to exclude the impacts from capital goods such as lorries, kilns for firing bricks and the woodworking machinery for producing timber, from the study. This approach is considered to give satisfactory results [Goedkoop and Oele, 2002] and has been adopted in this research project.

3.7.3.3 INPUTS AND OUTPUTS

The manufacture of any product involves a wide range of other processes that all have an impact on the environment. For instance, the production of clay bricks requires numerous processed materials such as fuels to supply the energy to fire the bricks and to heat and light the factory, and water to provide essential services to the factory. Each of these processed resources are the product of others processes which also have an impact on the environment. These interrelated processes can be mapped on a *Process Tree* which can easily extend to over 10,000 processes if all the processes associated with manufacture of a single product are included. However, because of their relatively insignificant contribution to the overall environmental impact of the end product, many of these processes can be neglected. It has therefore become common practice to simplify the L.C.A. by excluding data on inflows and outflows when the particular process contributes very little to the overall environmental impact, or burden; typically, this limit is set at 0.1 % for a single impact category, e.g. global warming [Goedkoop and Oele, 2004]. This approach was also adopted for this research project.

3.7.3.4 QUALITY REQUIREMENTS FOR INPUT DATA

In order to carry out a realistic L.C.A., it is essential that the input data which are to be used in the assessment are appropriate and relevant. For example, some L.C.A. studies might require the input and output data to be averaged for all the manufacturers of a certain product in the world, whilst other studies might only be concerned with determining the environmental impacts from a single factory in a particular country [Goedkoop and Oele, 2004]. In the latter case, the use of the averaged world data might be inappropriate as the local factory might be using old and obsolete equipment with a high environmental impact, or, equally, it might also be a modern, state of the art, highly efficient plant with a much lower environmental impact overall than a *typical* factory.

The reliability of the results from a L.C.A. are consequently affected by the quality of the input data. In particular, a lack of data can lead to inaccurate model results. The quality of an L.C.A. study is therefore directly related to the quality and quantity of the input data used in the study; this has been summarised by Friend (1996) as *'garbage in, garbage out'*.

In addition, often many assumptions have to be made to fully quantify the inputs and outputs associated with a particular product. For example, during the pre-factory gate stage of the production of clay bricks, the transport distances between the mining sites and the manufacturing plants might vary and the different plants might use different manufacturing processes. Although averaging the data across all of the plants might not be appropriate for many L.C.A. studies and the results might only be of limited value, it may not be feasible to conduct a study for each plant individually.

3.7.4 LIFE CYCLE INVENTORY (L.C.I.) DATABASES

A number of countries have developed their own life cycle inventory (L.C.I.) databases. These typically contain detailed information about the inputs (materials and utilities) and the outputs (the environmental impacts such as emissions, wastes, etc.) from the production of fuels such as electricity and petroleum. They also occasionally have data relating to the manufacture of a limited range of basic materials such as plastics, glass, aluminium, steel, timber and cardboard, and on other processes such as transportation and waste treatment.

This information is, however, generally specific to the country concerned and it may not be appropriate for use in different countries. For example, electricity in France is primarily generated from nuclear power stations but in the U.K. it is largely generated by gas and coal-fired power stations. Consequently, whilst the quantities of electricity involved may be similar, the environmental impacts from the two processes might be completely different and the environmental impacts from identical products manufactured in the two countries might also be different.

In addition, whilst some of the L.C.I. databases have been developed by academics, others are by industries with specific interests in life-cycle assessment, such as cardboard and paper manufacturers and glass producers. Equally, some are the result of collaboration between industry, academia and government departments.

Details of some of the databases available (which are usually described in terms of acronyms) are given in Table 3.1. Table 3.2 shows their particular focus. Virtually all of the databases in Tables 3.1 and 3.2 are, however, associated with commercial L.C.A. software packages and require the purchase of an operating license to be accessed.

Status of database: managed by:	***Completed databases (may be updated)***	***Ongoing, with data gathering underway***	***Planned or underway, but data gathering not yet underway***
National and multi-government [1]	Italy, Switzerland (BUWAL 250)	Australia, Canada, Chinese Taipei, Japan, Korea, Sweden (SPINE), Switzerland (Eco-Invent 2000)	U.S.A.
Consultants and Research Institute [2] *(data made available)*	Denmark (EDIP), Sweden (CPM)	Austria, Denmark, France, Germany, Sweden, Switzerland, U.K., U.S.A.	
Industrial (data made available) [3]	IISI, EAA, FEFCO, APME and PWMI, NiDI		
Academic / decentralized [4]		Belgium, China, Chile, Estonia, Finland, India, Norway, The Netherlands, Portugal, Poland, South Africa, Spain, Vietnam	Argentina, Malaysia, Thailand

[1] Co-ordinated effort to produce nationally representative and accessible database. Typically involves collaboration between several organisations and some degree of government funding.

[2] Inventories produced by research organisations or consultants and made publicly available in a database, sometimes for a fee (e.g. databases included with LCA software).

[3] Inventories produced and published under the auspices of a particular industry organisation. Includes cases where data made only partially available (e.g. for a fee, or only to parties with sufficient motivation for requesting the data). Most often data compiled by consultants, but includes cases where LCI development is done in-house, or by academic or other research organisations.

[4] Includes inventories compiled by academic or other research organisations, made either partially or fully available on an ad-hoc basis (e.g. through journal publications). Countries may have some degree of information sharing (e.g. an LCA society), but no co-ordinated data gathering effort (i.e. studies are not organised into an accessible database).

Table 3.1: Matrix of L.C.I. Databases by Project Status and Class of Managing Organisation

(United Nations Environmental Programme, 2004)

Database	Focus
ETH-ESU 96	Energy - Electricity generation and related processes like transport, processing, and waste treatment. Includes 1200 unit processes and 1200 system (results) processes.
BUWAL 250	Packaging materials (plastic, carton, paper, glass, tin plated steel, and aluminium), energy, transport, waste treatments.
IDEMAT 2001	Engineering materials (metals, alloys, plastics and wood), energy and transport.
IVAM 4.0	Materials, transport, energy and waste treatments. Mostly focused on Dutch data.
FEFCO database and scripts	European data on corrugated board production, partially based on BUWAL 250.

Table 3.2: Focus of Databases

(Goedkoop and Oele, 2002)

A further problem with current L.C.I. databases is that the formats for the data, from the initial inputs through to the final results, are very diverse with little commonality between them. This is because the packages were developed in isolation in separate countries and by different organisations, i.e. industry, academia and public authorities. It is therefore virtually impossible to directly compare or exchange data between different databases. One organisation which was involved in trying to address this issue was the Society for the Promotion of L.C.A. Development (S.P.O.L.D.), who developed a standard format for L.C.I. databases (available from http://lca-net.com/spold). This organisation was disbanded in 2001, however.

As previously noted, the majority of the databases shown in Table 3.2 either concentrate on generic processes such as the generation of electricity or on specific manufacturing processes. These databases are of limited use to the Construction Industry as they contain insufficient data on the many materials, products, product systems, and product processes which are commonly encountered in buildings, bridges, etc.

At present, there are very few L.C.I. databases that relate specifically to the Construction Industry – see Table 3.3. All of the databases in Table 3.3 are associated with commercial L.C.A. software packages and require the purchase of a license to operate. It should be noted, however, that even after the software and license are purchased, it is often not possible to gain access to the information contained in the database, as the programs act as *black boxes*, i.e. they only show the final results of an assessment rather than specifying the actual L.C.I. input data from which the results were derived.

L.C.A. SOFTWARE TOOL	**SOURCE OF INVENTORY DATA**
LCAid™ (Australia)	**Materials phase:** • Department of Public Works and Services (DPWS) LCA Database • Maintenance data from DPWS maintenance teams and material life cycle literature **Construction phase:** Waste data during construction from literature **Operation phase:** Water and waste calculation developed by DPWS from experience and literature; LCA of Australian energy supply; Links to thermal engines such as Eco-tect or simply enter energy requirements from other thermal engines or benchmarks) **Demolition phase:** Waste calculation developed by DPWS from literature
ATHENA™ (Canada)	Regionally specific life cycle inventory product databases owned by the ATHENA Institute and created with industry expert input.
The Green Guide to Specification, ***Envest II*** (B.R.E., U.K.)	Associated database of LCA data available on the Internet
Building for Environmental and Economic Sustainability (*BEES 2.0* – U.S.A.)	Database owned by BEES
Life-Cycle Explorer (U.S.A.)	• Data and modelling approaches for window energy use are from a variety of publications, most of which are traceable to the U.S. Department of Energy's Lawrence Berkeley National Laboratory (LBL). • Data on regional heating system shares and efficiencies are from LBL. • Data on life cycle inventory flows from U.S. electricity generation, residential fuel combustion and pre-combustion, and transportation come from Franklin Associates, 2000. • Data on the material input and energy requirements for manufacturing window frames are from a Swiss research institute (SZFF/EMPA 1996 Study: Ecological Assessment of Window Constructions Using Various Frame Materials (without Glazing).) • Life cycle inventory data for glazing are from the University of Amsterdam's IVAM Research Agency (IVAM 1999: University of Amsterdam, Life Cycle Inventory Database on Building Materials.) • Life cycle inventory data for manufacturing raw material inputs used in window frame manufacturing are from the LCI databases found in SimaPro (available from PRé Consultants, NL).

Table 3.3: Specific L.C.I. Databases for the Construction Industry

(U.S. Department of Housing and Urban Development, 2001)

This thesis is primarily concerned with the life-cycle inventory database developed for the Building Research Establishment's *Green Guide* series of publications and the associated *Envest II* life-cycle assessment computer-software package, as these are of most relevance to the U.K. Clay Brick Industry. It should be noted that, whilst Table 3.3 states that there is a B.R.E. L.C.A. database accessible via the internet, due to manufacturers' confidentiality this contains very little useful information.

3.7.4.1 PROPRIETARY AND COMPANY SPECIFIC L.C.I. DATA

A useful description of the difficulties that can arise during the compilation of a L.C.I. database for proprietary and company-specific products is provided in a report by the U.S. Department of Housing and Urban Development (H.U.D.) (available from < http://www.huduser.org//Publications/PDF/lifecycle.pdf >). This presents the findings of a one-day workshop held in 2001 at which a panel of international experts discussed L.C.A. issues. Whilst these findings were specifically directed towards the American market, they are considered to be relevant for the development of L.C.I. databases in other countries, generally.

The H.U.D. report disclosed that a particular problem was that the L.C.I. data that was provided by manufacturers was often reviewed by consultants who had a background knowledge in economics, engineering and environmental issues. As such, they were not experts in any particular field or industry. This made it difficult for them to identify problems with initial L.C.I. data and any assumptions that were made during the derivation of the data.

The report also described how L.C.A. tools that were available in 2001 did not usually make any allowance for the inherent variability of the manufacturing processes between different producers of the same product, or the need for individual companies to maintain their competitiveness by safeguarding trade secrets. As a consequence, legal counsel for the companies and organisations that were involved in product manufacturing often resisted releasing their manufacturing data as they were concerned with liability and proprietary issues. For example, the U.S. Government could use these data to conduct a mass-balance[†] calculation which might give rise to greater scrutiny of the company's performance by the federal authorities. At the same time, it might allow the company's competitors to obtain proprietary data on the product via the U.S.'s Freedom of Information Act < http://www.huduser.org//Publications/PDF/lifecycle.pdf >.

[†] A mass-balance calculation (also called budget calculations when applied to environmental monitoring) is a methodology for comparing the inputs and outputs in a process. It is based on Lomonosov-Lavoisier Law of the Conservation of Mass, i.e. that mass cannot be created or destroyed < http://en.wikipedia.org >.

The H.U.D. report also highlighted the very high cost of collecting all the necessary L.C.I. data to allow different building products to be compared accurately; an example of this was that an American company spent nearly U.S. $70,000 collecting a complete single dataset for an evaluation of the L.C.A. of a single window.

It is of interest to note that the consensus view of the practitioners who attended the H.U.D. workshop in 2001 was that, in their current (2001) format, L.C.A. tools were not useful to homebuilders, as the input data were sparse, whilst the L.C.A. tools also included many assumptions that were hidden from the users. In addition, it was felt that the L.C.A. output data was too complex for homebuilders to use and that the results needed to be considered in conjunction with other information such as relative cost, because L.C.A. data, in itself, is not an absolute measure of a product's value.

The recommendations of the H.U.D. report emphasised the need for the L.C.I. data to be presented more clearly and in greater detail. They also stressed the need for transparency throughout the process (such as in initial scope, with the input data, in any calculations and with any assumptions that are made about the material or process during the process) to permit users and third parties to review the outputs.

Although the H.U.D. report was published in 2001, it is considered that many of these issues are still relevant at the present time for L.C.A. studies.

The United Nations have recognised the need for greater accuracy and clarity in L.C.I. databases and have instigated a joint U.N.E.P. (United Nations Environmental Programme) / S.E.T.A.C. Life-Cycle Partnership programme. The aims of this are to promote the concept of life cycle thinking to governments, companies and the public generally; details available from < http://www.uneptie.org >. The main programme contains a smaller Life-Cycle Inventory Programme whose specific long-term aims are:

- Developing an information system which will provide easier access to peer-reviewed life-cycle inventory databases
- Developing a database of life cycle studies to identify the best practice in different industries and world regions
- Producing a manual for simplified tools and applications for developing L.C.I. datasets

As part of this work, the researchers from the Life-Cycle Inventory Programme carried out a feedback exercise. This highlighted the need for specific action on a range of issues related to life-cycle inventory data, including:

- The need for the databases to be publicly available notwithstanding the need to maintain confidentiality on proprietary products and / or processes
- The need to fill in any gaps and limit any uncertainties in existing life-cycle inventory databases as they determine the credibility of life-cycle assessments.
- The need to develop and provide sectoral databases for each industry which should be developed by the industries themselves on both a regional and country basis. It was also thought necessary to update these databases every two or three years to reflect improvements in technology.
- The need for a standard set of rules and methods for L.C.I.'s and the need to establish a common language between practitioners.

Whilst the comments from the feedback exercise were generic in nature and apply across the entire field of L.C.A., they are of relevance to this project which aims to quantify the post-factory gate environmental performance of clay brickwork masonry within the U.K., as reliable data on this subject are, at present, very limited.

In conclusion, the outputs from the inventory phase are simply known as the L.C.I. results. These are essentially a list (or best estimate) of the raw materials and energy used in, and the emissions caused by, the manufacture of a product or product system. In most cases, such lists are difficult to evaluate as they contain hundreds of different chemical substances, each of which have their own environmental impacts. For this reason, the process of life-cycle impact assessment (L.C.I.A.) is employed. This is described below.

3.7.5 LIFE-CYCLE IMPACT ASSESSMENT

Life-cycle impact assessment (L.C.I.A.) is a technique to improve the understanding of the results from a L.C.I. analysis by establishing links between a product or process and its potential impacts on a number of important categories. These typically include human health, the environment, and resource depletion.

There are a range of methods available for conducting L.C.I.A. These include, *inter alia*, the *CML92 Method* [Heijungs *et al*, 2001] which was updated by Guinée *et al* and re-released in 2002 as the *CML01 Method*, the *Eco-indicator 95* and updated *Eco-indicator 99* methods, the *EPS2000 Method*, the *EDIP Method* (all available from < http://www.pre.nl >), and the *Impact 2002 Method* (available from < http://gecos.epfl.ch >).

Methods of L.C.I.A. usually contain between 9 and 20 impact categories, against which most of the input and output data collated during the L.C.I. phase can be mapped (see Figure 3.3). Whilst some methods include a broad range of categories, others only focus on toxicity. All of the methods, however, contain impact categories for climate change, acid deposition, ozone depletion, fossil fuel depletion and extraction, and waste disposal, with the remaining categories covering such diverse themes as land occupation, noise and ionising radiation. These categories were originally developed by organisations involved in environmental management, such as the Society of Environmental Toxicology and Chemistry (S.E.T.A.C.) and the Institute of Environmental Sciences (C.M.L.) at the University of Leiden in Holland.

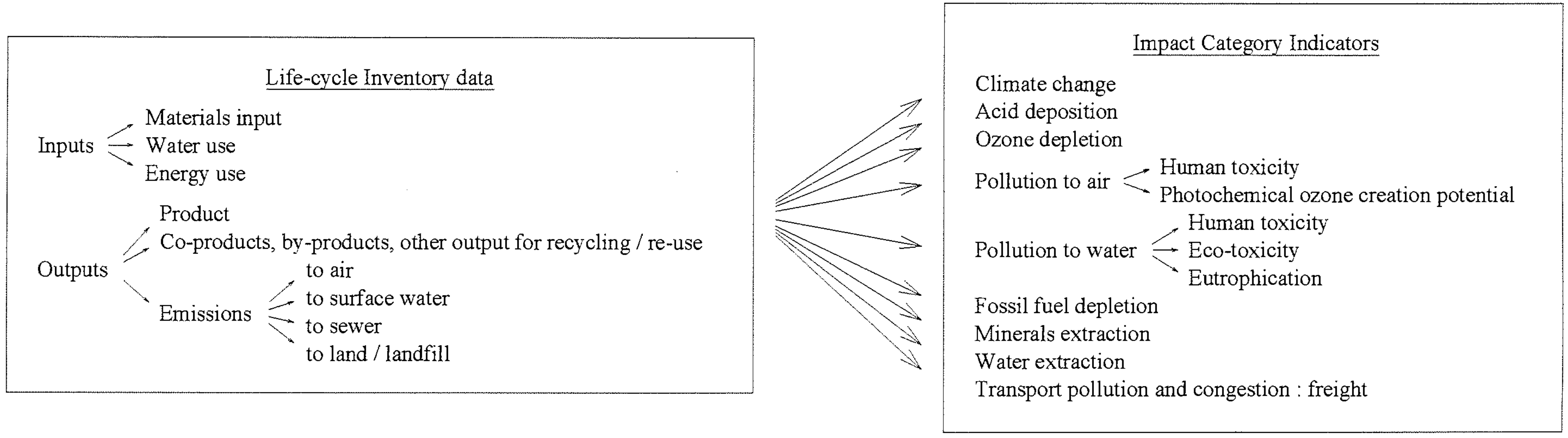


Figure 3.3: Example of the Relationship Between the Life-Cycle Inventory Data and the Life-Cycle Impact Assessment's Impact Category Indicators

Unlike the quantitative inventory data, where the masses of materials and the emissions from processes, etc. are quantified, impact categories are essentially *indicators*. Although the methods use numbers to imply that the results are quantitative and therefore absolute and meaningful, the factors which are used to derive them are essentially based on a series of unscientific assumptions, value-judgements and opinions [http://www.scienceinthebox.com]. The various impact categories of a L.C.I.A. should, therefore, be considered as *directional* only.

Although L.C.I.A. methods indicate that certain emissions are associated with specific environmental themes or impact categories, this does not mean that the products or systems being assessed actually cause these effects. Rather it more accurately indicates that the emissions that are generated throughout the product or system's life-cycle contribute to a pool of similar emissions known to be associated with these environmental themes or impact categories. As a consequence, the most effective use of life cycle impact assessment is as a tool to determine to what extent the emissions from a particular material, product or process are associated with a particular impact category [http://www.scienceinthebox.com].

The accuracy and validity of the results from a life-cycle impact assessment need to be carefully considered because of their dependence on the quality of the initial L.C.I. data and the assumptions from which the various impact category indicators were derived.

Finally, there is no generally accepted method for aggregating the results from the different impact categories in a L.C.I.A. and, as such, users must decide on their own trade-offs when they use the technique to choose between different products [http://unit.aist.go.jp]. For example, although one product might result in greater habitat destruction, it may produce less ozone depletion. The user would, therefore, have to decide which has the most significant impact. For the non-expert, and also even for the expert in L.C.A., this is probably very difficult.

3.7.5.1 MID-POINTS / END-POINTS

Some L.C.I.A. methods, such as that shown in Figure 3.4, reduce the various mid-point impact categories to a smaller number of specific damage categories, or *end-points* which cover broad environmental themes, such as human health, extinction of species and resource use.

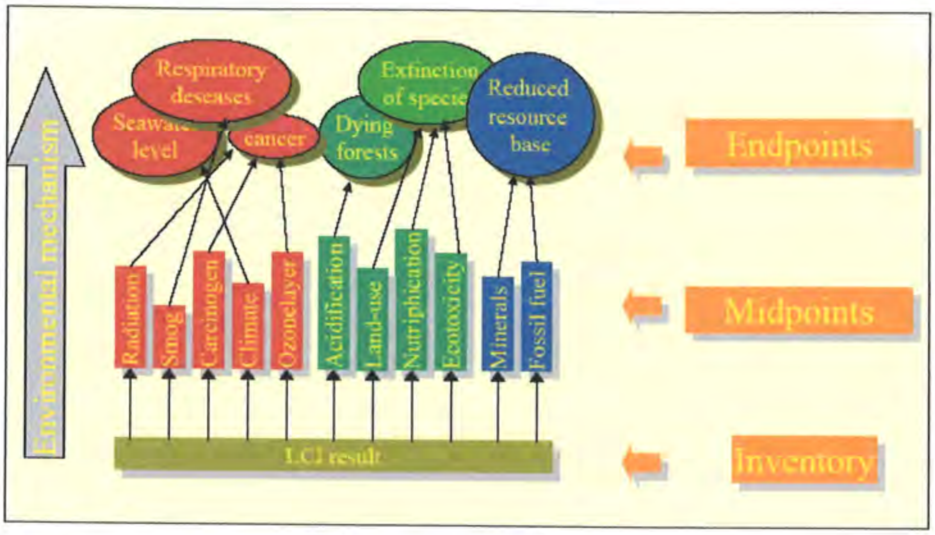


Figure 3.4: The Typical Structure of a Life-Cycle Impact Assessment Method (Goedkoop and Oele, M, (2004)

The advantages of these *damage-oriented* methods over the *mid-point* methods are that they are generally easier to understand as there are fewer impact categories to consider. It should be noted, however, that even the final indicators from a *damage-oriented* method can still appear very abstract. For instance, the final *end-point* result for climate change impact category is expressed in terms of Disability Adjusted Life Years (D.A.L.Y.) in the *Eco-Indicator 99 Method* - see Figure 3.5. Although it is used extensively by the World Health Organisation and World Bank to evaluate health statistics, the precise meaning of the term is not easily understood by most people,

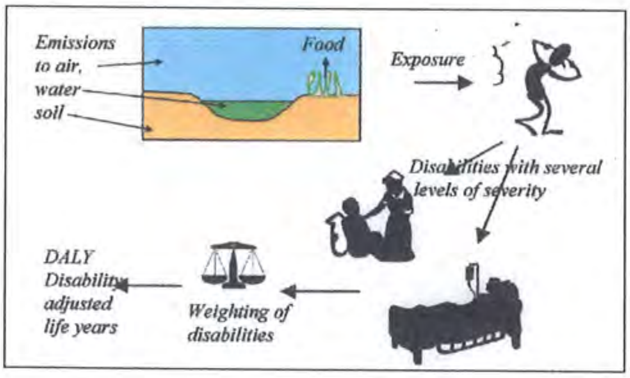


Figure 3.5: An Overview of the Environmental Model Used by the *Eco-Indicator 99* Methodology to Connect Life-Cycle Inventory Results to the *Human Health* Endpoint (Goedkoop and Oele, 2004)

3.8 METHODOLOGY OF LIFE CYCLE-IMPACT ASSESSMENT

There are, typically, five stages to a life-cycle impact assessment (L.C.I.A.), namely:

i. Classification
ii. Characterisation
iii. Normalisation
iv. Grouping and Ranking
v. Weighting.

Whilst items i. and ii. are obligatory for L.C.A. studies, items iii., iv. and v. are optional. Unless a study includes both the classification and characterisation stages, it can only be categorised as a life cycle inventory (L.C.I.). It is also important to remember, that if results from an L.C.I.A. study are to be used to draw comparisons between competing products and then released to the public, then the final stage, weighting, must not be applied, as it is essentially subjective [British Standard Institution, 2000[a]].

3.8.1 CLASSIFICATION

Classification is the process of allocating the various emissions or impacts from the raw materials and processes used in the manufacture of a product (as identified in the L.C.I. phase), to previously defined categories of environmental impact that are relevant to the study being undertaken. For example, both carbon dioxide (CO_2) and methane (CH_4) emissions are assigned to the climate change impact category, while sulphur dioxide (SO_2) and ammonia (NH_3) are assigned to the acidification category. Emissions can, however, be assigned to several impact categories, for example, SO_2 is also assigned to the human health and respiratory diseases impact categories.

As previously stated in Paragraph 3.7.5, different L.C.I.A. methods contain a range of different impact categories. These normally include categories for greenhouse effect (or climate change), natural resource depletion, stratospheric ozone depletion, acidification, photochemical ozone creation, eutrophication, human toxicity and aquatic toxicity – Table 3.4 lists the different environmental impact categories used specifically in the *Eco-Indicator 99 Method*. Many of the L.C.I.A. methods have been criticised in the past for concentrating on easily quantifiable impacts such as chemical emissions rather than issues such as habitat destruction when the latter might have more significance in many developing countries [http://unit.aist.go.jp]. The selection of appropriate impact categories to be used in an assessment is therefore very important. For example, if a

L.C.A. study were to compare the environmental impact of transporting goods by truck or by rail, a land use category would be a relevant, whereas if it were studying photocopiers, the land use issue would probably not be a relevant factor. Equally, impact categories that are important within Europe might not be as relevant elsewhere in the world.

Depletion of fossil fuel	Ozone layer depletion
Depletion of minerals	Carcinogenic substances
Land use	Respiratory effects (organic)
Acidification / Eutrophication*	Respiratory effects (inorganic)
Ecotoxicity	Ionising radiation
Climate change	

*water that is rich in nutrients and therefore supporting a dense plant population, which kills animal life by depriving it of oxygen

Table 3.4: The Environmental Impact Categories
Used by the *Eco-Indicator 99* Methodology
(Goedkoop and Oele, 2004)

As also previously stated in Paragraph 3.7.5, L.C.I.A. methods generally contain different numbers and types of impact categories. Therefore, L.C.I. data classified in accordance with one method invariably cannot be used in a different method and the final results from one method cannot be directly compared with those from a second.

3.8.2 CHARACTERISATION

Characterisation is the process of defining the contribution of individual compounds to a particular impact category, so that the emissions that are highly potent are given a greater weighting than emissions that have little effect [Howard *et al,* 1999]. The characterisation process is, therefore, essentially a measure of the potency of a compound relative to the chosen base compound.

Howard *et al* (1999) give a detailed description of the specific environmental damage associated with the impact categories used in their *BRE Methodology for Environmental* *profiles of Construction Materials, Components and Buildings* publication. For example, the climate change impact category, which is measured in tonnes of carbon dioxide (CO_2) equivalent, is associated with problems of increased desertification, rising sea levels, climatic disturbance and the spread of diseases. This has been the focus of major international activity, and methods for measuring it have been presented by the Inter-Governmental Panel on Climate Change (I.P.C.C.). In addition to CO_2, several other gases including Chlorofluorocarbons (CFC), hydrofluorocarbons (HFC), nitrous oxide (N_2O) and methane (CH_4) are also recognised as having a *greenhouse* or *radiative-forcing* effect. Their relative global warming potential (G.W.P.) was calculated by comparing their direct and indirect radiative-forcing effect to that of the same mass of CO_2 after 100 years. For example, CFC-11 is a 3,400 times more powerful greenhouse gas than CO_2 and, consequently, one tonne of CFC-11 is equivalent to 3,400 tonnes of CO_2. The global warming potential (G.W.P.), measured in CO_2 equivalents, can then be determined for each emission and added to the climate change environmental impact; the units for the climate change impact category within the B.R.E.'s environmental profile being CO_2 equivalent (100yrs). This timescale has been applied because the G.W.P. of different gases is related to the amount of time they are in the atmosphere and the amount of radiative-forcing that they induce over that period. In this respect it is important to recognise how long gases will last in the atmosphere. For example, although CO_2 and CFC-11 are both greenhouse gases, they have different half-lives in the atmosphere and will, therefore, have different effects over different timescales. There are essentially three different scenarios for G.W.P.; 20 years, 100 years and 500 years, with the 100 year scenario being the most commonly considered in L.C.A. studies.

Similarly, acid deposition (measured in kg SO_2 equivalent) on landscapes causes a varying degrees of ecosystem impairment / damage depending upon the nature of the landscape's ecosystem. The gases that are related to the acidification of one tonne of sulphur dioxide (SO_2) include ammonia (NH_3), hydrochloric acid (HCl), hydrogen fluoride (HF), nitrous oxides (N_2O_+) and sulphur oxides (SO_+). The equivalents are calculated by dividing a chemical compound's contribution of protons (H^+) to the ecosystem with their contribution from SO_2.

The waste disposal impact category often uses a specific mass of waste as a proxy for the impacts arising from waste disposal. This unit reflects the depletion of landfill capacity, the noise, dust and odour from landfill (and other disposal) sites, the gaseous emissions and leachate pollution from incineration and landfill, and the loss of resources from economic use and risk of underground fires, etc.

In practice it is not always possible to accurately determine the toxicity values for various characterisation factors, even under perfect laboratory conditions [*Anon.*

(unknown)]. Such uncertainties are further increased because of the complex nature of eco-systems and the fate of the emissions are not always known.

Table 3.5 shows examples of the factors that are used to convert L.C.I. data to the different categories of characterised impact data. The examples were extracted from Table A11 in the *BRE Methodology for Environmental profiles of Construction Materials, Components and Buildings* [Howard *et al*, 1999]. The characterisation process involves simply multiplying the basic L.C.I. data by the appropriate characterisation factor for each of the impact categories – a fully-worked example of this process for the manufacture of one-tonne of bricks is shown in Appendix A.2.

		Characterisation Factor
Climate Change		**kg CO_2 eq. (100years) / kg**
Source: IPCC 1995		
Emissions to Air	C_2F_6	9200
	C_3F_8	7000
	C_4F_{10}	7000
	C_6F_{14}	7400
	CH_4	21
	CO_2	1
Acid Deposition		**Kg SO_2 eq. / kg**
Source: Heijungs		
Emissions to Air	HCl	0.88
	HF	1.6
	NH3	1.88
Fossil Fuel Depletion		**per t.o.e. (tonne of oil equivalent)**
Fossil Fuels	Coal	1
	Oil	1
	Gas	1

Table 3.5: Examples of Factors Used to Convert L.C.I. Data to Different Categories of Characterised Impact Data (Howard *et al,* 1999)

3.8.3 NORMALISATION

The normalisation stage is optional in life-cycle impact assessments. It involves comparing the impacts from any product or product system, e.g. the generation of a kWh of electricity or the provision of 1m^2 of brickwork walling, with those from a common unit of activity such as the environmental impacts of an average citizen over a period of one year.

The normalisation factors used in the U.K. have been developed from data relating to the country's annual emissions, energy use, etc., in 1995 and 1996. The process involved applying characterisation factors to these data and dividing them by the population of the country. Details of a limited number of normalisation factors for air pollution in the U.K. are shown in Table 3.6 – a fully-worked example of the process for the manufacture of one-tonne of bricks is given in Appendices A.3 and A.4.

1996 Normalisation Factors					
1995 figures (in italics) used where 1996 figures not available					
Population Nos.					
UK	58,801,500				
GB	57,138,200				
England & Wales	52,010,200				
		UK	**Unit**	**Per UK Citizen**	
Air Pollution	CO2	574750	000's t	9774.411	kg/person
	CO	4641	000's t	78.92656	kg/person
	CH4	3712	000's t	63.12764	kg/person
	Nox (as NO2)	2052	000's t	34.89707	kg/person
	NMVOC	2030	000's t	34.52293	kg/person
	SO2	2026	000's t	34.4549	kg/person
	Particulates	*356*	000's t	6.054267	kg/person
	other unknown VOC	*279*	000's t	4.744777	kg/person
	other VOC	*257*	000's t	4.370637	kg/person
	PM10	213	000's t	3.622357	kg/person
	butane	191.51	000's t	3.25689	kg/person
	N2O	189	000's t	3.214204	kg/person
	toluene	136.36	000's t	2.318988	kg/person
	white spirit	*98.62*	000's t	1.677168	kg/person

Table 3.6: The U.K. Normalisation Factors for Air Pollution
(Howard *et al,* 1999)

The normalisation stage serves two purposes:

i. The impact categories that only contribute a very small amount compared to other impact categories can be ignored, thus reducing the number of issues that need to be evaluated in the L.C.I.A. phase.

ii. Normalised results show the order of magnitude of the environmental problems generated by the product's life cycle compared to the total environmental loads within the region being considered, e.g. the U.K., Europe or the U.S.A.

The function of the normalisation process is to allow simple comparisons to be drawn between the various environmental impact categories. Because the normalisation factors are based on historical data, the normalisation factors for industrialised countries with traditionally high rates of raw material usage, energy consumption and emissions, are considerably higher than those for countries with a low manufacturing base. As a result, unlike characterised data, the normalised environmental impacts cannot be used to judge the performance of the same products or processes in different countries or geographical regions.

3.8.4 GROUPING AND RANKING

The second optional stage in a life-cycle impact assessment is grouping and ranking. Because, as already stated in Paragraph 3.7.5, most L.C.I.A. methods consider between 9 and 20 different impact categories, an inherent problem is the difficulty of interpreting and grading the final results. For example, how does one compare impacts on the ozone layer with destruction of the ecosystem or waste disposal? To overcome this difficulty, some methods of L.C.I.A. such as the *Eco-Indicator 99* and *EPS2000* methods, adopt a grouping procedure. This divides the impact categories into one of three environmental endpoint / damage categories, e.g. resources, ecosystem quality and human health – see Figure 3.6. The impact categories which refer to the same endpoint are then all defined in terms of the same unit, which allows the indicator results to be added together to form an overall impact for each of the three groups. This avoids the need for weighting and condenses the original 9 to 20 individual impact categories into three simpler, and more easily understood, endpoints.

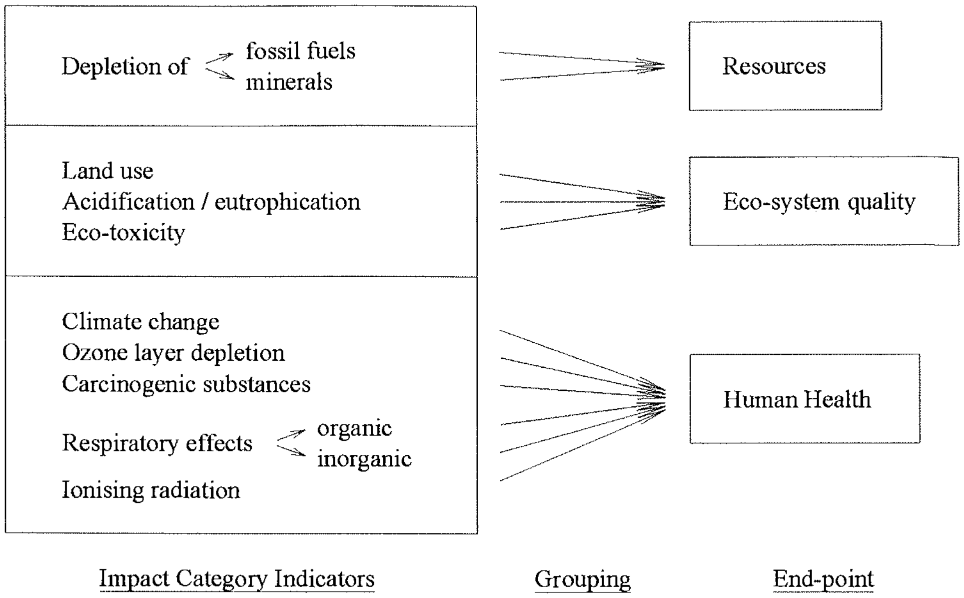


Figure 3.6: Groupings and End-Points Used by the *Eco-Indicator 99* Methodology

Ranking is a procedure in which impact categories are sorted by a panel in a descending order of significance to make the results easier to understand and, as such, the process is subjective in nature.

3.8.5 WEIGHTING

The final optional stage in a life-cycle impact assessment is weighting which is a method for converting the results from different impact categories to represent the importance of their effect. It is therefore essentially a quantitative method of *ranking* the impact categories. The results are converted through the use of numerical factors which are based on a series of value-choice judgements. As such, the process is subjective, rather than scientific, in nature. Weighting is recognised as being a very difficult process for midpoint methods as different individuals, organisations and societies may have different notions as to which are the most important impact categories. This may depend upon a group's particular interests or specialisms and it is likely, therefore, that different parties will reach different weighting results based on the same indicator results.

ISO 14042 [British Standards Institution, 2000[a]] states that, if the weighting process is carried out, it is desirable to use several different weighting factors and weighting methods in a single study, and then conduct a sensitivity analysis to assess their effect on the L.C.I.A. results; Figure 3.7 shows an example of a mixing triangle which can be used to display the different weightings used in the sensitivity analysis. The standard also recommends providing transparency in the final results by fully documenting and making available either the initial L.C.I. data and the subsequent L.C.I.A. indicator results or the un-weighted normalised results, and the weighting factors and weighting methods, so that decision-makers can fully appreciate the full extent and ramifications of the results.

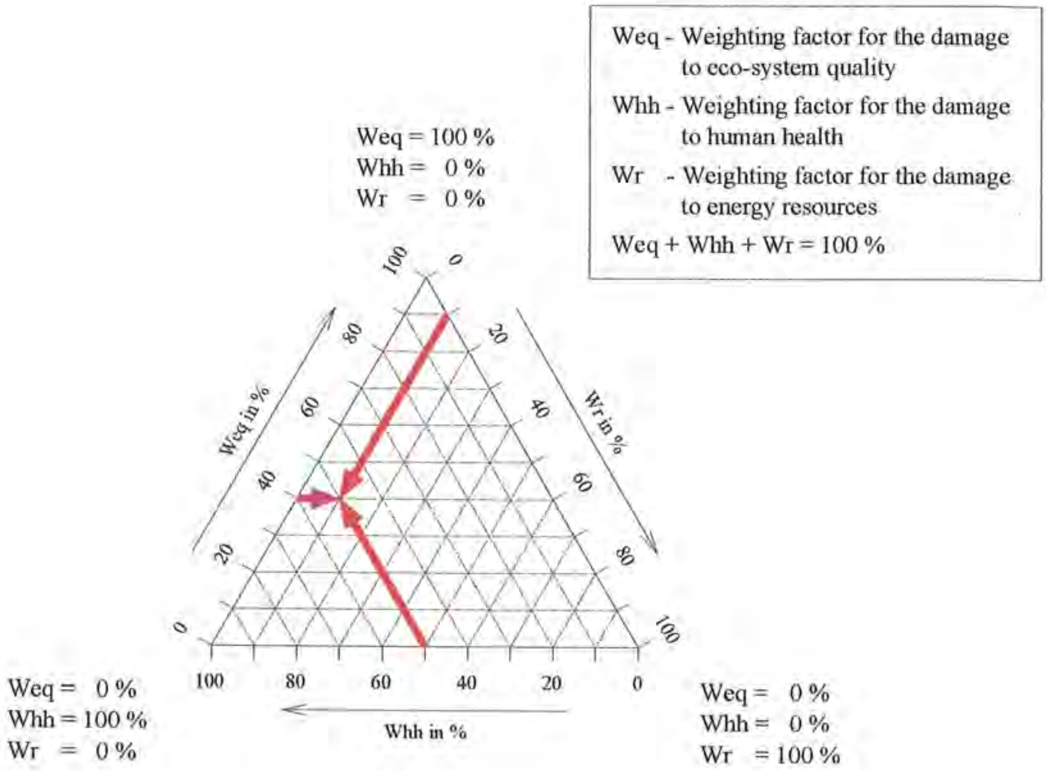


Figure 3.7: Example of a Mixing (or Weighting) Triangle
(Hofsetter *et al*, 1999)

Goedkoop and Oele (2004) propose two approaches to address the problem of weighting:

i. The use of an expert panel to derive the weightings for the results of individual impact categories. This has, however, been criticised on the grounds that it is very difficult to explain to a panel the precise meaning of all the impact categories as they are often defined in abstract terms, for instance *CO_2 equivalency* and *proton release*, whilst the *human health* end-point is similarly expressed using the theoretical *Disability Adjusted Life Years* parameter. In addition, panels tend to specify values within a very limited range of weights, typically between 1 and 3, a problem known as *framing* in social sciences.

ii. The *distance-to-target* method. This involves setting a target value for each impact category indicator which can then be used to derive an actual weighting factor; consequently, if the *distance* to the target is high then the weighting is high. The Swiss Ministry of the Environment (B.U.W.A.L.) have developed the *Ecopoints 1997 System* which is based on this method. The target values in the system are derived from, and therefore effectively regulated by, Swiss government policy. This approach, where government set the targets, can create problems, however, as anecdotal evidence suggests that the final targets would be based on a series of compromises between the competing special interest / pressure groups rather than, necessarily, on their true impact.

3.9 INTERPRETATION

ISO 14043 [British Standards Institution, 2000^{b}] specifies that checks are required to ensure that the conclusions that are drawn from a life-cycle assessment study are adequately supported by the data and procedures used. In reality, however, there are still very many uncertainties in L.C.A. studies due to gaps in L.C.I. data and the validity of the life-cycle models. Goedkoop and Oele, (2004) recommend carrying out a sensitivity analysis to investigate the effects of these uncertainties. This would involve changing the assumptions and recalculating the L.C.I.A. so that their effects could be examined and better understood. This approach can, however, sometimes give a contradictory result, e.g. based on one assumption product *A* has a higher environmental impact than product *B,* whilst under a different assumption the opposite occurs, and there may not be a *correct* answer, as everything depends on the assumptions. In this respect, it is of interest to note that in many situations it is considered impossible to prove conclusively that any one product or process is better in general terms than any other using life-cycle assessments as many of the parameters cannot be simplified sufficiently to justify such a conclusion [www.gdrc.org].

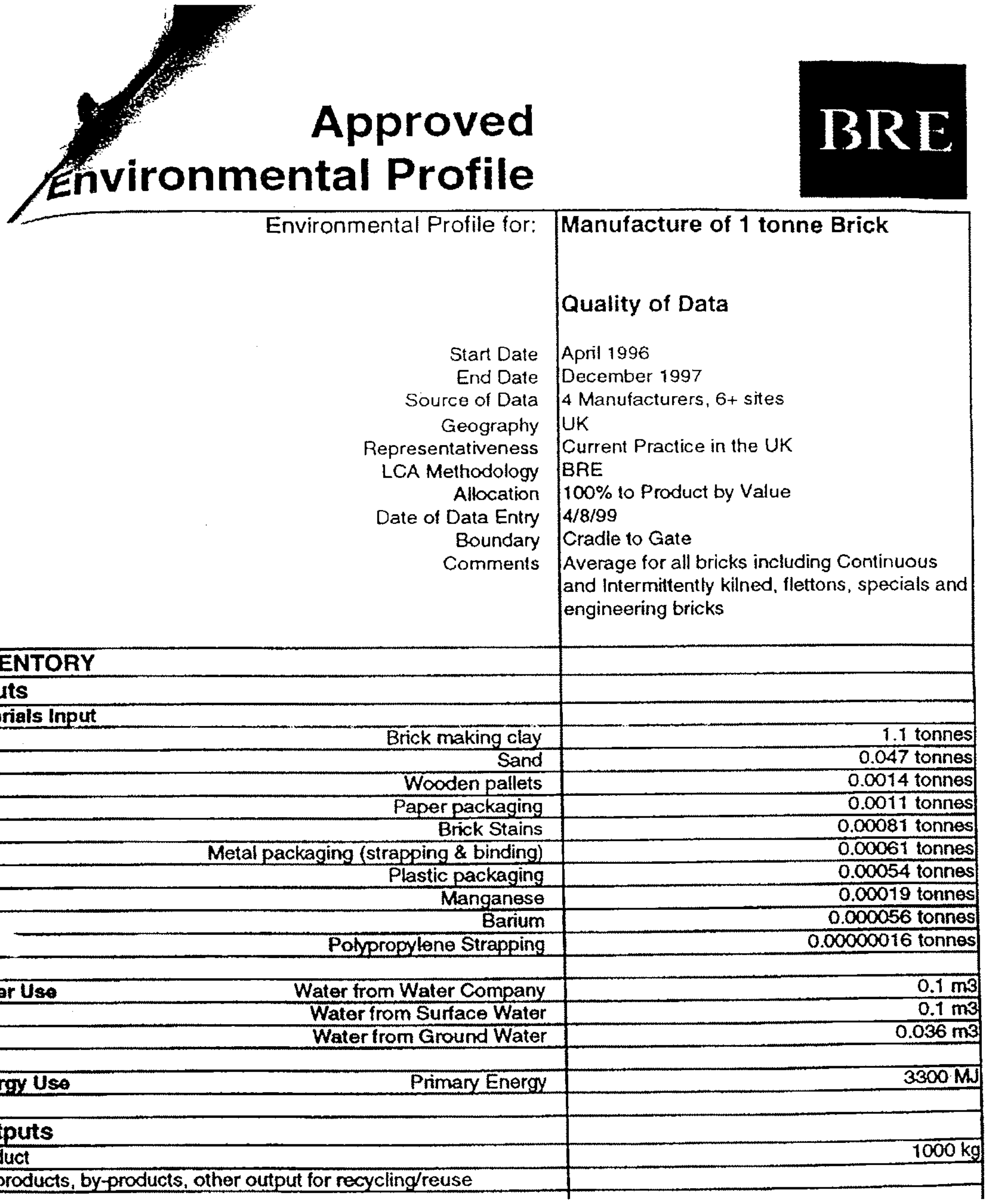
3.10 REVIEW OF THE WORK BY THE U.K. BUILDING RESEARCH ESTABLISHMENT INTO THE LIFE-CYCLE ASSESSMENT OF BUILDINGS

3.10.1 ENVIRONMENTAL PROFILES

During the late 1990's, the Building Research Establishment (B.R.E.) completed a project to compile a database for the environmental profiles of over 250 of the most commonly used building materials and components in the U.K. [http://cig.bre.co.uk/envprofiles]. The project was carried out in association with representatives from the U.K. Construction Materials sector. The initial L.C.I. data were derived from an analysis of the B.R.E.'s *Standard Questionnaire for Inventory Data Collection* form, which had been completed by the different trade organisations representing the materials sector. This requested information on the pre-factory gate inputs (the raw materials, fuels, transport, etc.) and outputs (the emissions to air, water, solid waste, etc.) for each of the manufacturer's products. Figure 3.8 is an extract from a B.R.E. *Inventory Data Sheet.* This shows the collated inventory data for the manufacture of 1 tonne of bricks; the full datasheet is shown in Figure A.1 in Appendix A.

These data were then analysed by the B.R.E. and the environmental impacts (burdens) for each product were determined and expressed in terms of the following characterised impact categories, which are based on the University of Leiden's *CML Methodology* for L.C.I.A.:

- Climate change
- Acid deposition
- Ozone depletion
- Air Pollution: human toxicity
- Air Pollution: low level ozone creation
- Fossil fuel depletion and extraction
- Water pollution: human toxicity
- Water pollution: Eco-toxicity
- Water pollution: Eutrophication
- Minerals extraction
- Water extraction
- Waste disposal
- Transport pollution and congestion: freight.



Approved Environmental Profile

BRE

Environmental Profile for:	**Manufacture of 1 tonne Brick**
	Quality of Data
Start Date	April 1996
End Date	December 1997
Source of Data	4 Manufacturers, 6+ sites
Geography	UK
Representativeness	Current Practice in the UK
LCA Methodology	BRE
Allocation	100% to Product by Value
Date of Data Entry	4/8/99
Boundary	Cradle to Gate
Comments	Average for all bricks including Continuous and Intermittently kilned, flettons, specials and engineering bricks

INVENTORY		
Inputs		
Materials Input		
	Brick making clay	1.1 tonnes
	Sand	0.047 tonnes
	Wooden pallets	0.0014 tonnes
	Paper packaging	0.0011 tonnes
	Brick Stains	0.00081 tonnes
	Metal packaging (strapping & binding)	0.00061 tonnes
	Plastic packaging	0.00054 tonnes
	Manganese	0.00019 tonnes
	Barium	0.000056 tonnes
	Polypropylene Strapping	0.00000016 tonnes
Water Use	Water from Water Company	0.1 m3
	Water from Surface Water	0.1 m3
	Water from Ground Water	0.036 m3
Energy Use	Primary Energy	3300 MJ
Outputs		
Product		1000 kg
Co-products, by-products, other output for recycling/reuse		

Figure 3.8: Extract from a B.R.E. Inventory Data Sheet for the Manufacture of One Tonne of Bricks (Building Research Establishment, 2002)

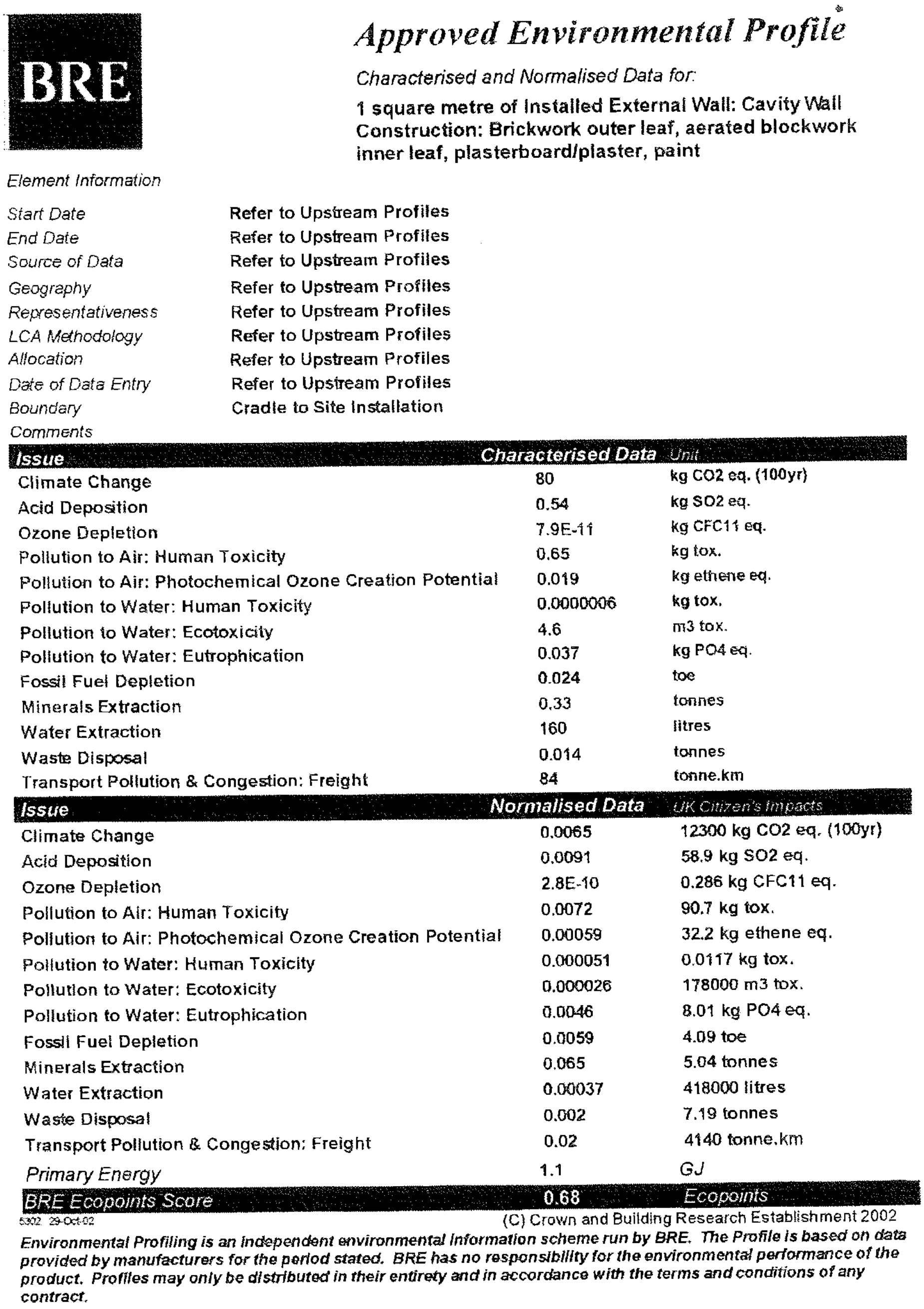
Environmental profiles are, in practice, a development from the earlier concept of the embodied energy of a product. Whilst embodied energy calculations involve similar procedures to those of L.C.A., they do not distinguish between the environmental impacts arising from, for instance, the different methods of generating the electricity required to manufacture products. As electricity can be generated using a variety of fuels from nuclear to coal fired power stations, the environmental impacts will vary but the embodied energy calculations would not reflect this.

The B.R.E. developed three types of environmental profile for their work:

i. **Product Environmental Profiles** these are cradle to factory gate profiles whose functional units are based on a standard mass of material, e.g. 1 tonne of bricks.
ii. **Installed Element Environmental Profiles** these are concerned with installed elements such as internal and external walls, floors, ceilings, etc. They include all of the environmental impacts from the cradle to the factory gate, the transport of the components or complete element to site and its / their installation on site. The functional unit for this profile is based on a standard area of element, e.g. 1 m^2 for clay brickwork masonry walling. See Figure 3.9 for an installed environmental profile for a brickwork / blockwork cavity wall.
iii. **Whole-Life Environmental Profiles** these are all based on a single 60 years lifespan and include all of the environmental impacts from cradle to the grave, i.e. the installed environmental profile data and any impacts from maintenance, replacement, demolition and disposal processes. The functional unit is again based on a standard area of element. The whole-life performance of the element was based on data supplied to the project by the B.R.E.'s Centre for Whole Life Performance, which has considerable experience of assessing the durability and expected life of components within buildings. See Figure 3.10 for a whole-life environmental profile for a brickwork / blockwork cavity wall.

Appendix A gives an example of the conversion of the initial inventory data to the product environmental profile for the manufacture of one tonne of bricks. Appendix B shows an example of how the whole-life environmental profile was developed from the installed element profile for a brickwork / blockwork cavity wall.

A major limitation with the B.R.E.'s work is that individual manufacturers have the final decision on whether the individual environmental profile for their particular product is published. As a result, most of these data are restricted on the grounds of commercial sensitivity and at present, only the timber and insulation producers appear to be willing to provide this information for their products. This is understandable, however, given that many of the heavier building products have relatively high pre-factory gate environmental impacts in categories such as climate change when compared with less dense products such as timber and insulation. As such, manufacturers of these products understandably feel disadvantaged, and possibly threatened, by LCA comparisons especially in relation to the installed element profiles, where there is no reference to the in-service performance of their product.



BRE

Approved Environmental Profile

Characterised and Normalised Data for:

1 square metre of Installed External Wall: Cavity Wall Construction: Brickwork outer leaf, aerated blockwork inner leaf, plasterboard/plaster, paint

Element Information

Start Date	Refer to Upstream Profiles
End Date	Refer to Upstream Profiles
Source of Data	Refer to Upstream Profiles
Geography	Refer to Upstream Profiles
Representativeness	Refer to Upstream Profiles
LCA Methodology	Refer to Upstream Profiles
Allocation	Refer to Upstream Profiles
Date of Data Entry	Refer to Upstream Profiles
Boundary	Cradle to Site Installation
Comments	

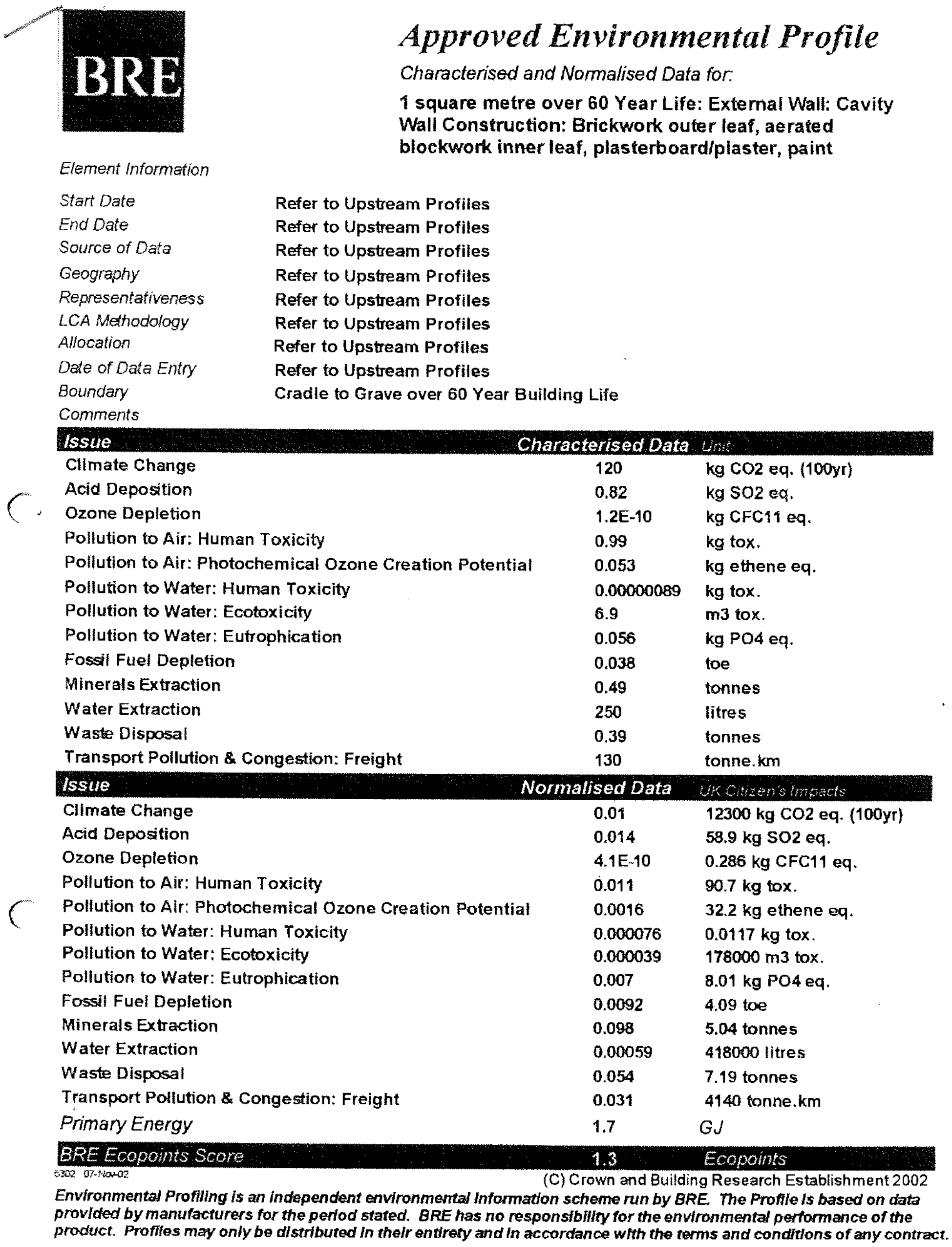
Issue	*Characterised Data*	*Unit*
Climate Change	80	kg CO2 eq. (100yr)
Acid Deposition	0.54	kg SO2 eq.
Ozone Depletion	7.9E-11	kg CFC11 eq.
Pollution to Air: Human Toxicity	0.65	kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.019	kg ethene eq.
Pollution to Water: Human Toxicity	0.0000006	kg tox.
Pollution to Water: Ecotoxicity	4.6	m3 tox.
Pollution to Water: Eutrophication	0.037	kg PO4 eq.
Fossil Fuel Depletion	0.024	toe
Minerals Extraction	0.33	tonnes
Water Extraction	160	litres
Waste Disposal	0.014	tonnes
Transport Pollution & Congestion: Freight	84	tonne.km

Issue	*Normalised Data*	*UK Citizen's Impacts*
Climate Change	0.0065	12300 kg CO2 eq. (100yr)
Acid Deposition	0.0091	58.9 kg SO2 eq.
Ozone Depletion	2.8E-10	0.286 kg CFC11 eq.
Pollution to Air: Human Toxicity	0.0072	90.7 kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.00059	32.2 kg ethene eq.
Pollution to Water: Human Toxicity	0.000051	0.0117 kg tox.
Pollution to Water: Ecotoxicity	0.000026	178000 m3 tox.
Pollution to Water: Eutrophication	0.0046	8.01 kg PO4 eq.
Fossil Fuel Depletion	0.0059	4.09 toe
Minerals Extraction	0.065	5.04 tonnes
Water Extraction	0.00037	418000 litres
Waste Disposal	0.002	7.19 tonnes
Transport Pollution & Congestion: Freight	0.02	4140 tonne.km
Primary Energy	1.1	*GJ*
BRE Ecopoints Score	**0.68**	*Ecopoints*

5302 29-Oct-02

Environmental Profiling is an independent environmental information scheme run by BRE. The Profile is based on data provided by manufacturers for the period stated. BRE has no responsibility for the environmental performance of the product. Profiles may only be distributed in their entirety and in accordance with the terms and conditions of any contract.

Figure 3.9: Approved Installed Environmental Profile for a Brickwork / Blockwork Cavity Wall (Building Research Establishment, 2002)



BRE

Approved Environmental Profile

Characterised and Normalised Data for:

1 square metre over 60 Year Life: External Wall: Cavity Wall Construction: Brickwork outer leaf, aerated blockwork inner leaf, plasterboard/plaster, paint

Element Information

Start Date	Refer to Upstream Profiles
End Date	Refer to Upstream Profiles
Source of Data	Refer to Upstream Profiles
Geography	Refer to Upstream Profiles
Representativeness	Refer to Upstream Profiles
LCA Methodology	Refer to Upstream Profiles
Allocation	Refer to Upstream Profiles
Date of Data Entry	Refer to Upstream Profiles
Boundary	Cradle to Grave over 60 Year Building Life
Comments	

Issue	*Characterised Data*	*Unit*
Climate Change	120	kg CO2 eq. (100yr)
Acid Deposition	0.82	kg SO2 eq.
Ozone Depletion	1.2E-10	kg CFC11 eq.
Pollution to Air: Human Toxicity	0.99	kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.053	kg ethene eq.
Pollution to Water: Human Toxicity	0.00000089	kg tox.
Pollution to Water: Ecotoxicity	6.9	m3 tox.
Pollution to Water: Eutrophication	0.056	kg PO4 eq.
Fossil Fuel Depletion	0.038	toe
Minerals Extraction	0.49	tonnes
Water Extraction	250	litres
Waste Disposal	0.39	tonnes
Transport Pollution & Congestion: Freight	130	tonne.km

Issue	*Normalised Data*	*UK Citizen's Impacts*
Climate Change	0.01	12300 kg CO2 eq. (100yr)
Acid Deposition	0.014	58.9 kg SO2 eq.
Ozone Depletion	4.1E-10	0.286 kg CFC11 eq.
Pollution to Air: Human Toxicity	0.011	90.7 kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.0016	32.2 kg ethene eq.
Pollution to Water: Human Toxicity	0.000076	0.0117 kg tox.
Pollution to Water: Ecotoxicity	0.000039	178000 m3 tox.
Pollution to Water: Eutrophication	0.007	8.01 kg PO4 eq.
Fossil Fuel Depletion	0.0092	4.09 toe
Minerals Extraction	0.098	5.04 tonnes
Water Extraction	0.00059	418000 litres
Waste Disposal	0.054	7.19 tonnes
Transport Pollution & Congestion: Freight	0.031	4140 tonne.km
Primary Energy	1.7	*GJ*
BRE Ecopoints Score	1.3	*Ecopoints*

5302 07-Nov-02

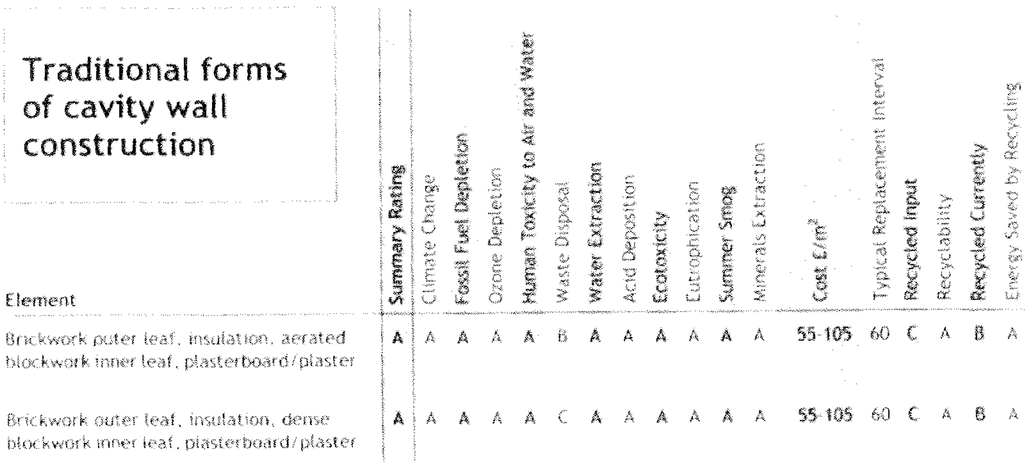
Environmental Profiling is an independent environmental information scheme run by BRE. The Profile is based on data provided by manufacturers for the period stated. BRE has no responsibility for the environmental performance of the product. Profiles may only be distributed in their entirety and in accordance with the terms and conditions of any contract.

Figure 3.10: Approved Whole-Life Environmental Profile for a Brickwork / Blockwork Cavity Wall (Building Research Establishment, 2002)

3.10.2 THE *GREEN GUIDE* SERIES

The B.R.E. subsequently used the data they had obtained for their environmental profiles to develop the *Green Guide to Specification* [Anderson, Shiers and Sinclair, 2002] and *The Green Guide to Housing Specification* [Anderson and Howard, 2000]. These are designed to be used by general designers in industry rather than specialist Environmental Engineers / LC.A. experts. Consequently, the *Green Guide to Specification* uses a simple *A-B-C* rating system to express the environmental performance of the functional element, rather than the 13 impact categories of an environmental profile. The B.R.E. methodology used to derive these ratings is, however, relatively simple. It essentially involves grouping the different forms of construction that can be used for a single building element, e.g. an external wall or a ground floor, together and identifying which have the greatest and least environmental impact for each of the 13 categories. These values then form the upper and lower limits of a range which is subsequently divided into three equal parts. The remaining elements are then plotted on this scale. Any forms of construction that fall within the lowest third of the range are given an *A* rating and, similarly, any that are in the upper third, e.g. the least environmentally friendly forms of construction, are given a *C* rating – see Figure 3.11. The *Green Guide to Housing Specification* uses a very similar system and, the *Green Guides* are, therefore, simple tools that enable users to carry out comparative assessments between pre-selected forms of construction.

The ratings are shown in a Ratings Table in the *Green Guide to Specification* - see Figure 3.11. There is a rating for 12 of the 13 impacts in an environmental profile and an overall summary rating for each of the different building elements. The summary rating was determined by multiplying each of the 13 impacts in an environmental profile by a weighting which allowed for some of the categories being considered more environmentally important than others [Anderson, Shiers and Sinclair, 2002]. It is not known if these weightings are similar to those discussed in Paragraph 3.10.4 which are used to convert the 13 impact categories into a single eco-point.



Traditional forms of cavity wall construction

Element	Summary Rating	Climate Change	Fossil Fuel Depletion	Ozone Depletion	Human Toxicity to Air and Water	Waste Disposal	Water Extraction	Acid Deposition	Ecotoxicity	Eutrophication	Summer Smog	Minerals Extraction	Cost £/m^2	Typical Replacement Interval	Recycled Input	Recyclability	Recycled Currently	Energy Saved by Recycling
Brickwork outer leaf, insulation, aerated blockwork inner leaf, plasterboard/plaster	A	A	A	A	A	B	A	A	A	A	A	A	55-105	60	C	A	B	A
Brickwork outer leaf, insulation, dense blockwork inner leaf, plasterboard/plaster	A	A	A	A	A	C	A	A	A	A	A	A	55-105	60	C	A	B	A

Figure 3.11: Extract from a Rating Table used in
The Green Guide to Specification
(Anderson, Shiers and Sinclair, 2002)

The B.R.E. used the Summary Rating Data to create the pie-chart shown in Figure 3.12. This was intended to illustrate the contribution of the different building elements to the overall impact of a typical building over a 60 year lifespan. It can be seen from the figure that the floor finishes have the greatest effect at approximately 40 % of the total impact. It can also be seen that the combined impacts of the flooring elements, i.e. the finishes and surfacing, together with the ground and upper floors, produce nearly 70 % of the total environmental impact of a building over its life. The B.R.E. do not specify what dimensions were assumed for their typical building and only state that is based on *'a number of generic models'*. It is therefore impossible to check if the impacts from the flooring are correct, or whether they may be artificially distorted by any assumptions made in the B.R.E.'s calculations. For instance, in the case of a two-storey building, there would a ground and upper floor and a roof and if, as in Figure 3.12, the impact of the upper floor is three-times that of the ground floor, the upper floor elements provide the major contribution to the overall environmental impact of the building. If the building is eight storeys high, however, and there are seven upper floors, the contribution of the upper floor would be less than half that of the ground floor. This lack of precise details about the buildings used in the B.R.E. modelling also prevents comparisons being made between the impacts of the flooring and the external walls. In Figure 3.12, the impacts from the external walls only equate to approximately 7 % of the total impact. Because of the limited amount of background information that is given by the B.R.E., it is impossible, however, to ascertain conclusively if this is because of different quantities of materials that were assumed for the external walls and the floors, or because the walls have less environmental impact than the floors. It should be noted, however, that Figure 3.13 suggests, to some extent, the latter.

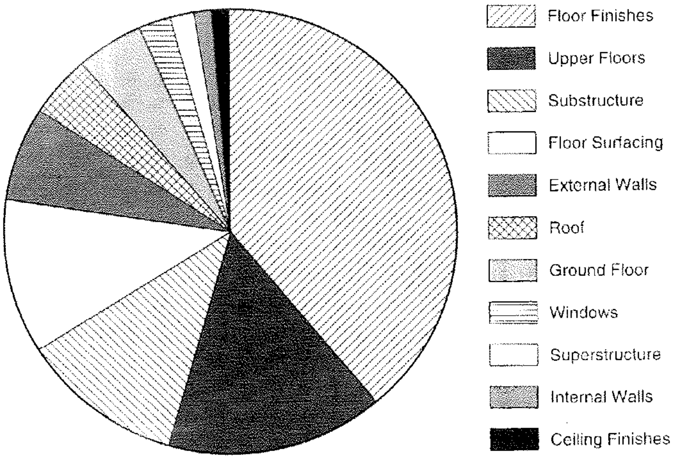
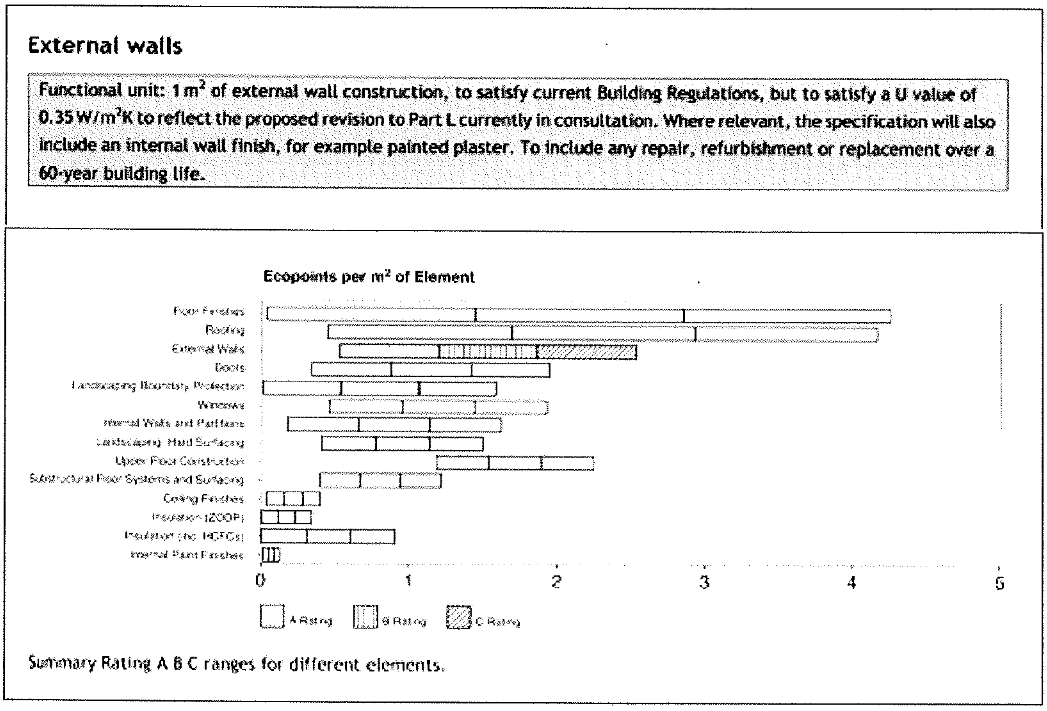


Figure 3.12: Contribution of Building Elements to Typical Building Impact Over a 60 year Lifespan

(Anderson, Shiers and Sinclair, 2002)



External walls

Functional unit: 1 m^2 of external wall construction, to satisfy current Building Regulations, but to satisfy a U value of 0.35 W/m^{2}K to reflect the proposed revision to Part L currently in consultation. Where relevant, the specification will also include an internal wall finish, for example painted plaster. To include any repair, refurbishment or replacement over a 60-year building life.

Summary Rating A B C ranges for different elements.

Figure 3.13: Contribution of the Different Building Elements to the Overall Environmental Impact of a Typical External Wall

(Anderson, Shiers and Sinclair, 2002)

3.10.2.1 MAINTENANCE ISSUES

In an explanation of the methodology that was used to develop the data in *The Green Guide to Specification*, Anderson *et al* (2002) describe how a series of *expected replacement intervals* were used to determine the whole-life performance of the different forms of construction. This involved dividing the life of the building, which was limited to 60 years, by the expected replacement interval for each material and then multiplying the initial installed mass of the material by this figure. This was demonstrated using a worked example for a 100 mm thick painted, plasterboard finished, dense concrete blockwork wall. The only maintenance that was included for this exercise was the internal face of the wall being repainted at five-year intervals. Table 3.7 shows a summary of the installed masses of the materials, their expected replacement intervals and the total masses of the materials used over the 60 year life of the blockwork wall.

	Installed mass (kg / m^2)	Expected replacement intervals (years)	Replacement factor	Whole-life mass (kg / m^2)
Dense block	195	60	(60 / 60) + 0.5 = 1.5	195 × 1.5 = 292.5
Mortar	12	60	(60 / 60) + 0.5 = 1.5	12 × 1.5 = 18
Plasterboard	18.2	60	(60 / 60) + 0.5 = 1.5	18.2 × 1.5 = 27.3
Paint	0.36	5	(60 / 5) + 0.5 = 12.5	0.36 × 12.5 = 4.5

Table 3.7: The Installed Mass and Replacement Intervals for a Solid Blockwork Wall
(Anderson, Shiers and Sinclair, 2002)

Table 3.7 shows that the walls would be painted a total of 12 times and that the mass of paint used over the life of the building would be 12 times the installed mass. Anderson *et al* also included a figure of 0.5 to allow for any uncertainties in the assumed replacement intervals. This allows for the fact that there was a 50 % chance that the wall might need repainting 13 times rather than 12.

This modification factor was apparently not included if the expected life of the component was more than 60 years, but it is of interest to note that, in the above example, it was actually applied to the dense block and mortar. This suggests that there is a 50 %

chance that the blockwork itself would be demolished and rebuilt during this period.

It can be seen in this example that such an approach does not significantly increase the final mass of paint used over the 60 year life of the building – if the factor is not included and the wall is assumed to only be repainted 12 times, the mass of paint used over the life of the wall would reduce by 4 %. However, in the case of the blockwork, where the expected replacement interval is 60 years, the use of the factor increases the final whole-life mass of the blockwork by 50 %. This has a significantly greater effect on whole-life impact of the wall compared to the paint.

It is essential that appropriate values be chosen for the replacement intervals when carrying out L.C.A. studies. Whilst the use of a simple, single modification factor to allow for any uncertainties in the replacement intervals may be acceptable for materials such as paint which have relatively low impacts and short, well-defined lives, this may well be overly simplistic and excessively conservative for long-lasting materials such as brickwork and blockwork.

As previously noted, *The Green Guide to Specification* states that the replacement factor is not included if the expected life of the component is more than 60 years. An analysis of Figures 3.9 and 3.10 (the Installed Environmental Profile and Whole-Life Environmental Profile for a brickwork / blockwork cavity wall) suggests otherwise, however, as the impacts associated with the whole-life profile is approximately 50 % higher than those for the installed profile (see Appendix B for the full derivation of these profiles).

This is somewhat surprising as *The Green Guide to Specification* acknowledges that materials such as brickwork are *'likely to have an effective life of many hundreds of years'*. In addition, the Guide also states that *'the effective life of brickwork (often over 100 years) far exceeds the scope of the* [Green Guide] *project, which is based on 60 years'*. This last statement could also possibly be interpreted as an admission that the Green Guide series, and the whole-life environmental profiles which appear to have been developed using the same methodology, do not deal adequately with long life materials such as brickwork, and that further research in this area is necessary.

The Green Guides also assume a maximum 60 year life span for all buildings after which all of the materials in the building are simply considered as demolition waste. In the case of the U.K. housing stock, a 60 year life span appears to be inadequate as there are still many pre-Victorian houses in existence and functioning well. In addition, there is no evidence of the wholesale failure of this older housing stock as the current rate of housing replacement for the U.K. is very low. According to the latest figures from the Office of the Deputy Prime Minister (2003^{b}), only 112,000 properties were demolished in the past decade, which is less than 0.6 % of the U.K. total.

In practice, it is probably unrealistic to expect that house buyers in the U.K. would be prepared to purchase a traditional brickwork / blockwork masonry construction house in the knowledge that it had a maximum life span of 60 years.

As a further aid to specifiers, *The Green Guide to Specification* contains guidance on the capital costs for the different forms of construction. As such, it recognises that environmental impacts are only one of a number of factors such as cost, durability, and appearance that should be considered when compiling a specification.

3.10.3 B.R.E. ENVIRONMENTAL ASSESSMENT METHOD (BREEAM)

The B.R.E. Environmental Profiles form an important component of the B.R.E.'s Environmental Assessment Method (*BREEAM*) particularly with respect to item viii. below. BREEAM was originally developed in the early 1990's to assess the environmental performance of both new and existing buildings across a broad range of areas, including:

i. Management: overall management policy, commissioning site management and procedural issues
ii. Energy use: issues relating to operational energy and carbon dioxide (CO_2)
iii. Health and well-being: internal and external issues affecting health and well-being
iv. Pollution: issues relating to air and water pollution
v. Transport: transport-related CO_2 and location-related factors
vi. Land use: *green-* and *brown-field* sites
vii. Ecology: ecological value conservation and enhancement of the site
viii. Materials: the environmental implication of building materials including life-cycle impacts
ix. Water: consumption and efficiency.

BREEAM encourages developers and designers to optimise their designs in relation to the above nine issues at the earliest opportunity in order to maximise their chances of achieving a high rating. Credits are awarded in each area according to performance and then a set of environmental weightings are applied to each of the credits in turn, to enable them to be added together to produce a single overall score. Buildings are then rated on a scale of Pass, Good, Very Good or Excellent, and a certificate that can be used for promotional purposes awarded. The original version of *BREEAM* has subsequently been extended to cover a range of building types, including:

- offices
- homes (known as *EcoHomes*)
- industrial units
- and, more recently, retail units.

3.10.4 *ENVEST* LIFE-CYCLE ASSESSMENT PACKAGE

Paragraph 3.10.2 noted that the *Green Guides* were originally intended for general practitioners rather than the specialist in L.C.A. Consequently, their aim was to provide designers with unambiguous data which could be easily incorporated into designs to produce lower embodied energy buildings [Anderson, Shiers and Sinclair, 2002]. The B.R.E. subsequently recognised, however, that there was a demand for a more comprehensive package that would enable decision-makers, who did not have the necessary resources or facilities to carry out complex, time-consuming and expensive full L.C.A. studies, to better understand the impact of their designs. The B.R.E. therefore developed the *Envest* L.C.A. computer-software package, which was first released in 2000. This was upgraded and re-released as *Envest II* in 2003 and is available as a subscription-based service on the internet. *Envest* and *Envest II* simplify the process of designing environmentally friendly buildings by expressing the results in terms of a single environmental score, rather than a series of impact categories. The results are also far more wide-ranging than those of the *Green Guides* as, in addition to the L.C.A. data, they give details of operational energy and whole life costs of buildings. This allows designers to investigate, and appreciate more fully, the inevitable trade-offs between whole life-cycle impacts, operational energy, and life-cycle costs.

The L.C.A. results from *Envest II* are derived from the same basic environmental impact data which was used for the *Green Guides*, although in the case of *Envest* the results are expressed in terms of *eco-points*. In this respect, it should be noted that all of the B.R.E.'s L.C.A. work, i.e. the *Green Guides* and *Envest* series, *EcoHomes,* the environmental profile database, etc., are based on the same environmental impact data - it is only the manner in which they are combined, and the results presented, that differ. An eco-point is defined as a notional unit in which 100 eco-points represent the environmental impact that one U.K. citizen will have in one year with respect to the thirteen environmental impact categories previously listed in Paragraph 3.10.1; for comparison purposes, one eco-point can be considered the equivalent of one of the following [Thistlethwaite, 2004]:

- 320 kWh electricity
- 83 m^3 water (equivalent to one-thousand baths)
- 65 miles by articulated truck
- The land-fill from 1.3 tonnes of waste
- Manufacturing ¾ tonne (250) of bricks
- 540 tonne.km of freight by sea
- The extraction of 1.38 tonnes of mineral
- 300 miles of urban driving in a new petrol-engine car.

Eco-points were originally developed by the B.R.E. to overcome one of the main difficulties associated with L.C.A studies, namely, that they simultaneously consider a wide range of complex and different environmental issues (e.g. climate change, mineral extraction, ozone depletion, etc.) each with different units of measurement. In order to evaluate the results from these various impact categories, users are required to make subjective *value-choice* judgement about the relative importance of the different issues, i.e. is climate change more onerous than ozone depletion?

For the development of the eco-point, the B.R.E. carried out a consultation exercise with various stakeholder groups drawn from the U.K. Construction Industry who had an interest in sustainability. These included construction professionals, material producers and local authorities which together formed an *expert-panel*. The purpose of this exercise was to obtain a broad consensus view on the relative importance, or weighting, of the different issues associated with the general concept of sustainability. Table 3.8 shows the different themes that the stakeholder groups were asked to weight.

Theme	**1 Environmental**	**2 Economic**	**3 Social**
Sub-theme	1.1 Global		
	1.2 Local and site		
	1.3 Internal		
Under each sub-theme an extensive range of issues was identified, including:			
Issues	Climate change	Profitability	Poverty
	Resources	Employment	Minorities
	Internal environment	Productivity	Inner cities
	External environment	Transport and utilities	Transport
	wildlife	Stock value	Communications

Table 3.8: Sustainable Construction Themes, Sub-Themes and Issues
(Dickie and Howard, 2000)

The results were then collated to produce the weightings shown in Figure 3.14.

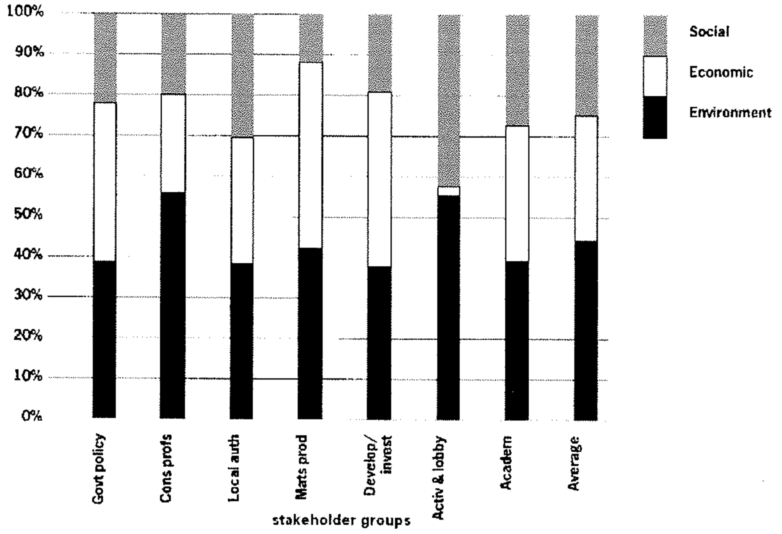


Figure 3.14: Overall Weightings
(Dickie and Howard, 2000)

From this, the B.R.E. researchers concluded that there was a general consensus between the majority of the stakeholder groups about the relative significance of the main sustainability themes with the aggregate weighting being 43.6 % for environmental issues, 32.2 % for economic issues and 24.2 % for social issues. Any results that departed significantly from these averages were attributed to the specific interests of the particular stakeholder group concerned.

Each stakeholder group was then asked to score the relative importance of various sub-issues within the sub-themes in order to produce an overall series of *expert panel* weightings; Table 3.9 shows a selection of these weightings; the complete list is given Tables C.1 (a) and C.1 (b) of Appendix C.

Theme	Sub-theme	Sub-issue	Weighting
Environment	**Global issues**	Climate change	8.4 %
		Acid deposition	1.1 %
		Ozone depletion	1.8 %
		Toxic Air pollution	1.4 %
		Fossil fuel depletion	2.0 %
		Marine water pollution	1.2 %
		Habitats and eco-systems	3.9 %
	Local and site issues	Local air pollution	2.6 %
		Water pollution	1.7 %
		Contaminated land	1.2 %
		Noise pollution	1.2 %
		Dust pollution	0.2 %
		Minerals extraction	0.8 %
		Fossil fuel extraction	0.7 %
		Water extraction	1.2 %
		Waste disposal	1.4 %
		Waste recycling	1.8 %
		Transport pollution and congestion	3.5 %
		Habitats and eco-systems	2.7 %
		Forestry	0.6 %
		Farming	0.4 %
	Internal environment	Health	2.6 %
		Comfort	1.2 %
		Sub-total	**43.6 %**

Table 3.9: A Selection of the Weightings Derived from the Consultation Exercise (Dickie and Howard, 2000)

As eco-points are only associated with environmental issues, Dickie and Howard (2000) subsequently adjusted the weightings of the various sub-issues shown in Table 3.9 to a new base of 43.6 %, the aggregate value for environmental effects in Figure 3.14. The weighting for climate change thus increased from 8.4 % (Table 3.11) to 19.3 % (8.4 / 43.6

× 100) whilst the value for ozone depletion increased from 1.8 % to approximately 4 %. Table 3.10 gives a selection of the re-revised weightings; the complete list is given Tables C.2 (a) and C.2 (b) of Appendix C.

Issues	**Sub-issues**		**Weighting (%)**
Global issues	Climate change		19 %
	Acid deposition		3 %
	Ozone depletion		4 %
	Toxic Air pollution	Human toxicity	2 %
		Eco-toxicity	2 %
	Fossil fuel depletion		5 %
	Marine water pollution	Eco-toxicity	1 %
		Eutrophication	1 %
	Habitats and eco-systems	Land	-
		River	5 %
		Sub-total	**42 %**

Table 3.10: A Selection of the Revised Weightings
(Dickie and Howard, 2000)

The environmental issues in Table 3.10 were then mapped against the B.R.E.'s 13 L.C.I.A. environmental impact categories to produce a final series of weightings for each of the categories. It should be noted, however, that this process involved ignoring many of the original environmental issues that were presented to the stakeholder groups / expert panel for their consideration.

The final weightings, shown in Table 3.11, were then combined with the normalisation factors for each impact category to create a conversion factor which could be used to convert characterised environmental impact data into an eco-point. An eco-point score is determined by simply multiplying the characterised data by the relevant weighting for each of the 13 categories and then totalling the individual results together to produce a final single figure in eco-points – an example of this is shown in Appendix C.

Categories	U.K. Impact per citizen	Weighting (%)	Conversion factor (per eco-point)
Climate change	12,269 kg CO_2eq. (100years)	35	0.0029
Acid deposition	58.9 kg SO_2 eq.	5	0.0849
Ozone depletion	0.3 kg CFC-11 eq.	8	26.67
Pollution to air: Human toxicity	90.7 kg tox.	6.5	0.077
Pollution to air: Low-level Ozone Creation	32.2 kg ethene eq.	3.5	0.12
Fossil fuel depletion and extraction	4.09 t.o.e.	11	200
Pollution to water: Human toxicity	0.01 kg tox.	2	0.00002
Pollution to water: Eco-toxicity	177,948 m^3 tox.	4	0.5
Pollution to water: Eutrophication	8.0 kg PO_4 eq.	4	2.69
Minerals extraction	5.0 tonnes	3	0.6
Water extraction	417,583 litres	5	0.00001
Waste disposal	7.2 tonnes	6	0.83
Transport pollution and congestion: Freight	4141 tonne.km	7	0.0017

Table 3.11: Conversion Factors Used to Convert Characterised Environmental Impact Data to an Eco-point (Dickie and Howard, 2000)

The derivation of the conversion factors in Table 3.11 was, essentially, a subjective process which was based on the various opinions and *value-choices* of a stakeholder group / expert panel. As already noted, these groups were drawn from a variety of areas, namely:

- Government policy makers and researchers
- Construction professionals
- Construction materials producers and manufacturers
- Property and institutional investors
- Environmental lobbyists
- Local authority policy makers and planners
- Academics and researchers.

Given the different backgrounds of the various groups, it is questionable whether they each had sufficient knowledge and understanding of the impact categories being considered to make fully informed judgements about all of the issues involved in an L.C.A. study.

In this respect, the problems with such an approach are similar to those of the quasi-science subject of *expert-based* risk assessment. Risk assessment assumes that all of incidents that might happen for a given task can be identified and that probabilities can be assigned to them to reflect their relative likelihood. As with L.C.A. techniques generally, risk assessments also require the use of numerous assumptions to fill in gaps and uncertainties in the data. The results are then often expressed with an unjustified precision and confidence, as a different set of assumptions would have produced different findings. The results from these risk assessment can, however, have dramatic implications on the choice of different technologies and policy options [Stirling, 2001].

In a similar manner, the concept of an eco-point cannot be used in isolation to define / quantify the complex qualitative and quantitative issues involved in sustainable development. The B.R.E. eco-point is therefore limited in meaning and should be viewed as such. This is recognised by ISO 14042 [British Standards Institution, 2000[a]] which states that L.C.A. studies should preferably not be reduced to a single point score through the use of weightings and, as such, the *Envest* (and several of the B.R.E.'s other L.C.A. packages) does not comply with the standard.

3.11 CONCLUSIONS

The following conclusions were revealed from the review of life-cycle assessment described in this chapter.

3.11.1 FRAMEWORK OF LIFE-CYCLE ASSESSMENT

1. Life-cycle assessment (L.C.A.) is a relatively new process to evaluate the environmental impacts associated with the manufacture of a product or product system / process. It should be seen as a technique for evaluating environmental issues which is one of the three principal components of the sustainability, the others being social and economic issues.

2. The process of L.C.A. is generic in nature and is, in theory, applicable to all types of manufactured goods and production processes.

3. L.C.A. differs from the earlier concept of the embodied energy of a product, as the latter only quantifies the total energy input into a product / process and not the actual environmental impacts caused by the manufacture of the product. The results from L.C.A. assessments are usually expressed in terms of resource use, pollution, effects on human health and ecological consequences.

4. L.C.A. is essentially a procedure for comparing the environmental impacts of alternative products, functional units or process systems. It is not a procedure that directly determines, or sets, acceptable overall limits for different categories of environmental impact. In addition, it does not consider the economics of competing products and, as such, is not an absolute measure of product value.

5. The information obtained from an L.C.A. study should be used as part of a more wide-ranging decision process involving economic and social issues, or to understand the general environmental trade-offs associated with alternative designs or competing products.

6. In some cases other forms of environmental management such as risk assessment, environmental auditing and environmental impact assessment may be more appropriate to use than L.C.A.

7. L.C.A. is not an exact science and whilst the results from an L.C.A. study may be quoted precisely, such apparent precision is fundamentally meaningless in view of the complex issues considered within the L.C.A. procedure itself, many of which are not yet fully understood.

8. Although much of the terminology used within L.C.A. is specialised (and probably over-complex), the actual procedure for carrying out a study, as recommended by the relevant series of British / International Standards, is relatively simple and straightforward. Essentially this involves collating the various inputs (raw materials, energy) and outputs (emissions, waste products) associated with the manufacture of a specific product / product system, i.e. the life cycle inventory stage, and then expressing this information, through the use of an appropriate life-cycle impact assessment (L.C.I.A.) methodology, in terms of pre-defined categories of environmental impact e.g. global warming, pollution to air and acidification. The overall environmental impact of a product in relation to the specified range of environmental issues can then be considered.

9. L.C.A. is a process that attempts to model a range of complex environmental processes involving both quantitative and qualitative issues associated with the natural sciences. Whilst parts of these modelling processes may involve scientific procedures, other aspects may be based primarily upon subjective *value-choice* decisions and judgements, which cannot be quantified in scientific terms.

10. Interpretation of the results from an L.C.A. study should ideally involve a decision-analytic framework which systematically integrates scientific and value judgements; in practice, this is very difficult to achieve. To minimise this problem, a number of L.C.I.A. methodologies attempt to condense the results from the various impact categories into a narrower range of more readily understandable environmental issues, e.g. effects on human health, destruction of the ecosystem and depletion of raw materials.

11. The quality of the results from an L.C.A. study are directly affected by the quality of the inventory data used and any assumptions made in the modelling processes.

12. Significant work remains to be done to develop accurate and comprehensive L.C.I. databases, especially in the case of long life materials such as clay brick / brickwork where little data on whole life environmental performance are

currently available. In addition, there is a need for such databases to be transparent and freely available to the public.

13. Comparing results of different L.C.A. studies is only possible if the assumptions and context of each study are the same. These assumptions should also be explicitly stated for reasons of transparency.

14. Whilst the results of L.C.A. studies may often be expressed as simple scores, ISO 14040 states that there is no scientific basis for this, since trade-offs and complexities exist for the systems analysed at different stages of their life cycle. In addition, this involves the difficult process of weighting – a subjective issue. The advantage of such an approach, however, is its simplicity for the end user.

15. Given the subjectivity involved in the choice, modelling and evaluation of impact categories and the possible problems with the accuracy / appropriateness of life cycle inventory data, a high degree of transparency is necessary when reporting L.C.A. studies generally, in order to ensure that all assumptions are clearly described and reported. On the other hand, there is often a need to maintain the confidentiality of manufacturers' data relating to the production of a product. As such, there is the potential for conflict in this area.

3.11.2 THE WORK OF THE BUILDING RESEARCH ESTABLISHMENT INTO L.C.A.

1. The data on whole life environmental impacts within the Green Guide(s) are limited to a design life for a building of 60 years, after which the materials in the building are assumed to be either recycled / re-used or considered as waste.

2. The *Green Guide* states that replacement factors for materials are not taken into account if the expected life of the component is more than 60 years (as in the case of masonry). Examination of the impact data given in the Green Guide, however, suggests that 50 % of the brickwork in the external leaf of an external cavity wall is assumed to be replaced over this 60 year period.

3. The *Green Guide* acknowledges that '*the effective life of brickwork (often over 100 years) far exceeds the scope of the* [Green Guide] *project, which is based on 60 years*'. In view of this it would appear sensible to conclude that the impact

data on masonry within the Green Guide may be inappropriate and / or inaccurate.

4. Much of the work published by the B.R.E. into the L.C.A. of building materials and functional units, involving the *Green Guide to Specification* and the software tool *Envest*, is based upon the concept of an *eco-point* – a notional unit of environmental impact. The derivation of this notional unit is complicated, being essentially based upon and derived from, the subjective opinions of 'stakeholder groups' and 'expert panels' drawn from a variety of professional backgrounds. In view of the difficulties with the modelling processes used in L.C.A., which involve both scientific and subjective issues, the use of eco-points to give a 'single score answer' for the environmental impact of a building product or functional unit should be treated with caution particularly in the light of the comments in item 14 in Paragraph 3.11.1.

5. Full access to the L.C.I. database developed by the B.R.E. is limited to a few materials, primarily on the grounds of commercial sensitivity: instead the B.R.E. provide data in terms of functional units. In the case of the 60 year impact data quoted by the B.R.E., it is, however, not clear as to how these have been developed as precise details of any assumptions made are not given. For example, the factors for the replacement rates for the different materials used in a building are not clearly evident. The user of the *Green Guide* and the *Envest II* package therefore has little idea of how the results are actually obtained, with *Envest II* in particular acting simply as a *black box*, giving answers which cannot be questioned or checked manually.

CHAPTER 4: METHODOLOGY OF RESEARCH

4.1 INTRODUCTION

This project was primarily concerned with evaluating the post-factory gate environmental performance of clay brickwork masonry and then using this data to develop environmental profiles for brickwork. The initial phase of the research involved acquiring a thorough understanding of the subject area so that a strategy could be developed for completing the project. To achieve this, a review of all of the available literature relating to sustainability, sustainable development, life-cycle assessment and environmental profiling of construction materials and forms of construction generally, was undertaken. The Brick Development Association's Working Party for Sustainable Development was also contacted. This was formed in 2000 to evaluate the sustainability of clay brickwork masonry, although it became apparent from discussions with the group that very little work had actually been done up to that time and very few, if any, formal meetings had been held. There was also a meeting with two of staff from the B.R.E.'s Sustainability Centre who had been involved with the development of B.R.E. publications on sustainability.

From this discussion, it quickly became apparent that very little work had been undertaken to investigate and quantify the complex issues associated with the sustainability of clay brickwork masonry. This lack of research reflects the fact that sustainability, as a concept, has only become an important issue for the Construction Industry over the past decade or so. The literature review also clearly showed that, to date, the principal U.K. work in this area had been undertaken by the B.R.E. who had developed a range of environmental performance indicators for construction materials, such as environmental profiles and the *Green Guide* series.

As previously noted in Paragraph 3.10.1, post-factory gate environmental profiles involve the consideration of a wide range of issues. Whilst some of these, e.g. transporting the materials to site, are relatively straightforward, others, such as whether to refurbish or demolish a building, are more complex as they invariably involve the consideration of less tangible issues associated with, for example, demographic changes, changes in the industrial landscape or value choice decisions being made by architects / designers. Overall, these are much harder to evaluate and readily quantify in a precise and meaningful manner.

In view of the time available for the project, a decision was made to limit the research to an investigation of the potential (physical) lifespan of structural brickwork and its in-service maintenance requirements, as it was considered that these are probably the most important and easily quantified issues for brickwork in any general debate on sustainability and / or sustainable development. It was anticipated that hard data on these aspects of the post factory gate environmental performance of clay brickwork in buildings could then be usefully translated into environmental profiles using data supplied by the Brick Development Association and the B.R.E., subject, of course, to the latter's approval.

The approach adopted here was similar to that of Steele *et al* (2003) who investigated the sustainability of the masonry arch bridges maintained by Surrey County Council. Steele's work has already been described in Chapter 2.6, but essentially consisted of reviewing the historical maintenance records for a number of arch bridges in Surrey. This was followed by the compilation of a maintenance database and the subsequent development of environmental impact data for the bridges considered. Whereas Steele's work involved consideration of a very limited number (two or three) bridges, it was anticipated that this project would investigate a much larger number of brickwork buildings, with different forms of masonry wall construction. It was decided to restrict the research to brickwork used in buildings as this has traditionally accounted for between 60 % and 70 % of the market share for new bricks sales in the U.K. [figures provided to author in private correspondence with Peter Watt of the Brick Development Association Ltd.]. It was considered that this approach would provide a more realistic evaluation of the overall post-factory gate environmental performance of brickwork than the work of Steele which was focused exclusively on arch bridges. It was also expected that useful comparisons could be made between the findings from this project and the B.R.E.'s environmental data relating to the long-term performance of brickwork in new buildings, i.e. particularly beyond the 60 year period used by the B.R.E.

4.2 DEVELOPMENT OF A MAINTENANCE DATABASE

The first six months of the project were spent making contact with various companies and organisations who, it was hoped, might be able to provide access to maintenance records for any masonry buildings they either owned or managed. This would allow a database of historical maintenance requirements to be compiled for clay brickwork used in buildings. During this period, over 800 companies were contacted, including;

- Local Authorities Highways and Housing Departments
- Housing Associations
- Banks and Building Societies

- Public Utilities (gas, electricity and water companies)
- Railtrack Plc.
- Various professional institutions including the Royal Institution of Chartered Surveyors, The Institution of Civil Engineers and the Institution of Structural Engineers
- English Heritage and The National Trust
- Naval Dockyards at Chatham and the Estates Department of the Ministry of Defence
- The Public Records Office at Kew and the British Library

From these, only some twelve replies were received offering either assistance on the project or access to their maintenance archives. When these were explored further, however, it was discovered that they were, in general, only of very limited use as the information offered related to either very recent brick buildings, i.e. built within the past 20 years or so, or the records were insufficiently detailed to identify exactly what maintenance had been carried out on the brickwork. In several cases, the records only detailed the final financial cost of the work rather than the problems that had occurred and the repairs that had been undertaken. Several organisations offered the records for a single, problematic, building. These were rejected because they were not thought to accurately represent the performance of the vast majority of the masonry buildings that the companies either owned or managed. Eventually all twelve of the offers were declined as they were not considered to be sufficiently representative of the whole life performance of brickwork used for U.K. buildings generally. An interesting issue that arose from this stage of the project was that much of the information relating to maintenance of brickwork, and indeed buildings generally, was anecdotal in nature and invariably based upon the opinions of a limited number of construction professionals such as those of the 80 building surveyors which was used to develop the data given in *The B.M.I.'s Life Expectancy of Building Components* [Harvey, 2001] which was previously discussed in Paragraph 2.3.

A particular problem encountered with public utility companies and the railways was that they had disposed of their old written maintenance records when computer based management systems were installed in the early 1990's. A further problem was that a number of organisations were extremely reluctant to release any maintenance data relating to buildings or structures generally as it was felt that, in doing so, they could potentially be exposing themselves to future legal action from third parties should any problems / accidents occur in / on their properties.

Overall, this phase of the project proved to be less productive than initially anticipated. Nevertheless it did provide a valuable basis from which to commence the project in that it was demonstrated that very little hard data on the long-term maintenance requirements of brickwork were available.

4.3 CONDITION SURVEYS

After detailed consideration of whether it would be worthwhile contacting more companies, it was decided that the type of historical data required for this project either did not exist or that it could not be accessed satisfactorily within the time available. A decision was made, therefore, to carry out a series of condition surveys on a selection of traditional low-rise brick buildings (mainly housing) of varying ages and forms of wall construction across the Yorkshire, Lincolnshire and Lancashire regions in order to create the required database. The towns and cities included in the survey included; Leeds, Bradford, Keighley and Dewsbury in West Yorkshire; Hull in East Yorkshire; Beverley, Malton, and York in North Yorkshire; and Manchester, Salford and Blackpool in Lancashire. These locations were selected because the budget for the project was not sufficient to permit surveys in other regions of the country. In this respect, it would obviously have been more desirable to extend the surveys across the country, time permitting of course. A small number of listed brick-built stately homes across North Yorkshire were also surveyed.

The surveys were designed to comply with the D.T.L.R.'s *Decent Homes: Capturing the Standards at Local Level* and the D.E.T.R.'s *Collecting, Managing and Using Housing Stock information – A Good Practice Guide* series. They were carried out in accordance with various R.I.C.S. recommendations which related to the size and scale of the survey, a suitable layout for the survey (i.e. how to conduct the survey and what to look for during it), how to record the data in a systematic manner, and the development of the final database. The information recorded from these surveys included:

- the age of the structure
- their typology (as defined in *Collecting, Managing and Using Housing,* i.e., Pre 1945 bungalows, post 1980 detached houses, etc.)
- the size of structure
- data on the form of wall construction (i.e. solid or cavity wall construction, lime or cement mortar, thin or normal width joints)

- a subjective assessment of the original quality of the brickwork (i.e. original selection of materials, quality of workmanship, etc.) and its present condition (i.e. the amount and quality of any maintenance, the current condition of the brickwork, etc.)
- an estimate of the percentage of the brickwork which has been re-pointed, repaired, and / or replaced
- if the wall ties or lintels had been replaced or a new D.P.C. had been inserted and any other significant maintenance issues that were likely to have influenced / affected the findings such as spalling of the brickwork due to frost attack, over-sliding of D.P.C., etc.

The historic buildings that were surveyed were identified using the various *Buildings of England* guides published by Pevsner for the Yorkshire region [Pevsner 1966, 1967, and 1972] and Lloyd's *A History of English Brickwork* (1925). An extract from the final database can be seen in Appendix D.

The majority of the structures included in the survey were selected after a careful consideration of the age and types of building stock within a specific town. The purpose here was to obtain a representative range of properties of different ages and forms of wall construction. In practice, however, it was impossible to identify the precise age of many of the structures because historical records were not always available. For example, whilst it proved relatively easy to date properties built after 1970 by talking to the residents or local populace in an area, it was more difficult when the buildings were significantly older. The ages of buildings built before 1970 were, therefore, estimated from the public records and maps obtained from local and central libraries. These were supplemented with books on the local history of an area which were published by local history societies and civic trusts, where necessary. As a result, the ages of buildings built in the 20th century were estimated to the nearest decade, properties from the 19th century ages were estimated to the nearest half century, and any buildings earlier than that date were estimated to the nearest century. Whilst this approach was far from ideal as, potentially, it meant that the age of the building might have been underestimated in the database by up to 99 years, it was the only option available from the sources of data that were available.

It was recognised that the decision to carry out condition surveys was far from ideal and that there were a number of obvious limitations to it. These included the distribution of the properties that were being surveyed, i.e. they were all located in the north of England and only 860 structures out of a potential 21 million properties in U.K. were surveyed in detail. It is difficult to suggest what would be a suitable number of properties to survey, however, and how the surveys should be distributed on a regional basis in order to ascertain a national picture for the long-term post-factory gate environmental performance of clay brickwork masonry. Nevertheless the approach adopted for this project is thought to provide a meaningful snapshot of brickwork's performance in the north of England.

A further restriction to the work was that it involved simple non-destructive visual inspections of the external envelope of the structures. Understandably it was not possible to either drill holes in the walls or take core samples from walls to ascertain their exact form of construction or the physical characteristics of the bricks and mortar used in the construction. It was however, normally possible to use the brickwork bond to establish whether the brickwork was of solid or cavity construction, and to assess whether the original mortar used in the wall was a hydraulic lime or a cement-based mortar.

As a check on the surveys, comparisons were made with data given in *Appraisal of Existing Structures* [The Institution of Structural Engineers, 1996] to ensure the historic availability of different forms of masonry construction - see Figure 4.1.

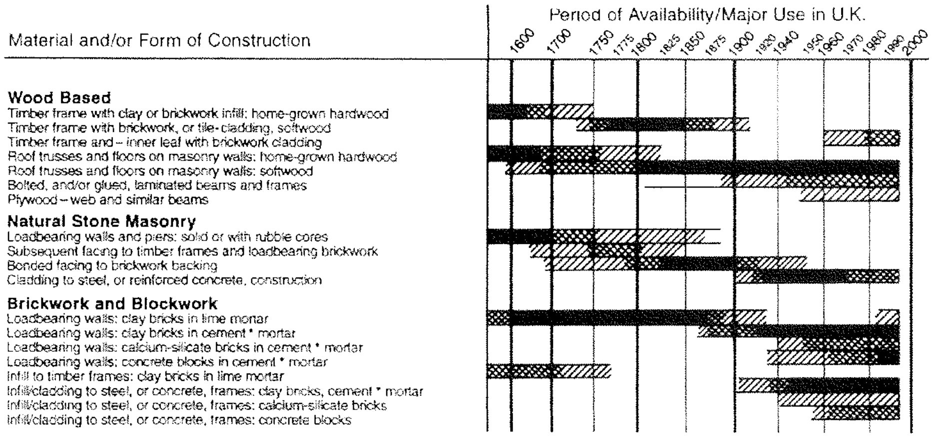


Figure 4.1: The Historic Availability of Different Forms of Construction in the U.K. (The Institution of Structural Engineers, 1996)

The surveys took approximately 18 months to complete, from early 2002 to late 2003, and, in total, 860 structures were surveyed.

4.4 ANALYSIS OF CONDITION SURVEY DATA

4.4.1 INITIAL CLASSIFICATION

After the condition surveys had been completed, the data were analysed to determine the ages of the different properties, the different forms of masonry wall construction, and the type and extent of the maintenance carried out specifically on the brickwork. The properties were categorised using the typology given in Appendix G5 of *Collecting, Managing and Using Housing Stock Information: Volume 2 - Key Principles and Methodological Issues* [Department of Environment, Transport and Regions (2000[b]] and general comparisons made between the problems with the brickwork detected from the surveys and those described by Lynch (2003) and The Institution of Structural Engineers (1996) in their *Appraisal of Existing Structures* publication.

4.4.2 MAINTENANCE DATA

The overall amounts and types of maintenance that had been carried out on the masonry walls were quantified in terms of the masses of materials that were likely to have been used to complete this work. As the surveys were limited to the visual inspection of buildings, it was, however, not normally possible to identify exactly when, or indeed how many times, such maintenance had been carried out in the past.

4.4.2.1 SOLID VERSUS CAVITY WALLS

The maintenance data relating to solid and cavity walls were considered separately. This was then used to identify the approximate ages at which the different maintenance activities had first been carried out for the two types of construction. For instance, whilst terraced houses built in the 1930's may not have had any maintenance carried out on them, 10 % of the brickwork on similar properties built in the 1920's may have been re-pointed. This enabled a theoretical value to be determined for the *average* age of the brickwork when it first required repointing for both solid and cavity masonry walls. This basic approach was also used to predict the frequency of the other maintenance activities such as the repairing of brickwork and the replacement of individual bricks.

4.4.2.2 MAINTENANCE REGIMES

It became apparent from the condition surveys that the frequency and amount of maintenance carried out on buildings varied considerably, with the owner of one property prepared to spend much more time and money on maintaining the fabric of his property than his / her neighbour. This is particularly so in the modern era, when spending on maintenance is considered to be *dead money* as it has no immediate payback, or the money can be spent elsewhere on consumables [Howell, 2003[b]]. Steele also found a similar effect when he collated his maintenance database for masonry arch bridges in Surrey.

In order to account for the variability in the amounts of maintenance that had been carried out on very similar properties, it was decided to follow the methodology of Steele *et al* (2003) and allocate the maintenance that had been carried into one of three levels, namely good, average and poor.

As part of the survey of a property a subjective judgement had been made of the original quality and the current condition of the brickwork. The assessment of the original quality of the brickwork included judging the suitability of the original materials and the quality of the original workmanship. This was determined by assessing the current condition of the properties including noting any current and historical defects in the brickwork and recording any maintenance that had been carried out in the past. The data were then collated and compared to other data that had been gathered on other similar properties. The assessment of the current condition of the brickwork included assessing the amount and quality of any previous maintenance that had been carried out and the general condition of the wall. These two categories, i.e. the original (i.e. at the time of construction) and the current condition of the brickwork, were then graded between zero and five and once all of the data from the condition surveys had been collated, the scores were used to divide the maintenance data into one of the three levels described above.

4.4.3 POTENTIAL LIFESPAN OF MASONRY BUILDINGS

As previously discussed in Paragraphs 2.1 and 2.3, there are many complex and inter-related reasons why buildings do not achieve their maximum potential (physical) lifespans. In practice, buildings are invariably demolished long before the main elements / fabric of the structure (the walls, floors, roof, etc.) have failed.

In view of the recognised durability of brickwork, it was decided, therefore, to use the survey data to try and predict a maximum potential lifespan for both clay bricks and clay brickwork walling. It should be noted, here, that the maximum life span of clay bricks is not, necessarily, the same as the maximum lifespan of clay brickwork masonry walling. Although the bricks themselves might last for, say, 500 years, the masonry wall itself can potentially last indefinitely if the individual bricks that it is constructed from are continually replaced at the end of their lives. This situation also applies to other materials, for example the concrete roof tiles used in modern domestic housing typically need replacing at 25 to 30 year intervals but the basic structure of the roof, the roof trusses, etc., will normally last 100+ years. Consequently, during the *life* of a typical roof, the concrete roof tiles might need to be replaced three-times before the roof is demolished.

The maximum potential life span of clay bricks was determined by plotting and extrapolating the replacement rate data for solid and cavity walls from the condition surveys to produce an estimate of the hypothetical time taken for all of the bricks in a wall to have been replaced. It should be noted, however, that although there was sufficient survey data available to determine the replacement rate of bricks in solid walls for various time intervals up to 500 years, there were only very limited data relating to cavity wall construction from the condition surveys. This reflects the fact that cavity wall construction is a relatively modern form of construction and that the replacement rate of bricks in such walls is very low. It is worth noting, however, that only two of the cavity wall buildings that were surveyed dated earlier than the 20th Century. The data for the replacement rate of bricks in cavity walls were consequently limited to this age range.

4.5 LIFE-CYCLE ASSESSMENT OF MASONRY WALLING

As noted in Paragraph 4.1, the principal objective of this project was to develop post factory gate environmental profiles for different forms of clay brickwork masonry walling construction used in traditional low-rise brick built buildings. It was anticipated that these could be determined from the data relating to the maintenance, renewal and replacement of brickwork obtained from the condition surveys. When added to the initial installed profiles this would then provide whole life environmental profiles for clay brickwork masonry walling at increasing ages in these types of buildings.

In order to develop these profiles, permission was sought from the B.R.E. to access their confidential database on environmental impacts for the various materials used in typical walling construction, i.e. brick, sand, cement, lime, timber, blockwork, insulation, plasterboard, and paint. These had been previously determined by the B.R.E. as part of their project to compile an Environmental Profiles Database, as referred to in Paragraph 3.10.1.

This part of the project proved extremely problematic and time consuming. It involved contacting each of the manufacturers / trade organisations that had participated in the original B.R.E. project to ask them for their permission for the B.R.E. to release information relating to their material or product. Several manufacturers took an extremely long time (in excess of six months) to deal with this request. It should be noted that the development of environmental profiles requires access to the impact data for all of the materials used in walls and without this, the project could not have been progressed in the manner proposed. Furthermore, a number of organisations insisted that any data which related to the pre-factory gate environmental impacts of their products could not be published in any form without their prior agreement.

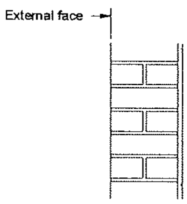
4.5.1 DEVELOPMENT OF WHOLE LIFE ENVIRONMENTAL PROFILES FOR WALLING

The whole-life environmental profile was determined by combining the initial installed environmental profile and the post-factory gate profile for the type and age of the walling being considered.

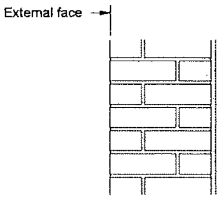
4.5.1.1 INITIAL INSTALLED PROFILE

Once all the pre-factory gate environmental impact data had been obtained from the B.R.E., an installed environmental profile was developed for a range of different forms of solid and cavity masonry wall constructions. These included a 215 mm and a 327 mm thick solid wall, a 102.5 mm brickwork / blockwork cavity wall, a 102.5 mm brickwork / brickwork cavity wall and a 102.5 mm brickwork / timber frame construction cavity wall – see walls 1, 2, 3, 7 and 8 in Figure 4.2 and Appendix B for an example of this process. These types of clay brickwork masonry walling were chosen because they were the most common form of wall types observed during the surveys. A number of other wall types were observed but they were not included in the analyses. These were generally found on the much older properties and included several four feet thick solid walls and massive rubble-filled cavity walls, where the leaves of the wall were, in fact, thicker than the overall thickness of cavity walling used in modern domestic housing. These were not included in the analyses as it was considered that they were exceptional and did not represent typical masonry construction. In addition, because of the prohibitive financial and time costs associated with the building of these types of walls and their massive structural redundancy, it is very unlikely that they will ever be built again.

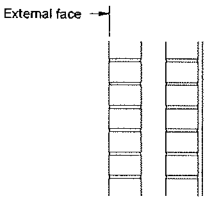
Environmental profiles were also developed for three further wall types. These were modified versions of the original two solid walls and the brickwork / brickwork cavity wall. These additional walls were added after it was discovered that the two solid walls and the brickwork / brickwork cavity wall that had been surveyed did not comply with the current requirements for the thermal performance of external walls described in the Building Regulations [Office of the Deputy Prime Minister, 2002].



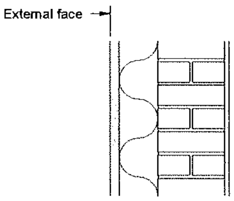
Wall type 1
215mm thk. brickwork
Painted plasterboard



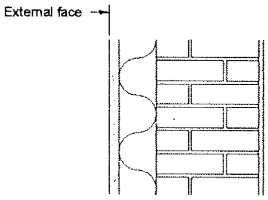
Wall type 2
328mm thk. brickwork
Painted plasterboard



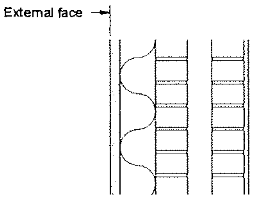
Wall type 3
102.5mm thk. brickwork
120mm cavity insulation
102.5mm thk. brickwork
Painted plasterboard



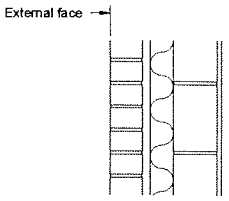
Wall type 4
Cement render
125mm external insulation
215mm thk. brickwork
Painted plasterboard



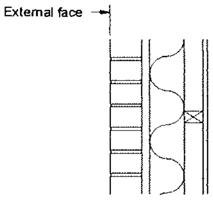
Wall type 5
Cement render
120mm external insulation
328mm thk. brickwork
Painted plasterboard



Wall type 6
Cement render
110mm external insulation
102.5mm thk. brickwork
75mm cavity insulation
102.5mm thk. brickwork
Painted plasterboard



Wall type 7
102.5mm thk. brickwork
75mm cavity insulation
140mm thk. blockwork
Painted plasterboard



Wall type 8
102.5mm thk. brickwork
110mm cavity insulation
Timber studwork
Painted plasterboard

Figure 4.2: Different Forms of Wall Construction Used in the L.C.A. and L.C.C. Analysis

4.5.1.2 POST-FACTORY GATE PROFILE

The maintenance data obtained from the condition surveys were used to estimate the typical amounts of maintenance carried out on solid and cavity wall forms of clay brickwork masonry at different ages, namely 60 years, 100 years, 150 years, 300 years, and at 500 years. The first of these, i.e. 60 years, was chosen so that the various profiles that were to be developed for this project could be easily compared with the equivalent data published by the B.R.E. The profiles at 100 years, 150 years, etc. enabled the longer-term post-factory gate performance to be compared with the 60 years values and the environmental impacts of clay brickwork over a potential life of up to 500 years to be evaluated. It should be noted here again, that the B.R.E. environmental profiles are limited to a single 60 year lifespan, after which the buildings were assumed to be demolished and the elements within them assumed to be recycled or disposed of as landfill.

4.5.1.3 WHOLE LIFE PROFILE

The overall aim of this process was to utilise the data obtained from the condition surveys to develop the whole-life environmental profiles for a range of brickwork wallings at the five ages listed in Paragraph 4.5.1.2. This was achieved by adding together the relevant installed and final post-factory gate profiles at each of the ages – see Appendix E for an example of this process.

4.5.2 COMPLIANCE WITH THE REQUIREMENTS FOR THE THERMAL PERFORMANCE OF EXTERNAL MASONRY WALLS

Most of the walls that were surveyed did not comply with the latest requirements for the thermal performance of external walls as specified in the Building Regulations. It was considered, however, that restricting the research to the development of whole-life environmental profiles for these forms of brickwork masonry construction which were no longer permitted would be of little value to the Clay Brickwork Industry and the public, generally. These walls were notionally upgraded by adding a layer of external insulation covered with a protective layer of cement render to the external face of the wall – see walls 4, 5 and 6 in Figure 4.2. The whole life environmental performance of these notional modified forms of walling was then evaluated in a similar manner to that described above. The same data relating to the maintenance of solid and cavity masonry walls was used for these walls even though the brickwork would be protected by the external render. As such, this is considered a worst-case assumption.

4.5.3 COMPARISON OF EMBODIED ENERGY AND DOMESTIC ENERGY CONSUMPTION

The *U*-values for the eight walls in Figure 4.2 were then used to calculate the energy required to heat a hypothetical room in a typical multi-storey building. This was to allow comparisons to be made between the embodied energy of the construction materials in the buildings and its in-service energy requirements and also the published values for the ratio, previously described in Paragraph 2.2.

The comparison was limited to a single age, 500 years, for simplicity.

4.6 LIFE-CYCLE COSTING

The life-cycle costings were calculated for the eight wall types at the five ages listed in Paragraph 4.5.1.2 so that comparisons could be made between the different walls to identify which was the most economic form of masonry construction at each age. The L.C.C. analyses used a very similar methodology to that of the L.C.A., i.e. the same wall types and maintenance data and lifespans which were developed for the L.C.A. analyses - see Appendix F.

The pricing data used in L.C.C. analysis were obtained from *Spon's Architects' and Builders' Price Book* [Davis *et al*, 2003].

4.7 COMBINING THE LIFE-CYCLE ASSESSMENT AND LIFE-CYCLE COSTING DATA

The results of the L.C.A. and L.C.C. at 500-years, for an average standard of maintenance for all eight walls, were then plotted against each other to determine which was the best overall form of construction in terms of combined L.C.A. / L.C.C. data. This is the approach recommended by both the B.R.E. in *Digest 452* [Edwards, Bartlett and Dickie, 2000] and the Institution of Structural Engineers [The Institution of Structural Engineers, 1999].

4.8 COMPARISONS WITH B.R.E. DATA

Where possible, the L.C.A. and L.C.C. data described in Paragraphs 4.5 and 4.6 were compared with the relevant data published by the B.R.E. This involved comparisons between the L.C.A., L.C.C. and maintenance data developed for this project and the B.R.E.'s whole-life environmental profile for a brickwork / blockwork cavity wall, the output from *Envest II* generally, the replacement intervals used by the *Green Guides* and *Envest II*, and the B.R.E.'s estimates of the contribution of different building elements to overall environmental impact of a building.

4.9 COMPARISON OF ENVIRONMENTAL PERFORMANCE OF AN EXISTING BUILDING AND A REPLACEMENT BUILDING

An analysis was completed to compare the environmental performance of an existing building. A building was chosen which did not comply with the current statutory requirements for the performance of buildings but whose age was between 60 and 80 year lifespans that the B.R.E. use in their *Green Guide* series and *Envest II* L.C.A. packages respectively. It was compared with an upgraded version of the building which met the current requirements for the thermal performance of buildings and a replacement building.

The embodied energy of the construction materials used to upgrade the building and to construct the replacement building were determined along with the operational energy requirements for three building types. These values were then added together for each of the buildings and the results were compared to determine which had the least environmental impact.

CHAPTER 5: RESULTS FROM CONDITION SURVEYS

5.1 AGE RANGE OF BUILDINGS

Table 5.1 shows the age range of the properties surveyed.

Oldest	1345
Youngest	1992
Average	1939

Table 5.1: Age Range of Surveyed Properties

The oldest brickwork included in the survey dates from 1345, according to Pevsner (1972). This formed a section of the external wall on the north side of the chancel at Holy Trinity Church in Hull, East Yorkshire – see Plates 1 and 2.

Plate 1: Holy Trinity Church, Hull, East Yorkshire

Plate 2: The North Side of the Chancel at Holy Trinity Church

Plates 3 and 4 show the second oldest structure surveyed for the project. This is *North Bar*, an early fifteenth century gatehouse in the North Yorkshire town of Beverley, which is still subjected to significant wear and tear from traffic passing through it.

Plate 3: North Bar, Beverley,
North Yorkshire

Plate 4: The Brickwork at North Bar

Holy Trinity Church and North Bar were specially chosen for inclusion in the survey as they illustrate that brickwork can potentially last for many hundreds of years. Out of the 860 properties surveyed, 18 were specifically chosen from Pevsner's *Buildings of England* guides (1966, 1967, and 1972) and Lloyd's *A History of English Brickwork* (1925).

An analysis of data obtained from *The 2002 Housing Statistics* [Office of the Deputy Prime Minister, 2003^b] showed that the age distribution of the surveyed properties slightly under-represented the number of older properties in England - see Table 5.2 and Figure 5.1. These official statistics show that approximately 22 % of the existing housing stock in England is over 140 years old, 34 % is over 100 years, 42 % is over 80 years and nearly 60 % of the stock is over 60 years old; the national statistics start at 1861 and there is no breakdown of ages before that date. As already noted, however, the B.R.E. use a single value of 60 years for the majority of their work associated with the whole-life environmental impact assessments of buildings.

In practice, it would have been possible to select additional properties of the required ages for inclusion in the condition surveys but it was considered that these supplementary data would have been unlikely to significantly affect the findings generally.

In relation to the U.K. stock of buildings, Holy Trinity Church at Hull and North Bar at Beverley should be considered as exceptional brickwork structures in that they are both Grade 1 listed and, as such, are probably maintained to the highest standard by specialists from conservation organisations such as English Heritage. The housing figures from both the survey and the national statistics do, nevertheless, indicate that large numbers of masonry structures are surviving for much longer than the figures suggested by the B.R.E., the British Standards, etc. which were discussed previously in Paragraph 2.3.

	Surveyed properties (cumulative)		Total number of homes in U.K. (cumulative)	
	Number of properties	% of total number surveyed	Number of homes in the U.K.	% of total number of homes
1501	3	0.35	-	-
1601	3	0.35	-	-
1701	8	0.93	-	-
1801	15	1.74	-	-
1861	21	2.44	4,206,000	20.06
1871	34	3.95	4,736,000	22.58
1881			5,291,000	25.23
1891			5,761,000	27.47
1901			6,612,000	31.53
1911	177	20.58	7,493,000	35.73
1921	206	23.95	8,161,000	38.91
1931	278	32.33	9,595,000	45.75
1941	348	40.47	11,050,000	52.69
1951	436	50.70	12,500,000	59.60
1961	616	71.63	13,9150,00	66.35
1971	700	81.40	15,951,000	76.06
1981	795	92.44	17,306,000	82.52
1991	853	99.19	19,213,000	91.61
2001	860	100.00	21,134,000	100.00

Table 5.2: Age Distribution of the Properties Included in the Survey and the Population of Homes in the England

Notes: Data on the population of homes in the U.K. obtained from *The 2002 Housing Statistics* [Office of the Deputy Prime Minister, 2003^{b}]

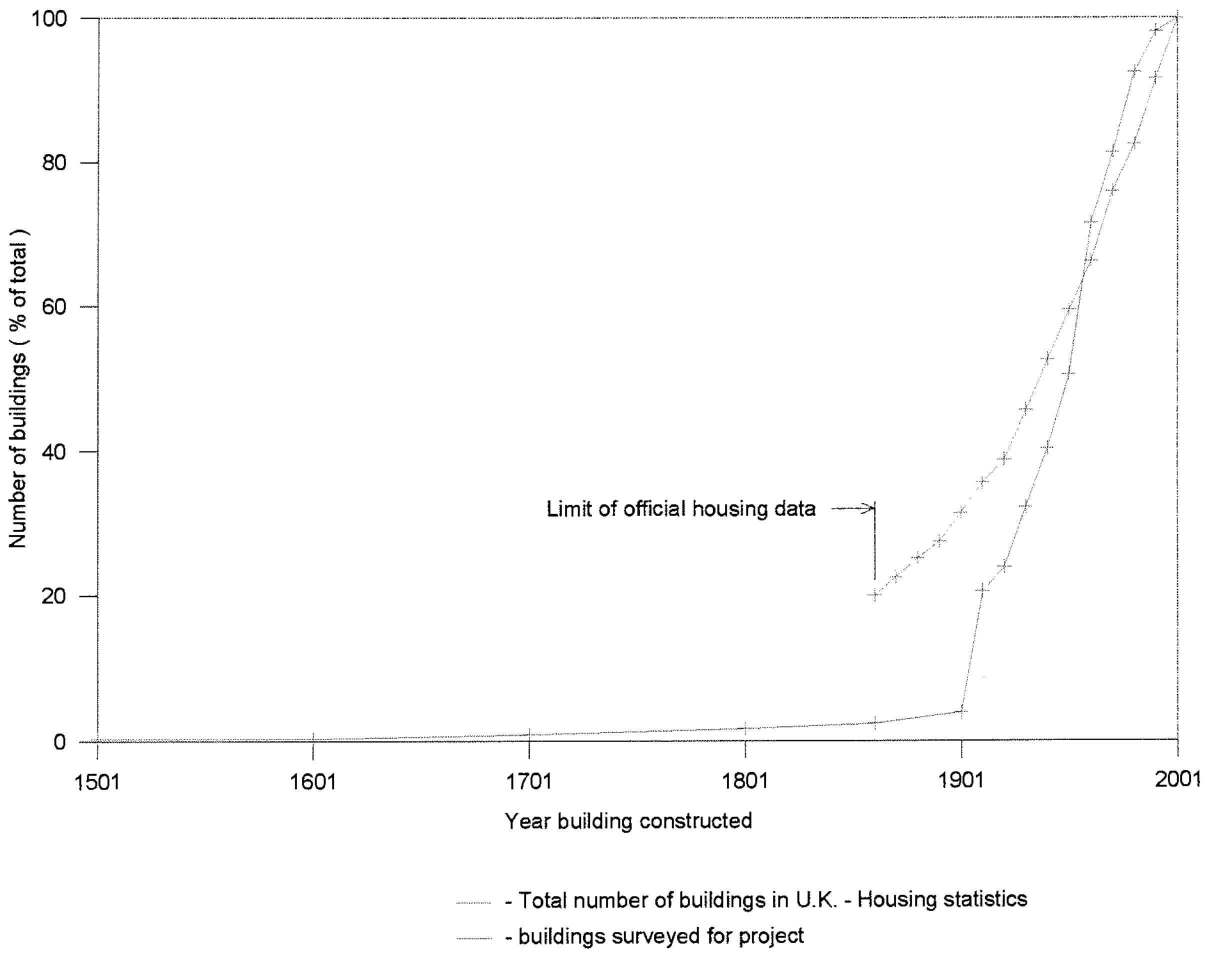


Figure 5.1: Age Distribution of the Surveyed Buildings and the Existing U.K. Housing Stock

5.2 TYPOLOGY OF BUILDINGS

Table 5.3 shows the typology of the buildings that were surveyed. These are based on the classifications given in Appendix G5 of *Collecting, Managing and Using Housing Stock Information: Volume 2 - Key Principles and Methodological Issues* [Department of Environment, Transport and Regions, 2000^{b}].

Typology of property	Number of properties
Pre 1919 terraced and semi-detached houses	138
Pre 1919 detached houses	4
Pre 1919 ground floor flats	0
Pre 1919 first floor flats	0
Pre 1919 above first floor flats	0
Pre 1945 bungalows	2
1919 – 1944 terraced and semi-detached houses	109
1919 – 1944 detached houses	22
1919 – 1944 ground floor flats	0
1919 - 1944 first floor flats	0
1919 - 1944 above first floor flats	0
1945 – 1980 terraced and semi-detached houses	308
1945 – 1980 detached houses	63
1945 – 1980 bungalows	56
1945 – 1980 ground floor flats	0
1945 - 1980 first floor flats	0
1945 - 1980 above first floor flats	0
Post 1980 terraced and semi-detached houses	36
Post 1980 detached houses	16
Post 1980 bungalows	5
Post 1980 ground floor flats	2
Post 1980 first floor flats	2
Post 1980 above first floor flats	0
Others	97
Total	860

Table 5.3: Typology of Properties Surveyed

It can be seen that the majority of the buildings surveyed were either traditional detached, or semi-detached, houses. A number of post-Second World War bungalows, approximately 7 % of the total, were also surveyed. It can also be seen from Table 5.3 that the survey included very few flats. This was not intentional and merely reflected the lack of suitable properties in the locations surveyed.

Despite an extensive search, no national statistics could be found for the distribution of these different types of buildings and / or properties in the U.K. and no comparisons could, therefore, be made with the data in Table 5.3.

5.3 MAINTENANCE OF SOLID AND CAVITY BRICKWORK WALLS

Table 5.4 gives details of the types of wall construction and the number of properties surveyed. It was assumed that hydraulic lime mortar was used for all solid walls. This was considered reasonable given that all of the buildings that had solid walls were built before the Second World War, this post-war period being the time when the use of O.P.C. cement became predominant.

Type of wall construction	Number of surveyed properties	Type of mortar joints	Number of surveyed properties
Solid	269	Lime	269
		Cement	0
Cavity	591	Lime	14
		Cement	577

Table 5.4: Breakdown of the Different Types of Wall Construction

In addition, because the condition surveys were conducted on a selection of traditional low-rise brick buildings, the vast majority of the properties had external walls that were built using traditional masonry construction techniques. As a result, the brickwork in the walls was either load-bearing (solid walls), or formed an outer covering to a load-bearing inner leaf (cavity walls). There were only four properties out of 860, where the brickwork appeared to be supported by a structural frame.

5.3.1 TYPES OF MAINTENANCE AND ASSOCIATED PROBLEMS IDENTIFIED

During the condition surveys, detailed notes were made of any brickwork maintenance that had been carried out on the properties and of any problems in the brickwork that might need attention in the future.

Plate 5: Example of Recently Repointed Brickwork

Apart from the general maintenance of the brickwork associated with activities such as the repointing of the mortar joints (see Plate 5) and repairing openings in brickwork when services (gas flues, etc.) had been passed through the external wall, the main repair that had been observed was the replacement of lintels. In 18 of the 860 properties surveyed, at least one of the lintels above an opening had either been substantially repaired or replaced. 12 of these 18 properties were relatively old and had either stone or brickwork arch lintels. Generally, the stone lintels had failed because the stone had eroded over time due to weathering. This necessitated their removal and replacement with new stone lintels. The brickwork lintels had been repaired when individual bricks had slipped out of position – see Plate 6. In three properties, the original bricks had been reused (see Plate 7) and in one property the original lintel had been replaced with a new arched brickwork lintel – see Plate 8. Of the 18 properties, six were newer properties situated on one 1950's housing estate in Leeds and were all of a very similar design. On all of these properties, the lintels and the brickwork above the main windows at ground floor level had been replaced. It is worth noting, that there were an additional 20 houses on the estate that were not surveyed and approximately three-quarters of them had the same repair.

Plate 6: Example of Brickwork Lintel where Bricks have Slipped but Currently Awaiting Repair

Plate 7: Example of Brickwork Lintel that was Repaired Using the Original Bricks

Plate 8: Example of a Brickwork Lintel that was Repaired Using New Bricks
(**Note:** The brickwork over lintel was also replaced)

A second maintenance activity noted on four houses was the replacement of the steel wall ties in cavity walls. These all occurred on a single housing estate in Leeds that had been built in the early 1980's.

There was also one property that had been retrofitted with an injected chemical damp proof course. This was the last house in a row of terraces that had been built in the early 1900's with solid masonry external walls. A chemical damp proof course had been injected into the external walls of the property at approximately 150mm above the external ground level. It could not be ascertained how successful the work had been but surprisingly none of the other houses in the row had been similarly treated and they all appeared to be in a satisfactory state of repair. In this respect it is probable that during the process of selling the property at some time in the past, a survey had been completed which noted that the property did not have a d.p.c. and it consequently became a condition of the sale that one should be fitted, probably irrespective of whether or not it was actually required.

During the survey, other maintenance work and repairs found on the brickwork included the bricking up and possible relocation of windows and doors (see Plate 9). In one early nineteenth century two-storey building, steel rods had been inserted through building at the first floor level to tie the outer walls together and to stop them from bulging – see Plate 10. On other properties where the bulging occurred but to a lesser extent, brickwork piers had been built onto the outside faces of the external walls in an attempt to arrest the movement.

Plate 9: Example of *Bricking-Up* of an Original Opening in External Wall to Suit New Use of Building

Plate 10: Example of Steel Tie Rod Inserted Through Building to Control Bulging in External Wall

A large number of the properties, including some of the oldest properties surveyed, exhibited some form of efflorescence on the external face of the brickwork – see Plate 11. It should be noted that the condition surveys were conducted over a full year, and the efflorescence was observed throughout the period and it did not appear to be causing any damage to the brickwork or building as a whole. A second common issue was the spalling of the external face of the bricks – see Plate 12. This was assumed to be caused by weathering, or more specifically frost attack of the brick, and even though it was observed on relatively young properties, i.e. as young as 20 years old, it generally became more prevalent with age. The only method of repairing spalled brickwork appears to be cutting out and replacing each affected brick individually, but it was apparent from the surveys that this problem was generally ignored until it covered large areas of the brickwork.

Plate 11: Efflorescence in 300 year Old Brickwork

(Note: Sandstone quoins and coping badly weathered - large sections have already been replaced)

Plate 12: Example of Spalled Brickwork

Lynch attributes most of the long-term problems with brickwork to poor detailing material selection and / or workmanship [http://www.buildingconservation]. This certainly appears to be the case with respect to premature failure of the lintels and wall ties on the two housing estates in Leeds which were described earlier in this paragraph.

The generalisation is probably unfair, however, for older properties, where most of their problems can be attributed to age and general *wear and tear* and it should be recognised that, although brickwork is a durable material, when placed in a harsh environment and subjected to extremes of weather it has a finite life.

In the surveys there were a number of properties that appeared to be generally neglected. The main problem with these was that the guttering or rainwater down-pipes had either been allowed to become blocked or disconnected so that water was being discharged directly onto the surface of the brickwork. In several cases, moss was actually growing on the wall around the guttering / down-pipes, indicating that the problem had occurred some time before the building was surveyed – see Plate 13. There were also several examples where the ground around the property had been landscaped and the new ground level was now above the level of the damp proof course, possibly leading to premature failure of the brickwork in the near future. These types of problem are defined by Lynch as the *induced decay* of the clay brickwork masonry. As previously stated in Paragraph 2.4, Lynch also refers to other problems such as vegetation being allowed to grow up the outside of buildings and the detritus from birds (especially pigeons). Possibly because of the type and relatively small size of most of the properties surveyed, these latter problems were not observed, although several of the stately homes did have vegetation growing on their external walls. In these cases, the growth appeared to be managed and the plants were constantly being pruned and did not appear to be causing any problems – see Plate 14.

Plate 13: Example of Brickwork being Damaged by Poorly Maintained Rainwater Down-Pipe

Plate 14: Example of Managed Growth of Vegetation on External Brickwork Wall

5.3.2 REPOINTING

Table 5.5 shows the average age at which the solid masonry walls were first repointed, depending upon the maintenance regime that had been followed. For properties subject to a good standard of maintenance, the average age of the brickwork at first repointing was 74 years, whilst for properties that had been poorly maintained it was 162 years. In the latter case this did not necessarily mean that the brickwork of the buildings was in a poor condition. Rather, it simply reflected the fact that buildings are invariably subjected to different levels of maintenance and that, whilst it would be desirable for all brickwork to be properly maintained, the failure to do this does not necessarily prevent the brickwork from fulfilling its basic function.

The average time to first repointing of 103 years for solid masonry walls shown in Table 5.5 is very similar to the anecdotal figure of 'at least 100 years' quoted by Howell (2003[a]). Howell also suggests that even when traditional solid brick walls built with lime mortar are neglected, that they are still capable of lasting for centuries and that the often unnecessary repointing of them with cement mortar, instead of a traditional lime mortar, can actually hasten their decay. This is because a lime mortar is comparatively flexible compared to a cement mortar and, consequently, whereas the bricks in a lime mortar are able to move relative to one another, they would be held rigid in cement mortar. Additionally, unless the cement mortar is specified correctly, it can very easily be stronger than the original bricks. This can result in the bricks cracking rather than the mortar if there is movement in the wall and, if it rains, the bricks are weathered instead of the mortar [Howell, 2003[a]].

Type of maintenance regime	Good	Average	Poor
Average time to first repointing of walls	74 years	103 years	162 years

Table 5.5: Average Time to First Repointing of Solid Clay Brickwork Masonry Walls

Table 5.6 shows the average age at which cavity walls were first repointed. Again this depended upon the maintenance regime that had been followed. For properties subject to a good standard of maintenance, the average age to first repointing was 52 years; this increased to 81 years for properties that had been poorly maintained.

Type of maintenance regime	Good	Average	Poor
Average time to first repointing of walls	52 years	71 years	81 years

Table 5.6: Average Time to First Repointing for Clay Brickwork Masonry Cavity Walls

When comparisons are made between the data shown in Tables 5.5 and 5.6, it can be seen that, on average, solid walls were repointed at a later age than cavity walls for all levels of maintenance. This would appear to indicate that the thin jointed lime mortars found in these solid walls are more durable than the thicker cement-based mortars used in modern forms of cavity wall construction. In this respect it should be noted that, whilst cavity walls generally have better resistance to rain penetration than solid walls, rain nevertheless does often penetrate the outer leaf of a cavity wall, via unfilled perpends. Also, the improved thermal performance of cavity wall construction may result in the external leaf being subjected to a greater range of temperatures than would be experienced by a solid wall. These two factors may well contribute to the poorer performance of cavity walls compared to solid walls with respect to repointing generally.

5.3.3 TOTAL MAINTENANCE CARRIED OUT ON WALLS

Tables 5.7 and 5.8 show the total amounts of maintenance that had been carried out on solid and the cavity walls at different periods of time. This information was based on an analysis of the condition survey data and consists of the percentage of brickwork that had been repaired and replaced and the number of times that it had been repointed at the five ages previously described in Paragraph 4.5.1.2. Any maintenance work that involved the refurbishment and reuse of the original bricks was classified as *repaired* (see Plate 15), whilst work which involved the original bricks being disposed of and replaced with new bricks was classified as *replaced* (see Plate 16). It was not possible to determine the precise number of times an older property would have been repointed during its history, and it was assumed, therefore, that it would have been undertaken at the same interval as the average time to the first repointing shown in Tables 5.5 and 5.6. As with Tables 5.5 and 5.6, the results have been allocated into three maintenance regimes; good, average and poor.

Type of maintenance regime	Good			Average			Poor		
	Number of times wall repointed within period	Area of brickwork repaired within period	Area of brickwork replaced within period	Number of times wall repointed within period	Area of brickwork repaired within period	Area of brickwork replaced within period	Number of times wall repointed within period	Area of brickwork repaired within period	Area of brickwork replaced within period
60 years	0	5 %	2 %	0	2 %	0 %	0	0 %	0 %
100 years	1	10 %	10 %	0	5 %	2 %	0	0 %	0 %
150 years	2	10 %	20 %	1	5 %	5 %	0	2 %	0 %
300 years	4	15 %	50 %	2	10 %	25 %	1	5 %	5 %
500 years	6	15 %	75 %	4	10 %	50 %	3	5 %	10 %

Table 5.7: Maintenance Undertaken on Solid Clay Brickwork Masonry Walls

Type of maintenance regime	Good			Average			Poor		
	Number of times wall repointed within period	Area of brickwork repaired within period	Area of brickwork replaced within period	Number of times wall repointed within period	Area of brickwork repaired within period	Area of brickwork replaced within period	Number of times wall repointed within period	Area of brickwork repaired within period	Area of brickwork replaced within period
60 years	1	10 %	5 %	0	2 %	2 %	0	0 %	0 %
100 years	1	15 %	15 %	1	5 %	2 %	1	0 %	0 %
150 years	2	25 %	40 %	2	10 %	15 %	1	5 %	5 %

Table 5.8: Maintenance Undertaken on Clay Brickwork Masonry Cavity Walls

Plate 15: Example of a Repair Where the Original Bricks have been Reused

Plate 16: 1930's End Terraced House Where Whole Gable Wall Was Recently Rebuilt with New Brickwork

Due to the limited number of older buildings surveyed, it was not possible to derive all of the values shown in Tables 5.7 and 5.8 direct from actual survey data. For instance, only three of the properties were over 500 years of age and because of their importance to the country, they had all been *listed* and their owners had a statutory duty to ensure that they were well maintained and they were all, therefore, classed as being subjected to a good standard of maintenance. As a consequence, there was no data available for the poor and average maintenance regimes at 500 years. A similar problem also occurred at 300 years as there were only eight buildings older than that age. To overcome this, the datasets for the poor and average maintenance regimes were derived to a maximum of 150 years and the dataset for the good maintenance regime to 500 years. The three datasets were then analysed and compared to determine estimates for the missing values.

It is recognised that this methodology was not ideal and that the data for the poor and average maintenance regimes at the higher ages for the solid and cavity walls, in Table 5.7 and Table 5.8 respectively, should be considered in the light of these comments. With hindsight, it might have been preferable to undertake a more thorough review of books such as the *Buildings of England* series [Pevsner, 1966, 1967, and 1972] and *A History of English Brickwork* [Lloyd, 1925] to identify additional historical buildings that could have been included in the survey work. It is unlikely, however, that even if these additional surveys had been undertaken, that there would have been a sufficient number of poorly or averagely maintained buildings to determine this information. This is because of the various schemes and laws that are designed to preserve historic buildings in the U.K.

In Tables 5.7 and 5.8, the maintenance data for solid walls is shown at intervals up to 500 years but only up to 150 years for cavity walls. This is because the oldest cavity walled buildings that were surveyed were between 100 years and 150 years old. From the analysis of the survey data it was observed that, generally, cavity walls do not appear to be as robust as traditional solid walls. It was decided, therefore, that the maintenance data for cavity walls should not be extrapolated past 150 years. It can be seen from Tables 5.7 and 5.8 that for buildings with cavity masonry walls that had been subjected to a good maintenance regime, approximately twice the amount of brickwork had been repaired and replaced as similar aged solid walls subject to similar good maintenance. This trend was not repeated for cavity walls up to 100 years old subject to average and poor maintenance regimes, where the amounts of maintenance carried out was very similar to that on solid walls. However, after 150 years, cavity walls had once again been apparently subjected to approximately twice the maintenance of 150 year old solid walls. There are several possible explanations for the poorer performance of cavity walls which have already been described in Paragraph 5.3.2.

5.4 MAXIMUM LIFE OF BRICKWORK

Figure 5.2, which was derived from the data in Tables 5.7 and 5.8, shows the percentage of brickwork that was replaced in solid and cavity walls subjected to a good standard of maintenance at different ages. It can be seen that, for solid walls, 20 % of the external skin had been replaced after 150 years whereas 40 % had been replaced in cavity walls after the same period. Using these figures it was possible to estimate the age at which 100 % of the original brickwork in the outer skin of the walls would have been replaced. It has to borne in mind that these values are derived from the initial survey data, which in itself was to a degree, inevitably, subjective. The results are, nevertheless, thought to be useful in that they provide a general indication of the longevity and possible maximum life span of the bricks originally used for the construction of the masonry walls that were originally surveyed.

It can be seen from Figure 5.2 that whilst it would take 650 years for the all of the original bricks in the outer skin of a solid masonry wall to be replaced, it would appear to only take some 197 years for the bricks in a cavity wall to be entirely replaced. This appears to confirm the early observation made in Paragraph 5.3.2 that the external leaf of cavity walls are less robust / durable than solid walls.

It is possible, however, that it might also be the consequence of using the maintenance data which were originally intended for the life-cycle assessment and life-cycle costing analyses only. For instance, because most of the solid walled properties included in the survey were at least 100 years old, it is possible that only the very best buildings now remain and any inferior buildings had previously been demolished. With the exception of two buildings, however, all of the cavity walls were less than 100 years old. As a consequence, they might present a more representative range of the quality of the brickwork walling found in housing generally. The problem of poorer performance might also be exacerbated by declining standards of modern workmanship and relatively recent changes in working practice on site that have increased the speed of construction. The actual reason for the apparent poorer performance of cavity walls compared to solid walls remains unknown however.

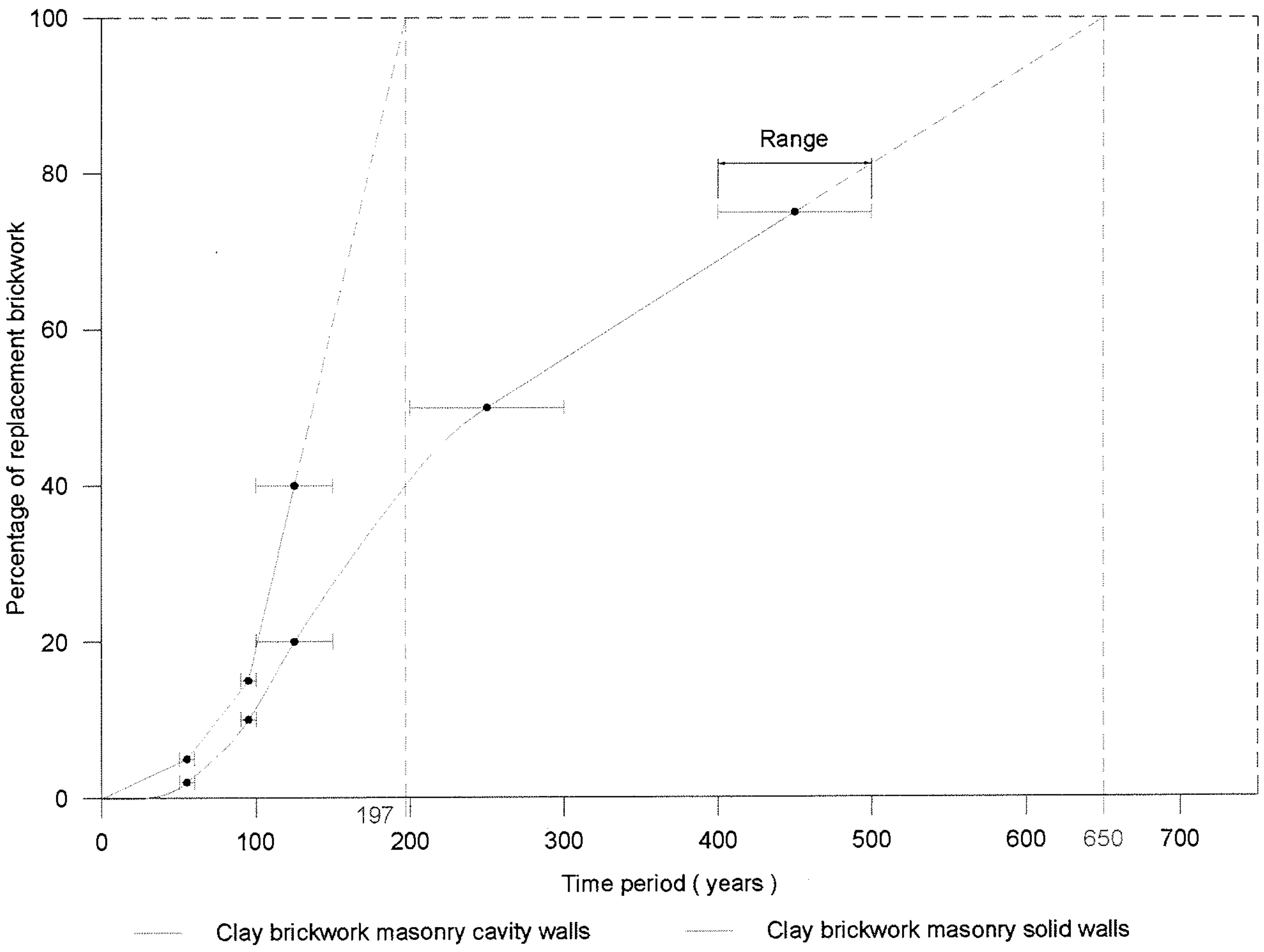


Figure 5.2: Replacement of Outer Skin Brickwork with Time for Solid and Cavity Walls

CHAPTER 6: LIFE-CYCLE ASSESSMENT AND LIFE-CYCLE COSTING ANALYSES

6.1 WALL TYPES USED IN LIFE-CYCLE ANALYSES

The eight forms of solid and cavity walls that were used in the life-cycle assessment and life-cycle costing analyses are shown in Figure 4.2; their selection was previously described in Paragraph 4.5.1.1.

6.1.1 *U* VALUES OF WALLS USED IN LIFE-CYCLE ANALYSES

As previously described in Paragraph 4.5.2, the *U*-values were determined for the eight wall types so that comparisons could be made between energy required to heat a building over its life and the embodied energy of the walling construction materials. The *U*-values for the walls are shown in Table 6.1; their derivation is described in Appendix E.

Description of wall		*U*-value for walls (W / m^2.$^\circ$K)
Wall 1	215 mm thick solid brickwork; painted plasterboard internal finish	2.59
Wall 2	328 mm thick solid brickwork; painted plasterboard internal finish	2.08
Wall 3	102 mm brickwork outer leaf; 75mm cavity, 102 brickwork inner leaf, painted plasterboard internal finish	1.79
Wall 4	Rendered 125 mm external insulation; 215 mm thick solid brickwork; painted plasterboard internal finish	0.35
Wall 5	Rendered 120 mm external insulation; 328 mm thick solid brickwork; painted plasterboard internal finish	0.35
Wall 6	Rendered 110 mm external insulation; 102 mm brickwork outer leaf; 102 brickwork inner leaf, painted plasterboard internal finish	0.35
Wall 7	102 mm brickwork outer leaf; 75 mm cavity insulation; 140 mm 7 N/mm^2 blockwork inner leaf, painted plasterboard internal finish	0.34
Wall 8	102 mm brickwork outer leaf; 110 mm cavity insulation; timber construction inner leaf, painted plasterboard internal finish	0.35

Table 6.1: *U*-values for the Walls Used in the Life-Cycle Analyses

It can be seen from Table 6.1 that the three externally insulated walls and the brickwork / blockwork and brickwork / timber cavity walls, Walls 4 to 8 respectively, have a maximum *U*-value of 0.35 W / m^2.°K. They therefore comply with the current requirement for the thermal performance of external walls.

Table 6.2 shows the current and historic legislative requirements for the thermal performance of externals walls. It can be seen that the requirements are becoming increasingly restrictive.

	Maximum *U* - value for external walls (W / m^2.°K)
1965	1.56 (converted from imperial units)
1976	1.00
1986	0.60
1990	0.45
1995	0.45
2002	0.35

Table 6.2: Legislative Revisions to the Requirements for the Thermal Performance of External Walls

Notes: The values from 1965 to 1995 values were obtained from Mitchell's Environment and Services [Burberry, 1997]. The 2002 value was taken from Table 1in The Building Regulations 2000 (2002 Edition). Approved Document L1: Conservation of Fuel and Power in Dwellings [Office of the Deputy Prime Minister, 2002].

The values in Table 6.2 were taken from The Building Regulations and are, consequently, only applicable to England and Wales. The regulations in Scotland are even more restrictive than those in the Building Regulations, however, and the current maximum allowable *U*-value is only 0.30 W / m^2.°K [Scottish Executive, 2001]. It is anticipated that the value in England and Wales will be reduced to 0.25 W / m^2.°K during the next comprehensive review of the Building Regulations in 2008 [Lowe and Bell, 2001]. As a consequence, the thickness of the insulation in / on masonry walls will need to be increased if they are to achieve such restrictive thermal performance targets. This will mean that the width of cavities in cavity walls will need to be widened to accommodate the extra insulation. The consequence on the long-term performance and structural stability of the wall from further separating the two structural leaves is unknown.

6.1.2 LIFESPAN OF WALLS USED IN LIFE-CYCLE ANALYSES

Table 6.3 shows the lifespans that were used in the life-cycle analyses for each of the wall types.

Description of wall	Assumed lifespan of brickwork in walls
Wall 1	500 years
Wall 2	500 years
Wall 3	150 years
Wall 4	500 years
Wall 5	500 years
Wall 6	150 years
Wall 7	150 years
Wall 8	100 years

Table 6.3: Lifespans for the Walls as Used in Life-Cycle Analyses

The lifespans shown in Table 6.3 are based on the earlier predictions of the maximum life of clay bricks described in Paragraph 5.4. The maximum potential lifespan was found by extrapolating the survey data to predict the theoretical age at which all of the bricks in the outer skin of the wall would have been replaced. Based on Figure 5.2, the maximum lifespan for bricks in solid walls was 650 years and 197 years in cavity walls. The lifespans used in the life-cycle analyses were reduced to 500 and 150 years respectively to provide a factor of safety in the calculations and to reflect the overall variability of the L.C.A. process generally. The lifespan for the brickwork / timber cavity wall (Wall 8) was limited to 100 years, however, as it was a relatively new form of construction whose long-term performance and durability were unknown. In addition, if the timber inner leaf fails before the brickwork outer leaf it would be near impossible to replace it without demolishing the whole wall. Also, again because of its relatively young age, it is unlikely that data from the condition surveys on brickwork / timber cavity walls would have significantly contributed towards the maintenance data in the Table 5.8 which was used to derive the lifespans.

The lifespan values used in these analyses were chosen because, whilst properly maintained brickwork walls are capable of surviving for millennia if individual bricks are replaced as necessary, the likelihood of them being demolished for other reasons increases with time. For instance, the whole-life environmental profile could be calculated for a solid wall at 1000 years if the same methodology that was used to extrapolate the L.C.A. data for cavity walls past 150 years was applied and an allowance was made for all of the bricks being replaced at 500 years. As previously discussed, however, there are many other factors that lead to buildings being demolished before they reach the end their physical lives and unless they are very exceptional, it is very unlikely that there would be a demand for buildings that can potentially last for millennia.

As noted in Chapter 5, there are difficulties with, and limitations to, the use of historical data to predict the future behaviour of a building. For instance, if a condition survey was carried out on a well-maintained property, the building would be assumed to have a long-life ahead of it and it would be scored accordingly. However, if it was then sold and neglected, its potential life could be severely shortened. This would not be reflected in the survey data and no allowance could be made for it in the subsequent analysis. A second example, which relates specifically to this project, is that of applying data that was collected on one wall to a second, possibly different wall. Although both of the walls might be solid walls constructed from bricks, the bricks in the second wall might have been manufactured differently or it might have been built to a different standard of workmanship. This reflects the difficulties of L.C.A. and L.C.C. generally.

6.2 RESULTS OF LIFE-CYCLE ASSESSMENT ANALYSIS

6.2.1 INTRODUCTION

Tables 6.4, 6.5 and 6.6 show the results of the life-cycle assessments for the eight wall types in Figure 4.2; each table relates to one of the three maintenance regimes discussed in Paragraph 4.4.2.2, namely, good, average and poor. The initial installed environmental profile data are the same in each case and were developed simply by multiplying the masses of construction materials in each of the walls with the relevant material environmental profile as provided by the B.R.E. The post-factory gate environmental profiles were developed by multiplying the maintenance data shown in Tables 5.7 and 5.8 at each of the ages in the tables by the relevant material environmental profile. The initial installed and post-factory gate environmental profile data were then combined to produce a final, whole life profile for each of the walls up to the maximum lifespan of the walls. For simplicity, it was assumed that at the end of their lives, the walls would be demolished and the waste disposed of in landfill.

The whole-life environmental profiles were then projected to 500 years so that comparisons could be made between the eight walls. In the case of Walls 3, 6 and 7, and 8 which had lifespans of 150 years and 100 years respectively, the walls were assumed to be demolished at the end of their lives and replaced with a new, similar wall. For instance, it was assumed that Wall 8 would be demolished five times during the 500-year period, at 100 years, 200 years, 300 years, 400 years and 500 years, and rebuilt four times, at 100 years, 200 years, 300 years and 400 years. This compares with Walls 1, 2, 4 and 5 which were assumed to be capable of surviving for 500 years. As a consequence, no allowance was made for them being rebuilt during the period (unless it had been specified in the maintenance data in Table 5.7).

The final output from the life-cycle assessment was a series of environmental profiles for each of the eight walls types. The profiles were originally expressed in terms of 13 impact categories but were converted to a single eco-point using the methodology described in *Digest 446* [Dickie and Howard, 2000] to allow them to be compared more easily. Because an eco-point does not include data relating to primary energy, it was included separately in Tables 6.4 to 6.6.

The data contained in Tables 6.4, 6.5 and 6.6 are also shown graphically in Figures 6.1 and 6.2. These two figures were developed so that any long-term trends in the data could be studied more easily.

		Installed environmental profile	60-year environmental profile	100-year environmental profile	150-year environmental profile	300-year environmental profile	500-year environmental profile
Wall 1	Eco-point	0.80 (0.64)	0.94 (0.66)	1.13 (0.71)	1.40 (0.77)	2.20 (0.94)	3.40 (1.11)
	Primary Energy (GJ)	1.46 (1.15)	1.90 (1.17)	2.33 (1.26)	2.85 (1.37)	4.32 (1.67)	5.64 (1.93)
Wall 2	Eco-point	1.18 (0.97)	1.34 (0.98)	1.63 (1.06)	2.01 (1.15)	3.15 (1.42)	4.90 (1.62)
	Primary Energy (GJ)	2.20 (1.73)	2.66 (1.76)	3.20 (1.89)	3.84 (2.05)	5.66 (2.50)	7.50 (2.83)
Wall 3	Eco-point	0.80 (0.64)	0.99 (0.67)	1.09 (0.71)	1.41 (0.82)	-	4.89 (2.92)
	Primary Energy (GJ)	1.46 (1.15)	1.96 (1.19)	2.30 (1.27)	2.88 (1.46)	-	9.37 (4.97)
Wall 4	Eco-point	0.99 (0.64)	1.32 (0.66)	1.55 (0.71)	1.91 (0.77)	2.81 (0.94)	3.78 (1.11)
	Primary Energy (GJ)	1.85 (1.15)	2.78 (1.17)	3.51 (1.26)	4.39 (1.37)	6.72 (1.67)	9.07 (1.93)
Wall 5	Eco-point	1.37 (0.97)	1.71 (0.98)	2.00 (1.06)	2.41 (1.15)	3.49 (1.42)	5.28 (1.62)
	Primary Energy (GJ)	2.58 (1.73)	3.53 (1.76)	4.37 (1.89)	5.37 (2.05)	8.05 (2.50)	10.92 (2.83)
Wall 6	Eco-point	0.98 (0.64)	1.34 (0.67)	1.53 (0.71)	1.92 (0.82)	-	6.58 (2.92)
	Primary Energy (GJ)	1.84 (1.15)	2.83 (1.19)	3.46 (1.27)	4.40 (1.46)	-	14.13 (4.97)
Wall 7	Eco-point	0.63 (0.32)	1.24 (0.34)	1.33 (0.37)	2.20 (0.44)	-	7.32 (1.56)
	Primary Energy (GJ)	1.06 (0.57)	2.01 (0.60)	2.32 (0.66)	3.15 (0.79)	-	10.08 (2.64)
Wall 8	Eco-point	0.48 (0.32)	0.76 (0.34)	0.97 (0.37)	-	-	4.50 (1.73)
	Primary Energy (GJ)	0.86 (0.58)	1.52 (0.60)	1.98 (0.66)	-	-	8.89 (2.97)

Table 6.4: Summary of the Life-Cycle Assessment Analysis Data for the Eight Walls Subjected to a Good standard of Maintenance

Notes: The figures in brackets, i.e. (0.64), are for the brickwork elements only

		Installed environmental profile	60-year environmental profile	100-year environmental profile	150-year environmental profile	300-year environmental profile	500-year environmental profile
Wall 1	Eco-point	0.80 (0.64)	0.91 (0.64)	0.95 (0.66)	1.12 (0.67)	1.66 (0.79)	2.69 (0.90)
	Primary Energy (GJ)	1.46 (1.15)	1.87 (1.15)	2.14 (1.17)	2.54 (1.21)	3.74 (1.40)	4.81 (1.58)
Wall 2	Eco-point	1.18 (0.97)	1.29 (0.97)	1.36 (0.98)	1.59 (1.01)	2.30 (1.19)	3.93 (1.40)
	Primary Energy (GJ)	2.20 (1.73)	2.60 (1.73)	2.89 (1.76)	3.36 (1.81)	4.75 (2.11)	6.48 (2.44)
Wall 3	Eco-point	0.80 (0.64)	0.93 (0.66)	0.98 (0.66)	1.19 (0.71)	-	4.21 (2.62)
	Primary Energy (GJ)	1.46 (1.15)	1.88 (1.15)	2.15 (1.17)	2.62 (1.27)	-	8.62 (4.44)
Wall 4	Eco-point	0.99 (0.64)	1.30 (0.64)	1.46 (0.66)	1.75 (0.67)	2.52 (0.79)	3.36 (0.90)
	Primary Energy (GJ)	1.85 (1.15)	2.74 (1.15)	3.31 (1.17)	4.08 (1.21)	6.14 (1.40)	8.24 (1.58)
Wall 5	Eco-point	1.37 (0.97)	1.68 (0.97)	1.85 (0.98)	2.17 (1.01)	3.04 (1.19)	4.11 (1.40)
	Primary Energy (GJ)	2.58 (1.73)	3.48 (1.73)	4.06 (1.76)	4.89 (1.81)	7.14 (2.11)	9.90 (2.44)
Wall 6	Eco-point	0.98 (0.64)	1.32 (0.66)	1.47 (0.66)	1.79(0.71)	-	6.22 (2.62)
	Primary Energy (GJ)	1.84 (1.15)	2.75 (1.17)	3.32 (1.17)	4.13 (1.27)	-	13.37 (4.44)
Wall 7	Eco-point	0.63 (0.32)	1.18 (0.32)	1.24 (0.33)	2.01 (0.37)	-	6.71 (1.33)
	Primary Energy (GJ)	1.06 (0.57)	1.94 (0.57)	2.22 (0.58)	2.95 (0.65)	-	9.48 (2.26)
Wall 8	Eco-point	0.48 (0.32)	0.71 (0.32)	0.89 (0.33)	-	-	4.08 (1.55)
	Primary Energy (GJ)	0.86 (0.58)	1.46 (0.58)	1.87 (0.59)	-	-	8.44 (2.65)

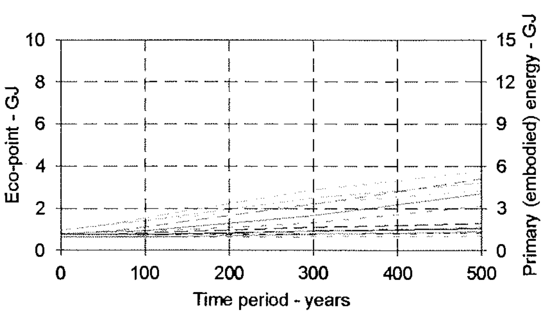
Table 6.5: Summary of the Life-Cycle Assessment Analysis Data for the Eight Walls Subjected to an Average standard of Maintenance

Notes: The figures in brackets, i.e. (0.64), are for the brickwork elements only

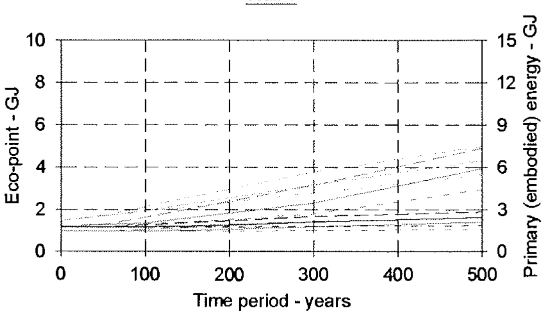
		Installed environmental profile	60-year environmental profile	100-year environmental profile	150-year environmental profile	300-year environmental profile	500-year environmental profile
Wall 1	Eco-point	0.80 (0.64)	0.90 (0.64)	0.92 (0.64)	1.00 (0.64)	1.32 (0.67)	2.11 (0.70)
	Primary Energy (GJ)	1.46 (1.15)	1.86 (1.15)	2.10 (1.15)	2.40 (1.15)	3.37 (1.20)	4.25 (1.25)
Wall 2	Eco-point	1.18 (0.97)	1.29 (0.97)	1.31 (0.97)	1.39 (0.97)	1.78 (1.01)	2.95 (1.05)
	Primary Energy (GJ)	2.20 (1.73)	2.60 (1.73)	2.83 (1.73)	3.14 (1.73)	4.19 (1.80)	5.46 (1.87)
Wall 3	Eco-point	0.80 (0.64)	0.91 (0.65)	0.96 (0.65)	1.08 (0.67)	-	3.86 (2.51)
	Primary Energy (GJ)	1.46 (1.15)	1.86 (1.15)	2.13 (1.15)	2.49 (1.19)	-	8.25 (4.22)
Wall 4	Eco-point	0.99 (0.64)	1.30 (0.65)	1.44 (0.65)	1.69 (0.65)	2.34 (0.68)	3.06 (0.71)
	Primary Energy (GJ)	1.85 (1.15)	2.74 (1.15)	3.27 (1.15)	3.94 (1.15)	5.78 (1.20)	7.68 (1.25)
Wall 5	Eco-point	1.37 (0.97)	1.69 (0.97)	1.82 (0.97)	2.07 (0.97)	2.75 (1.01)	3.57 (1.06)
	Primary Energy (GJ)	2.58 (1.73)	3.47 (1.73)	4.00 (1.73)	4.67 (1.73)	6.58 (1.80)	8.88 (1.87)
Wall 6	Eco-point	0.94 (0.64)	1.30 (0.64)	1.46 (0.64)	1.73 (0.67)	-	6.02 (2.47)
	Primary Energy (GJ)	1.84 (1.15)	2.73 (1.15)	3.29 (1.15)	4.00 (1.19)	-	13.01 (4.22)
Wall 7	Eco-point	0.63 (0.32)	1.17 (0.32)	1.22 (0.32)	1.91 (0.34)	-	6.41 (1.24)
	Primary Energy (GJ)	1.06 (0.57)	1.94 (0.57)	2.20 (0.57)	2.85 (0.60)	-	9.20 (2.12)
Wall 8	Eco-point	0.48 (0.32)	0.70 (0.32)	0.87 (0.32)	-	-	4.00 (1.52)
	Primary Energy (GJ)	0.86 (0.58)	1.45 (0.58)	1.85 (0.58)	-	-	8.36 (2.61)

Table 6.6: Summary of the Life-Cycle Assessment Analysis Data for the Eight Walls Subjected to a Poor standard of Maintenance

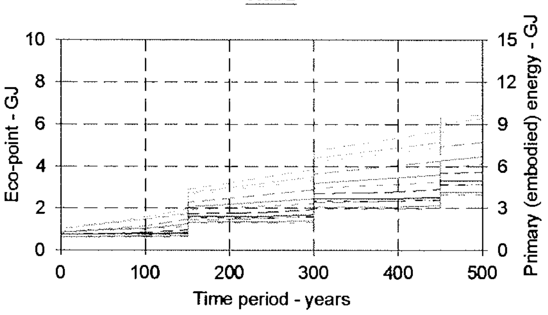
Notes: The figures in brackets, i.e. (0.64), are for the brickwork elements only



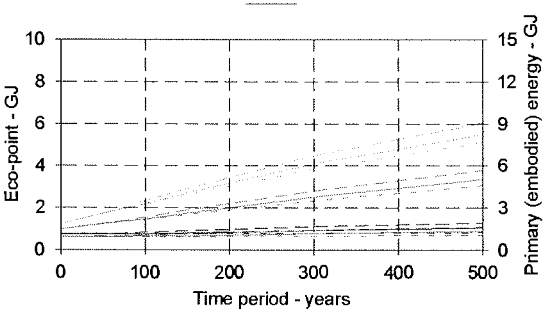
Wall 1



Wall 2



Wall 3



Wall 4

Key

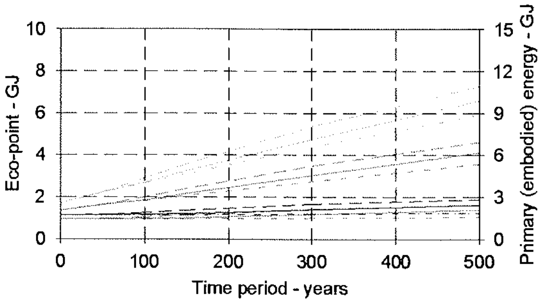
Eco-points for wall (good maintenance regime)
Eco-points for wall (average maintenance regime)
Eco-points for wall (poor maintenance regime)

Primary energy for wall (good maintenance regime)
Primary energy for wall (average maintenance regime)
Primary energy for wall (poor maintenance regime)

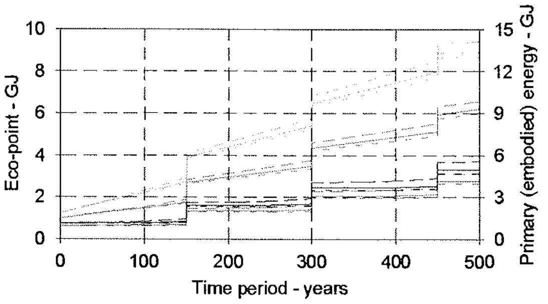
Eco-points for brickwork (good maintenance regime)
Eco-points for brickwork (average maintenance regime)
Eco-points for brickwork (poor maintenance regime)

Primary energy for brickwork (good maintenance regime)
Primary energy for brickwork (average maintenance regime)
Primary energy for brickwork (poor maintenance regime)

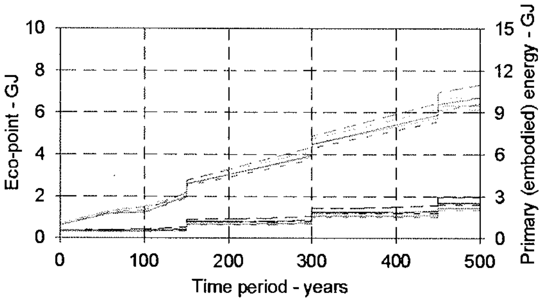
Figure 6.1: Walling Eco-points and Primary Energy at Different Lifespans



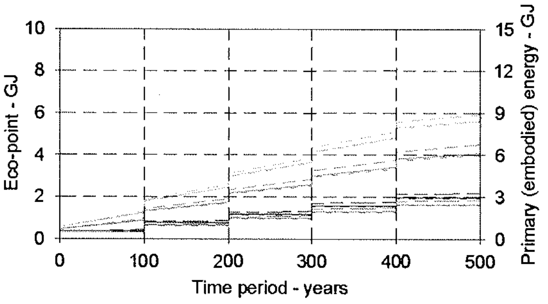
Wall 5



Wall 6



Wall 7



Wall 8

Key

Eco-points for wall (good maintenance regime)
Eco-points for wall (average maintenance regime)
Eco-points for wall (poor maintenance regime)

Primary energy for wall (good maintenance regime)
Primary energy for wall (average maintenance regime)
Primary energy for wall (poor maintenance regime)

Eco-points for brickwork (good maintenance regime)
Eco-points for brickwork (average maintenance regime)
Eco-points for brickwork (poor maintenance regime)

Primary energy for brickwork (good maintenance regime)
Primary energy for brickwork (average maintenance regime)
Primary energy for brickwork (poor maintenance regime)

Figure 6.2: Walling Eco-points and Primary Energy at Different Lifespans

6.2.2 LONG-TERM TRENDS IN THE RESULTS FROM THE L.C.A. ANALYSES

It can be seen from the results in Tables 6.4 to 6.6 that the wall with the least environmental impact over 500 years was Wall 1, i.e. a 215 mm thick solid clay brickwork masonry wall. This wall does not, however, comply with the current requirements for the thermal performance of external walls. The wall with the lowest impact that does comply with these requirements was Wall 4, a 215 mm solid masonry wall with external insulation and a cement render finish. The wall with the highest environmental impact in terms of eco-points over the 500-year period was Wall 7 (a brickwork / blockwork cavity wall with cavity insulation) and with respect to primary energy, Wall 6, a brickwork / brickwork cavity wall with external insulation and a cement render finish.

Considering the eco-point data only, the environmental impact of fully maintaining solid walls amounted to between 9 % and 33 % (1.29 eco-points / 1.18 eco-points and 1.32 eco-points / 0.99 eco-points, respectively) of the initial installed post factory gate environmental profile for the complete wall at 60 years and between 150 % and 325 % (2.95 eco-points / 1.18 eco-points and 3.40 eco-points / 0.80 eco-points, respectively) at 500 years. This compares to cavity walls, where at 60 years, the environmental impact of fully maintaining the wall was between 14 % and 97 % (0.91 eco-points / 0.80 eco-points and 1.24 eco-points / 0.63 eco-points, respectively) of the initial installed post factory gate environmental profile. At 500 years this then rose to between 383 % and 1062 % (3.86 eco-points / 0.80 eco-points and 7.32 eco-points / 0.63 eco-points, respectively). There is, consequently, a significant difference between the environmental impact of maintaining solid walls and cavity walls at all ages. Although the initial environmental profile for a cavity wall is, on average, only two-thirds that of a solid wall (0.72 eco-points compared to 1.09 eco-points), the environmental impacts produced from maintaining the wall to 500 years are nearly double those from maintaining a solid wall ((5.31 – 0.72 = 4.59 eco-points) compared to (3.52 – 1.09 = 2.43 eco-points)).

If only the maintenance of the brickwork is considered, i.e. replastering and repainting, etc. are ignored, the environmental impacts produced from maintaining the brickwork for both solid and cavity walls varied between 0 % and 5 % (0.64 eco-points / 0.64 eco-points and 0.67 eco-points / 0.64 eco-points, respectively) of the initial installed post factory gate environmental profile at 60 years and between 9 % and 440 % (1.05 eco-points / 0.97 eco-points and 1.73 eco-points / 0.32 eco-points, respectively) at 500 years. These are considerably less that the environmental impacts produced from maintaining the whole wall especially as the brickwork provided between 50 % and 82 % (0.32 eco-points / 0.63 eco-points and 0.97 eco-points / 1.18 eco-points, respectively) of the initial environment impact of the walls. This shows the general robustness of brickwork compared to other construction materials and demonstrates its good value over the longer term.

6.2.3 PRINCIPAL SOURCE OF LONG-TERM INCREASES IN LIFE-CYCLE ASSESSMENT RESULTS

From an analysis of the data, it is apparent that the main cause of the increases in the environmental impacts over the five ages considered in this project is the repainting of the internal face of the walls. Although the individual impact of repainting a wall is small, because it is carried out at 5-year intervals, the combined impact over the different ages is large. For instance, the installed mass of paint is 0.36 kg / m^2 [Anderson, Shiers and Sinclair, 2002], therefore, if the wall is assumed to be repainted at 5 years intervals, over 150 years it will be repainted 30 times and the total mass of the paint used will be 11 kg. The climate change figure for paint is 1200 kg.CO_2 / tonne and the waste disposal is 850 kg / tonne. This compares to 46 kg.CO_2 / tonne and 51 kg / tonne respectively for dense-blockwork [*ibid*, 2002]. For a 140 mm thick internal dense-blockwork wall at 150 years, the climate change impact of the blockwork is 12.6 kg.CO_2 and 26.4 kg.CO_2 for the paint (assuming that both faces of the wall are painted). The paint has nearly twice the climate change impact as the blockwork at 150 years; this compares to less than one-tenth the amount when the wall was originally built. Using a similar process, if a brickwork / blockwork external cavity wall is assumed to last for 500 years and the internal face of the wall is assumed to be repainted at regular intervals, the environmental burden from it becomes significant.

6.2.4 ENVIRONMENTAL IMPACTS - SOLID VERSUS CAVITY WALLS

As noted in Paragraph 6.2.2, there were significant differences between the environmental impacts from maintaining solid walls and cavity walls at all of the ages considered in this project. These were generally due to the lifespans used in the analyses - see Table 6.3. For instance, because the solid masonry walls were assumed to have lifespans of 500 years, the only environmental impact associated with them was from maintenance. However, because the survey data suggested that cavity walls were only capable of surviving up to 150 years, they were assumed to be demolished and rebuilt at regular intervals and an allowance was made for this in the calculations. Consequently, the environmental burden of the four solid walls, Walls 1, 2, 4, and 5 in Figure 4.2, are considerably lower than the four cavity walls, Walls 3, 6, 7 and 8.

6.2.5 EFFECT OF MAINTENANCE REGIME ON THE RESULTS FROM THE LIFE-CYCLE ASSESSMENT

As previously described in Paragraph 6.2.2, the environmental impacts for both solid and cavity walls increase with age. For both types of walls, the lowest increase was found in walls subjected to a poor standard of maintenance and the highest increase in walls subjected to a good standard of maintenance. This was expected, as the walls which were subjected to the better maintenance regimes, obviously, had more work carried out on them which required more materials to be used.

Based on the results in Tables 6.4 to 6.6 at 500 years, solid walls that are subjected to a good maintenance regime produces, on average, 23 % more environmental impacts than an average regime (4.34 eco-points compared to 3.53 eco-points); similarly, a poor standard of maintenance produces nearly 40 % less environmental impact than an average standard at the same age (2.16 eco-points compared to 3.53 eco-points). There are similar reductions in the results for cavity walls, and again when only the environmental impacts of the brickwork are considered.

It was assumed in both the L.C.A. and L.C.C. analyses that the lifespans of the walls were constant irrespective of the standard of maintenance that they were subjected to. For instance, all of the solid masonry walls in Table 6.3 were assumed to have a 500 year lifespan whether they were subjected to a poor, average, or good standard of maintenance. In reality, it is more probable that walls that are subjected to a good or average maintenance regime would survive to a greater age than similar walls subjected to either a poorer level or no maintenance. It should also be borne in mind that, as noted in Paragraph 5.3.2, maintaining brickwork does not always prolong its life as incorrect maintenance may actually hasten its decay.

6.3 COMPARISON OF THE EMBODIED ENERGY OF THE WALLS AND TYPICAL OPERATIONAL ENERGIES FOR BUILDINGS

6.3.1 ENERGY CONSUMPTION IN THE U.K.

Figure 6.3 the shows the typical breakdown of operational energy consumption for domestic housing in the U.K. This is based on Department of Trade and Industry's estimates of domestic energy consumption shown in Figure 6.4.

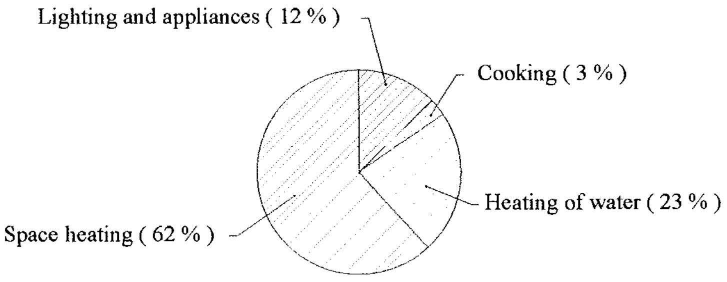


Figure 6.3: Breakdown of Operational Energy Consumption for Domestic Housing in the U.K.

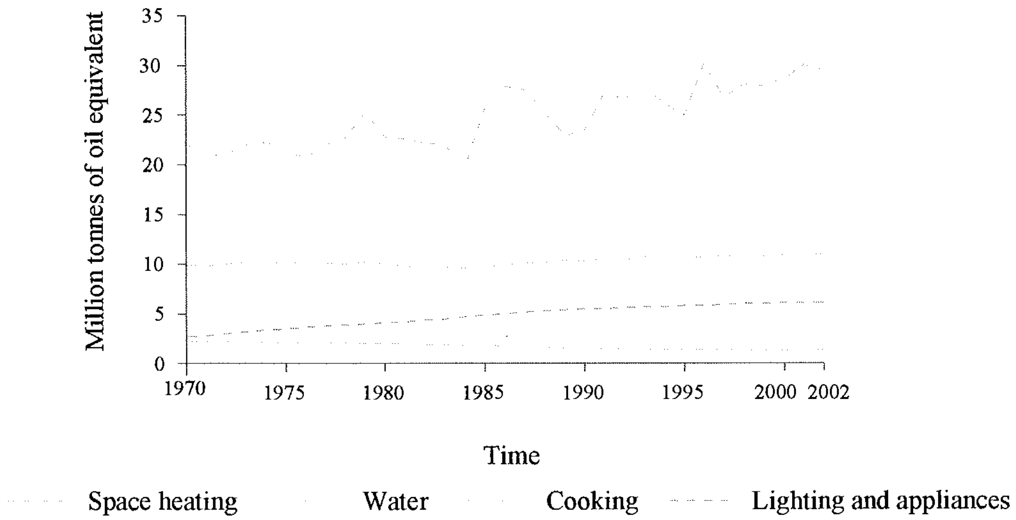


Figure 6.4: Domestic Energy Consumption in the U.K. between 1970 and 2002 (Department of Trade and Industry, 2004^{b})

Figure 6.4 shows that 85 % of energy consumed in domestic housing is used to either heat spaces or water. These are both dependent on weather conditions and, in particular, variations in temperature [Department of Trade and Industry, 2004^{c}]. It can be seen that the overall consumption of domestic energy has increased by 32 % since 1970 and by 19 % since 1990. This compares to a 10 % increase in the number of houses in the U.K. and a 4 % increase in the population of the U.K. since 1990 [*ibid*, 2004^{c}]. The Department of Trade and Industry (2004^{c}) suggest that domestic energy consumption would have increased even further if it were not for energy efficiency improvements such as increased levels of insulation and the introduction of more efficient electrical appliances.

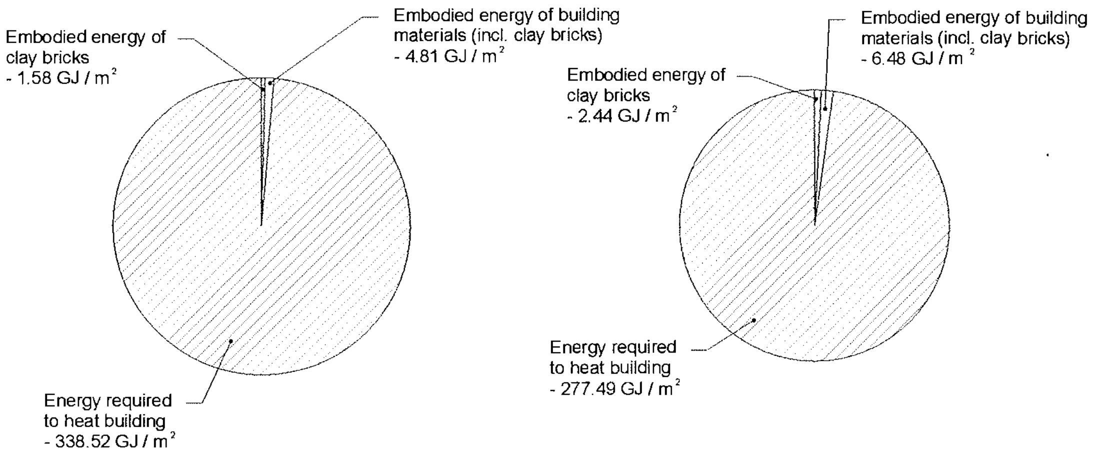
6.3.2 EMBODIED ENERGY VERSUS DOMESTIC ENERGY CONSUMPTION

Table 6.7 and Figure 6.7 compares the operational energy requirements of a room in a typical building with the embodied energy of the construction materials used in the eight external walls types considered in the earlier L.C.A. analysis. Operational energy was determined by calculating the energy required to heat the building in accordance with the methodologies described in *Mitchell's Environment and Services* [Burberry, 1997], *Environmental Science in Buildings* [McMullan, 2002] and *Appendix A* of *Approved Document L1* of The Building Regulations 2000 [Office of the Deputy Prime Minister, 2002] – Note: the building is described in Appendix E.2. A figure of 0.17 GJ / m^2 / annum was then derived from Figure 6.3, to convert heating space energy to operational energy. The values were initially determined for a single year but were then extrapolated to 500 years so that comparison could be made with the embodied energy data from the L.C.A. analysis; the embodied energy data were for an average standard of maintenance taken from Table 6.5.

It should be noted that the analysis assumes that operational energy consumption will remain constant over the whole of the study period.

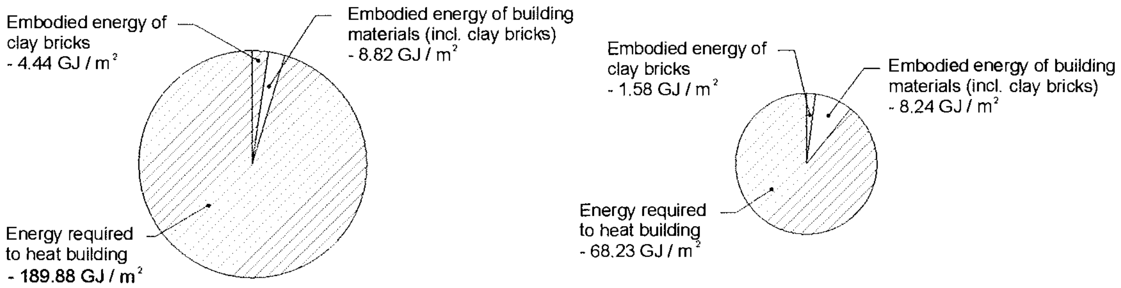
	Energy Required to Heat Building	Operational Energy Consumption over 500 years	Embodied Energy of building material (over 500-years)	
			Total	Clay brickwork only
	(GJ / m^2)	(GJ / m^2)	(GJ / m^2)	(GJ / m^2)
Wall 1	338.52	423.52	4.81	1.58
Wall 2	277.49	362.49	6.48	2.44
Wall 3	189.88	274.88	8.82	4.44
Wall 4	68.23	153.23	8.24	1.58
Wall 5	68.23	153.23	9.90	2.44
Wall 6	68.81	153.81	13.37	4.44
Wall 7	67.28	152.28	9.48	2.26
Wall 8	56.49	141.49	8.44	2.65

Table 6.7: Comparison of Operational Energy and Embodied Energy over 500-years



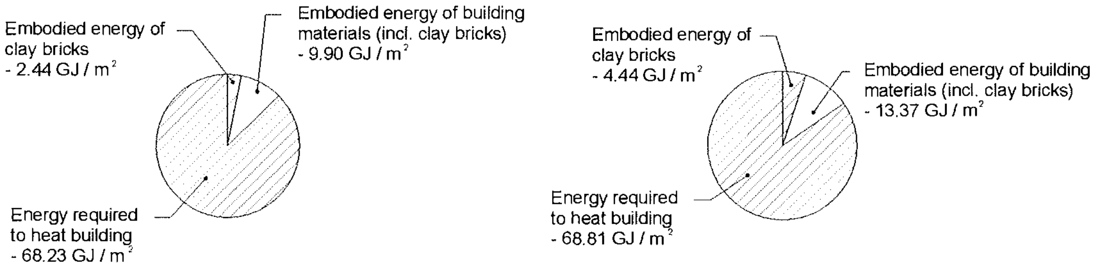
Energy requirements of Wall 1 over 500 years

Energy requirements of Wall 2 over 500 years



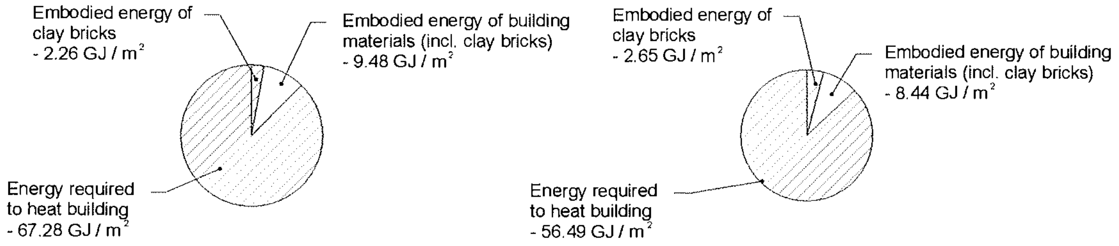
Energy requirements of Wall 3 over 500 years

Energy requirements of Wall 4 over 500 years



Energy requirements of Wall 5 over 500 years

Energy requirements of Wall 6 over 500 years



Energy requirements of Wall 7 over 500 years

Energy requirements of Wall 8 over 500 years

Figure 6.5: Comparison of Operational Energy and Embodied Energy over 500-years

Table 6.7 shows that over 500-years, the embodied energy of the walling is between 1 % and 9 % (4.81 GJ / m^2 / 425.52 GJ / m^2 and 13.37 GJ / m^2 / 153.81 GJ / m^2, respectively) of the operational energy consumption of the building depending on the wall type.

The upper figure is similar to Edwards and Hyett's (2002) estimate of the typical ratio of the *in-use* energy and embodied energy. The Institution of Structural Engineers (1999) also reported a similar figure to Edwards and Hyett in their *Building for a Sustainable Future. Construction Without Depletion* publication. In it, the authors of the comparison concluded that, '*For buildings of up to six-storeys, or so, the embodied energy* [of the structural frame and floors] *is 2.5 – 3.0 GJ / m^2, increasing in unusual circumstances to 5 GJ / m^2. This represents only 10 % of the total target energy profile required for a 60-year building life - 60 GJ / m^2*' (*ibid*, 1999). It should be borne in mind, however, that their work was based on data obtained from the B.R.E. and, as such, was based on their 60 years lifespan rather than the 500 years in Table 6.7.

The Institution of Structural Engineers figures for embodied energy and operational energy (their total target energy minus embodied energy) are very similar to those for Wall 1 at 60 years. At this age, the embodied energy of the construction materials is 1.9 GJ / m^2 and the domestic energy consumption, 51 GJ / m^2. Wall 1 is a 215 mm thick solid clay brickwork masonry wall, however, with a U-value of 2.59 W / $m^2.^\circ K$ (see Table 6.1) and as a result, it does not to comply with the current requirements for the thermal performance of external walls. If the maximum permitted *U*-value is used, the domestic energy consumption over 60 years reduces to approximately 19 GJ / m^2 and if this value is used with the embodied energy data from Table 6.5, the embodied energy represents between 7 % and 15 % of the operational energy consumed over the life of the building. This is again comparable to the two published ratios. It should be noted, however, that the published ratios are based on typical values for the building as a whole and that the figures from this thesis quoted here are for external walling only.

It can be seen from the Figure 6.5 that for the traditional and upgraded solid and brickwork / brickwork cavity masonry walls, significant reductions can be achieved in the energy required to heat a building without accompanying massive increases in the embodied energy of the construction materials. For instance, the embodied energy of the buildings materials for Wall 1 (a 215 mm thick solid) is 4.81 GJ / m^2 and the energy required to heat the building is 338.52 GJ / m^2. This compares to 13.37 GJ / m^2 and 68.81 / m^2 respectively for Wall 4, an upgraded, externally insulated, 215 mm solid wall. This means that the energy required to heat the building was reduced by nearly 270 GJ / m^2 (338.52 GJ / m^2 - 68.81 GJ / m^2) compared to a 9 GJ / m^2 increase in the embodied energy of the construction materials. This is a net saving of 260 GJ / m^2.

This would have a major impact on the U.K.'s consumption of fossil fuels and emissions of greenhouse gases, if these measures could be applied to the bulk of the existing housing stock. It also, again, demonstrates the general adaptability and flexibility of brickwork and shows its good value over the longer term.

6.3.3 LONG-TERM EFFECT ON DOMESTIC ENERGY CONSUMPTION OF INCREASING REQUIREMENTS FOR THERMAL PERFORMANCE FOR EXTERNAL WALLS

As previously discussed in Paragraph 6.1.1, it is very unlikely that the requirements for the thermal performance of external walls will remain at their current level. As the energy required to heat the building reduces, the apparent *burden* of the embodied energy of the construction materials will increase even if the actual embodied energy remains constant. It should be noted, however, that if the thermal requirements increase, the thickness of the insulation will also have to increase which would increase the embodied energy of the construction materials.

Table 6.8 shows the results from a comparison of the in-service energy requirements of a building which has external walls with *U*-values of 0.35 W / m^2.°K, 0.30 W / m^2.°K and 0.25 W / m^2.°K. In accordance with the methodologies described in Paragraph 6.3.2, 1 °C was added to the mean internal temperature for walls of heavyweight construction and 1 °C subtracted for lightweight constructed walls.

Using the data from Paragraph 6.3.2, if the *U*-value of the external walls are reduced to 0.30 W / m^2.°K and 0.25 W / m^2.°K, the operational energy consumed over 60 years would similarly reduce to approximately18 GJ / m^2 and 17 GJ / m^2 respectively. At 60 years, the ratio of the embodied energy to domestic energy for Wall 5 would increase from 15 % to 21 % if the *U*-value was reduced from 0.35 W / m^2.°K to 0.25 W / m^2.°K.

	U-value of walls	Mean Internal temperature	Mean external temperature	Energy required to heat building	Operational Energy Consumption
	($W / m^2.^\circ K$)	($^\circ C$)	($^\circ C$)	(GJ / m^2 / annum)	(GJ / m^2 / annum)
Heavyweight construction	0.35	17.5	5.5	0.14	0.31
	0.30	17.5	5.5	0.12	0.29
	0.25	17.5	5.5	0.11	0.28
Lightweight construction	0.35	15.5	5.5	0.09	0.26
	0.30	15.5	5.5	0.08	0.25
	0.25	15.5	5.5	0.07	0.24

Table 6.8: Comparison of Different *U*-Values on the Energy Required to Heat a Building

6.4 RESULTS OF LIFE-CYCLE COSTING ANALYSIS

Tables 6.9, 6.10 and 6.11 show the results of the life-cycle costing analyses carried out on the eight wall types shown in Figure 4.2; each table relates to one of the three maintenance regimes discussed in Paragraph 4.4.2.2, namely, good, average and poor.

Data on initial costs of construction data were obtained from *Spon's Architects' and Builders' Price Book* [Davis, Langdon and Everest, 2003]. The costings were developed using a similar methodology to that used to develop the whole-life environmental profiles described in Paragraph 4.5.1, i.e. the same maintenance data and lifespans. Again, as with the whole-life environmental profiles, the initial and post-factory gate costings were then combined to produce a final, *cradle-to grave* life costing for each of the wall types.

Once the whole-life costing had been obtained for each of the walls, the results for the cavity walls were projected to 500 years to allow comparisons to be made with that for solid walls. As with the life-cycle assessment analyses, the cavity walls were again assumed to have a lifespan of between 100 and 150 years and an allowance was made in the calculations for them being demolished and replaced several times during the 500 years.

It should be noted that the prices given in *Spon's Architects' and Builders' Price Book* [Davis, Langdon and Everest, 2003] are divided into two sections; a section for major works (where the value of the works exceeds £ 40,000), and a section for minor works. It was decided to use the prices from the Major Works section for the initial cost of construction during the life-cycle costing analyses and the prices from the Minor Works section for the maintenance and demolition works. This was because it was assumed that the likely cost of constructing a new building would be in excess of £ 40,000 whereas the cost of the maintenance and demolition would be below that value, especially if the activities were carried out at regular intervals.

The data contained in Tables 6.9, 6.10 and 6.11 are also shown graphically in Figures 6.6 and 6.7. These were developed so that any long-term trends in the data could be identified more easily.

Description of wall	Initial cost of construction	Whole-Life Cost at 60 Years	Whole-Life Cost at 100 years	Whole-Life Cost at 150 years	Whole-Life Cost at 300 years	Whole-Life Cost at 500 Years
	(£ / m^2)	(£ / m^2)	(£ / m^2)	(£ / m^2)	(£ / m^2)	(£ / m^2)
Wall 1	81.41 (61.14)	168.04 (70.63)	214.68 (93.35)	285.20 (107.46)	493.92 (146.95)	735.66 (188.51)
Wall 2	108.26 (87.99)	198.68 (101.27)	249.12 (127.79)	319.64 (141.90)	532.16 (185.19)	779.44 (232.29)
Wall 3	87.60 (66.10)	187.73 (89.09)	218.86 (96.30)	302.69 (123.72)	-	1155.15 (480.29)
Wall 4	174.18 (61.14)	303.17 (70.63)	611.37 (93.35)	681.90 (107.46)	1060.08 (146.95)	1473.38 (188.51)
Wall 5	197.35 (87.99)	330.14 (101.27)	714.26 (127.79)	784.79 (141.90)	1166.76 (185.19)	1585.60 (232.29)
Wall 6	172.16 (66.10)	314.65 (89.09)	430.51 (96.30)	514.34 (123.72)	-	1890.33 (480.29)
Wall 7	96.73 (33.05)	209.20 (56.04)	248.81 (63.25)	371.26 (90.67)	-	1246.07 (327.87)
Wall 8	89.09 (33.05)	196.68 (56.04)	249.58 (63.25)	-	-	1214.68 (331.83)

Table 6.9: Summary of the Life-Cycle Costing Analysis Data for the Eight Walls Subjected to a Good Standard of Maintenance

Notes:

- The figures are based on 2003 prices with no annual inflation
- The figures in brackets, i.e. (61.14), are the life-cycle costings for the brickwork elements only

Description of wall	Initial cost of construction	Whole-Life Cost at 60 Years	Whole-Life Cost at 100 years	Whole-Life Cost at 150 years	Whole-Life Cost at 300 years	Whole-Life Cost at 500 Years
	(£ / m^2)	(£ / m^2)	(£ / m^2)	(£ / m^2)	(£ / m^2)	(£ / m^2)
Wall 1	81.41 (61.14)	162.17 (64.76)	191.96 (70.63)	260.93 (83.19)	455.54 (137.91)	697.28 (150.13)
Wall 2	108.26 (87.99)	190.54 (93.13)	222.60 (101.27)	291.58 (113.84)	489.98 (172.35)	737.26 (190.11)
Wall 3	87.60 (66.10)	167.18 (68.54)	205.99 (83.43)	282.18 (103.21)	-	1134.60 (418.71)
Wall 4	174.18 (61.14)	297.30 (64.76)	411.82 (70.63)	480.79 (83.19)	844.86 (137.91)	1258.16 (150.13)
Wall 5	197.35 (87.99)	321.99 (93.13)	438.79 (101.27)	507.76 (113.84)	875.62 (172.35)	1294.46 (190.11)
Wall 6	172.16 (66.10)	294.10 (68.54)	417.65 (83.43)	493.83 (103.21)	-	1828.76 (418.71)
Wall 7	96.73 (33.05)	179.09 (35.49)	221.78 (50.38)	324.78 (70.16)	-	1124.93 (266.29)
Wall 8	89.09 (33.05)	170.66 (35.49)	227.08 (50.38)	-	-	1124.71 (280.38)

Table 6.10: Summary of the Life-Cycle Costing Analysis Data for the Eight Walls Subjected to an Average Standard of Maintenance

Notes:

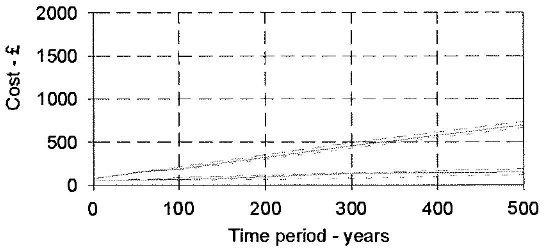
- The figures are based on 2003 prices with no annual inflation
- The figures in brackets, i.e. (61.14), are the life-cycle costings for the brickwork elements only

Description of wall	Initial cost of construction	Whole-Life Cost at 60 Years	Whole-Life Cost at 100 years	Whole-Life Cost at 150 years	Whole-Life Cost at 300 years	Whole-Life Cost at 500 Years
	(£ / m^2)	(£ / m^2)	(£ / m^2)	(£ / m^2)	(£ / m^2)	(£ / m^2)
Wall 1	81.41 (61.14)	158.55 (61.14)	182.47 (61.14)	242.50 (64.76)	430.16 (83.19)	667.47 (120.32)
Wall 2	108.26 (87.99)	185.40 (87.99)	209.32 (87.99)	270.87 (93.13)	460.81 (113.84)	703.66 (156.51)
Wall 3	87.60 (66.10)	164.74 (66.10)	200.56 (78.00)	263.07 (84.10)	-	1074.85 (358.96)
Wall 4	174.18 (61.14)	293.68 (61.14)	402.33 (61.14)	462.36 (64.76)	819.48 (83.19)	1228.35 (120.32)
Wall 5	197.35 (87.99)	316.85 (87.99)	425.50 (87.99)	487.05 (93.13)	846.45 (113.84)	1260.86 (156.51)
Wall 6	172.16 (66.10)	291.67 (66.10)	412.22 (78.00)	474.74 (84.10)	-	1769.00 (358.96)
Wall 7	96.73 (33.05)	173.87 (33.05)	209.69 (44.95)	293.46 (51.05)	-	1025.75 (206.54)
Wall 8	89.09 (33.05)	166.23 (33.05)	216.37 (44.95)	-	-	1081.85 (258.65)

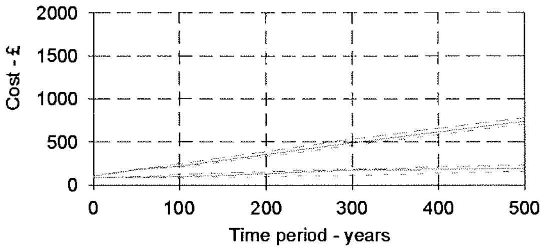
Table 6.11: Summary of the Life-Cycle Costing Analysis Data for the Eight Walls Subjected to a Poor Standard of Maintenance

Notes:

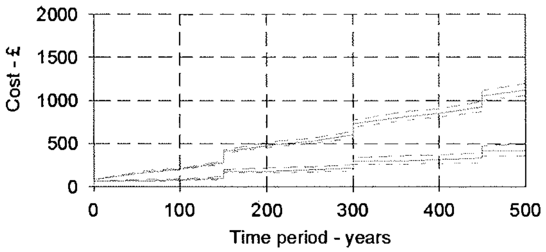
- The figures are based on 2003 prices with no annual inflation
- The figures in brackets, i.e. (61.14), are the life-cycle costings for the brickwork elements only



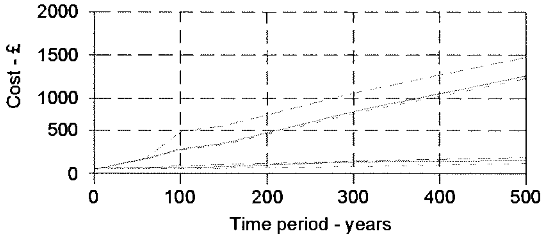
Wall 1



Wall 2



Wall 3

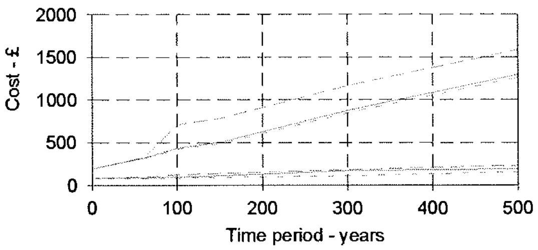


Wall 4

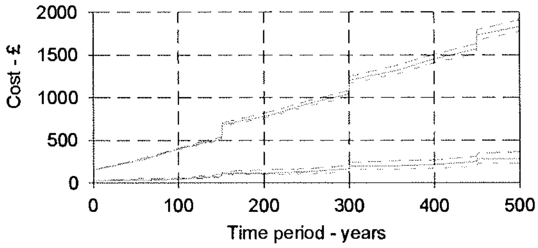
Key

Whole-life cost for 1 m^2 wall (good maintenance regime)
Whole-life cost for 1 m^2 wall (average maintenance regime)
Whole-life cost for 1 m^2 wall (poor maintenance regime)
Whole-life cost for 1 m^2 brickwork (good maintenance regime)
Whole-life cost for 1 m^2 brickwork (average maintenance regime)
Whole-life cost for 1 m^2 brickwork (poor maintenance regime)

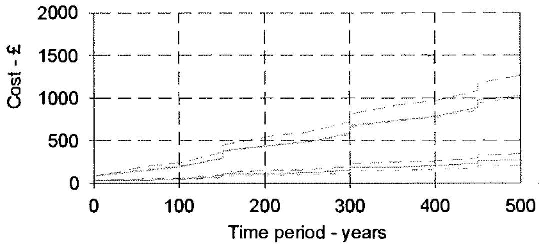
Figure 6.6: Results from the Life-Cycle Costing Analyses for Walls 1 to 4



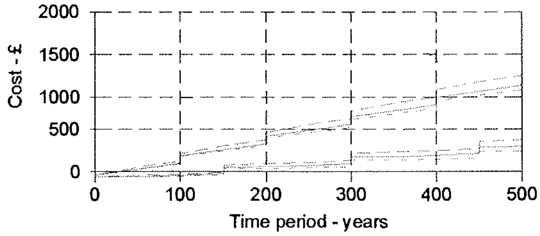
Wall 5



Wall 6



Wall 7



Wall 8

Key

Whole-life cost for 1 m^2 wall (good maintenance regime)
Whole-life cost for 1 m^2 wall (average maintenance regime)
Whole-life cost for 1 m^2 wall (poor maintenance regime)
Whole-life cost for 1 m^2 brickwork (good maintenance regime)
Whole-life cost for 1 m^2 brickwork (average maintenance regime)
Whole-life cost for 1 m^2 brickwork (poor maintenance regime)

Figure 6.7: Results from the Life-Cycle Costing Analyses for Walls 5 to 8

It can be seen from Figures 6.6 and 6.7 that, as expected, the costings for the walls increase with age. As with the life-cycle assessment, it can be seen that of the eight walls considered in the analysis, Wall 1 (a 215mm solid brickwork wall) had the lowest whole-life costs over 500 years. Again, as with the life-cycle assessment, the wall with the lowest whole-life costs that complied with the current Building Regulations requirements for the thermal performance of external walls [Office of the Deputy Prime Minister, 2002] was Wall 4 - a 215mm solid brickwork wall with external insulation and a cement render finish. The wall with the greatest whole-life costs over 500 years (for all maintenance regimes) was Wall 6, an externally rendered brickwork / brickwork cavity wall.

The analysis showed that during the first 60 years, the cost of maintaining a solid wall amounted to between 61 % and 106 % (£ 316.85 m^{-2} / £ 197.35 m^{-2} and £ 168.04 m^{-2} / £ 81.41 m^{-2}, respectively) of the initial cost of construction for the wall. Similarly at 100 years it ranged between 72 % and 162 % of the initial cost and at 500 year between 539 % and 804 % (£ 185.40 m^{-2} / £ 108.26 m^{-2}, £ 214.68 m^{-2}/ £ 81.41 m^{-2}, £ 1260.86 m^{-2} / £ 197.35 m^{-2} and £ 735.66 m^{-2}/ £ 81.41 m^{-2}, respectively). If only the maintenance of the brickwork is considered, i.e. excluding the cost of replastering, repainting, etc., the maintenance at 60 years reduces to between 0 % and 6 % (£ 61.14 m^{-2} / £ 61.14 m^{-2} and £ 93.13 m^{-2} / £ 87.99 m^{-2}, respectively) of the initial cost of the wall and even at 500 years, the cost of maintaining the brickwork was still only between 78 % and 146 % (£ 156.51 m^{-2} / £ 87.99 m^{-2} and £ 150.13 m^{-2} / £ 61.14 m^{-2}, respectively) of the initial cost of construction.

Similarly for cavity walls, the cost of maintaining the wall during the first 60 years, amounts to between 69 % and 120 % (£ 291.67 m^{-2} / £ 172.16 m^{-2} and £ 196.68 m^{-2} / £ 89.09 m^{-2}, respectively) of the initial cost of wall construction and at 500 year between 928 % and 1264 % (£ 1769.00 m^{-2} / £ 172.16 m^{-2} and £ 1214.68 m^{-2} / £ 89.09 m^{-2}, respectively). If only the maintenance of the brickwork is considered, the cost over the first 60 years is between 0 % and 70 % (£ 61.14 m^{-2} / £ 61.14 m^{-2} and £ 56.04 m^{-2} / £ 33.05 m^{-2}, respectively) of the initial cost of the wall and at 500 years it is between 443 % and 900 % (£ 120.32 m^{-2} / £ 66.10 m^{-2} and £ 331.83 m^{-2} / £ 33.05 m^{-2}, respectively).

These values show that the maintenance requirements of the brickwork were lower than those of the wall as a whole. As with the L.C.A. data, this was partially expected because of the values that were used for the maintenance requirements in the models. For instance, it was assumed that a poorly maintained solid masonry wall would only require minimal maintenance to the brickwork up to 300 years but that the internal face of the wall would be repainted 60 times during the same period. Despite this, the difference between the maintenance requirements of the wall as a whole and the brickwork demonstrates the robustness, and general good value, of brickwork compared to other construction materials over the longer term.

The results are similar to the findings from the L.C.A. analysis, i.e. that over the long-term, solid walls appear to outperform cavity walls. This was only partially explained by the difference in maintenance requirements assumed for the two wall types. It is also caused by the different lifespans, which means an allowance had to be made in the cavity wall calculations for them being demolished and rebuilt which was not required in the solid wall calculations.

For both wall types, the lowest costs were associated with walls subjected to a poor standard of maintenance. Similarly, the highest values in the range were for walls subjected to a good standard of maintenance. Based on the L.C.C. data in Tables 6.9 to 6.11, subjecting a solid brickwork wall to a good standard of maintenance costs 17 % more than subjecting it to an average standard of maintenance at 500 years (£ 1003.22 m^{-2} compared to £ 856.49 m^{-2}); there is, however, only a 6 % increase in the same cost for a cavity wall (£ 1265.16 m^{-2} compared to £ 1191.86 m^{-2}). Similarly, if a solid brickwork wall is subjected to a poor, rather than average, standard of maintenance, there is a 5 % reduction in the costs for both wall types; £ 824.79 m^{-2} compared to £ 856.49 m^{-2} for solid walls and £ 1126.47 m^{-2} compared to £ 1191.86 m^{-2} for cavity walls. There are similar differences when only the brickwork is considered rather than the walls as a whole.

The life-cycle costing analysis also showed that the cheapest wall at all ages was a poorly maintained 215mm solid masonry wall. This was because, unlike a cavity wall that requires additional components such as insulation, wall ties, etc., a solid masonry wall is, essentially, just bricks and mortar. In addition, the condition surveys indicated that solid walls were more durable than cavity walls. Whole-life operational energy costs associated with each of the walls are not, however, included in final costs shown in Tables 6.9 to 6.11. It is unlikely that an un-insulated solid wall would continue to be the cheapest form of walling if the operational energy costs were also included.

Finally, the L.C.C. analysis assumed that the lifespan of the walls would not be influenced by the maintenance regime that they were subjected to. This is a simplistic assumption which was previously discussed in Paragraph 5.3.3.

6.4.1 USE OF ACCOUNTING TECHNIQUES AND INCLUSION OF INFLATION IN LIFE-CYCLE COSTING ANALYSES

The whole-life costings in Tables 6.9 to 6.11 were determined using a simple aggregation calculation, where the costs of the materials, maintenance and replacement were added together over the life of a building and no account was taken of the future value of money [Williams, 2001]. There are, however, several more sophisticated accounting techniques that could have been used to evaluate the life-cycle costings of buildings. These include, *inter alia,* the Net Present Value (N.P.V.) method which is based on Discount Cash Flow analysis (D.C.F.). This essentially works on the principle that if the cost of some work (such as maintenance) can be delayed to a later date, then the money that the work would cost can be invested elsewhere and the interest earned in the intervening period can be used to reduce the future cost of the work. For example, a team of designers might be given the choice between two items of plant. Using a simple aggregation method, if the first costs £ 10,000 and has a design life of 20 years and the second costs £ 6,000 and has a design life of 10 years, and the plant is required for a period of 20 years, the designers might choose to install the first item of plant. If D.C.F. analysis is used instead and it is assumed that the designers could achieve a net return of 6 % on their investment, they would only have to invest £ 3350.37 [Williams, 2001] at the start of the work for it to be worth £ 6,000 10 years later. Therefore, over a 20-year period, the second item of plant would only *cost* £ 9350.37 at *today's* prices and it would therefore be the most cost-effective option. The N.P.V. is the net value of all of the discounts [The British Constructional Steelwork Association Ltd., 2002], therefore, in the above example, the N.P.V. of the first item of plant would be £ 10,000 and the N.P.V. of the second item would be £ 9350.37. The effects of inflation and changes in prices are normally included in D.C.F. analysis but, for simplicity, these items were disregarded in the above example.

For this research project, it was originally intended that various scenarios would be tested using D.C.F. analysis to assess its effect on the whole-life costings of masonry walling and to validate the final costings in Tables 6.9 to 6.11. For instance, if the whole-life costings of Wall 3 (a brickwork / brickwork cavity wall) are compared to those of Wall 8 (a brickwork / timber cavity wall), using the simple aggregation method it can be seen that Wall 8 costs approximately twice as much as Wall 3 at 500 years. Although the initial costs of construction of both walls are very similar and both have similar maintenance requirements, the lifespan assumed for Wall 8 was 100 years and the lifespan of Wall 3 was 150 years. In such circumstances, it was thought that the results from a D.C.F. analysis might be of interest in relation to assessing L.C.C.

An original aim was to assess the effect of monetary inflation on the whole-life costings of masonry walling. It quickly became apparent during the project that, because of the relatively long periods of time that were being considered any such results that were calculated were virtually meaningless. This is not unique to this project and would, in fact, occur whenever attempts are made to project the annual rate of inflation particularly, or any other relatively large and volatile variable, over such long periods of time. For example, if the current value of an object is £1 and the net annual rate of inflation is 5 %, in one-year it would only be worth £ 0.95 and in ten years £ 0.62. However, if the rate of inflation is increased to 6 %, in one year it would be worth £ 0.94 and in ten years £ 0.56. If the figures are projected forward 60 years, the object would be worth £ 0.05 if the rate of inflation is 5% and £ 0.03 if the rate of inflation is 6 % [Davidson, 1989]. For masonry, with lifespans in excess of three figures, the process becomes futile.

Further problems arise in attempting to predict sensible values for the rate of inflation over the periods being considered. For instance although the U.K.'s annual rate of inflation peaked at almost 27 % in 1975, the average rate over the last three decades was 8 %. Since 1997 when the control for the country's monetary policy was transferred from the Government to the Bank of England via *The Bank of England Act 1998*, the average rate has been approximately 1.5 %, however. These figures basically show that it is almost impossible to include any realistic allowances for inflation in the life-cycle costing analyses of construction materials and products with long lives. By comparison, such data for inflation can be used, and indeed are ideal, for items with relatively short lives such as photocopiers. In practice, therefore, published tables that show the effects of D.C.F. analysis or monetary inflation at different ages are, in general, limited to 25 years. It is worth noting that the B.R.E., however, automatically include D.C.F.'s in the life-cycle costings in *Envest II* software package, and users must actively deselect it if they do not want it applied. In addition, although the program allows users to select occupancy periods for their buildings of between 5 and 100 years, it provides very little guidance about D.C.F. generally and no guidance about how to choose appropriate values at different ages.

Because of the inherent problems associated with these variables, it was decided not to include any allowance for inflation or to apply D.C.F. accounting techniques to the results from the life-cycle costing analyses shown in Tables 6.9 to 6.11.

6.5 COMPARISON OF RESULTS FROM L.C.A. AND L.C.C. ANALYSES

The results from the life-cycle assessment and life-cycle costing analyses show that, overall, Wall 1, i.e. a 215 mm solid brickwork wall, has the least environmental and economic impact of the eight wall types considered. As previously noted, this wall does not, however, comply with the current requirements for the thermal performance of external walls in the U.K. With respect to the life-cycle costings and primary energy environmental impact category, Wall 6 had the greatest overall impact of the eight walls.

In terms of both life-cycle assessment and life-cycle costing analyses, the biggest increases occurred in cavity walls. This was due to the fact that they required more maintenance than solid walls and additionally, their maintenance requirements were more problematic, e.g. the replacement of cavity wall ties, which would have made them more expensive.

The principal cause of the increases in both life-cycle impacts and costings was the re-painting of the wall. This was because of the frequent nature of this activity compared to the other forms of maintenance that were carried out on the walls.

6.5.1 COMBINING THE RESULTS FROM L.C.A. AND L.C.C. ANALYSES

Figure 6.8 shows life-cycle assessment data plotted against life-cycle costings for each of the walls. This was done to produce a *best value* solution, as recommended by both the B.R.E. in their Digest 452 [Edwards, Bartlett and Dickie, 2000] and the Institution of Structural Engineers [The Institution of Structural Engineers, 1999].

The results for both life-cycle impacts and costings were based on the average standard of maintenance at 500 years only – see Tables 6.5 and 6.10. It is possible to produce a separate table and figure for each of the maintenance regimes at each of the ages but this would have resulted in eighteen different sets of tables and figures. An evaluation of these data showed that the walls, in practice, followed the same pattern of behaviour as that shown in Figure 6.8, and, therefore, these graphs have not been included here.

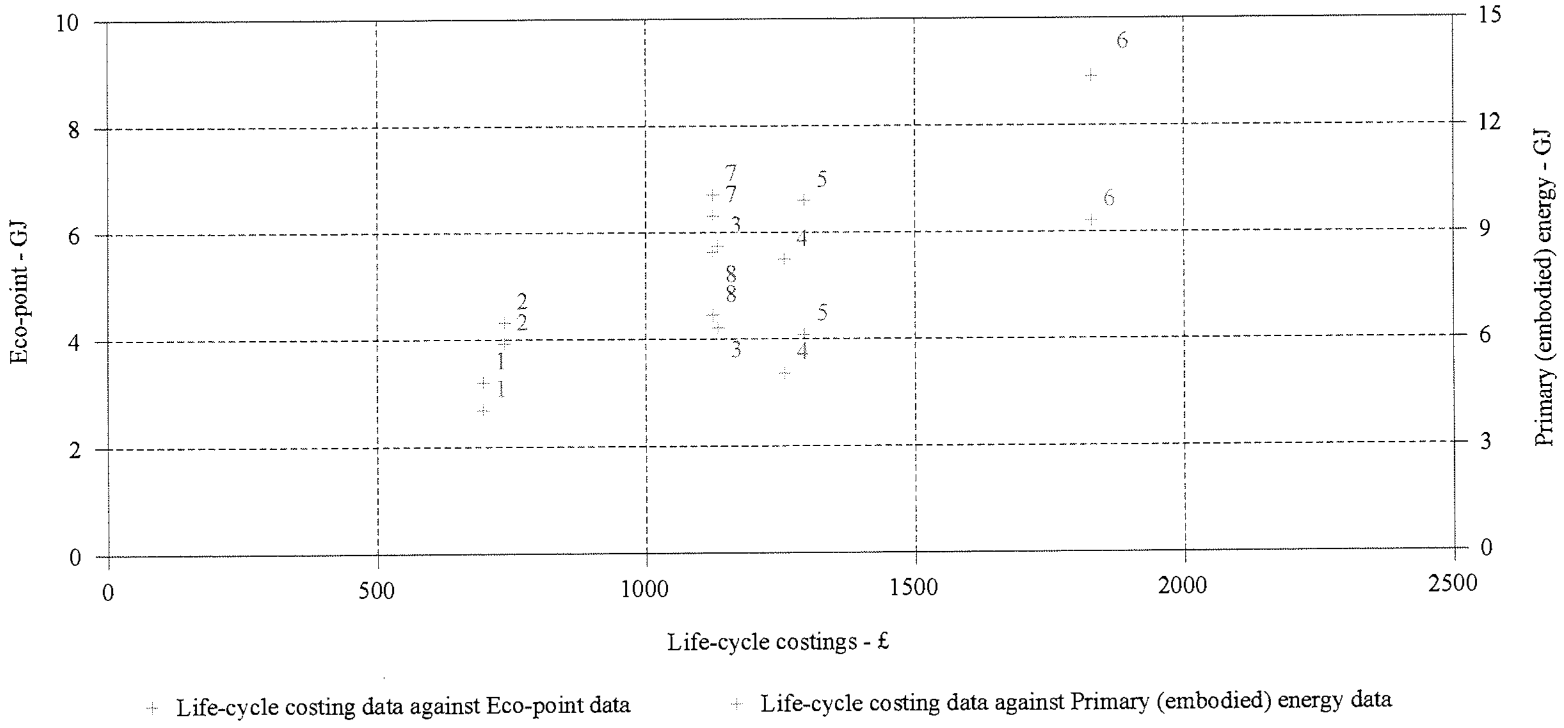


Figure 6.8: Combining Life-Cycle Assessment and Life-Cycle Costing Analyses Data at 500 years to Determine the Most Sustainable Form of Masonry External Wall Construction

Based on the B.R.E.'s (*ibid*, 2000] and the Institution of Structural Engineer's (*ibid*, 1999) recommendations, Figure 6.8 shows that the most sustainable form of external masonry walling found from this project was Wall 1, a 215mm thick solid brickwork wall. The most sustainable wall that complied with the current requirements for the thermal performance of external walls was Wall 4, a 215 mm solid masonry wall with external insulation and a cement render finish. The least efficient wall, in terms of its whole-life environmental impacts and costings, was Wall 6, a brickwork / brickwork cavity wall with external insulation and a cement render finish.

In practice, it is worth noting that an external layer of insulation could easily be retrofitted to the majority of masonry walls in domestic housing to improve their thermal performance. This could also be removed relatively easily and replaced at a later date with a thicker layer of insulation to increase the thermal performance of the wall should this be required. In addition, because the insulation is attached to the outer face of the wall and is consequently easily accessible, the building could continue to be occupied throughout the works and would not require any strengthening before the work began. It is considered that this form of retrofit construction could relatively easily be employed to increase the thermal performance of many of the 3.2 million homes that the *Low Carbon Futures: The 40 % House Project* earmarked for demolition.

Based on the results of the L.C.A. and L.C.C. analyses, the insulated solid masonry walls appear to be more *sustainable* than the cavity walls. This is principally because of the lifespans assumed for the two types of walls. This was discussed previously in Paragraph 6.2.1.

6.6 COMPARISONS WITH B.R.E. LIFE-CYCLE DATA

6.6.1 INTRODUCTION

As part of this project, it was intended to compare the results from this project with the B.R.E. whole-life environmental profiles for clay brickwork walling. A design life of 60 years was, therefore included in this project. Later, it was discovered that the form of insulation used to develop their profiles was different to that supplied for this project. Direct comparisons with these B.R.E. whole-life environmental profiles were, consequently, not possible.

In an attempt to overcome this problem, an investigation was carried out to determine how the B.R.E. environmental profiles had been produced. This involved analysing the basic material profiles and the final installed and whole-life environmental profiles for brickwork walling. This, however, proved inconclusive due to the number of indeterminates involved.

Although it was not possible to directly compare whole-life environmental profiles of clay brickwork walling developed as part of this project with the equivalent values from the B.R.E., it was nevertheless possible to draw useful comparisons between the results from the condition surveys and the B.R.E. data relating to rates of material replacement (Paragraph 6.6.2). In addition, comparisons could also be made with the whole-life environmental impacts and life-cycle costs of the brickwork outer leaf predicted from *Envest II* (Paragraph 6.6.3). These provide a useful insight into the relative differences between the results from this project and published B.R.E. data relating to brickwork.

6.6.2 MATERIAL REPLACEMENT RATES

Table 6.12 shows the three sets of replacement rates assumed for the different construction materials used to build a standard brickwork / blockwork masonry cavity wall; this being the form of construction used in the illustrated examples in the *Green Guide to Specification*. The replacement data for this project (150 + years) was derived from an analysis of maintenance data as previously described in Paragraph 5.3. Whilst there was sufficient information within the B.R.E. Green Guide series to determine the assumed replacement rates for the different materials (60 years), this proved more problematic with *Envest II* (80 years).This is because the software package is only available on the internet and, therefore, there do not appear to be any manuals for the program. The replacement rate was determined by constructing a basic model of a building and varying the occupation period until there was a significant increase in the L.C.A. and L.C.C. data. This proved to be relatively straightforward, as the B.R.E. do not appear to have allowed for any maintenance in their L.C.A. model – see Table 6.13. This shows that the environmental impacts for both the brickwork outer leaf and blockwork inner leaf, expressed in eco-points, double between 80 and 85 years. This means that the computer model assumes that the building is demolished and replaced with a new building at sometime between 80 years and 85 years. This even occurs when users specify an occupation period of 85 years.

Element	Replacement rates based on:		
	Condition survey data (years)	B.R.E.'s *Green Guide to Specification* (years)	B.R.E.'s *Envest II* Software package (years)
Brickwork outer leaf	150+	60	80
Cavity insulation	150+	60	80
Blockwork inner leaf	150+	60	80
Mortar	71	60	80
Plasterboard	60	60	60
Paint	5	5	5

Table 6.12: Replacement Rates for the Construction Materials to be Used in the Life-Cycle Assessment Analyses on a External Brickwork / Blockwork Cavity Wall

Operational life (years)	Outer structural leaf: brick		Inner structural leaf: aerated blockwork	
	Eco-point (per / m^2)	Life-cycle costing (£ / m^2)	Eco-point (per / m^2)	Life-cycle costing (£ / m^2)
5	0.36 / m^2	£ 57.15 / m^2	0.32 / m^2	£ 40.60 / m^2
60	0.36 / m^2	£ 74.20 / m^2	0.32 / m^2	£ 40.60 / m^2
80	0.36 / m^2	£ 80.40 / m^2	0.32 / m^2	£ 40.60 / m^2
85	0.72 / m^2	£ 137.24 / m^2	0.63 / m^2	£ 81.19 / m^2
100	0.72 / m^2	£ 141.89 / m^2	0.63 / m^2	£ 81.19 / m^2

Table 6.13: Results from a Life-Cycle Analysis performed on an External Brickwork / Blockwork Cavity Wall using the *Envest II* software package

After the replacement rate data were determined, they were then used to develop maintenance data at various ages – see Table 6.14. These were then used in a L.C.A. analysis on 1 m^2 of insulated brickwork / blockwork external cavity walling. The initial results from this analysis were expressed in the 13 impact categories of a B.R.E. environmental profile. They were then converted to a single eco-point using the methodology described in *Digest 446* [Dickie and Howard, 2000] – see Table 6.15 and Figure 6.9, so that the three datasets could be more easily compared.

Replacement rate derived from:	Lifespan (Years)	Construction Material					
		Brickwork outer leaf	Cavity insulation	Blockwork inner leaf	Mortar	Plasterboard	Paint
Survey data	60	0.04	0	0.02	0	1	12
	100	0.07	0	0.035	1	1	20
	150	0.25	0	0.125	2	2	30
Green Guide to Specification	60	1.5	1.5	1.5	1.5	1.5	12.5
	100	1.5	1.5	1.5	1.5	1.5	20.5
	150	2.5	2.5	2.5	2.5	2.5	30.5
Envest II	60	0	0	0	0	1	12
	100	1	1	1	1	1	20
	150	1	1	1	1	2	30

Table 6.14: Maintenance Data for the Different Elements of an External Brickwork / Blockwork Cavity wall at Various Ages based on the Replacement Rates from the Green Guide Series, Envest II and the Condition Surveys

Replacement rate based on:	Installed (Eco-points)	60-years (Eco-points)	100-years (Eco-points)	150years (Eco-points)
Analysis of condition survey data	0.64	0.82	0.91	1.14
B.R.E.'s *Green Guide to Specification*	0.64	1.74	1.77	2.47
B.R.E.'s *Envest II* Environmental software package	0.64	0.81	1.47	1.58

Table 6.15: Results from a L.C.A. on an External Brickwork / Blockwork Cavity wall based on the Replacement Rates in Table 6.15

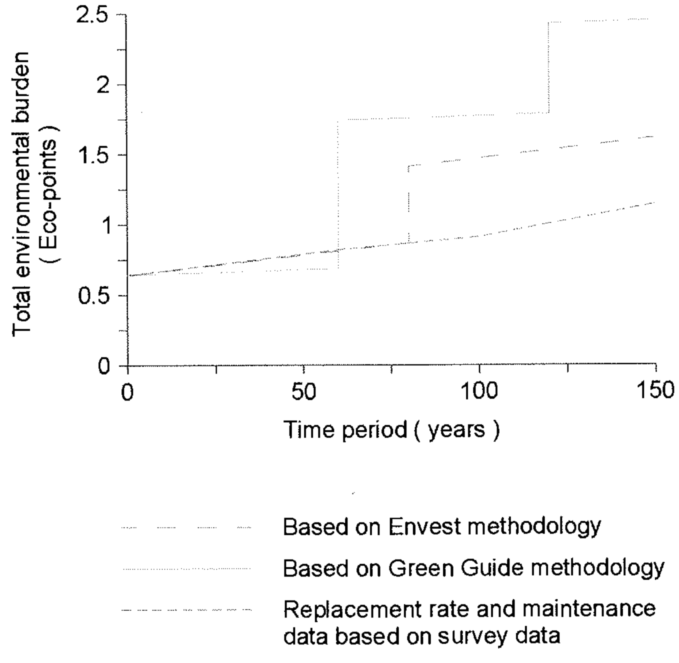


Figure 6.9: Comparison of Results from a L.C.A. on an External Brickwork / Blockwork Cavity wall based on the replacement rates in Table 6.15

Table 6.15 and Figure 6.9 show that, compared to the results from this project, both of the B.R.E.'s methodologies considerably overestimate the environmental impact for the brickwork / blockwork cavity wall past 80 years. For instance, at 150 years, *Envest II* calculates that the impact is 39 % more than that predicted by this project (1.58 eco-points / 1.14 eco-points) and the *Green Guide to Specification* is 117 % greater than those from this project (2.47 eco-points / 1.14 eco-points). It is considered that this could have a serious impact on the future viability and use of masonry walling, as the results from the B.R.E.'s packages are used for comparisons with other, alternative forms of construction materials. For instance, designers who use *Envest II* might not realise that if they specify an occupation period of 85 years, the program appears to allow for the building being demolished at 80 years and replaced with a new building, which would be demolished 5 years later. This would be unlikely to happen in practice but it is unlikely that the users of the program would be aware of this factor, however, unless they tried analysing their designs at a number of different ages. Similarly, the user might not realise the implications of the B.R.E.'s use of the 0.5 modification factor in lieu of specific maintenance data in the *Green Guide* series and whole-life environmental profiles or, indeed, their use of a single lifespan of 60 years. It is worth noting that in a recent consultation exercise regarding the updating of the *Green Guide to Specification* publication, many of the contributors expressed concern about the latter issue [available from http://www.bre.co.uk/greenguide/section.jsp?id=558].

As previously noted in Paragraph 3.11.2, there is an additional major problem that prevents users from evaluating the reliability of the final results from the B.R.E.'s environmental assessment products, namely the overall lack of transparency throughout the process. It is impossible, therefore, to investigate / evaluate the assumptions that underpin the analysis. This lack of transparency is against the ethos of the ISO 14040 [British Standards Institution, 1998[a]].

The lack of transparency can also create problems when interpreting results generally. For example, the *Envest II* results in Table 6.13 show that, whilst the environmental impact of the brickwork outer leaf is unchanged between 5 years and 80 years, the life-cycle costings increase by 41 % over the same period. There is no similar increase in either of the datasets for the blockwork inner leaf over this period, however. The user is therefore left guessing whether the increase in the L.C.C. in the outer leaf is the result of some form of maintenance that does not produce any environmental impacts, or something else. Whatever the cause of this is, it does not appear to similarly affect the blockwork inner leaf.

6.6.3 COMPARISON WITH *ENVEST II*

A comparison was made between whole-life environmental impacts and costings for the brick outer leaf of the brickwork / blockwork cavity wall only, using the results from this project and those produced by *Envest II*. This differed from the earlier comparisons, which, essentially, only investigated the environmental impacts of the replacement rates for the construction materials in a brickwork / blockwork cavity wall. The intention of this later exercise was to compare the actual results from *Envest II* and this project.

Table 6.16 shows the life-cycle assessment and costing data for the brickwork outer leaf as developed for this project and from the B.R.E.'s *Envest II* software package. The results for this project are taken from Tables 6.4 to 6.6 and 6.9 to 6.11, with the results for *Envest II* from Table 6.14. Because of the three maintenance regimes used in the analysis, namely good, average and poor, there are a range of values at 60 and 100 years. The comparison of the two datasets is limited to a maximum operational life of 100 years this being the maximum value that can be selected in *Envest II*.

Operational life (years)	Outer structural skin: brick			
	Condition survey		*Envest II*	
	Eco-point (per m^2)	Life-cycle costing (per m^2)	Eco-point (per m^2)	Life-cycle costing (per m^2)
Installed	0.32	£ 33.05	0.36	£ 74.20
60	0.32 – 0.34	£ 33.05 - £ 56.04	0.36	£ 74.20
100	0.32 – 0.37	£ 44.95 - £ 63.25	0.72	£ 141.89

Notes: The range of figures at 60 years and 100 year is caused by different maintenance regimes

Table 6.16: Summary of the Whole-Life Data for the Outer Brickwork Skin of an External Brickwork / Blockwork Cavity Wall

These life-cycle costing data are shown graphically in Figure 6.16. It can be seen that the costings produced by *Envest II* are consistently higher than those from this project. The B.R.E. calculate that the initial cost of the outer leaf of brickwork would be 73 % (£ 74.20 / m²/ £ 33.05 / m²) higher than those developed for this project. The basic prices were taken from the *Major Works* section of *Spon's Architects' and Builders' Price Book* [Davis, Langdon and Everest, 2003]. This section is intended for building works that cost over £ 40,000. If the *Minor Works* prices are used instead, the price would increase from £ 33.05 / m² to approximately £ 36 / m². This only partially explains the differences between the two datasets. As the B.R.E. give no details of how their data were developed, this could not be investigated further.

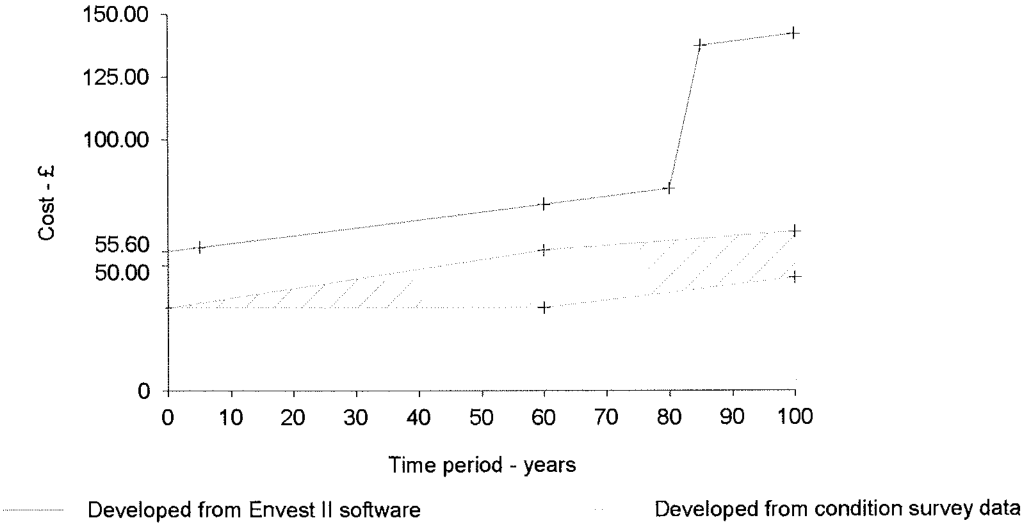


Figure 6.10: Comparison of Life-Cycle Costing Data Developed for this Project and from the *Envest II* Software Package

Although the B.R.E.'s L.C.C. figures are consistently higher over the first 80 years, they follow a similar pattern to those developed from the condition surveys for a wall subjected to a good standard of maintenance. During the first 60 years, for example, the B.R.E. predict that the cost will increase by £ 18.60 / m². This compares to the £ 22.99 / m² at the upper range of costings developed for this project. There was, however, no increase at the bottom end of the range with this project. This suggests that the B.R.E. have allowed for a similar amount of maintenance in the life-cycle costings in *Envest II* to that developed for a good maintenance regime in this project. The B.R.E.'s costings continue to increase by a similar amount until when, between 80 years and 85 years, they almost double. This is because, as previously explained in Paragraph 6.6.2, the B.R.E. assume that any buildings that have operational lives in excess of 80 years will be demolished and replaced at that age. This is a very simplistic assumption and although it may be correct for some buildings, there are very many which are considerably older than this and survive. As already noted in Paragraph 5.1, 42 % of the U.K.'s current housing stock is over 80 years old. In addition, unless the U.K.'s current demolition rate of 20,000 properties per year [*ibid*, 2003^b] increases substantially, it will take over 1000 years to demolish the existing housing stock. This implies that today's buildings must last to this age, although this is thought unrealistic since the analysis of the condition survey data showed that the maximum lifespan of masonry cavity walls was 197 years and 650 years for solid walls – see Figure 5.2.

It is therefore considered that the B.R.E.'s use of a single lifespan for a building is unreasonable. As an alternative to this, it might be more reasonable to produce a series of whole-life environmental profiles at different ages (as with this project) along with guidance about selecting the most appropriate age for different types of properties and let the end-user select which is most suitable. For instance, during a recent consultation exercise about the future development of the *Green Guide to Specification*, one of the contributors suggested that '*Service life requirements for housing must be greater than other buildings and should not be brought to an unrealistic low figure by averaging with service requirements of other building types which are often much shorter. For example, B. & Q. state that their "sheds" are designed to a service life of under 10 years and will probably be demolished around that service life ending*' [Anon., 2006]. A range of service lives (operation lives) for different types of buildings were then suggested, i.e.:

- office - 20 years
- domestic - 200 years
- education - 60 years
- healthcare - 50 years
- retail and warehouse - 10 years

Because of this significant increase in costing between 80 and 85 years evident in the *Envest II* package, the B.R.E. predict that at 100 years, the cost of the brickwork outer leaf in a masonry cavity wall would be between 124 % and 216 % higher than the findings from this project (£ 141.89 / m^2 compared to £ 63.25 / m^2 and £ 44.95 / m^2, respectively). In addition, whereas the B.R.E.'s *Envest II* package estimates that it will cost £ 67.69 / m^2 (£ 141.89 / m^2 - £ 74.20 / m^2) to maintain the outer leaf over 100 years, the findings from this project suggest that a figure of between £ 11.90 / m^2 and £ 30.20 / m^2

(£ 44.95 / m^2- £ 33.05 / m^2 and £ 63.25 / m^2 - £ 33.05 / m^2, respectively) is, perhaps, more realistic. This is a significant difference between the two datasets. That could well have a very serious effect on the choice of clay masonry wall construction in comparative exercises with other forms of walling construction.

6.6.4 IMPACT OF EXTERNAL MASONRY WALLING COMPARED TO OVERALL IMPACT OF A BUILDING

Figure 6.11 repeats Figure 3.12. This shows the B.R.E.'s estimate of the contribution of the different building elements to the overall whole-life (60 years) impact of a *typical* building. It indicates that the external walls contribute approximately 10 % of the total environmental impact of the building.

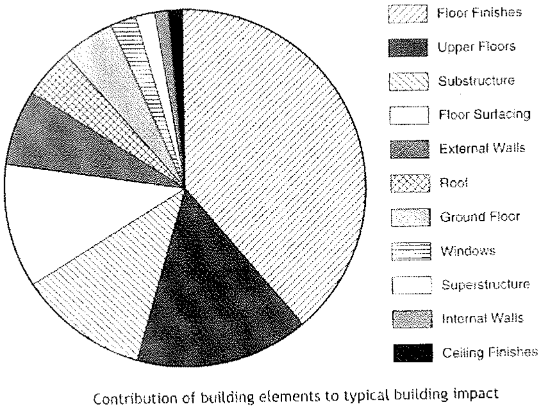
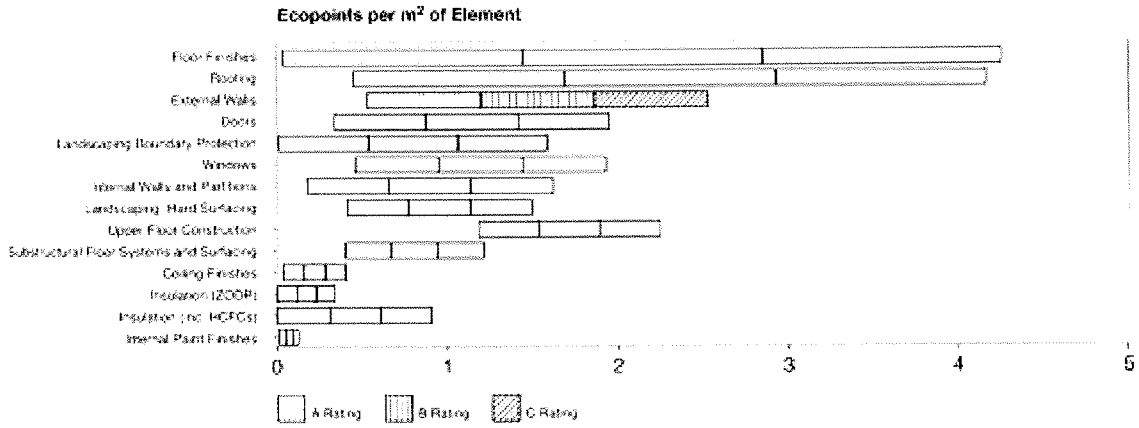


Figure 6.11: Contribution of Building Elements to Typical Building Impact (Anderson, Shiers and Sinclair, 2002)

An attempt was made to replicate Figure 6.11 using the data from the condition surveys obtained as part of this project. However, because of the very limited amount of information given about Figure 6.11, this proved impossible. For example, the B.R.E. simply state that '[the] *BRE has calculated the typical embodied environmental impacts relating to a number of generic building models and broken them down into the constituent elements. The contribution of each building element to a typical office building (based on the analysis of a large number of models) is shown as a pie chart'* [Anderson, Shiers and Sinclair, 2002].



Summary Rating A B C ranges for different elements.

Figure 6.12: Range of Summary Ratings for Different Building Elements
(Anderson, Shiers and Sinclair, 2002)

Figure 6.11 is based on the B.R.E.'s generic models and their assumptions regarding maintenance. In view of this, it was thought useful to carry out a very similar exercise substituting the results for external walling obtained from this project; details are given in Appendix H.

The environmental impact for each of the building elements was based on an analysis of the distribution of the summary ratings shown in Figure 6.12. For instance, in the Rating Tables in Figure 6.12, reproduced from the *Green Guide to Specification* [*ibid, 2002*], 27 of the external walls receive an *A* rating, 22 a *B* rating and only 4 a *C* rating. This produces an average value of 1.27 eco-points / m^2 which compares to a mid-range value of 1.59 eco-points / m^2.

In addition, because of time restraints it was not possible to duplicate the B.R.E.'s use of *'a large number of* [building] *models'*. It was decided to concentrate instead on the four generic building types that are used to illustrate the contribution of the different building elements in the *Green Guide to Specification* – see Figure 6.13. It is not known if these four generic building types were part, or even all, of the *'large number of models'* that the B.R.E. used to determine Figure 6.11.

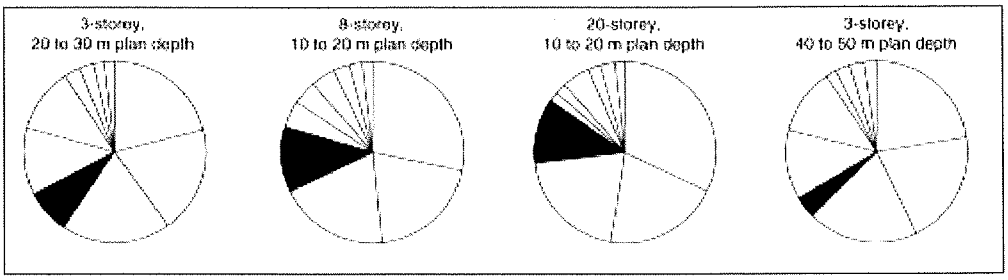


Figure 6.13: The Four Generic Buildings used in the Green Guide to Specification (Anderson, Shiers and Sinclair, 2002)

Table 6.17 show impact values from this process for the different buildings. Figure 6.14 displays the results as a pie-chart and allows comparisons to be made with Figure 6.11.

Element	Impact over the life of the building (eco-points)
Floor finishes	3272
Upper floors	3419
Substructure	2032
Floor surfacing	1982
External walls	1521
Roof	716
Ground floor	645
Windows	628
Superstructure	290
Internal walls	193
Ceiling finishes	463
Paint	74
Total	15235

Table 6.17: Contribution of Building Elements to the Whole-Life Impact of a Building

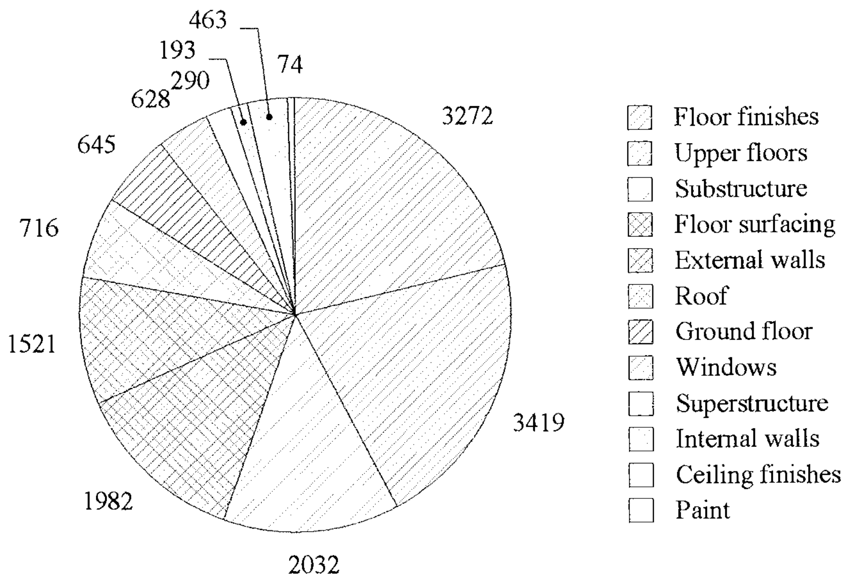


Figure 6.14: Contribution of Building Elements to the Whole-Life (60-years) Impact of a Typical Building

The main difference between Figures 6.11 and 6.14 is the impacts of the floor and ceiling finishes. In Figure 6.11, the floor finishes contribute nearly 40 % of the total impact of the building compared with less than 20 % in Figure 6.14. Conversely, the ceiling finishes produce nearly twice the impact in the second figure as they did in the first. The reasons for this are unknown and because of the limited amount of data available about the B.R.E.'s model, it could not be investigated further. The remaining building elements have (proportionally) very similar impacts in both figures.

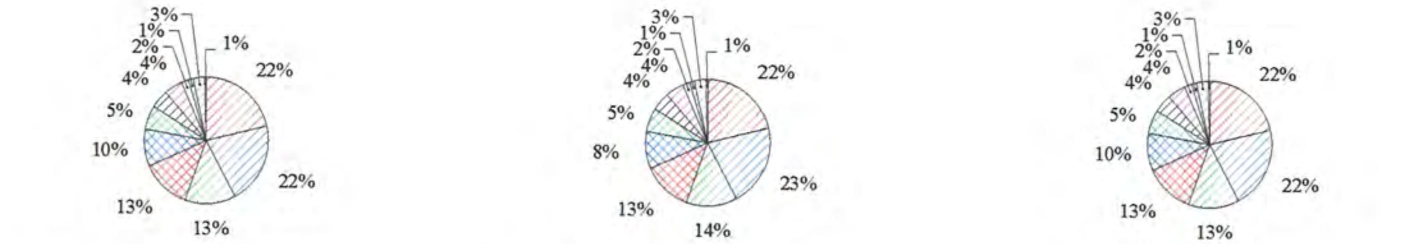
A further model was developed which used the environmental impact for the external masonry walling developed for this project instead of the generic value in Figure 6.14 – see Appendix H.2. The impacts from solid and cavity walls were considered separately and the results from the analysis are shown in Table 6.18 and Figure 6.15. The environmental impacts used were those for an average standard of maintenance given in Table 6.5. The contribution was initially limited to 60 years to allow comparisons to be drawn with the two previous pie charts (Figures 6.11 and 6.14), but was then extended to 500 years to correspond with the earlier work on L.C.A. and L.C.C. analyses.

It can be seen from Figure 6.15 that the results from this project predict that the impact of the external wall will be considerably lower over the very long-term than that predicted by the B.R.E. At 500 years, the value for a cavity wall is half that predicted by the B.R.E and it is only a third of the value for solid walls. Based on the findings from the previous comparisons discussed in Paragraphs 6.6.2 and 6.6, this was as expected. It was not thought, however, that the three figures for external walls at 60 years would be so similar. This is considered to be a coincidence, as the B.R.E. have included a 0.5 modification factor in their calculations in place of any specific data on maintenance. Their figure equates to a 50 % replacement rate (this item is discussed in more detail in Paragraph 3.10.2) whilst Table 5.9 shows that solid walls require virtually no maintenance during the first 60-years of their life. This discrepancy indicates that the initial environmental impact of solid masonry walls must be approximately 30 % higher than the median initial impact of the external walls given in the *Green Guide*.

Although they are not shown in Table 6.18, the impacts were also determined at 100, 150 and 300 years. At 100 years, the B.R.E. predict that the environmental impact of an external wall would be 3,042 eco-points, whereas this project determined that it would be 1,521 eco-points for a solid wall and 1,245 eco-points for a cavity wall. This repeats the trend which was observed at 500 years, i.e. that the B.R.E.'s value are approximately twice those of external walls determined for this project.

Building element	Impacts based on:					
	The B.R.E.'s *Green Guide to Specification*		Project's results for solid walls		Project's results for cavity walls	
	Impact at 60 years (eco-points)	Impact at 500 years (eco-points)	Impact at 60 years (eco-points)	Impact at 500 years (eco-points)	Impact at 60 years (eco-points)	Impact at 500 years (eco-points)
Floor finishes	3272	27538	3272	27538	3272	27538
Upper floors	3419	30767	3419	30767	3419	30767
Substructure	2032	18286	2032	18286	2032	18286
Floor surfacing	1982	16843	1982	16843	1982	16843
External walls	1521	13689	1521	4213	1245	6356
Roof	716	6090	716	6090	716	6090
Ground floor	645	5805	645	5805	645	5805
Windows	628	5342	628	5342	628	5342
Superstructure	290	2463	290	2463	290	2463
Internal walls	193	1642	193	1642	193	1642
Ceiling finishes	463	3936	463	3936	463	3936
Paint	74	625	74	625	74	625
Total	15235	133025	15235	123549	14959	125692

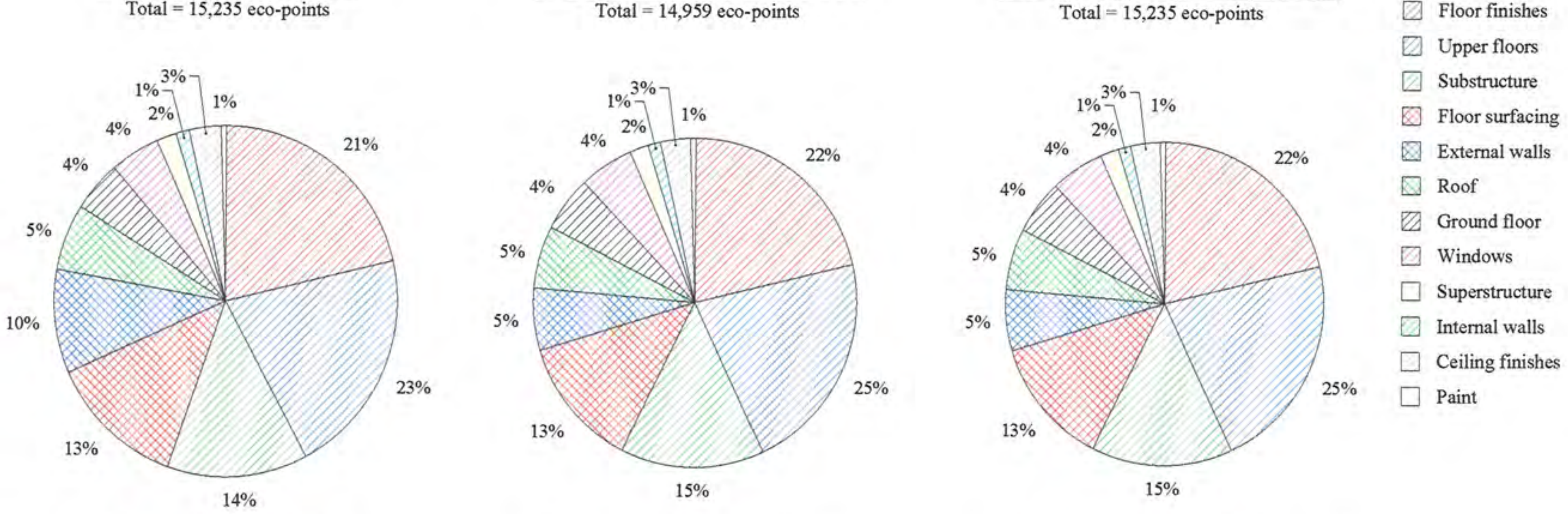
Table 6.18: Contribution of Building Elements to Whole-Life Impact of a Typical Building



Distribution of Impacts at 60 years
Based on the B.R.E. Impact Data
Total = 15,235 eco-points

Distribution of Impacts at 60 years
Based on the Impact Data for Solid Walls
Total = 14,959 eco-points

Distribution of Impacts at 60 years
Based on the Impact Data for Cavity Walls
Total = 15,235 eco-points



Distribution of Impacts at 500 years
Based on the B.R.E. Impact Data
Total = 133,025 eco-points

Distribution of Impacts at 500 years
Based on the Impact Data for Solid Walls
Total = 125,692 eco-points

Distribution of Impacts at 500 years
Based on the Impact Data for Cavity Walls
Total = 123,549 eco-points

Figure 6.15: Contribution of Building Elements to Whole-Life Impact of a Typical Building

6.6.5 LIMITATIONS IN B.R.E.'S LIFE-CYCLE ANALYSIS DATA

The B.R.E. state that environmental profiles were originally designed to enable designers to assess the overall environmental impact of their design. This was to be achieved by providing a *level playing field* about the relative performance of different materials, components, and forms of construction [Howard, Edwards and Anderson, 1999]. Although this was an appropriate aim, there are, in reality, many weaknesses in the B.R.E.'s approach to achieving this. These include their apparent assumptions about the use of a universal figure of 0.5 in the *Green Guide to Specification* to allow for uncertainties in replacement intervals. There is also a general lack of transparency throughout the B.R.E. process. For instance, their pie-chart for the contribution of different building elements to the whole building impact, shown in Figure 6.15, was derived from the analysis of a large number of generic buildings. The *Green Guide* does not, however, describe these buildings. This makes it impossible for third parties to check the validity of these results. In addition, the B.R.E. do not explain why they chose to use a single lifespan of 60 years for all buildings in the *Green Guide* series and their whole-life environmental profiles. During the 2005/06 consultation exercise about updating the *Green Guide to Specification*, referred to previously in Paragraph 6.6.2, many of the contributors expressed concern about this particular issue. It is apparent from the B.R.E.'s response note [http://www.bre.co.uk/greenguide/files/ResponseNoteToBriefingNote6-WholeLifePerformance.pdf] that the 60 year study period will remain and they will not be updating the *Green Guide to Specification* to reflect any concerns in this respect.

The lack of transparency in the B.R.E. life-cycle data contradicts the ethos of the new ISO standards on environmental management. ISO 14040 [British Standards Institution, 1997], in particular, states that the *'scope, assumptions, description of data quality, methodologies and output of LCA studies should be transparent. LCA studies should discuss and document the data sources, and be clearly and appropriately communicated'*. Although the B.R.E. are to some extent limited by the need to respect the confidentiality of input data, there are provisions in ISO 14040 to allow for this.

In addition, it is questionable whether the B.R.E. approach of quantifying environmental performance in terms of eco-points is appropriate given that ISO 14040 [*ibid,* 1997] states that *'there is no scientific basis for reducing LCA results to a single overall score or number, since trade-offs and complexities exist for the systems analysed at different stages of their life cycle'*. It would be preferable, if the B.R.E. published it together with the 13 impact categories from the relevant environmental profile as they do on their *Approved Environmental Profile* datasheets. This would, at least, give the users the option of basing their comparisons on Climate change, Pollution to Air / Water or wherever their particular interest lay. Although the *Green Guide* series is intended for general practitioners in industry rather than experts, who have the time and resources available to gain a sufficient understanding of all issues involved in L.C.A., the B.R.E. could satisfy both of these factions, and comply with ISO 14040, if it published both datasets.

At the present time, it might be preferable to adopt Simon Allford's attitude to sustainability [quoted in Slavid, 1998 and detailed in Paragraph 1.3], i.e. it is more important to have a positive attitude to the subject which can be applied throughout the design process, rather than treating it like an physical object which can be given a score and compared against other items.

6.7 ENVIRONMENTAL IMPACTS OF AN EXISTING BUILDING, A REFURBISHED BUILDING AND A REPLACEMENT BUILDING

An analysis was completed to compare the environmental performance of an existing building – see Plate 17. A building was chosen which did not comply with the current statutory requirements for the performance of buildings but whose age was between 60 and 80 year lifespans that the B.R.E. use in their *Green Guide* series and *Envest II* L.C.A. packages respectively. It was compared with an upgraded version of the building which met the current requirements for the thermal performance of buildings and a replacement building. The design and layout of the new building was based on a new row of terraced housing which were recently built in Leeds – see Plate 18.

The existing building consisted of four terrace houses. There were four similar buildings in the same street. The houses have 215mm thick solid brickwork external walls with thin lime mortar joints and, consequently, do not comply with the current requirements for the thermal performance of external walls. There has not been any maintenance carried out on the brickwork of the building as a whole since it was built but all of the original doors and windows have been replaced with new PVC-U double-glazed units. In addition, the northern end-terrace house, which was the only one which could be surveyed internally, the loft had been insulated with glass wool insulation although, when it was analysed, it was only half the thickness required for the roof to comply with the current requirements for the thermal performance of roofs.

In the analysis, only the energy required to heat the building was determined rather than the operational energy of the building. This was because it was considered that, apart from the energy required to heat the building, the other operational energies, i.e. lighting, cooking, etc. would be constant irrespective of whether the existing building remained, or was upgraded or replaced.

The embodied energy of the construction materials in the existing building were not considered in this analysis. This was because, as the architect Quinlan Terry stated (see Paragraph 2.2) *'the fossil fuel emissions that were produced during the construction of the existing homes are already in the atmosphere'*. It was decided, therefore, that because the existing buildings was still fulfilling its basic function – providing shelter – and it was only being demolished to improve its thermal performance that the embodied energy of the construction materials should not be considered.

It was also decided to only consider the maintenance requirements of the brickwork in the analysis. This was because the other elements, i.e. the windows, boiler, carpets, etc., would need to be replaced at similar ages irrespective of the building they were installed in. In addition to the external walling, the only other major element which would also have a different replacement interval between the two buildings was the roof. The existing building had slate tiles and the new roof had concrete tiles and, whereas the replacement interval for slate tiles is 50 years, it is only 20 years for concrete tiles. Despite an extensive search, no information could be found about the environmental impacts of slates tiles, however, so the replacement of these items could not be considered in this analysis.

The analysis was based on a lifespan of 100 years which was chosen because it was the maximum lifespan for a brickwork / timber cavity wall used in the life-cycle analysis in this thesis – see Table 6.3. A survey was conducted on the existing building to confirm that it is capable of continuing to survive until at least this age. The maintenance requirements of the walls were based on those for an average standard of maintenance given in Table 5.8 and 5.9.

The full analysis of the three buildings is given in Appendix I. The results from this analysis are summarised in Table 6.19.

i. Front Elevation ii. Rear elevation

Plate 17: Existing Building

i. Front Elevation ii. Rear Elevation

Plate 18: Replacement Building

	Embodied energy of the construction materials	Energy required to maintain the building (over 100 years)	Energy required to heat building (over 100 years)	Total (at 100 years)
	(eco-points)	(eco-points)	(eco-points)	(eco-points)
The existing building	0	47	15644	15691
The upgraded existing building	124	93	5950	6167
Existing building demolished and replaced with new building	690	90	5789	6569

Table 6.19: Summary of Analysis

6.7.2 COMPARISON OF THE RESULTS

The results in Table 6.19 show that the most efficient solution, with respect to the whole-life environmental impacts, is to upgrade the existing building. This was closely followed by demolishing and replacing the existing structure with a new, more energy efficient, building. The analysis showed that, over 100 years, the original existing building would produce nearly 140 % more environmental impact (15691 eco-points / 6569 eco-points) than if it were replaced with a building and over 150 % more (15691 eco-points / 6167 eco-points) than if it were simply upgraded to comply with the statutory requirements for the thermal performance of buildings. It should be noted, that the environmental impacts produced from demolishing the existing building to allow the replacement building to be built on the site were not included in the analysis.

This solution would also produce the following additional benefits:

- It would not produce the vast amount of demolition waste that would be produced if the building was demolished
- The building could continue to be occupied during the works
- The insulation can be upgraded at a later stage to make the buildings even more energy efficient.

Although the whole-life costings were not considered in the analysis in Appendix I, it is thought that this solution would also be the most cost-efficient over the long-term.

The results in Table 6.19 show that the upgrading solution would save the equivalent of the energy required to heat the building for over half a decade compared to if the existing building were replaced. If this solution could be applied to even a small proportion of the existing housing stock that have solid brickwork masonry external walls (or any other form of external wall construction that does not comply with the current statutory requirements for the thermal performance of external walls), it would reduce the U.K.'s consumptions of fossil fuels and emissions of greenhouse gases. This would help the Government to meet the ambitious target it set itself. For instance, its agreement to reduce the country's emissions of carbon dioxide to 5 % below their 1990 level in accordance with the Kyoto Agreement – see Paragraph 1.4.

Figure 6.16 shows the actual amounts of gas used by end-terrace at the north end of the existing row of houses. These span over a single year and show that during this period, the building consumed 16738 kWh of gas. It should be noted that the only appliance in the property that used gas was the combination boiler which was used to power both the central heating and the hot water system. This was installed in the property approximately 5 years ago.

How we calculated your statement

Your gas charges A = Actual read, E = Estimated, C = Customer read

Period 07/04/05 to 04/10/05 (Calorific value: 40.2 Volume correction: 1.022640)

Description	Start	End	Units	Price(kWh@p)	Total (£)
Capped - Domestic Tariff				2618@1.204	£31.52
Meter: 00275926	4549A	4630A	81		
Standing charge				181Days@14.150	£25.61
Total gas					£57.13

Your gas charges A = Actual read, E = Estimated, C = Customer read

Period 05/10/05 to 02/01/06 (Calorific value: 40.5 Volume correction: 1.022640)

Description	Start	End	Units	Price(kWh@p)	Total (£)
Capped - Domestic Tariff				5860@1.204	£70.55
Meter: 00275926	4630A	4810A	180		
Standing charge				90Days@14.150	£12.74
Total gas					£83.29

How we calculated your statement

Your gas charges A = Actual read, E = Estimated, C = Customer read

Period 03/01/06 to 05/04/06 (Calorific value: 40.5 Volume correction: 1.022640)

Description	Start	End	Units	Price(kWh@p)	Total (£)
Capped - Domestic Tariff				8270@1.204	£99.57
Meter: 00275926	4810A	5064A	254		
Standing charge				93Days@14.150	£13.16
Total gas					£112.73

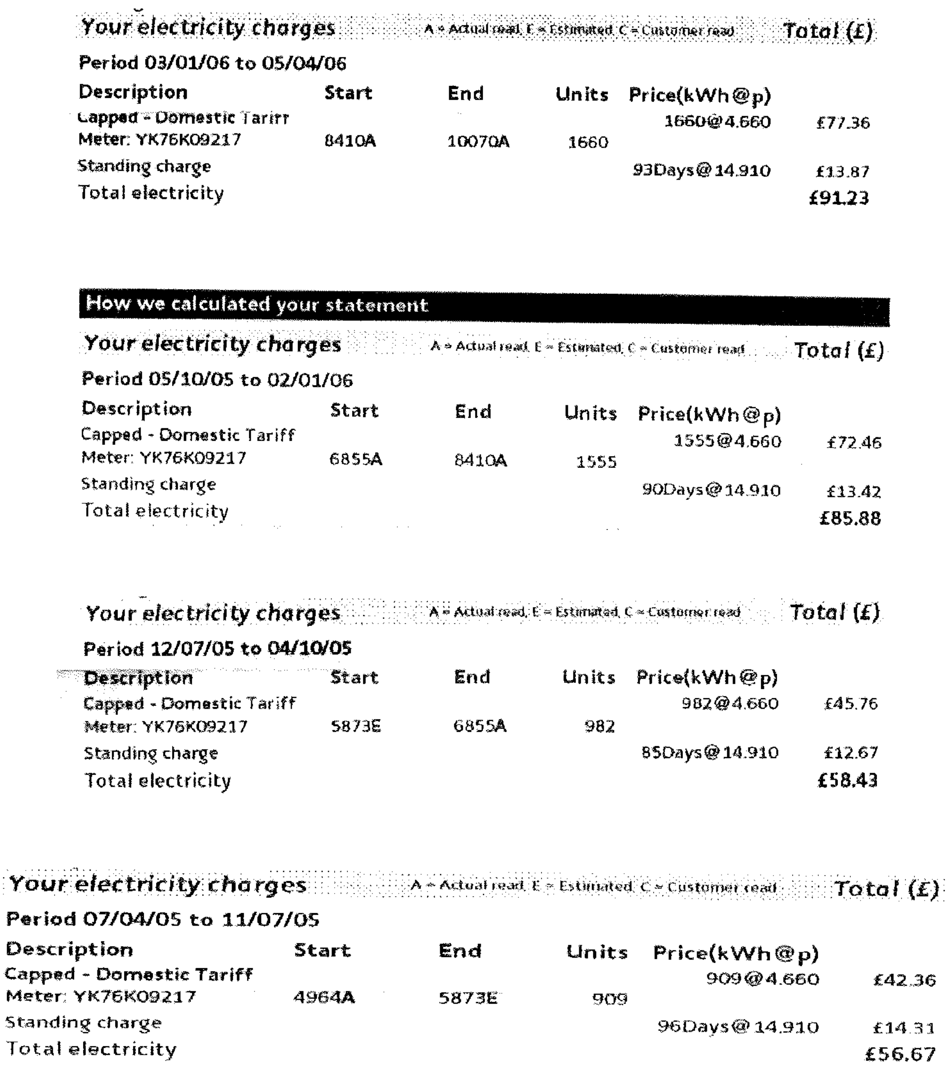
Figure 6.16: Utility Invoice (Gas) for the *Existing Building*

If the conversion factor in Appendix I.4 is applied to the total amount of gas used in the building, it equates to 60.2 GJ of energy per year. As the end-terraced house contains nearly 32 % of the brickwork in the building, 28 % of the roof and 26 % of the glazing, if the amount of gas used in the property is applied to the whole building using these data, the energy required to heat the whole building and the water used in the building would be 200.7 GJ / year. If the energy required to heat the building in Appendix I.4 is correct, the energy required to heat the water in the whole building would be 20.6 GJ / year (200.7 GJ / year – 180.1 GJ / year).

The figure above is considerably lower than the proportion for heating spaces and water suggested by Figure 6.4, however. This shows that the energy required to heat the water is approximately a third of that required to heat the building, whereas the above figure suggests that it would be about a tenth of the value. It should be noted, however, that in reality the family that live in the property use a dishwasher and generally take showers rather than baths. In addition, because the house is fitted with a combination boiler, the water is heated by the boiler when it is required rather than it being heated and stored in a hot water cylinder. As a consequence, the figures determined in the above analysis are considered valid.

Figure 6.17 shows the electricity utility invoice for the existing property for the same period as the gas bills shown in Figure 6.16. During this period, 5106 kWh of electrical energy was consumed. This converts to 18.4 GJ of energy per year. The total operational energy of the building was therefore 219.1 GJ / year and consequently, the operational energy requirement of the whole building, excluding the energy required to heat the building, was 39.0 GJ / year (219.1 GJ / year – 180.1 GJ / year).

If the latter figure is assumed to be constant for the three buildings types in the analysis, i.e. the exiting building, the upgraded existing building and the replacement building, the operational energy requirement of the replacement building would be 96.9 GJ / year (57.9 GJ / year + 39.0 GJ / year). This amounts to 5814 GJ when it is projected to 60 years and, consequently, the ratio of the embodied energy of the construction materials to operational energy is approximately 1 : 8 (690 GJ compared to 5814 GJ) for the replacement building. This is higher than the ratios Edwards and Hyett's (2002) and De Vekey's (1999) suggest for this which were previously discussed in Paragraph 2.2 and were based on a lifespan of 60 years.



Your electricity charges A = Actual read, E = Estimated, C = Customer read **Total (£)**

Period 03/01/06 to 05/04/06

Description	Start	End	Units	Price(kWh@p)	
Capped - Domestic Tariff				1660@4.660	£77.36
Meter: YK76K09217	8410A	10070A	1660		
Standing charge				93Days@14.910	£13.87
Total electricity					**£91.23**

How we calculated your statement

Your electricity charges A = Actual read, E = Estimated, C = Customer read **Total (£)**

Period 05/10/05 to 02/01/06

Description	Start	End	Units	Price(kWh@p)	
Capped - Domestic Tariff				1555@4.660	£72.46
Meter: YK76K09217	6855A	8410A	1555		
Standing charge				90Days@14.910	£13.42
Total electricity					**£85.88**

Your electricity charges A = Actual read, E = Estimated, C = Customer read **Total (£)**

Period 12/07/05 to 04/10/05

Description	Start	End	Units	Price(kWh@p)	
Capped - Domestic Tariff				982@4.660	£45.76
Meter: YK76K09217	5873E	6855A	982		
Standing charge				85Days@14.910	£12.67
Total electricity					**£58.43**

Your electricity charges A = Actual read, E = Estimated, C = Customer read **Total (£)**

Period 07/04/05 to 11/07/05

Description	Start	End	Units	Price(kWh@p)	
Capped - Domestic Tariff				909@4.660	£42.36
Meter: YK76K09217	4964A	5873E	909		
Standing charge				96Days@14.910	£14.31
Total electricity					**£56.67**

Figure 6.17: Utility Invoice (Electricity) for the *Existing Building*

CHAPTER 7: CONCLUSIONS

A programme of research was undertaken to investigate and quantify the post-factory gate environmental performance and whole life costs of clay brickwork masonry used in domestic and low rise buildings for ages of up to 500 years.

In general, the research found that clay brickwork requires very little maintenance and that under the right circumstances, masonry buildings have the potential to last many centuries. Although the embodied energy of clay brickwork is relatively high, its general robustness and potential long life mean that, over the longer term, the whole life environmental impacts and cost of masonry buildings may well be less than those of buildings constructed using materials with lower embodied energies but shorter lifespans which necessitates their replacement at more-frequent intervals.

The findings from this research project have established the environmental credentials of clay brickwork masonry and its effectiveness as a sustainable construction material.

The research also revealed the following detailed conclusions:

1. Based on the enquiries conducted as part of programme of research, it appears that there are very few, if any, archive records of detailed information on the maintenance carried out specifically on brickwork in buildings within the U.K. generally.

2. Much of the historical data that is available relates to the general maintenance of buildings and is usually limited to the costs of the maintenance, rather than the types of maintenance undertaken.

3. Much of the information relating to the maintenance of clay brickwork used in buildings appears to be anecdotal in nature.

4. Condition surveys of a limited number (860) domestic and low rise brick-built properties across the north of England showed that, under the right circumstances, clay bricks have the potential to remain serviceable up to 650 years. This is approximately the time at which clay brickwork was first introduced in to the U.K. from the continent.

5. From the condition surveys carried out as part of this research, it was found that average age to first repointing and the general maintenance requirements varied

between wall types. The average age to first repointing was 113 years for sold walls and 68 years for cavity walls.

6. Whilst the overall environmental impact of a poorly maintained solid wall increased by an average of 25 % over the first 150 years of its life compared to the initial installed environmental impact of the wall, these increases were not caused by the brickwork but were the result of the repainting and replastering of the internal face of the wall.

7. For a solid masonry wall subjected to a good standard of maintenance, the environmental impacts increases by 70 % over 150 years compared to the initial, installed, environmental impact of the wall. Only 21 % of this increase associated with the maintenance of the brickwork and the remaining 79 % was again caused by the repainting and replastering of the internal face of the wall.

8. In solid masonry walls after 500 years, the environmental impacts associated with the maintenance of the brickwork were still very low compared to other activities such as repainting and replastering. This is due to the durability of the brickwork compared to the other materials in the walls. Under the most comprehensive maintenance regime, less than three quarters of the brickwork had been replaced at 500 years. By comparison, the paint on the internal face of the wall would have been replaced 100 times at this age.

9. After 150 year old, there was a 5 % increase in the environmental impact associated with the maintenance of the brickwork in cavity masonry walls subjected to a poor standard of maintenance compared to the initial installed profile for the brickwork outer leaf only. Over the same period, there was a 35 % increase in the overall environmental impact for the same wall compared to the initial, installed impact of the whole wall.

10. On average, solid masonry walls were repointed at a later age than cavity walls.

11. Extrapolation of the condition survey data suggested that the bricks in solid masonry walls were capable of lasting for up to 650 years. A similar analysis for cavity walls suggested that all of the bricks would have been replaced after approximately 200 years. These suggest maximum lifespans of bricks in the two

types of brickwork walling. Walls may, however, be demolished at a younger age for a variety of issues unrelated to the physical performance of the clay bricks.

12. From the condition survey data, solid masonry walls built with thin jointed lime mortars are more robust than cavity walls constructed with thicker cement based mortar joints. Possible reasons for this include:
    - the improved thermal performance of cavity walls resulting in the external leaf being subjected to a greater range of temperature than solid walls
    - rain penetrating the external leaf of cavity walls via unfilled perpends

13. At all ages, the greatest increases in the L.C.A. data were the result of the repainting of the inner face of the wall. This was because of the frequency that it was assumed to be carried out.

14. Based on the findings from this project, a simple 215 mm solid brickwork wall had the least environmental impact over 500 years. The wall with the least environmental impacts which complies with the current requirements for thermal performance of external walls that does comply with these standards was an externally insulated 215 mm solid brickwork wall.

15. In terms of eco-points, the wall with the highest environmental impact was a brickwork / blockwork cavity wall, and with respect to primary energy, an external rendered and insulated brickwork / brickwork cavity wall

16. Based on the L.C.A. data for an average standard of maintenance, over a 500 year period, solid walls produced 49 % less environmental impacts compared to cavity walls.

17. During the first 60 years, the environmental impact of maintaining a solid wall amounted to between 9 % and 33 % of the initial installed post factory gate environmental profile. At 500 years, this increased to between 150 % and 325 % of the initial installed profile.

18. When the maintenance of the brickwork was considered in isolation, during the first 60 years, the environmental impact from maintaining the brickwork in a solid wall amounted to between 0 % and 3 % of the initial installed post factory gate environmental profile. Similarly, at 500 years the environmental impact was

between 9 % and 74 % of the initial installed post factory gate environmental profile for the wall. These were very low compared to the impacts of other maintenance activities such as repainting the inner face of the wall and show the robustness of brickwork in comparison with other construction materials.

19. During the first 60 years, the environmental impact produced from maintaining a cavity wall amounted to between 14 % and 97 % of the initial installed post factory gate environmental profile. At 500 years the environmental impact of a cavity wall was between 383 % and 1062 % of the initial installed post factory gate environmental profile

20. At 60 years, the ratio of the embodied energy of the construction materials in the external wall used in the life-cycle analyse and the operational energy (the energy required for heating the building, heating water, using lighting and other electrical appliances, and for cooking) was found to be between 1 : 7 and 1 : 14. These are very similar to published ratios of approximately 1 : 10 given by Edwards and Hyett, and De Vekey.

21. If existing clay brickwork masonry walls do not meet the current statutory requirements for the thermal performance of buildings, external insulation can be retrofitted in order to achieve compliance. Significant reductions in the operational energy of the building can then be achieved with very small increase in the embodied energy of the construction materials.

22. External render / insulation applied to the existing housing stock of the U.K. would reduce the country's consumptions of fossil fuels and emissions of greenhouse gases considerably. This would help the Government to meet its commitments under, amongst others, the Kyoto Agreement.

23. As with the L.C.A. data, the life-cycle costings increased with time. The greatest contributor to this increase was the repainting of the inner face of the wall.

24. Based on the findings from this project, a simple 215 mm solid brickwork wall was the most cost-effective wall over 500 years. The most cost-effective wall that complied with the statutory requirements for the thermal performance of external walls was an externally insulated 215 mm solid brickwork wall.

25. The most expensive wall over 500 years was an external rendered and insulated brickwork / brickwork cavity wall

26. During the first 60 years, the cost of maintaining a solid wall amounted to between 61 % and 106 % of the initial cost of construction for the wall. At 500 years, the whole-life cost of a solid wall was between 539 % and 834 % of the initial cost of the wall. The cost of maintaining the brickwork in a solid wall is very low. Typically, this ranges between 0 % and 6 % of the initial cost of construction for the wall over the first 60 years. Similarly, after 500 years, the cost of maintaining the brickwork ranges between 78 % and 146 % of the initial cost of the wall. This difference is primarily due to the high costs associated with other maintenance activities carried out on the wall, e.g. the repainting of the inner face of the wall at 5 year intervals.

27. During the first 60 years, the cost of maintaining a cavity wall amounted to between 69 % and 120 % of the initial cost of the wall and at 500 years, the cost was between 928 % and 1264 % of the initial cost of the wall

28. When the maintenance of the brickwork was considered in isolation, during the first 60 years, the cost of maintaining a cavity wall was between 0 % and 70 % of the initial cost. Similarly, at 500 years the cost was between 443 % and 900 % of the initial cost of the wall.

29. Based on an average standard of maintenance, cavity walls are, on average, 32 % more expensive then solid walls over a 500 year period. As with the results from the L.C.A. analysis, this is due to the shorter lifespans of cavity walls and the additional costs associated with the extra components they require, e.g. wall ties.

30. Apart from over very short periods of time, attempts to include for inflation and / or apply accounting techniques such as Net Present Value / Discount Cash Flow analyses to life-cycle analysis are meaningless. These techniques are more suited to life-cycle analyses on objects, such as photocopiers, which have relatively short and fixed lives than construction materials which have, in comparison, very long lives.

31. Based on the combined findings from the L.C.A. and L.C.C. analyses for an average standard of maintenance, the most sustainable form of masonry

construction of the eight considered in this project was a 215mm thick solid brickwork wall.

32. A 215mm solid brickwork wall does not, however, comply with the current requirements for the thermal performance of external walls. From the modelling, the most sustainable form that does meet the statutory requirements is an externally insulated 215mm solid brickwork wall.

33. Based on comparisons with the findings from this project, the B.R.E. life-cycle analysis publications and software package consistently overestimate the whole-life environmental impacts and costs of clay brickwork masonry construction.

34. The B.R.E.'s use of a single maximum 60 year design life for all building elements is over simplistic and is incorrect for the vast majority of masonry structures; this is confirmed from a review of the U.K. Government's National Housing Statistics.

35. An modification factor of 0.5 is used in the *Green Guide to Specification* to allow for uncertainties in replacement rate data. This is too simplistic for long-life material such as brickwork. This factor is the equivalent of a 50 % increase in the initial environmental impact for the materials. An analysis of the condition survey data found, however, that only between 0 % and 5 % of the brickwork had been replaced in clay brickwork buildings of a similar age.

36. From an analysis of a typical building with clay brickwork masonry external walls using *Envest II*, it was apparent that if an operational life of 85+ years was specified, the program simply assumed that the walls would be demolished and rebuilt at 80 years. This means that if a user specifies a life of 85 years instead of 80 years, than the environmental impact of the external walls is doubled.

37. Analysis of same data showed that there is no allowance in the L.C.A. data for maintenance of the brickwork.

38. A similar analysis of the L.C.C. data indicates that an allowance is included in the costings for maintenance of the brickwork.

39. Unless several different scenarios are tested to effectively complete a sensitivity analysis, it is impossible to clearly understand the accuracy and significance of the final results that the *Envest II* software package produces.

40. The findings of this project support those of Steele who found that brickwork is good value in environmental terms in that it has the potential for a long life and requires very low levels of maintenance.

41. From the modelling, the most sustainable form of masonry construction that complies with the current requirements for thermal performance was an externally insulated solid brickwork masonry wall

42. This form of construction can be used for new build. In addition, the external layer of insulation could easily be retrofitted to existing stock of solid masonry walls to improve their thermal performance. If this solution was applied to even a small proportion of the existing housing stock of the U.K., it would reduce the country's consumptions of fossil fuels and emissions of greenhouse gases considerably. This would help the Government to meet its commitments under, amongst others, the Kyoto Agreement.

CHAPTER 8: RECOMMENDATIONS FOR FUTURE WORK

The recommendations for future work include:

1. More research into the factors that influence the post-factory gate environmental performance of brickwork used for buildings. This involves demographic changes and other assorted social trends, re-use / recycle, etc.

2. Complete additional condition surveys of the existing building stock in other areas of the country to allow comparisons to be made with the findings from this project and to verify the B.R.E.'s estimates of their life spans and maintenance requirements for other construction materials.

3. Investigate further the actual life spans of buildings and the reasons why buildings are demolished.

4. Develop further environmental profiles for different scenarios and other forms of clay brickwork construction.

5. Investigate ways of exploiting thermal mass potential of brickwork to reduce the operational energy requirements of buildings further.

REFERENCES

Allaby, M. (1988) *Dictionary of the Environment.* 3rd Ed. London, MacMillan Press Ltd.

Anderson, J., and Howard, N. (2000) *The Green Guide to Housing Specification.* Garston, Watford, B.R.E (Building Research Establishment).

Anderson, J., Shiers, D. and Sinclair, M. (2002) *The Green Guide to Specification: An Environmental Profiling System for Building Materials and Components.* 3rd Ed. Garston, Watford, B.R.E. (Building Research Establishment).

[*Anon. (unknown)*] *Life-Cycle Assessment: Life-Cycle Impact Assessment.* [Internet] Available from http://www.utexas.edu/research/ceer/che302/greenproduct/dfe/PDF/1A.PDF <Accessed 1st August, 2005>

[*Anon.* (2006)] *Green Guide Update: BRE Response to Comments on Whole Life Performance Briefing Note (6).* [Internet] Available from http://www.bre.co.uk/greenguide/files/ResponseNoteToBriefingNote6-WholeLifePerformance.pdf <Accessed 4th April, 2006>

Barbier, E. (1989) *Economics, Natural Resource Scarcity and Development.* London, Earthscan Publications Ltd.

Brick Development Association Ltd. (2003^{a}) *Brick. Made for Generations: A Sustainable Strategy for the Brick Industry.* Windsor, Berkshire, B.D.A. (Brick Development Association Ltd.).

Brick Development Association Ltd. (2003^{b}) *Brick. Made for Generations: The Case for Sustainability.* Windsor, Berkshire, B.D.A. (Brick Development Association Ltd.).

Brick Industry Association (2003) *Brick Revisited: Just How Green is it?* Brick Industry Association, Reston, Virginia, U.S.A. [Internet] Available from http://www.gobrick.com/pdfs/greenNew.pdf <Accessed 1st August, 2005>

The British Constructional Steelwork Association Ltd. (2002) *Publication 33/02: Financial Handbook for Steelwork Contractors.* 1st ed. London, B.C.S.A. (The British Constructional Steelwork Association Ltd.).

British Standards Institution (2003) BS 7543: 2003 *Guide to Durability of Buildings and Building Elements, Products and Components.* London, B.S.I. (British Standards Institution).

British Standards Institution (2004) BS EN ISO 14001: 2004 *Environmental Management Systems – Requirements with Guidance for Use.* London, B.S.I. (British Standards Institution).

British Standards Institution (1997) BS EN ISO 14040: 1997 *Environmental Management – Life-Cycle Assessment – Principles and Framework.* London, B.S.I. (British Standards Institution).

British Standards Institution (1998a) BS EN ISO 14041: 1998 *Environmental Management – Life-Cycle Assessment – Goal and Scope Definition and Inventory Analysis.* London, B.S.I. (British Standards Institution).

British Standards Institution (2000a) BS EN ISO 14042: 2000 *Environmental Management – Life-Cycle Assessment – Life-Cycle Impact Assessment.* London, B.S.I. (British Standards Institution).

British Standards Institution (2000b) BS EN ISO 14043: 2000 *Environmental Management – Life-Cycle Assessment – Life-Cycle Interpretation.* London, B.S.I. (British Standards Institution).

British Standards Institution (2002) BS EN ISO 14048: 2002 *Environmental Management – Life-Cycle Assessment – Data Document Format.* London, London, B.S.I. (British Standards Institution).

British Standards Institution (2000c) BS EN ISO 14049: 2000 *Environmental Management – Life-Cycle Assessment – Examples of Application of ISO 14041 to Goal and Scope Definition and Inventory Analysis.* London, B.S.I. (British Standards Institution).

British Standards Institution (1998^b) BS EN ISO 14050: 1998 *Environmental Management - Vocabulary.* London, B.S.I. (British Standards Institution).

British Standards Institution (2000^c) BS EN ISO 15686: 2000 *Building and Constructed Assets: Service Life Planning.* London, B.S.I. (British Standards Institution).

Boardman, B. (2005) Brave New World. [Internet] Available from http://society.guardian.co.uk/ societyguardian/story/0,1447411,00.html <Accessed 10th June, 2005>

Broadman, B., Killip, G., Darby, S., and Sinden, G. (2005) *Low Carbon Futures: The 40 % House Project.* [Internet] Available from http://www.eci.ox.ac.uk/lowercf/40house.html <Accessed 10th June, 2005>

Burberry, P (1997) *Mitchell's Environment and Services.* 8th Ed. Longman Scientific and Technical, Harlow, Essex, p.p. 98 - 101

Cambridge Econometrics, 2004 *D.T.I. – Digest of U.K. Energy Statistics 2004* [Internet] Available from http://www.environment-agency.gov.uk/commondata/103608/i1_energy_r2_dt_4333.html <Accessed 28th February, 2005>

Clover, C. (2005) 3m Homes 'Should be Demolished' to Cut Global Warming. Daily Telegraph, 30th May, 2005

Davidson, A. W. (1989) *Parry's Valuation and Investment Tables.* 11th ed. Estates Gazette.

Davis, Langdon and Everest, ed. (2003) *Spon's Architects' and Builders' Price Book.* 128th Ed. London, Spon Press - Taylor and Francis Group

Department of the Environment, Fisheries and Rural Affairs (2003) *Sustainable Energy: Sustainable Building Initiative.* [Internet] Available from http://www.defra.gov.uk/environment/energy/betterbuildings.htm <Accessed 1st August, 2005>

Department of the Environment, Transport and the Regions (1998^{a}) *Sustainable Development: Opportunities for Change.* London, H.M.S.O. (Her Majesty's Stationary Office).

Department of the Environment, Transport and the Regions (1998^{b}) *Opportunities for Change: Sustainable Construction.* London, H.M.S.O. (Her Majesty's Stationary Office).

Department of the Environment, Transport and the Regions (2000) *Building A Better Quality Of Life: A Strategy For More Sustainable Construction.* London, H.M.S.O. (Her Majesty's Stationary Office).

Department of the Environment, Transport and the Regions (2000^{a}) *Collecting, Managing and Using Housing Stock information – A Good Practice Guide: Volume 1 – An Overview of the Key principles.* London, H.M.S.O. (Her Majesty's Stationary Office).

Department of the Environment, Transport and the Regions (2000^{b}) *Collecting, Managing and Using Housing Stock information – A Good Practice Guide: Volume 2 – Key Principles and Methodological Issues.* London, H.M.S.O. (Her Majesty's Stationary Office).

Department of the Environment, Transport and the Regions (2000^{c}) *Collecting, Managing and Using Housing Stock information – A Good Practice Guide: Volume 3 – Specifying Stock Surveys.* London, H.M.S.O. (Her Majesty's Stationary Office).

Department of Trade and Industry (2004^{a}) *Better Buildings - Better Lives: The Sustainable Buildings Task Group Report.* London, H.M.S.O. (Her Majesty's Stationary Office).

Department of Trade and Industry (2004^{b}) *Table 3.6: Domestic Energy Consumption by End Use, 1970 to 2002.* [Internet] Available from http://www.dti.gov.uk/energy/inform/energy_consumption/table.shtml <Accessed 1st March, 2005>

Department of Trade and Industry (2004^{c}) *Energy Consumption in the U.K.* [Internet] Available from http://www.dti.gov.uk/energy <Accessed 1st March, 2005>

Department of Trade and Industry (2004^{d}) *Energy White Paper: Our Energy Future – Creating a Low Carbon Economy.* Norwich, T.S.O. (The Stationary Office)

Department for Transport, Local Government and the Regions (2002) *A Decent Home: The Revised Definition and Guidance for Implementation.* London, H.M.S.O. (Her Majesty's Stationary Office).

De Vekey, R. C. (1999) B.R.E. *Digest 441, Part 2: Clay Bricks and Clay Brick Masonry.* Garston, Watford, B.R.E. (Building Research Establishment).

Dickie, I. and Howard, N. (2000) *Digest 446: Assessing Environmental Impacts of Construction - Industry Consensus, BREEAM and UK Eco-points.* Garston, Watford, B.R.E. (Building Research Establishment).

Discussion of a paper: *Engineering Buildings for a Small Planet: Towards Construction Without Depletion,* The Structural Engineer, 21st May 2002, p.p. 36-37

Edwards, S., Bartlett, E. and Dickie, I (2000) *Digest 452: Whole-Life Costing and Life-Cycle Assessment for Sustainable Building Design.* Garston, Watford, B.R.E. (Building Research Establishment).

Egan, J. (1998) *Rethinking Construction: The Report of the Construction Task Force.* London, T.S.O. (The Stationary Office).

Finance Act 2000 (c. 17) London, H.M.S.O. (Her Majesty's Stationary Office).

Finance Act 2001 (c. 9) London, H.M.S.O. (Her Majesty's Stationary Office).

Friend, G. (1996) [Internet] Available from <http://www.natlogic.com/resources/nbl/v05/n13.html>

Goedkoop, M. and Oele, M. (2002) *SimaPro 5.1 User Manual: Introduction into L.C.A. Methodology and Practice with SimaPro 5.* Netherlands, PRé Consultants

Goedkoop, M. and Oele, M. (2004) *SimaPro 6: Introduction to L.C.A. with SimaPro. PRé Consultants, Netherlands.* [Internet] Available from http://www.pre.nl/download/manuals/UserManual.pdf

Gregory, R. and Hughes, T. (2005) *Brick Recycling Work: Information Database: Masonry Recycling Work.* Cardiff School of Engineering. [Internet] Available from http://carlos.engi.cf.ac.uk/db/conmas%20index/richard%20work.htm <Accessed 19th July, 2005>

Guinée *et al.* (2002) *Handbook on Life-Cycle Assessment.* Dordrecht, Kluwer Academic Publishers, p.p. 704

Harvey, N. (2001) *BMI Life Expectancy of Building Components: Surveyors' Experience of Buildings in Use: A Practical Guide.* London, Building Cost Information Service Ltd. (The Royal Institution of Chartered Surveyors).

Heijungs R, Guinée JB, Huppes G, Lankreijer R M, Udo De Haes H A, Wegener Sleeswijk A, Ansems AMM, EggelsPG, Van Duin R, De Goede HP (1992): *Environmental Life-Cycle Assessment of Products.* Leiden, The Netherlands, C.M.L. (The University of Leiden)

Hertwich, E. G. and. Pease, W. S. (1998). *International Journal of Life Cycle Assessment.* 3 (4) p.p. 180 – 181

H.M. Treasury (2003[a]) *CM 5776: U.K. Membership of the Single Currency: An Assessment of the Five Economic Tests.* London, The Public Enquiry Unit, H.M. Treasury

H.M Treasury (2003[b]) *The New Monetary Policy Framework.* London, The Public Enquiry Unit, H.M. Treasury

Hofsetter, P., Branschweig, A. Mettier, M. Müller-Wenk, R., Tietje, O. (1999) *Dominance analysis in the Mixing Triangle: A Graphical Decision Support Tool for Product Comparisons.* Journal of Industrial Ecology.

Howard, N., Edwards, S. and Anderson, J. (1999) *B.R.E. Methodology for Environmental Profiles of Construction Materials, Components and Buildings.* Garston, Watford, B.R.E. (Building Research Establishment).

Howard, N., Shiers, D. and Sinclair, M. (1998) *The Green Guide to Specification: An Environmental Profiling System for Building Materials and Components.* 2nd Ed. Garston, Watford, B.R.E. (Building Research Establishment).

Howell, J. (2003^a) Maintenance: Walls. *The Sunday Telegraph's Home Values Supplement.* June, p.p. 27 - 28.

Howell, J. (2003^b). Which of These Houses Costs More to Maintain? *The Sunday Telegraph; House and Homes Supplement.* 9th November, p.p. 3

Edwards, B. and Hyett, P. (2002) *Rough Guide to Sustainability.* London. R.I.B.A. Companies Ltd.

I.U.C.N. – World Conservation Union (1993). *Guide to Preparing and Implementing National Development Strategies and Other Multi-Sectoral Environment and Development Strategies.*

Landfill Tax: The Landfill Tax Regulations 1996 S.I. 1996 / 1527. London, H.M.S.O. (Her Majesty's Stationary Office)

Lloyd, N. (1925) *A History of English Brickwork.* London, H. Greville Montgomery.

Lowe, R. and Bell, M. (2000) *A Trial of Dwelling Energy Performance Standards for 2008: Prototype Standards for Energy and Ventilation Performance.* Department of the Environment, Transport and the Regions Partners in Innovation contract. Reference number: CI 39 / 03 / 604, Centre for the Built Environment, Leeds Metropolitan University, Leeds.

Lynch, G. (2003) *Brickwork: The Historical Development.* [Internet] Available from http://www.buildingconservation.com/articles/brick/brickwork.html <Accessed 17th February, 2005>

McMullan, R. (2002) *Environmental Science in Buildings.* 5th ed. Basingstoke, Hampshire. Palgrave MacMillan

N.H.B.C. (2004) *N.H.B.C. Buildmark: Your Warranty and Insurance Cover.* National Housebuilding Council, Amersham, Buckinghamshire.

Office of the Deputy Prime Minister (2002). *The Building Regulations 2000 (2002 Edition). Approved Document L1: Conservation of Fuel and Power in Dwellings.* Norwich, T.S.O. (The Stationary Office).

Office of the Deputy Prime Minister (2003[a]) *Possible Future Performance Standards for Part L:* [sic. The Building Regulations] http://www.odpm.gov.uk/stellent/groups/odpm_buildreg/documents/page/odpm_breg_024792.hcsp

Office of the Deputy Prime Minister (2003[b]) *The 2002 Housing Statistics.* Norwich, T.S.O. (The Stationary Office).

Pevsner, N. (1966) *Yorkshire: The North Riding.* Harmondsworth, .Penguin Books.

Pevsner, N. (1967) *Yorkshire: West Riding.* Harmondsworth, .Penguin Books.

Pevsner, N. (1972) *Yorkshire: York and the East Riding.* Harmondsworth, .Penguin Books.

Sayce, S. (2002) *The Quest for Sustainable Buildings: Is Longevity the Key?* Proceedings of the Eighth Annual International Sustainable Development Research Conference.

Sayce, S. and Ellison, L. (2003) *Integrating Sustainability into the Appraisal of Property Worth: Identifying Appropriate Indicators of Sustainability.* Proceeding of the American Real Estate And Urban Economics Association Conference

Scottish Executive (2001) *Technical Standards for Compliance with the Building Standards (Scotland) Regulations. Part J: Conservation of Fuel and Power.* [Internet] Available from: http://www.scotland.gov.uk/build_regs/ <Accessed 25th August, 2005>

S.E.T.A.C. (1991) *A Technical Framework for Life-Cycle Assessment.* S.E.T.A.C. (Society of Environmental Toxicology and Chemistry).

Slavid, R. (1998) What is Sustainability? *The Architects' Journal.* 5th February, p.p. 44 – 45

Steele, K. N. P., Cole, G., Parke, G., Clarke, B. and Harding J. (2003) *The Application of Life-Cycle Assessment Technique in the Investigation of Brick Arch Highway Bridges.* [Internet] Available from http://www.brick.org.uk/

Sustainable and Secure Buildings Bill 2004 (c. 2004) London, H.M.S.O. (Her Majesty's Stationary Office).

The Environmental Protection Act 1990 (c. 43) London, H.M.S.O. (Her Majesty's Stationary Office).

The Institution of Civil Engineers (1998) *Local Agenda 21: Engineering the future.* London, The Institution of Civil Engineers.

The Institution of Structural Engineers (1996). *Appraisal of Existing Structures.* 2nd ed. London, The Institution of Structural Engineers.

The Institution of Structural Engineers (1999) *Building for a Sustainable Future. Construction Without Depletion.* London, S.E.T.O.

The Sustainable Construction Focus Group (2000) *Toward Sustainability: A Strategy for the Construction Industry.* London, Department of Trade and Industry (via H.M.S.O.).

The Sustainable Construction Task Group (2003) *The UK Construction Industry: Progress Towards more Sustainable Construction (2000-2003).* London, Department of Trade and Industry (via H.M.S.O.).

Thistlethwaite, P. (2004) *Assessing the Sustainability of Construction Projects.* [Internet] Available from http://www.bfafh.de/inst4/45/ppt/2sustcon.pdf <Accessed 31st July, 2005>

[*U.K. Government Publication*] (1999) *A Better Quality of Life: A Strategy for Sustainable Development for the U.K.* [Internet] Available from http://www.sustainable-developemnt.gov.uk/publicationsuk-strategy99/ <Accessed 1st August, 2005>

U.S. Department of Housing and Urban Development (2001) *Life-Cycle Assessment Tools to Measure Environmental Impacts: Assessing Their Applicability to the Home Building Industry.* Washington, U.S.A., U.S. Department of Housing and Urban Development.

Williams, B. (2001) *Facilities Economics in the European Union.* 1st ed. Bromley, Kent, Building Economics Bureau Ltd.

World Commission on Environment and Development, (1987). *Our Common Future (The Bruntland Report).* Oxford and New York, Oxford University Press.

Data from the following websites was also cited in the main text:

- http://www.uneptie.org/pc/sustain/reports/lcini/Database%20overview.pdf
- http://www.huduser.org/Publications/PDF/lifecycle.pdf
- http://www.huduser.org//Publications/PDF/lifecycle.pdf
- http://www.dti.gov.uk/construction/stats/bulletin/pdf/dec02.pdf
- http://www.pre.nl
- http://gecos.epfl.ch/lcsystems/Fichiers_communs/impact2002/LCA-2003-324-330.pdf
- http://www.uneptie.org/pc/sustain/reports/lcini/Marketing%20Brochure1.pdf
- http://www.scienceinthebox.com/en_UK/main/sustainability_en.html
- http://unit.aist.go.jp/lca-center/lca-activity/symposium/02_sympo/021107_document/155.pdf
- http://unit.aist.go.jp]/lca-center/lca-activity/symposium/02_sympo/021107_document/155.pdf
- http://cig.bre.co.uk/envprofiles
- http://www.gdrc.org/uem/lca/life-cycle.html

BIBLIOGRAPHY

Anink, D., Boonstra, C. and Mak, J. (1996) *Handbook of Sustainable Building: An Environmental Preference Method for Selection of Materials for Use in Construction and Refurbishment.* London, James and James (Science Publishers) Ltd.

British Cement Association (2003) *Sustainable Development in the Cement and Concrete Sector.* [Internet] Available from http://www.concretecentre.com

British Standards Institution (1981) BS 4721: 1981 *Specification for Ready-Mixed Building Mortars.* London, B.S.I. (British Standards Institution).

Centre for Strategic Studies in Construction (1989) *Investing in Building 2001*

Clarkson, R. and Deyes, K. (2002) *Government Economic Service Working Paper 140: Estimating the Social Cost of Carbon Emissions.* London, The Public Enquiry Unit, H.M. Treasury.

Construction Economics (Tampere University of Technology, Finland) (1992) *Special Publication 82: The U.K. Construction Industry: A Continental View.* London, C.I.R.I.A. (Construction Industry Research and Information Association)

Corus U.K. Ltd. (2003) *Insite on Environmental Impact.* London, B.S.C.A. (The British Constructional Steelwork Association Ltd.) [Multi-media CD-ROM]

Corus U.K. Ltd. (2003) *Insite on Life-Cycle Costs.* London, B.S.C.A. (The British Constructional Steelwork Association Ltd.) [Multi-media CD-ROM]

Parrott, L. (2002) *Cement, Concrete and Sustainability: A Report on the Progress of the U.K. Cement and Concrete Industry Towards Sustainability.* Crowthorne, U.K., B.C.A. (The British Cement Association). [Internet] Available from http://www.concemsus.info

Plank, R. and Dowling, J. (2003) *B.C.S.A. Publication Number 35 / 03 – Steel Buildings - Chapter 21: Sustainable Construction.* London, B.S.C.A. (The British Constructional Steelwork Association Ltd.) [Multi-media CD-ROM] p.p. 175 - 180

S.P.O.L.D. (Society for the Promotion of L.C.A. Development) and Business in the Environment (1993) *The L.C.A. Sourcebook: A European Business Guide to Life-Cycle Assessment Sustainability. Society for the Promotion of LCA Development.* London, S.P.O.L.D.

Trotman-Dickenson D.I. (1996) *Economics of the Public Sector.* Houndsmills, Basingstoke, Hampshire, MacMillan Press Ltd.

Working party of the Materials Forum and the Institution of Civil Engineers (1987) *Materials for Construction and Building in the United Kingdom.* London, The Institute of Metals.

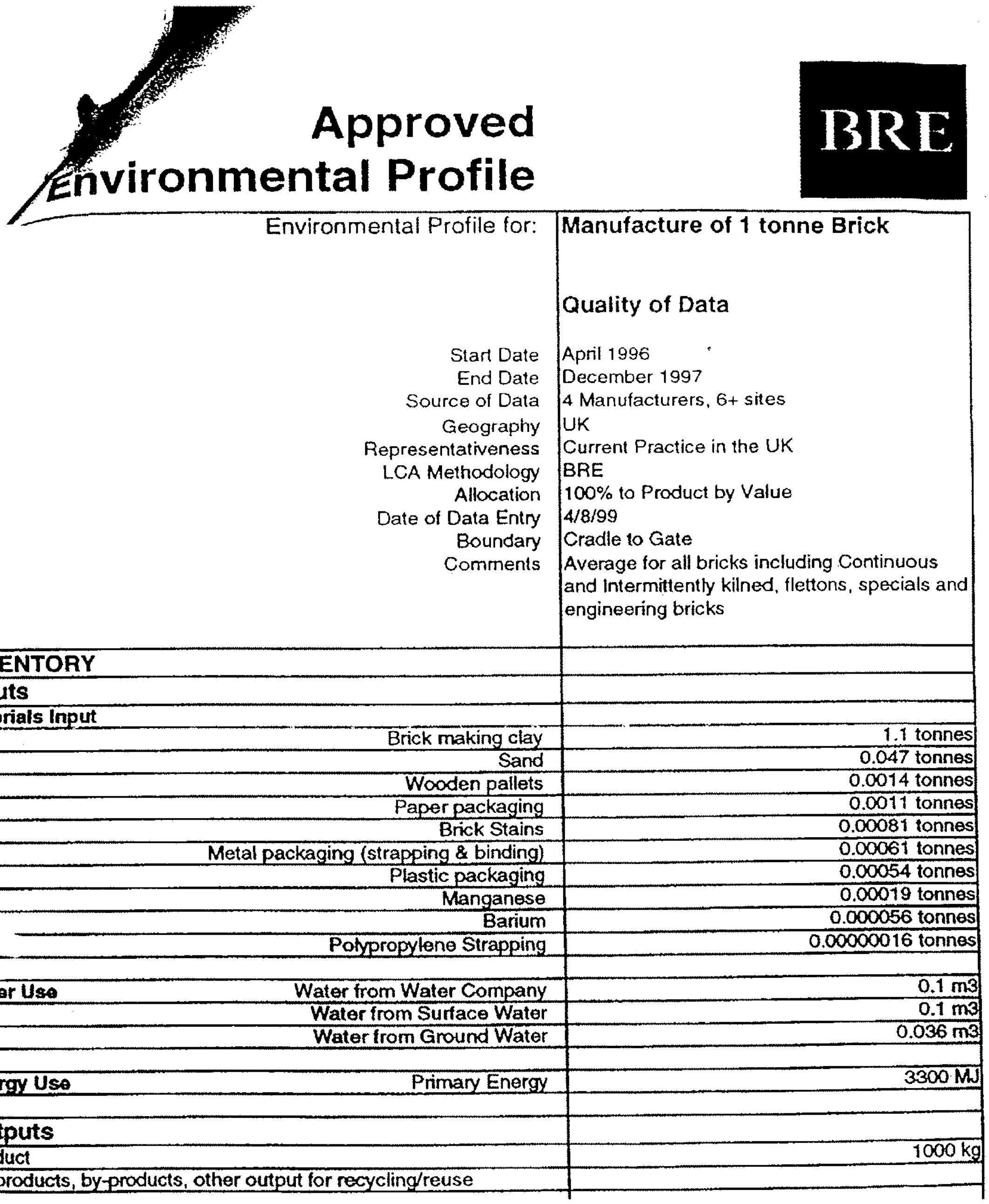
APPENDIX A: CONVERSION OF INITIAL INVENTORY DATA TO CHARACTERISED AND NORMALISED DATA

A.1 INTRODUCTION

The following appendix gives an example of how the Life Cycle Inventory (L.C.I.) data is converted into Characterised and Normalised data using the methodology described in *BRE Methodology for Environmental profiles of Construction Materials, Components and Buildings* [Howard, Edwards and Anderson, 1999].

In this example, the L.C.I. data is that for the manufacture of one tonne of bricks. The initial inventory data shown in Figures A.1 were supplied to the B.R.E. by the masonry industry via their trade representatives, the Brick Development Association Ltd, in 1998. The B.R.E. then converted it to characterised and normalised data using the conversion factors given in Annex A.11 in *BRE Methodology for Environmental profiles of Construction Materials, Components and Buildings* [Howard, Edwards and Anderson, 1999]. This conversion of the initial inventory data to characterised and normalised for the manufacture of one tonne of bricks is repeated in Appendix A.2 and A.3 respectively.

The B.R.E.'s Approved Environmental Profile which shows the characterised and normalised impact data for the manufacture of one tonne of bricks is shown in Figure A.2. Appendix A.4 compares the characterised and normalised data as calculated in Appendices A.2 and A.3.2 with the Approved Environmental Profile values shown in Figure A.2.



Approved Environmental Profile

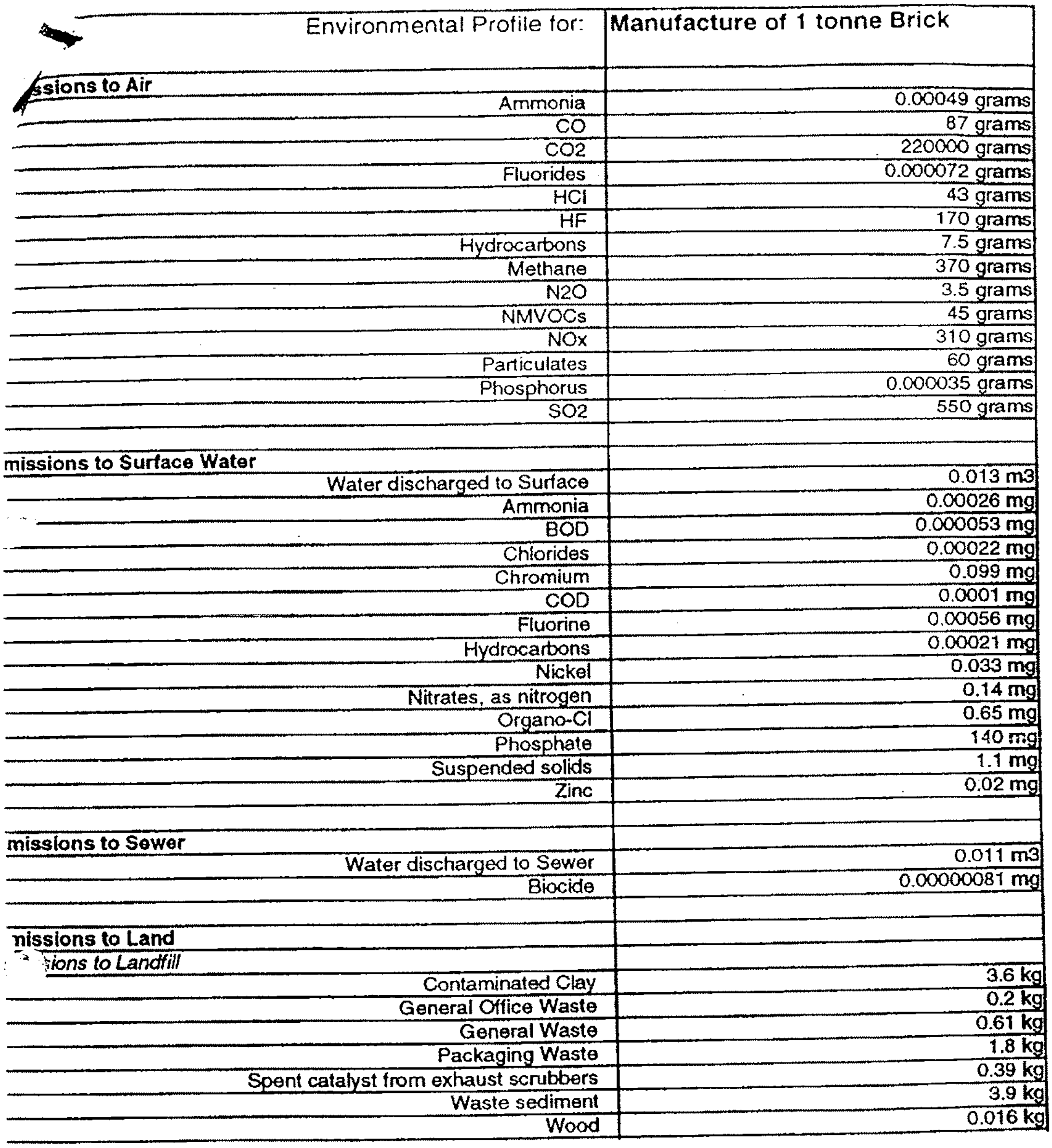
BRE

Environmental Profile for:	**Manufacture of 1 tonne Brick**
	Quality of Data
Start Date	April 1996
End Date	December 1997
Source of Data	4 Manufacturers, 6+ sites
Geography	UK
Representativeness	Current Practice in the UK
LCA Methodology	BRE
Allocation	100% to Product by Value
Date of Data Entry	4/8/99
Boundary	Cradle to Gate
Comments	Average for all bricks including Continuous and Intermittently kilned, flettons, specials and engineering bricks

INVENTORY		
Inputs		
Materials Input		
	Brick making clay	1.1 tonnes
	Sand	0.047 tonnes
	Wooden pallets	0.0014 tonnes
	Paper packaging	0.0011 tonnes
	Brick Stains	0.00081 tonnes
	Metal packaging (strapping & binding)	0.00061 tonnes
	Plastic packaging	0.00054 tonnes
	Manganese	0.00019 tonnes
	Barium	0.000056 tonnes
	Polypropylene Strapping	0.00000016 tonnes
Water Use	Water from Water Company	0.1 m3
	Water from Surface Water	0.1 m3
	Water from Ground Water	0.036 m3
Energy Use	Primary Energy	3300 MJ
Outputs		
Product		1000 kg
Co-products, by-products, other output for recycling/reuse		

Figure A.1 (i): Inventory Data Sheets from the Approved Environmental Profile for the Manufacture of One Tonne of Bricks (Part 1 of 2)

(Copyright Crown and Building Research Establishment 2002)



Environmental Profile for:	Manufacture of 1 tonne Brick
ssions to Air	
Ammonia	0.00049 grams
CO	87 grams
CO2	220000 grams
Fluorides	0.000072 grams
HCl	43 grams
HF	170 grams
Hydrocarbons	7.5 grams
Methane	370 grams
N2O	3.5 grams
NMVOCs	45 grams
NOx	310 grams
Particulates	60 grams
Phosphorus	0.000035 grams
SO2	550 grams
missions to Surface Water	
Water discharged to Surface	0.013 m3
Ammonia	0.00026 mg
BOD	0.000053 mg
Chlorides	0.00022 mg
Chromium	0.099 mg
COD	0.0001 mg
Fluorine	0.00056 mg
Hydrocarbons	0.00021 mg
Nickel	0.033 mg
Nitrates, as nitrogen	0.14 mg
Organo-Cl	0.65 mg
Phosphate	140 mg
Suspended solids	1.1 mg
Zinc	0.02 mg
missions to Sewer	
Water discharged to Sewer	0.011 m3
Biocide	0.00000081 mg
nissions to Land	
sions to Landfill	
Contaminated Clay	3.6 kg
General Office Waste	0.2 kg
General Waste	0.61 kg
Packaging Waste	1.8 kg
Spent catalyst from exhaust scrubbers	0.39 kg
Waste sediment	3.9 kg
Wood	0.016 kg

Figure A.1 (ii): Inventory Data Sheets from the Approved Environmental Profile for the Manufacture of One Tonne of Bricks (Part 2 of 2)

(Copyright Crown and Building Research Establishment 2002)

A.2 CONVERSION OF INVENTORY DATA TO CHARACTERISED DATA FOR THE MANUFACTURE OF ONE TONNE OF BRICKS

The following section shows how the initial L.C.I. data given in Figures A.1 are converted to characterised data using the conversion factors given in Annex A.11 in *BRE Methodology for Environmental profiles of Construction Materials, Components and Buildings* [Howard, Edwards and Anderson, 1999]. Table A.1 shows a summary of the final characterised data.

- **Climate Change** (emissions to air)

Inventory Data		Characterisation factor	Impact data
CH_4 (Methane)	370 g	× 21	= 8 kg CO2 eq. (100 yrs)
CO_2	220000 g	× 1	= 220 kg CO_2 eq. (100 yrs)
N_2O	3.5 g	× 310	= 1 kg CO_2 eq. (100 yrs)
		Total	**= 229 kg CO_2 eq. (100 yrs)**

- **Acid Deposition** (emissions to air)

Inventory Data		Characterisation factor	Impact data
HCl	43 g	× 0.88	= 0.0 kg SO2 eq.
HF	170 g	× 1.6	= 0.3 kg SO2 eq.
NH_3 (Ammonia)	0.00049 g	× 1.88	= 0.0 kg SO2 eq.
Nox	310 g	× 0.7	= 0.2 kg SO2 eq.
SO_2	550 g	× 1	= 0.6 kg SO2 eq.
		Total	**= 1.1 kg SO2 eq.**

- **Ozone Depletion** (emissions to air)

Inventory Data	Characterisation factor	Impact data
-	-	-
	Total	**= 0 kg CFC-11 eq.**

- **Pollution to Air: Human Toxicity** (emissions to air)

Inventory Data		**Characterisation factor**	**Impact data**
Hydrocarbons	7.5 g	× 3.9	= 0 kg tox.
CO	87 g	× 0.012	= 0 kg tox.
NH_3 (Ammonia)	0.00049 g	× 0.02	= 0 kg tox.
NMVOCs	45 g	× 0.022	= 0 kg tox.
Nox	310 g	× 0.78	= 0 kg tox.
SO_2	550 g	× 1.2	= 1 kg tox.
		Total	**= 1 kg tox.**

- **Pollution to Air: Photochemical Ozone Creation Potential** (emissions to air)

Inventory Data		**Characterisation factor**	**Impact data**
Hydrocarbons	7.5 g	× 0.761	= 0.006 kg ethene eq. (P.O.C.P.)
NMVOCs	45 g	× 0.416	= 0.019 kg ethene eq. (P.O.C.P.)
		Total	**= 0.024 kg ethene eq. (P.O.C.P.)**

- **Pollution to Water: Human Toxicity** (emissions to water)

Inventory Data		**Characterisation Factor**	**Impact data**
Cr (Chromium)	0.099 mg	× 0.57	= 0.000000056 kg tox.
Hydrocarbons	0.00021 mg	× 0.66	= 0.000000000 kg tox.
Ni (Nickel)	0.033 mg	× 0.057	= 0.000000002 kg tox.
Nitrates, as nitrogen	0.14 mg	× 0.00078	= 0.000000000 kg tox.
Zinc	0.02 mg	× 0.0029	= 0.000000000 kg tox.
		Total	**= 0.000000059 kg tox.**

- **Pollution to Water: Ecotoxity** (emissions to water)

Inventory Data		Characterisation factor	Impact data
Hydrocarbons	0.00021 mg	× 0.029	= 0.000 m^3 tox.
Ni (Nickel)	0.033 mg	× 0.33	= 0.011 m^3 tox.
Zinc	0.02 mg	× 0.38	= 0.008 m^3 tox.
		Total	**= 0.018 m^3 tox.**

- **Pollution to Water: Eutrophication** (emissions to water)

Inventory Data		Characterisation Factor	Impact data
NH_3 (Ammonia)	0.00026 mg	× 0.33	= 0.000 kg PO4 eq.
BOD	0.000053 mg	× 0.11	= 0.000 kg PO4 eq.
COD	0.0001 mg	× 0.022	= 0.000 kg PO_4 eq.
Nitrates, as nitrogen	0.14 mg	× 0.1	= 0.000 kg PO_4 eq.
Phosphates	140 mg	× 1	= 0.000 kg PO_4 eq.
		Total	**= 0.000 kg PO_4 eq.**

- **Fossil Fuel Depletion**

Inventory Data		Characterisation factor	Impact data
Primary Energy	3300 MJ	× 0.0000239	= 0.079 tonnes oil eq.
		Total	**= 0.079 tonnes oil eq.**

- **Minerals Extraction**

Inventory Data		Characterisation Factor	Impact data
Clays / earth:			
Brick making clay	1.1 tonnes	× 1	= 1.1 tonnes
Brick stains	0.00081 tonnes	× 1	= 0.0 tonnes
Sand / gravel:			
Sand	0.047 tonnes	× 1	= 0.0 tonnes
Others:			
Manganese	0.00019 tonnes	× 1	= 0.0 tonnes
Barium	0.000056 tonnes	× 1	= 0.0 tonnes
		Total	**= 1.1 tonnes**

- **Water Extraction**

Inventory Data		Characterisation Factor	Impact data
Water from water company	0.1 m^3	× 1000	= 100 litres
Water from surface water	0.1 m^3	× 1000	= 100 litres
Water from ground water	0.036 m^3	× 1000	= 36 litres
		Total	**= 236 litres**

- **Waste Disposal** (To landfill)

Inventory Data		Characterisation factor	Impact data
Contaminated clay	3.6 kg	× 1	= 0.004 tonnes
General office waste	0.2 kg	× 1	= 0.000 tonnes
General waste	0.61 kg	× 1	= 0.001 tonnes
Packaging waste	1.8 kg	× 1	= 0.002 tonnes
Spent catalyst from exhaust scrubbers	0.39 kg	× 1	= 0.000 tonnes
Waste sediment	3.9 kg	× 1	= 0.004 tonnes
Wood	0.016 kg	× 1	= 0.000 tonnes
		Total	**= 0.011 tonnes**

- **Transport Pollution and Congestion**

Inventory Data	Standard conversion factor	Impact data
-	-	= 13 tonne.km
	Total	**= 13 tonne.km**

- **Primary Energy**

Inventory Data	Standard conversion factor	Impact data
Primary Energy 3300 MJ	-	= 3.3 GJ
	Total	**= 3.3 GJ**

A.3 DETERMINATION OF FACTORS USED TO CONVERT CHARACTERISED DATA TO NORMALISED DATA

The following appendix shows how the characterised data are converted to normalised data using the conversion factors given in Annex A.11 in *BRE Methodology for Environmental profiles of Construction Materials, Components and Buildings.* [Howard, Edwards and Anderson, 1999].

- **Climate Change** (emissions to air)

Inventory data	Characterisation factor (kg CO2eq. (100years) / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg CO2eq. (100years))
CCl_4	-650	0.192512	-125
CF_4	6500	0.001344	9
CFC-11	2100	0.004983	10
CFC-113	3600	0.00051	2
CFC-114	7000	0.00119	8
CFC-12	7100	0.018911	134
CH_2Cl_2	9	0.252375	2
CH_3CCl_3	-320	0.334005	-107
CH_4	21	63.12764	1326
CO_2	1	9774.411	9774
HCFC-141b	370	0.063961	24
HCFC142b	1700	0.02238	38
HCFC-22	1400	0.115932	162
N_2O	310	3.214204	996
SF_6	23900	0.000595	14
	Total		**12269**

- **Acid Deposition** (emissions to air)

Inventory data	Characterisation factor (kg SO2 eq. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg SO2 eq.)
NO_x (as NO_2)	0.7	34.89707	24.4
SO_2	1	34.4549	34.5
	Total		**58.9**

- **Ozone Depletion** (emissions to air)

Inventory data	Characterisation factor (kg CFC-11 eq. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg CFC-11 eq.)
CCl_4	1.1	0.192512	0.212
CFC-11	1	0.004983	0.005
CFC-113	0.8	0.00051	0.000
CFC-114	1	0.00119	0.001
CFC-12	1	0.018911	0.019
CH3CCl3	0.1	0.334005	0.033
HCFC-141b	0.11	0.063961	0.007
HCFC142b	0.065	0.02238	0.001
HCFC-22	0.055	0.115932	0.006
Other CFC	1	0.335536	0.000425
	Total		**0.286**

- **Pollution to Air: Human Toxicity** (emissions to air)

Inventory data	Characterisation factor (kg tox. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg tox.)
124 tri-methyl benzene	3.9	0.405942	1.6
22 di-methyl propane	0.022	0.200505	0.0
2 methyl hexane	1.6	0.124997	0.2
2 methyl pentane	0.022	0.277544	0.0
3 methyl hexane	1.6	0.136901	0.2
3 methyl pentane	0.022	0.178397	0.0
4 methyl pentan2one	0.022	0.24081	0.0
Acetone	0.022	0.379242	0.0
Acetylene	0.022	0.503048	0.0
Aromatic Hydrocarbons	3.9	0.001454	0.0

- **Pollution to Air: Human Toxicity** (continued)

Inventory data	Characterisation factor (kg tox. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg tox.)
Benzene	3.9	0.702873	2.7
But2ene	0.022	0.193703	0.0
Butan2one	0.022	0.238089	0.0
Butane	0.022	3.25689	0.1
Butanols	0.022	0.153397	0.0
Butylacetate	0.022	0.196424	0.0
CCl_4	1.9	0.192512	0.4
CFC-11	0.022	0.004983	0.0
CFC-113	0.022	0.00051	0.0
CFC-114	0.022	0.00119	0.0
CFC-12	0.022	0.018911	0.0
CFC-502	0.022	0.002925	0.0
CH_2Cl_2	0.069	0.252375	0.0
CH_3CCl_3	2.4	0.334005	0.8
CO	0.012	78.92656	0.9
Ethane	0.022	0.53281	0.0
Ethanol	0.022	1.666964	0.0
Ethene	0.022	1.114427	0.0
Ethyl acetate	0.022	0.195233	0.0
Ethyl benzene	3.9	0.384684	1.5
Formaldehyde	0.022	0.438084	0.0
Glycols	0.0083	0.203396	0.0
HCFC-141b	0.022	0.063961	0.0
HCFC-142b	0.022	0.02238	0.0
HCFC-22	0.022	0.115932	0.0
Heptane	1.6	0.445737	0.7

- **Pollution to Air: Human Toxicity** (continued)

Inventory data	Characterisation factor (kg tox. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg tox.)
Hexane	0.022	0.738587	0.0
Isobutane	0.022	0.757124	0.0
Iso-pentane	0.022	0.940622	0.0
Methyl heptanes	1.6	0.421588	0.7
M-ethyl toluene	3.9	0.127888	0.5
M-xylene	2.2	0.66682	1.5
NMVOC	0.022	34.52293	0.8
NO_x (as NO_2)	0.78	34.89707	27.2
Octane	1.6	0.335536	0.5
Other CFC	0.022	0.000425	0.0
Other HCFC	0.022	0.009507	0.0
Other paraffins	0.022	0.685867	0.0
Other unknown VOC	0.022	4.744777	0.1
Other VOC	0.022	4.370637	0.1
O-xylene	2.2	0.554748	1.2
Pb	160	0.018707	3.0
Pent2ene	0.022	0.13299	0.0
Pentane	0.022	1.502002	0.0
Pentaneisomers	0.022	0.26734	0.0
P-ethyl toluene	3.9	0.127038	0.5
Propan1ol	0.022	0.368358	0.0
Propan2ol	0.022	0.39999	0.0
Propane	0.022	1.297416	0.0
Propylene	0.022	0.516143	0.0
P-xylene	2.2	0.715628	1.6
RH	0.022	0.304924	0.0

- **Pollution to Air: Human Toxicity** (continued)

Inventory data	Characterisation factor (kg tox. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg tox.)
SO_2	1.2	34.4549	41.3
Tetra-chloro ethene	0.047	0.18588	0.0
Toluene	0.039	2.318988	0.1
Tri-chloro ethene	0.061	0.446077	0.0
White-spirit	0.022	1.677168	0.0
Xylenes	2.2	0.600155	1.3
	Total		**90.0**

- **Pollution to Air: Photochemical Ozone Creation Potential** (emissions to air)

Inventory data	Characterisation factor (kg ethene eq. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg ethene eq.)
124 tri-methyl benzene	1.2	0.405942	0.5
22 di-methyl propane	0.398	0.200505	0.1
2 methyl hexane	0.492	0.124997	0.1
2 methyl -pentane	0.524	0.277544	0.1
3 methyl hexane	0.492	0.136901	0.1
3 methyl pentane	0.431	0.178397	0.1
4 methyl pentan2one	0.326	0.24081	0.1
Acetone	0.178	0.379242	0.1
Acetylene	0.168	0.503048	0.1
Aromatic Hydrocarbons	0.761	0.182989	0.1
Benzene	0.189	0.702873	0.1
But2ene	0.992	0.193703	0.2
Butan2one	0.326	0.238089	0.1
Butane	0.41	3.25689	1.3

- **Pollution to Air: Photochemical Ozone Creation Potential** (continued)

Inventory data	Characterisation factor (kg ethene eq. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg ethene eq.)
Butanols	0.196	0.153397	0.0
Butylacetate	0.323	0.196424	0.1
CCl_4	0.021	0.192512	0.0
CFC-11	0.021	0.004983	0.0
CFC-113	0.021	0.00051	0.0
CFC-114	0.021	0.00119	0.0
CFC-12	0.021	0.018911	0.0
CFC-502	0.021	0.002925	0.0
CH_2Cl_2	0.021	0.252375	0.0
CH_3CCl_3	0.021	0.334005	0.0
CH_4	0.007	63.12764	0.4
Ethane	0.082	0.53281	0.0
Ethanol	0.268	1.666964	0.4
Ethene	1	1.114427	1.1
Ethyl acetate	0.218	0.195233	0.0
Ethyl benzene	0.593	0.384684	0.2
Formaldehyde	0.421	0.438084	0.2
Glycols	0.196	0.203396	0.0
HCFC-141b	0.021	0.063961	0.0
HCFC-142b	0.021	0.02238	0.0
HCFC-22	0.021	0.115932	0.0
Heptane	0.529	0.445737	0.2
Hexane	0.421	0.738587	0.3
Iso-butane	0.315	0.757124	0.2
Iso-pentane	0.296	0.940622	0.3
Methyl heptanes	0.469	0.421588	0.2

- **Pollution to Air: Photochemical Ozone Creation Potential** (continued)

Inventory data	Characterisation factor (kg ethene eq. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg ethene eq.)
M-ethyl-toluene	0.794	0.127888	0.1
M-xylene	0.993	0.66682	0.7
NMVOC	0.416	34.52293	14.4
Octane	0.493	0.335536	0.2
Other CFC	0.021	0.000425	0.0
Other HCFC	0.021	0.009507	0.0
Other paraffins	0.761	0.685867	0.5
Other unknown VOC	0.337	4.744777	1.6
Other VOC	0.337	4.370637	1.5
O-xylene	0.666	0.554748	0.4
Pent2ene	0.93	0.13299	0.1
Pentane	0.408	1.502002	0.6
Pentane-isomers	0.296	0.26734	0.1
P-ethyl toluene	0.725	0.127038	0.1
Propan1ol	0.196	0.368358	0.1
Propan2ol	0.196	0.39999	0.1
Propane	0.42	1.297416	0.5
Propylene	1.03	0.516143	0.5
P-xylene	0.888	0.715628	0.6
Tetra-chloro ethene	0.005	0.18588	0.0
Toluene	0.563	2.318988	1.3
Tri-chloro ethene	0.066	0.446077	0.0
White-spirit	0.761	1.677168	1.3
Xylenes	0.888	0.600155	0.5
	Total		**32.1**

- **Pollution to Water: Human Toxicity** (emissions to water)

Inventory data	Characterisation factor (kg tox. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg tox.)
As	1.4	0.001454	0.002
Atrazine	0.57	2.44E-05	0.000
Azinphos-methyl	1.1	1.48E-05	0.000
CCl_4	0.71	0.000149	0.000
Cd	2.9	0.000324	0.001
CH_2Cl_2	0.048	0.000836	0.000
$CHCl_3$	0.095	0.000925	0.000
Cr	0.57	0.005459	0.003
Cu	0.02	0.007806	0.000
DDT	0.14	2.72E-06	0.000
Dichlorvos	0.71	1.4E-05	0.000
Drins	29	6.89E-06	0.000
Endosulfan	0.48	2.21E-06	0.000
Fenitrothion	0.57	1.09E-05	0.000
Fenthion	2.9	9.44E-06	0.000
Hexa-chloro benzene	5.7	2.3E-06	0.000
Hexa-chloro butadiene	2.9	2.13E-06	0.000
Hg	4.7	5.61E-05	0.000
Lindane	2.9	5.31E-06	0.000
Malathion	0.14	1.02E-05	0.000
Ni	0.057	0.005437	0.000
Orthophosphate	0.000041	0.516994	0.000
Parathion	0.57	2.89E-06	0.000
Parathion-methyl	0.14	1.03E-05	0.000
Pb	0.79	0.005255	0.004
PCB's	32	1.26E-05	0.000

- **Pollution to Water: Human Toxicity** (continued)

Inventory data	Characterisation factor (kg tox. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg tox.)
Pentachlorophenol	0.095	5.08E-05	0.000
Pesticides	2.9	2.31E-05	0.000
Simazine	1.4	3.22E-05	0.000
Tetra-chloroethene	0.18	0.00023	0.000
Tri-butyltin	5.7	0.002636	0.015
Tri-chloro benzene	5.7	2.47E-05	0.000
Tri-chloro ethane	0.2	0.000148	0.000
Tri-chloro ethene	0.2	0.000254	0.000
Tri-fluralin	0.14	8.25E-06	0.000
Tri-phenyltin	5.7	1.36E-06	0.000
Zn	0.0029	0.035713	0.000
	Total		**0.027**

- **Pollution to Water: Ecotoxity** (emissions to water)

Inventory data	Characterisation factor (m^3 tox. / mg)	Normalisation factor (mg / person)	U.K. citizens' impact (m^3 tox.)
As	0.2	1454	291
Atrazine	5	24.4	122
Azinphos-ethyl	100	12.2	1220
Azinphos-methyl	100	14.8	1480
CCl_4	0.0074	149	1
Cd	200	324	64800
CH_2Cl_2	0.00094	836	1
$CHCl_3$	0.17	925	157
Cr	1	5459	5459

- **Pollution to Water: Ecotoxity** (continued)

Inventory data	Characterisation factor (m^3 tox. / mg)	Normalisation factor (mg / person)	U.K. citizens' impact (m^3 tox.)
Cu	2	7806	15612
DDT	1.3	2.72	4
Dichlorvos	2000	14	28000
Drins	53	6.89	365
Endosulfan	100	2.21	221
Fenitrothion	100	10.9	1090
Fenthion	250	9.44	2360
Hexa-chloro benzene	53	2.3	122
Hexa-chloro butadiene	11	2.13	23
Hg	500	56.1	28050
Lindane	2.5	5.31	13
Malathion	67	10.2	683
Ni	0.33	5437	1794
Parathion	250	2.89	723
Parathion-methyl	8.3	10.3	85
Pb	2	5255	10510
PCB's	100	12.6	1260
Pentachlorophenol	5.6	50.8	284
Pesticides	2.5	23.1	58
Simazine	1	32.2	32
Tetra-chloro ethene	0.02	230	5
Tri-butyltin	250	2636	659000
Tri-chloro benzene	0.83	24.7	21
Tri-chloro ethane	0.00028	148	0
Tri-chloro ethene	0.046	254	12
Tri-fluralin	5	8.25	41

- **Pollution to Water: Ecotoxity** (continued)

Tri-phenyltin	20	1.36	27
Zn	0.38	35713	13571
	Total		**837497**

- **Pollution to Water: Eutrophication**

	Inventory data	Characterisation factor (kg.PO4 eq. / kg)	Normalisation factor (kg / person)	U.K. citizens' impact (kg.PO4 eq.)
Emissions to Air	N_2O	0.13	3.214204	0.42
	NO_x (as NO_2)	0.13	34.89707	4.54
		Sub-total		**4.95**
Emissions to Water	Ammoniacal N	0.33	1.079904	0.36
	Orthophosphate	1	0.516994	0.52
	Total Nitrogen	0.42	5.186943	2.18
		Sub-total		**3.05**
		Total		**8.01**

Fossil Fuel Depletion

	Inventory data	Characterisation factor (per tonne oil eq.)	Normalisation factor (t.o.e. / person)	U.K. citizens' impact (t.o.e.)
Fossil Fuels	Coal	1	0.782446	0.78
	Oil	1	1.859442	1.86
	Gas	1	1.443603	1.44
		Total		**4.09**

- **Minerals Extraction**

Minerals Extracted	Characterisation factor (per tonne)	Normalisation factor (tonne / person)	U.K. citizens' impact (tonne)
Stone / rock	1	2.984295	2.98
Clays / earth	1	0.293377	0.29
Sand / gravel	1	1.632611	1.63
Others	1	0.129248	0.13
	Total		**5.04**

- **Water Extraction**

Source of water	Characterisation factor (per litre)	Normalisation factor (l / person)	U.K. citizens' impact (litres)
Water Company	1	144539.7	144540
Surface Water	1	417583.4	417583
Ground Water	1	417583.4	417583
	Total		**979707**

- **Waste Disposal** (To landfill)

Destination	Characterisation factor (per tonne)	Normalisation factor (t / person)	U.K. citizens' impact (tonnes)
To Landfill	1	7.19	7.19
To Incineration	1	7.19	7.19
	Total		**14.39**

- **Transport Pollution and Congestion**

Characterisation factor (per tonne.km)	Normalisation factor (t.km / person)	U.K. citizens' impact (tonne.km)
1	4141	4141
	Total	**4141**

A.4 CONVERSION OF CHARACTERISED DATA TO NORMALISED DATA FOR THE MANUFACTURE OF ONE TONNE OF BRICKS

The normalised data are determined by dividing the characterised data from Appendix A.2 by the conversion factors calculated in Appendix A.3.1.

- **Climate Change** (emissions to air)
  Normalised data for the manufacture of one-tonne of bricks,
  = 229 / 12,269 = 0.019 kg CO_2 eq. (100years)

- **Acid Deposition** (emissions to air)
  Normalised data for the manufacture of one-tonne of bricks,
  = 1.1 / 58.9 = 0.019 kg SO_2 eq.

- **Ozone Depletion** (emissions to air)
  Normalised data for the manufacture of one-tonne of bricks,
  = 0 / 0.286 = 0 kg CFC-11 eq.

- **Pollution to Air: Human Toxicity** (emissions to air)
  Normalised data for the manufacture of one-tonne of bricks,
  = 1 / 90.0 = 0.011 kg tox.

- **Pollution to Air: Photochemical Ozone Creation Potential** (emissions to air)
  Normalised data for the manufacture of one-tonne of bricks,
  = 0.024 / 32.1 = 0.00075 kg ethene eq.

- **Pollution to Water: Human Toxicity** (emissions to water)

  Normalised data for the manufacture of one-tonne of bricks,

  = 0.000000059 / 0.027 = 0.0000022 kg tox.

- **Pollution to Water: Ecotoxity** (emissions to water)

  Normalised data for the manufacture of one-tonne of bricks,

  = 0.018 / 837497 = 0.00000002 m^3 tox.

- **Pollution to Water: Eutrophication**

  Normalised data for the manufacture of one-tonne of bricks,

  = 0.000 / 8.01 = 0.0000 kg PO_4 eq.

- **Fossil Fuel Depletion**

  Normalised data for the manufacture of one-tonne of bricks,

  = 0.079 / 4.09 = 0.019 tonnes oil equivalent

- **Minerals Extraction**

  Normalised data for the manufacture of one-tonne of bricks,

  = 1.1 / 5.04 = 0.22 tonnes

- **Water Extraction**

  Normalised data for the manufacture of one-tonne of bricks,

  = 236 / 979707 = 0.00024 litres

- **Waste Disposal** (To landfill)

  Normalised data for the manufacture of one-tonne of bricks,

  = 0.011 / 14.39 = 0.0007 tonnes

- **Transport Pollution and Congestion**

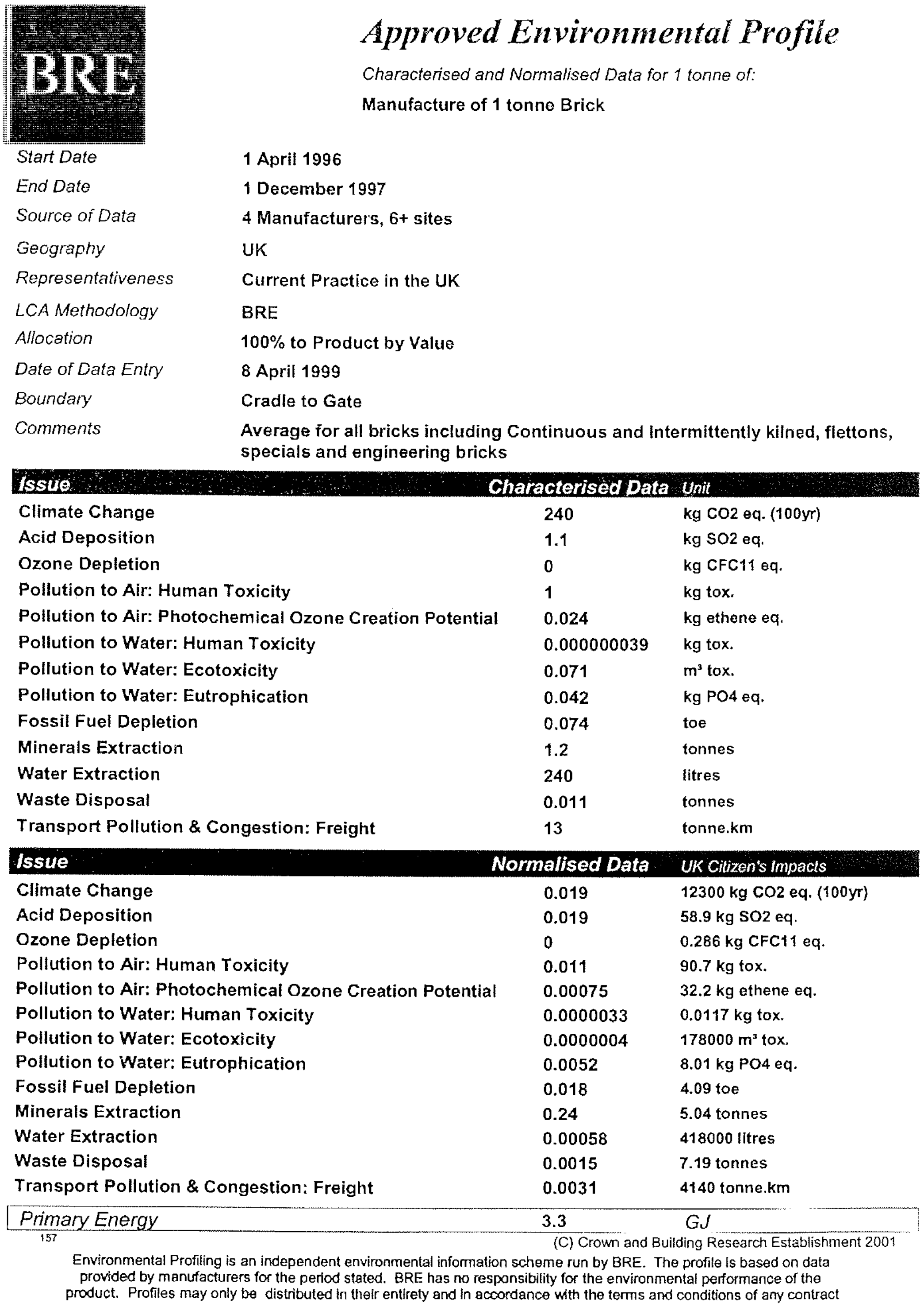
  Normalised data for the manufacture of one-tonne of bricks,

  = 13 / 4141 = 0.0031 tonne.km

Impact category	**Characterised data**	**Unit**
Climate Change	229	kg CO_2 eq. (100 yrs)
Acid Deposition	1.1	kg SO_2 eq.
Ozone Depletion	0	kg CFC-11 eq
Pollution to Air: Human Toxicity	1	kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.024	kg ethene eq. (P.O.C.P.)
Pollution to Water: Human Toxicity	0.000000059	kg tox.
Pollution to Water: Ecotoxity	0.018	m^3 tox.
Pollution to Water: Eutrophication	0.000	kg PO_4 eq.
Fossil Fuel Depletion	0.079	tonnes oil eq.
Minerals Extraction	1.1	tonnes
Water Extraction	236	litres
Waste Disposal (To landfill)	0.011	tonnes
Transport Pollution and Congestion	13	tonne.km
Primary Energy	3.3	GJ

	Normalised data	**U.K. citizen's impact**
Climate Change	0.019	12,269 kg CO_2 eq. (100 yrs)
Acid Deposition	0.019	58.9 kg SO_2 eq.
Ozone Depletion	0	0.286 kg CFC-11 eq
Pollution to Air: Human Toxicity	0.011	90.0 kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.00075	32.1 kg ethene eq. (P.O.C.P.)
Pollution to Water: Human Toxicity	0.0000022	0.027 kg tox.
Pollution to Water: Ecotoxity	0.00000002	837497 m^3 tox.
Pollution to Water: Eutrophication	0.0000	8.01 kg PO_4 eq.
Fossil Fuel Depletion	0.019	4.09 tonnes oil eq.
Minerals Extraction	0.22	5.04 tonnes
Water Extraction	0.00024	979707 litres
Waste Disposal (To landfill)	0.0007	14.39 tonnes
Transport Pollution and Congestion	0.0031	4141 tonne.km

Table A.1: Summary of Calculated Impact Data



BRE

Approved Environmental Profile

Characterised and Normalised Data for 1 tonne of:

Manufacture of 1 tonne Brick

Start Date	1 April 1996
End Date	1 December 1997
Source of Data	4 Manufacturers, 6+ sites
Geography	UK
Representativeness	Current Practice in the UK
LCA Methodology	BRE
Allocation	100% to Product by Value
Date of Data Entry	8 April 1999
Boundary	Cradle to Gate
Comments	Average for all bricks including Continuous and Intermittently kilned, flettons, specials and engineering bricks

Issue	*Characterised Data*	*Unit*
Climate Change	240	kg CO2 eq. (100yr)
Acid Deposition	1.1	kg SO2 eq.
Ozone Depletion	0	kg CFC11 eq.
Pollution to Air: Human Toxicity	1	kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.024	kg ethene eq.
Pollution to Water: Human Toxicity	0.000000039	kg tox.
Pollution to Water: Ecotoxicity	0.071	m³ tox.
Pollution to Water: Eutrophication	0.042	kg PO4 eq.
Fossil Fuel Depletion	0.074	toe
Minerals Extraction	1.2	tonnes
Water Extraction	240	litres
Waste Disposal	0.011	tonnes
Transport Pollution & Congestion: Freight	13	tonne.km

Issue	*Normalised Data*	*UK Citizen's Impacts*
Climate Change	0.019	12300 kg CO2 eq. (100yr)
Acid Deposition	0.019	58.9 kg SO2 eq.
Ozone Depletion	0	0.286 kg CFC11 eq.
Pollution to Air: Human Toxicity	0.011	90.7 kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.00075	32.2 kg ethene eq.
Pollution to Water: Human Toxicity	0.0000033	0.0117 kg tox.
Pollution to Water: Ecotoxicity	0.0000004	178000 m³ tox.
Pollution to Water: Eutrophication	0.0052	8.01 kg PO4 eq.
Fossil Fuel Depletion	0.018	4.09 toe
Minerals Extraction	0.24	5.04 tonnes
Water Extraction	0.00058	418000 litres
Waste Disposal	0.0015	7.19 tonnes
Transport Pollution & Congestion: Freight	0.0031	4140 tonne.km
Primary Energy	3.3	*GJ*

157

Environmental Profiling is an independent environmental information scheme run by BRE. The profile is based on data provided by manufacturers for the period stated. BRE has no responsibility for the environmental performance of the product. Profiles may only be distributed in their entirety and in accordance with the terms and conditions of any contract

Figure A.2: Approved Environmental Profile for Characterised and Normalised Data Produced During the Manufacture of One Tonne of Bricks (Copyright Crown and Building Research Establishment 2002)

A.5 DISCUSSION OF RESULTS

It can be seen that there are number of differences between the characterised and normalised data calculated in Appendices A.2.1 and A.3.2 and those given in the Approved Environmental Profile shown in Figure A.2. The reasons for this are unknown as the calculations in the Appendices were based on the B.R.E.'s methodology described in *BRE Methodology for Environmental profiles of Construction Materials, Components and Buildings*.

Table A.1 shows a summary of the characterised data determined in Appendix A.2. If these figures are compared to the *official* characterised data shown in Figure A.2, it can be seen that the majority of the impacts are very close to their published values but the three values which relate to Pollution to Water are significantly different. In the case of the Human Toxicity impact, the value determined in Appendix A.2 was approximately 50 % higher than the *official* value whilst the Ecotoxicity impact was 75 % lower and, whilst according to Appendix A.2, there was no eutrophication impact, Figure A.2 states that there was. Again, the reasons for this are unknown as the same methodology was used to determine the impacts for all of the categories and the results for the remaining categories are acceptable.

Appendix A.4 shows the normalised data for the manufacture of one tonne of bricks. It can be seen that when the normalised values, which were determined in this appendix, are compared to the published values shown in Figure A.2 that, in addition to the categories relating to the Pollution of Water discussed above, there were also significant differences between the values for the Water Extraction and Waste Disposal impact categories. In both cases, the B.R.E. appear to have only considered one normalisation factor rather than combining all of the relevant factors. For instance, for the Water Extraction Category the *BRE Methodology for Environmental profiles of Construction Materials, Components and Buildings* lists three sources of water; a water company, surface water and ground water, however, they only seem to use the normalisation factor for either the surface or the ground water (417583 litres – see U.K.'s citizen's impacts in Figure A.2). Similarly, for the Waste Disposal category uses only one of the normalisation factors rather than combining the two it lists. Again, the reasons for these discrepancies are unknown as the results for the other impact categories are satisfactory.

APPENDIX B: METHODOLOGIES FOR CONVERTING INSTALLED ENVIRONMENTAL PROFILE DATA TO WHOLE-LIFE DATA

B.1 INTRODUCTION

The following appendix shows how the installed environmental profile data are converted to whole-life environmental profile data. Appendix B.2.1 gives an example for an external brickwork / blockwork cavity wall to illustrate how the B.R.E. determine their whole-life data. The example is based on the methodology described in Appendix 2 in *The Green Guide to Specification* [Anderson, Shiers and Sinclair (2002)]. Appendix B.3 gives an example of how the whole-life data were determined for this project. In effect both of these use the same basic methodology it is only the predictions of the masses of material that will be used over the life of the wall that will differ.

In both Appendices B.2 and B.3, only the results for the Climate Change category are given although the same methodology can be used to determine the values for the remaining twelve categories. This is because, when the material producers were originally asked for their product's Environmental Profile, they were guaranteed anonymity. With the exception of brickwork, however, the climate change impacts have already been published in *The Green Guide to Specification* [Anderson, Shiers and Sinclair (2002)] and it was decided, therefore, that these values could be repeated in this work without contravening the earlier agreement.

B.2 B.R.E. METHODOLOGY FOR CONVERTING INSTALLED ENVIRONMENTAL PROFILE DATA TO WHOLE-LIFE DATA

Table B.1 to B.4 show a worked example of the methodology that the B.R.E. use to convert the installed environmental profile data to whole-life data for a external brickwork / blockwork cavity wall. This initially involves determining the installed mass for each of the materials in the wall, i.e. 0.36 kg for paint – see Table B.1. They then predict a replacement interval / design life for the material and divide the design life of the element (they use the same 60 year lifespan for all elements, even if, as in the case of brickwork, it is capable of lasting much longer) by this figure to determine the number of times that the material will be replaced; they estimate that the replacement interval for paint is 5 years, therefore, it will be replaced 12 times in 60 years. They then add a 0.5 modification factor to this sum to allow for errors in the replacement intervals, i.e. 12 + 0.5 = 12.5. They then multiply this final value by the installed mass of the material to determine the mass of the material used over the life of the element, i.e. 4.5 kg for paint –

see Table B.2 - before finally multiplying the mass of the material by the impact data in the Approved Environmental Profile to determine the final, whole-life impacts – see Table B.3.

The final figures for the climate change impact category in Table B.4 are identical to the figures in the B.R.E.'s Installed Element Environmental Profile and Whole-Life Environmental Profiles - see Figures B.1 and B.2.

Materials		Installed volume / m^2 (m^3)	Density (kg / m^3)	Installed mass / m^2 (kg)	Replacement Interval (years)
102.5 mm brickwork		0.085	1950	165.26	60
Brickwork mortar (1 : 1 : 6)	Cement - 13.25 % by mass	0.003	1700	5.81	60
	Lime - 5 % by mass	0.003	650	2.22	
	Sand - 81.25 % by mass	0.021	1850	37.93	
140mm aerated blockwork		0.130	505	65.49	60
Blockwork mortar (1 : 1 : 6)	Cement - 13.25 % by mass	0.001	1700	2.19	60
	Lime - 5 % by mass	0.001	650	0.84	
	Sand - 81.25 % by mass	0.008	1850	14.33	
Plasterboard (per face)		0.025	725	18.13	60
Paint (per face)		-	-	0.36	5

Table B.1: The Installed Mass and Replacement Intervals for the Materials

Materials		Replacement Interval (years)	Replacement factor	Mass over 60-years / m^2 (kg)
102.5 mm brickwork		60 +	$(60 / 60) + 0.5^{*} = 1.5$	247.88
Brickwork mortar (1 : 1 : 6)	Cement - 13.25 % by mass	60	$(60 / 60) + 0.5^{*} = 1.5$	8.71
	Lime - 5 % by mass			3.33
	Sand - 81.25 % by mass			56.90
140mm aerated blockwork		60	$(60 / 60) + 0.5^{*} = 1.5$	98.23
Blockwork mortar (1 : 1 : 6)	Cement - 13.25 % by mass	60	$(60 / 60) + 0.5^{*} = 1.5$	3.29
	Lime - 5 % by mass			1.26
	Sand - 81.25 % by mass			21.49
Plasterboard (per face)		60	$(60 / 60) + 0.5^{*} = 1.5$	27.19
Paint (per face)		5	$(60 / 5) + 0.5^{*} = 12.5$	4.50

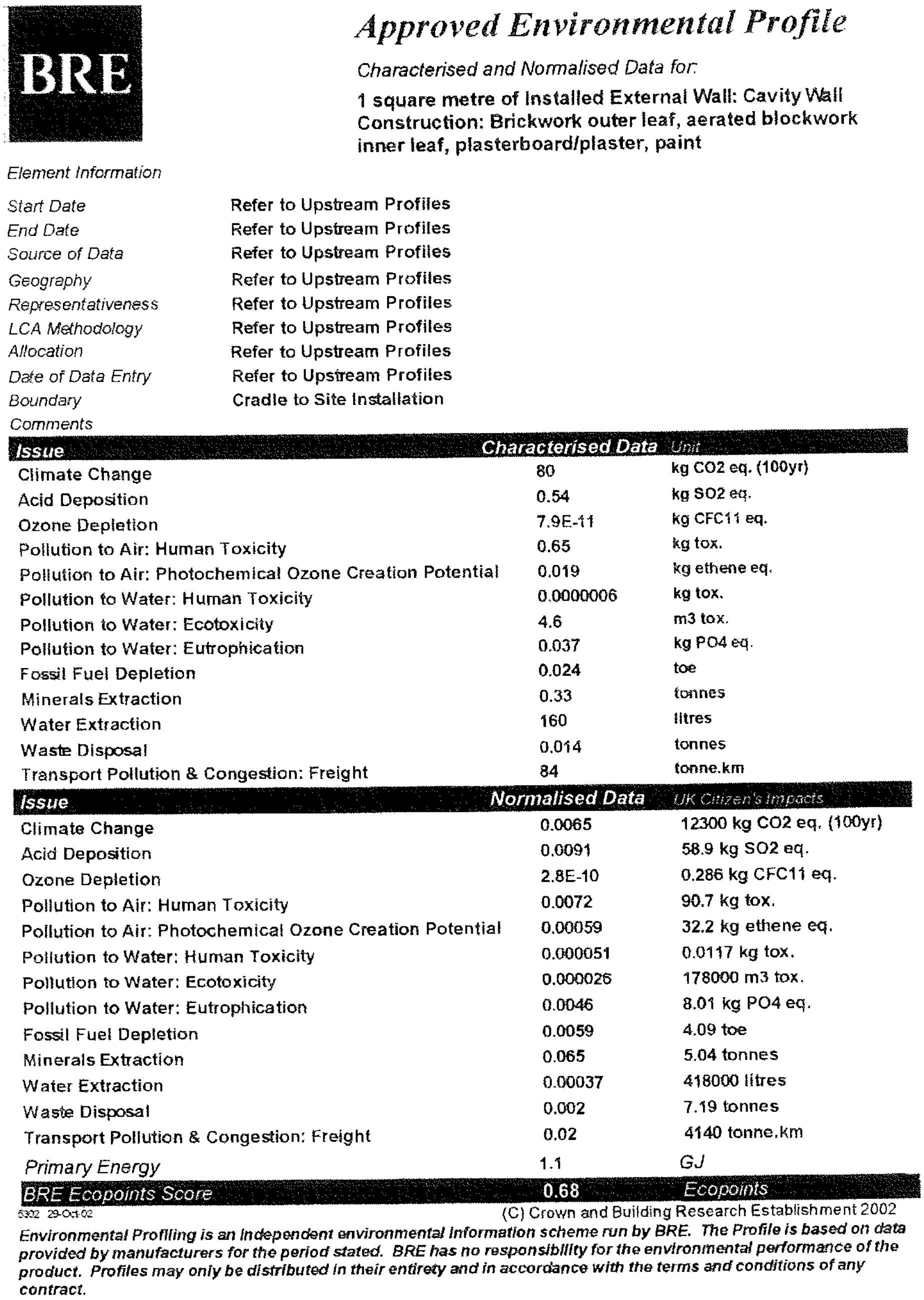
Table B.2: The Mass of the Materials used over the 60-year Life of the Building

Materials		Mass of materials / m^2 (kg)		Climate change per tonne of materials (kg CO_2 eq. (100 yrs))	Impact on climate change from the mass of materials / m^2 (kg CO_2 eq. (100 yrs))	
		Installation on site	Over 60-years		Installation on site	Over 60-years
102.5 mm brickwork		165.26	247.88	240	39.66	59.49
Brickwork mortar (1 : 1 : 6)	Cement - 13.25 ٪ by mass	5.81	8.71	1100	6.39	9.59
	Lime - 5 ٪ by mass	2.22	3.33	245	0.54	0.82
	Sand - 81.25 ٪ by mass	37.93	56.90	4.1	0.16	0.23
140mm aerated blockwork		65.49	98.23	240	15.72	23.57
Blockwork mortar (1 : 1 : 6)	Cement - 13.25 ٪ by mass	2.19	3.29	1100	2.41	3.62
	Lime - 5 ٪ by mass	0.84	1.26	245	0.21	0.31
	Sand - 81.25 ٪ by mass	14.33	21.49	4.1	0.06	0.09
Plasterboard (per face)		18.13	27.19	150	2.72	4.08
Paint (per face)		0.36	4.50	1200	0.43	5.40

Table B.3: The Impact of Materials on Climate Change over the 60-year Life of the Building

Materials		Impact on climate change from the mass of materials / m^2 (kg CO_2 eq. (100 yrs))	
		Installation on site	Over 60-years
102.5 mm brickwork		39.7	59.5
Brickwork mortar (1 : 1 : 6)	Cement - 13.25 % by mass	6.4	9.6
	Lime - 5 % by mass	0.5	0.8
	Sand - 81.25 % by mass	0.2	0.2
140mm aerated blockwork		15.7	23.6
Blockwork mortar (1 : 1 : 6)	Cement - 13.25 % by mass	2.4	3.6
	Lime - 5 % by mass	0.2	0.3
	Sand - 81.25 % by mass	0.1	0.1
Plasterboard (per face)		2.7	4.1
Paint (per face)		0.4	5.4
Transport to site		12.0	12.0
End of life disposal		-	0.0
Total		**80.3**	**119.2**

Table B.4: The Installed and Whole-Life Climate Change Impact from a Brickwork/Blockwork Cavity Wall



BRE

Approved Environmental Profile

Characterised and Normalised Data for:

1 square metre of Installed External Wall: Cavity Wall Construction: Brickwork outer leaf, aerated blockwork inner leaf, plasterboard/plaster, paint

Element Information

Start Date	Refer to Upstream Profiles
End Date	Refer to Upstream Profiles
Source of Data	Refer to Upstream Profiles
Geography	Refer to Upstream Profiles
Representativeness	Refer to Upstream Profiles
LCA Methodology	Refer to Upstream Profiles
Allocation	Refer to Upstream Profiles
Date of Data Entry	Refer to Upstream Profiles
Boundary	Cradle to Site Installation
Comments	

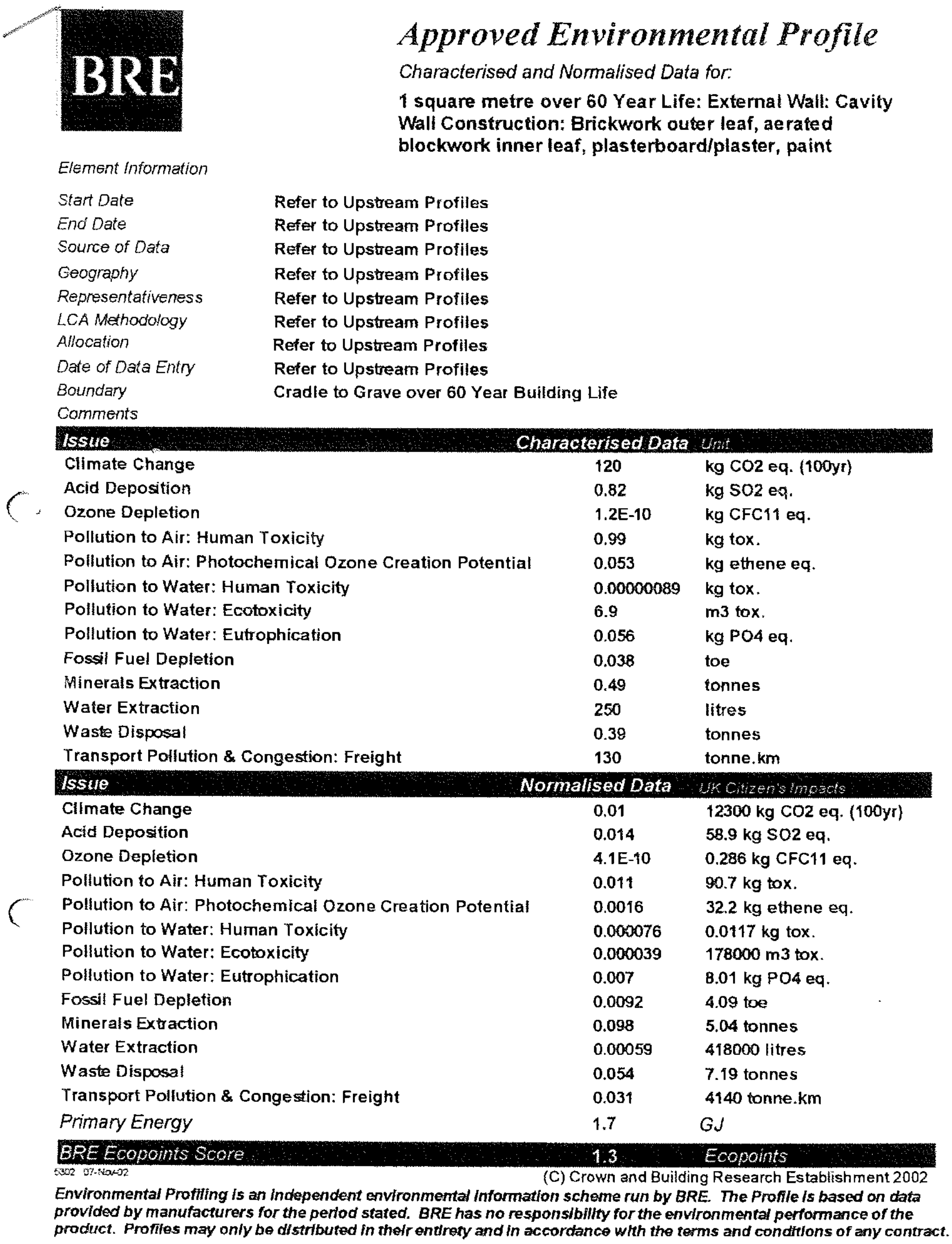
Issue	*Characterised Data*	*Unit*
Climate Change	80	kg CO2 eq. (100yr)
Acid Deposition	0.54	kg SO2 eq.
Ozone Depletion	7.9E-11	kg CFC11 eq.
Pollution to Air: Human Toxicity	0.65	kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.019	kg ethene eq.
Pollution to Water: Human Toxicity	0.0000006	kg tox.
Pollution to Water: Ecotoxicity	4.6	m3 tox.
Pollution to Water: Eutrophication	0.037	kg PO4 eq.
Fossil Fuel Depletion	0.024	toe
Minerals Extraction	0.33	tonnes
Water Extraction	160	litres
Waste Disposal	0.014	tonnes
Transport Pollution & Congestion: Freight	84	tonne.km

Issue	*Normalised Data*	*UK Citizen's Impacts*
Climate Change	0.0065	12300 kg CO2 eq. (100yr)
Acid Deposition	0.0091	58.9 kg SO2 eq.
Ozone Depletion	2.8E-10	0.286 kg CFC11 eq.
Pollution to Air: Human Toxicity	0.0072	90.7 kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.00059	32.2 kg ethene eq.
Pollution to Water: Human Toxicity	0.000051	0.0117 kg tox.
Pollution to Water: Ecotoxicity	0.000026	178000 m3 tox.
Pollution to Water: Eutrophication	0.0046	8.01 kg PO4 eq.
Fossil Fuel Depletion	0.0059	4.09 toe
Minerals Extraction	0.065	5.04 tonnes
Water Extraction	0.00037	418000 litres
Waste Disposal	0.002	7.19 tonnes
Transport Pollution & Congestion: Freight	0.02	4140 tonne.km
Primary Energy	1.1	*GJ*
BRE Ecopoints Score	**0.68**	*Ecopoints*

5302 29-Oct-02

Environmental Profiling is an independent environmental information scheme run by BRE. The Profile is based on data provided by manufacturers for the period stated. BRE has no responsibility for the environmental performance of the product. Profiles may only be distributed in their entirety and in accordance with the terms and conditions of any contract.

Figure B.1: Approved Installed Environmental Profile for a Brickwork / Blockwork Cavity Wall (Copyright Crown and Building Research Establishment 2002)



BRE

Approved Environmental Profile

Characterised and Normalised Data for:

1 square metre over 60 Year Life: External Wall: Cavity Wall Construction: Brickwork outer leaf, aerated blockwork inner leaf, plasterboard/plaster, paint

Element Information

Start Date	Refer to Upstream Profiles
End Date	Refer to Upstream Profiles
Source of Data	Refer to Upstream Profiles
Geography	Refer to Upstream Profiles
Representativeness	Refer to Upstream Profiles
LCA Methodology	Refer to Upstream Profiles
Allocation	Refer to Upstream Profiles
Date of Data Entry	Refer to Upstream Profiles
Boundary	Cradle to Grave over 60 Year Building Life
Comments	

Issue	*Characterised Data*	*Unit*
Climate Change	120	kg CO2 eq. (100yr)
Acid Deposition	0.82	kg SO2 eq.
Ozone Depletion	1.2E-10	kg CFC11 eq.
Pollution to Air: Human Toxicity	0.99	kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.053	kg ethene eq.
Pollution to Water: Human Toxicity	0.00000089	kg tox.
Pollution to Water: Ecotoxicity	6.9	m3 tox.
Pollution to Water: Eutrophication	0.056	kg PO4 eq.
Fossil Fuel Depletion	0.038	toe
Minerals Extraction	0.49	tonnes
Water Extraction	250	litres
Waste Disposal	0.39	tonnes
Transport Pollution & Congestion: Freight	130	tonne.km

Issue	*Normalised Data*	*UK Citizen's Impacts*
Climate Change	0.01	12300 kg CO2 eq. (100yr)
Acid Deposition	0.014	58.9 kg SO2 eq.
Ozone Depletion	4.1E-10	0.286 kg CFC11 eq.
Pollution to Air: Human Toxicity	0.011	90.7 kg tox.
Pollution to Air: Photochemical Ozone Creation Potential	0.0016	32.2 kg ethene eq.
Pollution to Water: Human Toxicity	0.000076	0.0117 kg tox.
Pollution to Water: Ecotoxicity	0.000039	178000 m3 tox.
Pollution to Water: Eutrophication	0.007	8.01 kg PO4 eq.
Fossil Fuel Depletion	0.0092	4.09 toe
Minerals Extraction	0.098	5.04 tonnes
Water Extraction	0.00059	418000 litres
Waste Disposal	0.054	7.19 tonnes
Transport Pollution & Congestion: Freight	0.031	4140 tonne.km
Primary Energy	1.7	*GJ*
BRE Ecopoints Score	1.3	*Ecopoints*

5302 07-Nov-02

Environmental Profiling is an independent environmental information scheme run by BRE. The Profile is based on data provided by manufacturers for the period stated. BRE has no responsibility for the environmental performance of the product. Profiles may only be distributed in their entirety and in accordance with the terms and conditions of any contract.

Figure B.2: Approved Whole-Life Environmental Profile for a Brickwork / Blockwork Cavity Wall (Copyright Crown and Building Research Establishment 2002)

B.2.1 COMPARISONS BETWEEN THE PREDICTED AND PUBLISHED DATA

It can be seen that Climate Change impacts predicted in Table B.4 are identical to the published value given in Figure B.1 and B.2. There are, however, a number of impacts categories, including Waste Disposal, where the values do not match.

Generally, for the Approved Environmental Profiles of other building elements, the whole-life waste disposal impact is determined by simply multiplying the value of the installed impact by 1.5 and then adding the total mass of the materials used in the element over its life. In this example, however, it can be seen that from Table B.3 that the total mass of the materials used in the wall over 60 years is 494 kg. Therefore, using this methodology, the Characterised Data for Waste Disposal would be 0.52 tonnes, i.e. (0.014 × 1.5) + 0.494 = 0.52 tonnes. The actual figure, as shown in Figure B.2, is 0.39 tonnes, however. It is impossible to confirm the reason for this discrepancy because, as discussed before, the B.R.E. do not describe how they derived their values.

One possible explanation is, however, that the B.R.E. did not use their 0.5 modification factor which they included to allow for uncertainties in the replacement rates. If this is omitted, the total mass of the materials over the life of the wall reduces from 494 kg to 368 kg and the Whole-Life Waste Disposal Impact would become 0.39 tonnes, i.e. (0.014 × 1.5) + 0.368 = 0.389 tonnes. Although it is not known if this is the case with respect to this particular example, similar discrepancies were discovered during other analyses of data published by the B.R.E. For instance, it can be seen in Table 6.14 from the results for the brickwork outer leaf that the B.R.E. appear to have included an allowance for maintenance in the life-cycle costings but not in their life-cycle assessment results.

B.3 THE METHODOLOGY USED TO CONVERT THE INSTALLED ENVIRONMENTAL PROFILE DATA TO WHOLE-LIFE DATA FOR THIS PROJECT

The methodology used to convert the installed environmental profile data to whole-life data for this project was similar to that of the B.R.E.'s in Appendix B.2. This was because, except from their data relating to the in-service performance of the materials, the B.R.E.'s methodology appeared sound. As a consequence, the following example, which shows how the whole-life environmental profiles were derived for this project, is very similar to that in Appendix B.2 except that the maintenance requirements for the brickwork and blockwork were taken from the condition survey database - see Table B.5

which was developed from Table 5.8. Because of its sheltered location inside the cavity, it was assumed that the blockwork inner leaf would only require half of the maintenance of the brickwork outer leaf. In addition, because no better data could be found, the B.R.E.'s maintenance data for plasterboard and paint was reused.

Design life	Maintenance activity (brickwork outer leaf only)		
	Number of times wall repointed within period	Area of brickwork repaired within period	Area of brickwork replaced within period
60 years	1	10 %	5 %

Table B.5: Maintenance Requirements of Brickwork Outer Leaf in External Cavity Walls

In the calculations it was assumed that the repointing of the brickwork would require the existing mortar joints to be cleaned to a depth of 25 mm and repointed with a 1 : 1 : 6 mortar. There is no allowance for the blockwork inner leaf being repointed.

The Installed Mass and Mass of the materials at 60 years are shown in Table B.6 and the final, whole-life Climate Change impact is shown in Table B.7.

Materials		Installed mass / m^2 (kg)	Replacement Interval (years)	Replacement factor	Increase in mass over 60 years	Mass over 60-years / m^2 (kg)
102.5 mm brickwork		165.26	See Table B.5	-	5 %	173.52
Brickwork mortar (1 : 1 : 6)	Cement (13.25 % by mass)	5.81	See Table B.5	-	25 % + 10 % + 5 % = 40 %	8.13
	Lime (5 % by mass)	2.22			25 % + 10 % + 5 % = 40 %	3.08
	Sand (81.25 % by mass)	37.93			25 % + 10 % + 5 % = 40 %	53.10
140mm aerated blockwork		65.49	Appendix B.3	-	5 % / 2 = 2.5 %	67.13
Blockwork mortar (1 : 1 : 6)	Cement (13.25 % by mass)	2.19	Appendix B.3	-	10 % + 5 % = 7.5 %	2.35
	Lime (5 % by mass)	0.84			10 % + 5 % = 7.5 %	0.90
	Sand (81.25 % by mass)	14.33			10 % + 5 % = 7.5 %	15.40
Plasterboard (per face)		18.13	60	(60 / 60) = 1	100 %	18.13
Paint (per face)		0.36	5	(60 / 5) = 12	1200 %	4.32

Table B.6: The Installed Mass and Replacement data and Whole-Life Mass for the Materials

Materials		Mass of materials over 60-years / m^2 (kg)	Climate change per tonne of materials (kg CO_2 eq. (100 yrs))	Impact on climate change from the mass of materials / m^2 (kg CO_2 eq. (100 yrs))
102.5 mm brickwork		173.52	240	41.65
Brickwork mortar (1 : 1 : 6)	Cement - 13.25 % by mass	8.13	1100	8.94
	Lime - 5 % by mass	3.08	245	0.75
	Sand - 81.25 % by mass	53.10	4.1	0.22
140mm aerated blockwork		67.13	240	16.11
Blockwork mortar (1 : 1 : 6)	Cement - 13.25 % by mass	2.35	1100	2.59
	Lime - 5 % by mass	0.90	245	0.22
	Sand - 81.25 % by mass	15.40	4.1	0.06
Plasterboard (per face)		18.13	150	2.72
Paint (per face)		4.32	1200	5.18
Transport to site		-	-	12.00
End of life disposal		-	-	0
Total				**90.44**

Table B.7: The Whole-Life Climate Change Impact from a Brickwork / Blockwork Cavity Wall

B.4 METHODOLOGY USED TO EXTRAPOLATE THE WHOLE-LIFE DATA TO 500 YEARS

The example shown in Tables B.6 and B.7 is based on a lifespan of 60 years to suit the B.R.E.'s Approved Whole-Life Environmental Profile, however, as part of this project, the L.C.A. data were extrapolated to 500 years to allow comparisons to be made between solid and cavity wall construction. The following shows an example of how this was done using the example of a cavity wall, which was assumed to have lifespans of less than 500 years.

In the earlier life-cycle assessment and life-cycle costing analyses, the maximum lifespan for a brickwork / blockwork cavity wall (Wall 7) was assumed to be 150 years - see Table 6.3. Using the methodology described in Appendix B.3 and data from Table 5.8, Table B.8 shows the maintenance requirements for a brickwork / blockwork cavity wall at 150 years and Table B.9 shows the whole-life impact on climate change.

Materials		Installed mass / m^2 (kg)	Replacement Interval (years)	Replacement factor	Increase in mass over 150 years	
					(%)	(kg)
102.5 mm brickwork		165.26	-	-	25 %	41.32
Brickwork mortar (1 : 1 : 6)	Cement (13.25 % by mass)	5.81	-	-	50 % + 65 % = 115 %	6.68
	Lime (5 % by mass)	2.22			50 % + 65 % = 115 %	2.55
	Sand (81.25 % by mass)	37.93			50 % + 65 % = 115 %	43.62
140mm aerated blockwork		65.49	-	-	25 % / 2 = 12.5 %	8.19
Blockwork mortar (1 : 1 : 6)	Cement (13.25 % by mass)	2.19	-	-	65 % / 2 = 32.5 %	0.71
	Lime (5 % by mass)	0.84			65 % / 2 = 32.5 %	0.27
	Sand (81.25 % by mass)	14.33			65 % / 2 = 32.5 %	4.66
Plasterboard (per face)		18.13	60	(150 / 60) = 2	200 %	36.26
Paint (per face)		0.36	5	(150 / 5) = 30	3000 %	10.80

Table B.8: The Installed Mass, Replacement data and Increases in Mass over the Life of the Cavity Wall

Materials		Installed mass of materials / m^2 (kg)	Increase in mass over 150-years / m^2 (kg)	Climate change per tonne of materials (kg CO_2 eq. (100 yrs))	Impact on climate change from the mass of materials / m^2 (kg CO_2 eq. (100 yrs))	
					Installed	Over 150 years
102.5 mm brickwork		165.26	41.32	240	39.66	9.92
Brickwork mortar (1 : 1 : 6)	Cement	5.81	6.68	1100	6.39	7.35
	Lime	2.22	2.55	245	0.54	0.62
	Sand	37.93	43.62	4.1	0.16	0.18
140mm aerated blockwork		65.49	8.19	240	15.72	1.97
Blockwork mortar (1 : 1 : 6)	Cement	2.19	0.71	1100	2.41	0.78
	Lime	0.84	0.27	245	0.21	0.05
	Sand	14.33	4.66	4.1	0.06	0.02
Plasterboard (per face)		18.13	36.26	150	2.72	5.44
Paint (per face)		0.36	10.80	1200	0.43	12.96
Transport to site		-	-		12.0	-
End of life disposal		-	-		-	0.00
Total					**80.30**	**39.29**

Table B.9: The Whole-Life Climate Change Impact from a Brickwork / Blockwork Cavity Wall

Initial impact of construction on Climate Change	80.30 kg CO_2 eq. (100 yrs)
Impact on Climate Change over 150 years including disposal at 150 years.	39.29 kg CO_2 eq. (100 yrs)
Impact of construction on Climate Change at 150 years	80.30 kg CO_2 eq. (100 yrs)
Impact on Climate Change over 150 years including disposal at 300 years.	39.29 kg CO_2 eq. (100 yrs)
Impact of construction on Climate Change at 300 years	80.30 kg CO_2 eq. (100 yrs)
Impact on Climate Change over 150 years including disposal at 450 years.	39.29 kg CO_2 eq. (100 yrs)
Impact of construction on Climate Change at 450 years	80.30 kg CO_2 eq. (100 yrs)
Impact on Climate Change over 150 years including disposal at 450 years.	11.31 kg CO_2 eq. (100 yrs)
Total	**450.38 kg CO_2 eq. (100 yrs)**

Table B.10: Whole-Life Impact on Climate Change of a Brickwork / Blockwork Cavity Wall Extrapolated to 500 Years

APPENDIX C: THE B.R.E.'S METHODOLOGY FOR CONVERTING CHARACTERISED ENVIRONMENTAL IMPACT DATA TO AN ECO-POINT

C.1 INTRODUCTION

The following appendix shows how the Characterised Data from an Approved Environmental Profile for the manufacture of one tonne of bricks (see Figure A.2) was converted to an Eco-point. The derivation of the weightings used to convert the characterised data to an eco-point are described and shown in Appendix C.2. The B.R.E.'s value for the manufacture of one tonne of bricks is shown in Figure C.2. Comparisons are made between these figures in Appendix C.3.

C.2 DERIVATION OF WEIGHTINGS USED TO CONVERT CHARACTERISED ENVIRONMENTAL IMPACT DATA TO ECO-POINTS

The weightings used to convert the Characterised Data from an Approved Environmental Profile to an Eco-point are based on the results of a consultation exercise that the B.R.E. carried out. Figure C.1 shows an overview of the issues that the stakeholders / expert panel were asked to consider in the exercise. Table C.1 gives a detailed breakdown of the information together with the final weightings from the consultation.

Because the B.R.E. only wanted the data relating to certain environmental issues, they disregarded the data from the Economic and Social themes. Because the weightings from the Environmental Theme only totalled 43.6 % of the original weighting, the weightings in this theme were multiplied by a modification factor of 2.294 (100 / 43.6) so that they once again totalled 100 % - see Table C.2.

Similarly, because are only 13 of the 31sub-categories in the environmental theme were suitable for an environmental profile, they subsequently discarded a further 18 issues - see Table C.3. This meant that they eventually discarded 40 out of the original 53 themes they asked the expert panel to score / assign. As above, because the weightings from the thirteen issues only amounted to 52 % to applied a second modification factor of 1.923 (100 / 52) to return them to 100 %.

The weightings in Table C.3 were then divided by the U.K. Impact per Citizen modification factor which is used to convert characterised environmental impact data to normalised data. For instance, the U.K. Impact per Citizen for the Climate Change was 12,269 kg CO_2 eq. (100 years) and its weighting was 35 % - see Table C.3. The conversion factor per eco-point for Climate Change is;

$$\frac{35}{12{,}269} = 0.0029 \ / \text{eco-point}$$

The final conversion factors for the thirteen characterised impact categories are shown in Table C.4. These factors were then used in Table C.5 to convert the characterised data from the manufacture of one tonne of bricks (taken from Figure B.3) to their eco-point rating.

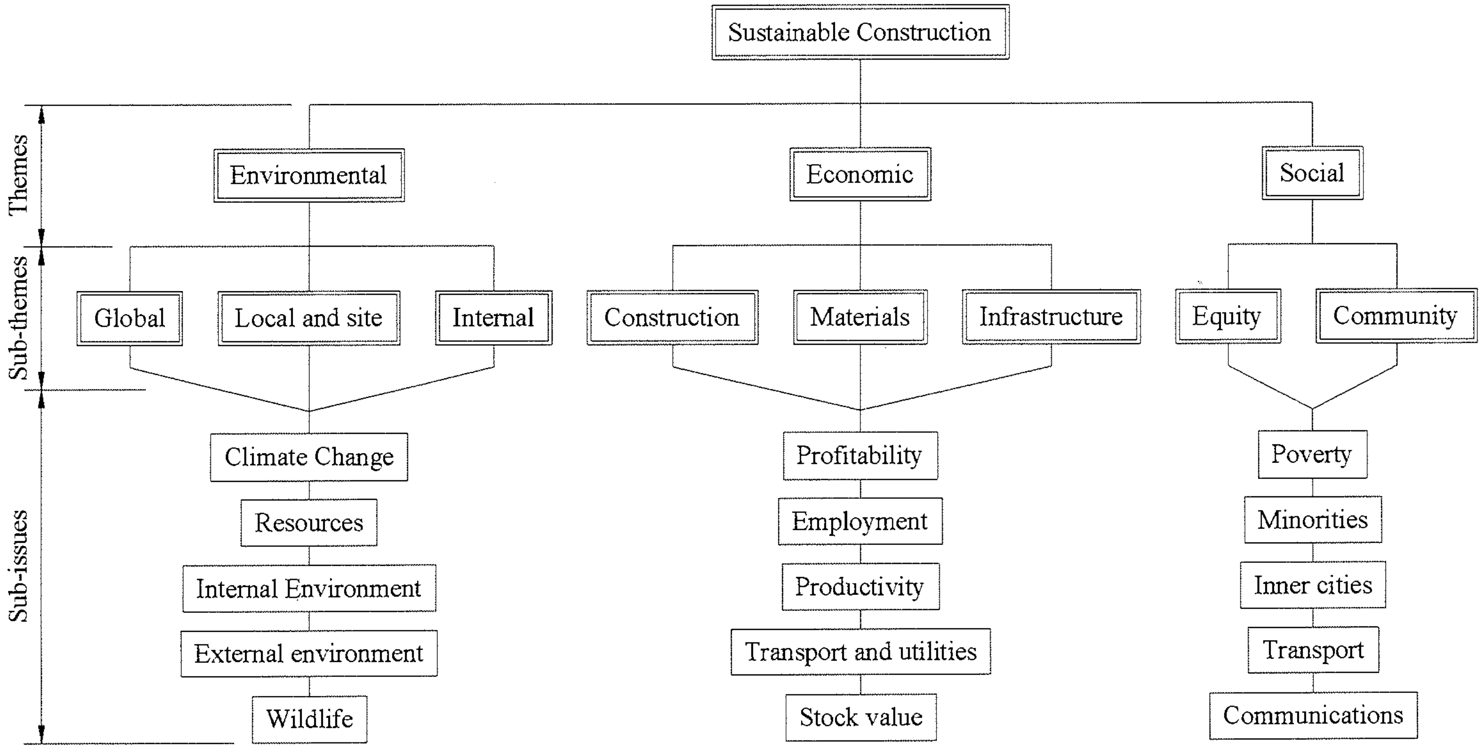


Figure C1: The Themes, Sub-Themes and Sub-Issues Considered in the B.R.E.'s Consultation Exercise to Determine Suitable Weightings for Converting Characterised Environmental Impact Data to Eco-points (Dickie and Howard, 2000)

Theme	Sub-theme	Sub-issue	Weighting (%)
Environment	Global issues	Climate change	8.4
		Acid deposition	1.1
		Ozone depletion	1.8
		Toxic Air pollution	1.4
		Fossil fuel depletion	2.0
		Marine water pollution	1.2
		Habitats and eco-systems	3.9
	Local and site issues	Local air pollution	2.6
		Water pollution	1.7
		Contaminated land	1.2
		Noise pollution	1.2
		Dust pollution	0.2
		Minerals extraction	0.8
		Fossil fuel extraction	0.7
		Water extraction	1.2
		Waste disposal	1.4
		Waste recycling	1.8
		Transport pollution and congestion	3.5
		Habitats and eco-systems	2.7
		Forestry	0.6
		Farming	0.4
	Internal environment	Health	2.6
		Comfort	1.2
Sub-total			**43.6**
Economy	Construction	Profitability	2.3
		Employment	3.3
		Productivity	1.4
		New build	1.2
		Refurbishment	2.5
		Maintenance and repair	2.1
		Overseas competitiveness	0.8

Table C1 (i): The Weightings Derived from the Consultation Exercise (Part 1 of 2) (Dickie and Howard, 2000)

Theme	**Sub-theme**	**Sub-issue**		**Weighting (%)**
Economy (cont.)	**Construction materials**	Profitability		2.2
		Employment		2.6
		Productivity		1.4
		Product value		2.0
		Overseas competitiveness		1.2
	Infrastructure	Energy and water		2.7
		Telecommunications		1.7
	Building Stock	**Stock value**	Housing	1.7
			Industrial	1.4
			Commercial	1.4
			Other	0.3
Sub-total				**32.2**
Social	**Equity**	**Social exclusion**	Affordable housing	1.6
			Healthy housing	1.6
			Employment	5.6
			Security	2.3
			Education	3.2
			Worship	0.2
			Transportation	1.0
	Community	**Urban**	Identity stewardship	2.5
			Integration	1.4
			Consultation	0.7
		Transport	Cities	1.4
		Town and rural communications		**2.7**
Sub-total				**24.2**
Total				**100.0**

Table C1 (ii): The Weightings Derived from the Consultation Exercise (Part 2 of 2) (Dickie and Howard, 2000)

Issues	Sub-issues		Weighting (%)
Global issues	Climate change		19
	Acid deposition		3
	Ozone depletion		4
	Toxic Air pollution	Human toxicity	2
		Eco-toxicity	2
	Fossil fuel depletion		5
	Marine water pollution	Eco-toxicity	1
		Eutrophication	1
	Habitats and eco-systems	Land	-
		River	5
Sub-total			**42**
Local and site issues	Air pollution	Human toxicity	2
		Eco-toxicity	2
		Asthma	2
	River water pollution	Human toxicity	1
		Eco-toxicity	1
		Eutrophication	1
	Contaminated land		3
	Noise pollution		3
	Dust pollution	Black smoke	1
	Minerals extraction		2
	Fossil fuel extraction		2
	Water extraction		3
	Waste disposal		3
	Waste recycling		4
	Transport pollution and congestion	People	4
		Freight	4
	Habitats and eco-systems		8

Table C2 (i): The Revised Weightings Based on the Environmental Theme Only (Part 1 of 2) (Dickie and Howard, 2000)

Issues	**Sub-issues**	**Weighting (%)**
Local and site issues (cont.)	Forestry	1
	Farming	1
Sub-total		**48**
Internal environment	Health	6
	Comfort	3
Sub-total		**9**
Total		**99**

Table C2 (ii): The Revised Weightings Based on the Environmental Theme Only (Part 2 of 2) (Dickie and Howard, 2000)

Environmental impact categories		Weighting (%)
Climate change		35
Acid deposition		5
Ozone depletion		8
Pollution to air:	Human toxicity	6.5
	Low-level Ozone Creation	3.5
Fossil fuel depletion and extraction		11
Pollution to water:	Human toxicity	2
	Eco-toxicity	4
	Eutrophication	4
Minerals extraction		3
Water extraction		5
Waste disposal		6
Transport pollution and congestion	Freight	7
Total		**100**

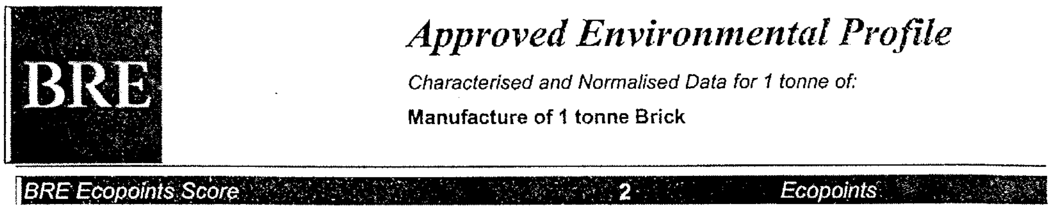
Table C3: The Final Weightings used to Convert Characterised Environmental Impact Data to Eco-points (Dickie and Howard, 2000)

Categories	U.K. Impact per citizen	Weighting (%)	Conversion factor (per eco-point)
Climate change	12,269 kg CO_2eq. (100years)	35	0.0029
Acid deposition	58.9 kg SO_2 eq.	5	0.0849
Ozone depletion	0.3 kg CFC-11 eq.	8	26.67
Pollution to air: Human toxicity	90.7 kg tox.	6.5	0.077
Pollution to air: Low-level Ozone Creation	32.2 kg ethene eq.	3.5	0.12
Fossil fuel depletion and extraction	4.09 t.o.e.	11	200
Pollution to water: Human toxicity	0.01 kg tox.	2	0.00002
Pollution to water: Eco-toxicity	177,948 m^3 tox.	4	0.5
Pollution to water: Eutrophication	8.0 kg PO_4 eq.	4	2.69
Minerals extraction	5.0 tonnes	3	0.6
Water extraction	417,583 litres	5	0.00001
Waste disposal	7.2 tonnes	6	0.83
Transport pollution and congestion: Freight	4141 tonne.km	7	0.0017

Table C4: The Factors Used to Convert Characterised Environmental Impact Data to Eco-points (Dickie and Howard, 2000)

Characterised data from the manufacture of one-tonne of bricks		Conversion factor (per eco-point)	Eco-point score (Eco-points)
Climate change	240 kg CO_2 eq. (100 yrs)	0.0029	0.7
Acid deposition	1.1 kg SO_2 eq.	0.0849	0.1
Ozone depletion	0 kg CFC_{11} eq.	26.67	0.0
Pollution to air: Human toxicity	1 kg tox.	0.077	0.1
Pollution to air: Low-level Ozone Creation	0.024 kg ethene eq. (POCP)	0.12	0.0
Fossil fuel depletion and extraction	0.000000039 kg tox.	200	0.0
Pollution to water: Human toxicity	0.071 m^3 tox.	0.00002	0.0
Pollution to water: Eco-toxicity	0.042 kg PO_4 eq.	0.5	0.0
Pollution to water: Eutrophication	0.074 tonnes oil eq.	2.69	0.2
Minerals extraction	1.2 tonnes	0.6	0.7
Water extraction	240 litres	0.00001	0.0
Waste disposal	0.011 tonnes	0.83	0.0
Transport pollution and congestion: Freight	13 tonne.km	0.0017	0.0
Total			**2**

Table C5: The Eco-Points Produced by the Manufacture of One Tonne of Bricks



BRE

Approved Environmental Profile

Characterised and Normalised Data for 1 tonne of:

Manufacture of 1 tonne Brick

BRE Ecopoints Score	**2**	*Ecopoints*

Figure C.2: Eco-Point Data from the Approved Environmental Profile for the Manufacture of One Tonne of Bricks (Copyright Crown and Building Research Establishment 2002)

C.3 COMPARISONS WITH PUBLISHED DATA

When comparisons were made between the eco-point predicted for the manufacture of one tonne of bricks in Table C.5 and the B.R.E.'s figure shown in Figure C.2, they were found to be identical. This indicates that the methodology used in this appendix is correct.

APPENDIX D: EXTRACT FROM MAINTENANCE DATABASE

D.1 INTRODUCTION

As previously described in Paragraph 4.3, it proved necessary to construct a database on the maintenance requirements of clay brickwork masonry buildings, so that a life-cycle assessment and life-cycle costing analyses could be completed. The database was compiled from condition survey data which was amassed on 860 properties because there were no existing records which could be used instead.

The surveys were designed to comply with D.T.L.R.'s *Decent Homes: Capturing the Standards at Local Level* [Department for Transport, Local Government and the Regions, 2002] and D.E.T.R.'s *Collecting, Managing and Using Housing Stock information – A Good Practice Guide* series [Department of the Environment, Transport and the Regions, 2000] and were carried out in accordance with various Royal Institution of Chartered Surveyors (R.I.C.S.) recommendations.

The information that is contained within this database was analysed and used to compile Tables 5.7 and 5.8 which essentially formed the basis of the life-cycle assessment and life-cycle costing analyses. Figures D.1 and D.2 show an extract from the database for ten of the buildings that were surveyed; the full database has the same information for all the properties that were surveyed. In the database the buildings are arranged by age, consequently, the details shown in Figures D.1 and D.2 are for the oldest buildings that were surveyed.

The information in the columns in Figures D.1 and D.2 relate to the following:

DESCRIPTION OF BUILDING

- Type - the relationship of the structure to surrounding structures; buildings were classified as being either detached, (D), semi-detached (SD) or terraced (T) and any other structures were classified as other (O)
- Current use of structure - this was used to classify the current use of the structure. It was divided for buildings into residential (R), educational establishments - including ancillary buildings - (E), churches and other religious buildings (C), public buildings (PB), railway or bus station (ST), commercial buildings were divided into the following categories, offices (OFF), manufacturing (M), industrial (I), retail (R), warehousing or other storage facilities (W) and hotels and guest houses (H). All other structures were classified as other (O).

- Typology - the typology of the building as defined in Appendix G5 of *Collecting, Managing and Using Housing Stock Information: Volume 2 - Key Principals and Methodological Issues* [Department of Environment, Transport and Regions (2000] – see Paragraph 5.2.

INFORMATION ON THE BRICKWORK

- Previous and current levels of maintenance - the subjective classification of maintenance described in Paragraph 4.4.2.2
- Area of brickwork repointed, repaired, replaced, and weathered / spalled - as described, the areas of the brickwork that had been the repointed, repaired, replaced, and weathered or spalled. The difference between the repaired and replaced category was that if the brickwork had been repaired and the original bricks were re-used, it was classified as being repaired. Alternatively, if it was repaired and the original bricks had been replaced, it was class as being replaced.

The remaining columns in the tables are self-explanatory.

Building ref.	Location	Date the structure was built	Description of building					Details of external wall construction		
			Type	Current use of structure	Number of storeys	Any additional information	Typology	Cavity or solid wall construction	Lime or cement based mortar	Average width of mortar joints
1	Hull, East Yorks.	1345	D	C	1	-	-	s	1	> 5 mm
2	Beverley, East Yorks.	1409	T	-	2	-	-	s	1	> 5 mm
3	York, North Yorks.	1483	D	E	2	-	-	s	1	> 5 mm
4	Temple Newsam, Leeds	1628	D	R	4	-	-	s	1	-
5	Sutton, North Yorks.	1667	D	R	3	-	2	s	1	> 5 mm
6	Sutton, North Yorks.	1670	D	BO	2	-	-	s	1	> 5 mm
7	York, North Yorks.	1684	D	C	3	-	-	s	1	> 5 mm
8	York, North Yorks.	1692	D	C	3	-	-	s	1	> 5 mm
9	Beningbrough, North Yorks.	1716	D	R	3	-	2	s	1	≤ 5 mm
10	York, North Yorks.	1727	T	PB	4	-	-	s	1	≤ 5 mm

Figure D.1: Extract from Survey Database (Part 1 of 2)

Building ref.	Information on the brickwork									Notes on any additional maintenance				
	Area of external brickwork walling (m^2)	Previous and current levels of maintenance (out of 5)				Area of brickwork: (estimated)				Original Wall ties replaced	Original Lintels		Damp proof course	
		Quality of maintenance		Overall condition of building		repointed (%)	repaired (%)	replaced (%)	weathered or spalled (%)					
		Previous	Current	Original	Current						Repaired	Replaced	Added	Replaced
1	229	5	5	4	3	100	5	25	15	-	No	No	No	No
2	62	5	5	4	3	100	0	5	10	-	No	No	No	No
3	575	5	5	5	4	100	0	45	10	-	No	No	No	No
4	1683	5	5	5	4	100	2	10	5	-	No	No	No	No
5	712	5	5	4	3	100	0	0	45	-	No	No	No	No
6	426	5	5	4	3	100	5	15	40	-	No	No	No	No
7	162	5	5	5	4	100	0	15	10	-	No	No	No	No
8	221	5	5	5	4	100	0	1	10	-	No	No	No	No
9	1822	5	5	4	4	100	5	2	20	-	25 %	No	25 %	No
10	204	5	5	4	3	100	2	5	25	-	No	No	No	No

Figure D.2: Extract from Survey Database (Part 2 of 2)

APPENDIX E: CALCULATION OF THE *U*-VALUES AND OPERATIONAL ENERGY REQUIREMENTS FOR USE IN THE LIFE-CYCLE ANALYSES

E.1 CALCULATION OF *U*-VALUES FOR THE WALLS USED IN THE LIFE-CYCLE ANALYSES

The following calculations are based on the methodologies described in Mitchell's Environment and Services [Burberry, 1997], Environmental Science in Buildings [McMullan, 2002] and Appendix A of Approved Document L1 of The Building Regulations 2000 [Office of the Deputy Prime Minister (2002)].

- **SURFACE RESISTANCES** (taken from Mitchell's Environment and Services [Burberry (1997)])

Internal surface layer, R_{si}	0.123 m^2 K / W
Air space (cavity), R_a	0.180 m^2 K / W
External surface layer, R_{so}	0.053 m^2 K / W

- ***U*-VALUE FOR WALL 1:** 215 mm thick solid brickwork; painted plasterboard internal finish

Materials	*k* value (W / m.°K)	Thickness, L (m)	Thermal resistance, R_w (m^2.°K / W)
Brickwork (average density, commons)	1.200	0.215	0.179
plasterboard	0.400	0.013	0.031
Total			**0.210**

$$U\text{-value for Wall 1} = \frac{1}{R_{si} + R_{so} + \Sigma R_{w1}} = \frac{1}{0.123 + 0.053 + 0.210} = 2.59 \text{ W / m}^2.^\circ\text{K}$$

- ***U*-VALUE FOR WALL 2:** 328 mm thick solid brickwork; painted plasterboard internal finish

Materials	*k* value (W / m.°K)	Thickness, L (m)	Thermal resistance, R_w (m^2.°K / W)
Brickwork (average density, commons)	1.200	0.328	0.273
plasterboard	0.400	0.013	0.031
Total			**0.304**

$$U\text{-value for Wall 2} = \frac{1}{R_{si} + R_{so} + \Sigma R_{w1}} = \frac{1}{0.123 + 0.053 + 0.304} = 2.08 \text{ W / m}^2.^\circ\text{K}$$

- ***U*-VALUE FOR WALL 3:** 102 mm brickwork outer leaf; 75mm cavity, 102 brickwork inner leaf, painted plasterboard internal finish

Materials		*k* value (W / m.°K)	Thickness, L (m)	Thermal resistance, R_w (m^2.°K / W)
Brickwork (average density, commons)	Outer leaf	1.200	0.102	0.085
	Inner leaf	1.200	0.102	0.085
plasterboard		0.400	0.013	0.031
Total				**0.202**

$$U\text{-value for Wall 3} = \frac{1}{R_{si} + R_{a} + R_{so} + \Sigma R_{w1}}$$

$$= \frac{1}{0.123 + 0.180 + 0.053 + 0.202}$$

$$= 1.79 \text{ W / m}^2.^\circ\text{K}$$

- **U-VALUE FOR WALL 4:** Rendered 125 mm external insulation; 215 mm thick solid brickwork; painted plasterboard internal finish

Materials	k value (W / m.°K)	Thickness, L (m)	Thermal resistance, R_w (m^2.°K / W)
Rendered 125 mm external insulation	-	-	2.475
Brickwork (average density, commons)	1.200	0.215	0.179
plasterboard	0.400	0.013	0.031
Total			**2.685**

$$U\text{-value for Wall 4} = \frac{1}{R_{si} + R_{so} + \Sigma R_{w1}} = \frac{1}{0.123 + 0.053 + 2.685} = 0.35 \text{ W / m}^2.^\circ\text{K}$$

- **U-VALUE FOR WALL 5:** Rendered 120 mm external insulation; 328 mm thick solid brickwork; painted plasterboard internal finish

Materials	k value (W / m.°K)	Thickness, L (m)	Thermal resistance, R_w (m^2.°K / W)
Rendered 120 mm external insulation	-	-	2.376
Brickwork (average density, commons)	1.200	0.328	0.273
plasterboard	0.400	0.013	0.031
Total			**2.680**

$$U\text{-value for Wall 5} = \frac{1}{R_{si} + R_{so} + \Sigma R_{w1}} = \frac{1}{0.123 + 0.053 + 2.680} = 0.35 \text{ W / m}^2.^\circ\text{K}$$

- ***U*-VALUE FOR WALL 6:** Rendered 110 mm external insulation; 102 mm brickwork outer leaf; 75mm cavity, 102 brickwork inner leaf, painted plasterboard internal finish

Materials		*k* value (W / m.°K)	Thickness, L (m)	Thermal resistance, R_w (m^2.°K / W)
Rendered 110 mm external insulation		-	-	2.278
Brickwork (average density, commons)	Outer leaf	1.200	0.102	0.085
	Inner leaf	1.200	0.102	0.085
plasterboard		0.400	0.013	0.031
Total				**2.480**

$$U\text{-value for Wall 6} = \frac{1}{R_{si} + R_a + R_{so} + \Sigma R_{wl}}$$

$$= \frac{1}{0.123 + 0.180 + 0.053 + 2.480}$$

$$= 0.35 \text{ W / m}^2.^\circ\text{K}$$

- ***U*-VALUE FOR WALL 7:** 102 mm brickwork outer leaf; 75 mm cavity insulation; 140 mm 7 N/mm2 blockwork inner leaf, painted plasterboard internal finish

Materials	*k* value (W / m.°K)	Thickness, L (m)	Thermal resistance, R_w (m^2.°K / W)
Brickwork outer leaf (average density, commons)	1.200	0.102	0.085
75 mm cavity insulation	-	-	1.485
Aerated blockwork	0.140	0.140	1.000
plasterboard	0.400	0.013	0.031
Total			**2.601**

$$U\text{-value for Wall 7} = \frac{1}{R_{si} + R_a + R_{so} + \Sigma R_{w1}}$$

$$= \frac{1}{0.123 + 0.180 + 0.053 + 2.601}$$

$$= 0.34 \ \mathrm{W / m^2.^\circ K}$$

- ***U*-VALUE FOR WALL 8:** 102 mm brickwork outer leaf; 110 mm cavity insulation; timber construction inner leaf, painted plasterboard internal finish

Materials		*k* value (W / m.°K)	Thickness, L (m)	Thermal resistance, R_w (m^2.°K / W)
Brickwork outer leaf (average density, commons)		1.200	0.102	0.085
110 mm cavity insulation		-	-	2.278
Timber	Softwood	0.140	0.016	0.113
	Plywood	0.138	0.019	0.138
plasterboard		0.400	0.013	0.031
Total				**2.645**

$$U\text{-value for Wall 8} = \frac{1}{R_{si} + R_a + R_{so} + \Sigma R_{w1}}$$

$$= \frac{1}{0.123 + 0.180 + 0.053 + 2.645}$$

$$= 0.35 \ \mathrm{W / m^2.^\circ K}$$

E.2 DETERMINATION OF THE OPERATIONAL ENERGY REQUIREMENTS FOR THE WALLS USED IN THE LIFE-CYCLE ANALYSES

E.2.1 INTRODUCTION

The following example was based on a hypothetical 4.00 m × 6.00 m × 2.50 m high room in a mid-storey corner flat of a block of flats. The room had 25 m^2 of external walling and the internal volume of the room was 60 m^3. The mean internal temperature of the room was 16.5 °C and, in accordance with the methodologies, 1 °C was added to the internal temperature if the walls were of heavyweight construction and 1 °C subtracted if they were of lightweight construction. The building was assumed to be in a sheltered location in the north of England and the mean external temperature was assumed to be 5.5 °C. The insulation of the room (excluding any wall insulation) was of standard 2A and heating was assumed to be used between 6.00 a.m. and 9.00 a.m. in the morning and 5.00 p.m. and 11.00 p.m. in the evening. The house efficiency factor was based on the value for either electricity fuelled storage radiators or warm air / under-floor heating.

The heating energy was calculated in accordance with the methodologies described in Mitchell's Environment and Services [Burberry, P. 1997] and Appendix A of Approved Document L1 of The Building Regulations 2000 [Office of the Deputy Prime Minister (2002)]. The *u*-values for the walls were those calculated in Appendix E.1.

E.2.2 SAMPLE CALCULATION SHOWING THE DETERMINATION OF THE OPERATIONAL ENERGY REQUIREMENTS FOR WALL 1

- **HEAT LOSSES THROUGH THE EXTERNAL WALLS**

Surface area of external wall = 25 m^2

U-value of wall (from Appendix E.1) = 2.59 $W/m^2.^\circ K$

Mean Internal temperature, $t_i{}^a$ (based on insulation standard 2A, i.e heating provided from 0600 - 0900 and 1700 - 2300 and no additional insulation) = 17.5 °C

Mean external temperature (based on a building in north-east of England) = 5.5 °C

Temperature difference = 17.5 °C - 5.5 °C = 12 °C

Rate of fabric heat loss = $25\ m^2 \times 2.59\ W / m^2.^\circ K \times 12\ ^\circ C$ = 776.4 W

- **VENTILATION LOSSES THROUGH THE EXTERNAL WALLS**

Volume of room = 60 m^3

Ventilation heat loss rate per m^3 (based an average dwelling in a sheltered position) = 0.34 $W/m^3.^\circ K$

Temperature difference (from above calculation) = 12 °C

Rate of ventilation heat loss = $60\ m^3 \times 0.34\ W/m^3.^\circ K \times 12\ ^\circ C = 244.8\ W$

Rate of fabric heat loss (from above calculation) = 776.4 W

Overall heat loss rate = 244.8 W + 776.4 W = 1021.2 W = 1.0 kW

- **HEAT GAINS THROUGH THE EXTERNAL WALLS**

- **Solar gain through window**

Orientation of window = North

Surface area of windows = 6 m^2

Solar gain through window = 0.25 GJ / m^2 per season

(a standard figure from Mitchell's Environment and Services [Burberry, P. 1997])

Total solar gain through window = $6\ m^2 \times 0.25\ GJ/m^2$ per season
= 1.5 GJ per season

- **Occupants**

Assuming the occupants are out during day = 0.6 GJ / person per season

(a standard figure from Mitchell's Environment and Services [Burberry, 1997])

Assuming that three people share the flat, total seasonal gain
= 1.8 GJ per season

- **Total seasonal gains** = 1.5 GJ + 1.8 GJ = 3.3 GJ

- **SEASONAL ENERGY REQUIREMENTS FOR THE ROOM**

Overall heat loss rate = 1.0 Kw

Seasonal heat loss = 1.0 Kw × 18.3 = 18.7 GJ

(a standard conversion factor 1 kW = 18 GJ)

Total seasonal gains (from above calculation) = 3.3 GJ

Net seasonal requirements = 18.7 GJ – 3.3 GJ = 15.4 GJ

House efficiency factor (based on electricity fuelled storage radiators / warm air or under-floor heating) = 1.1

(a standard figure from Mitchell's Environment and Services [Burberry, 1997])

Gross energy requirements = 15.4 GJ × 1.1 = 16.9 GJ / season

Energy required over 500 years = 16.9 GJ / season × 500 = 8463.0 GJ

	Surface area of external wall (m^2)	U – value (from Appendix E.1) ($W / m^2.{}^\circ K$)	Mean Internal temperature, t_i [a] (°C)	Mean external temperature (°C)	Temperature difference (°C)	Rate of fabric heat loss (W)
Wall 1	25.00	2.59	17.5 [b]	5.5 [d]	12	776.4
Wall 2	25.00	2.08	17.5 [b]	5.5 [d]	12	624.8
Wall 3	25.00	1.79	15.5 [c]	5.5 [d]	10	448.0
Wall 4	25.00	0.35	17.5 [b]	5.5 [d]	12	105.0
Wall 5	25.00	0.35	17.5 [b]	5.5 [d]	12	105.0
Wall 6	25.00	0.35	17.5 [b]	5.5 [d]	12	106.4
Wall 7	25.00	0.34	17.5 [b]	5.5 [d]	12	102.6
Wall 8	25.00	0.35	16.5	5.5 [d]	11	96.3

Table E.1: Heat Losses through the External Walls for All Wall Types

Notes:

[a] insulation standard 2A, i.e heating provided from 0600 - 0900 and 1700 - 2300 and no additional insulation

[b] 1 °C added for heavy weight construction

[c] 1 °C subtracted for lightweight construction

[d] designing for a building in north-east of England

	Volume (m^3)	Ventilation heat loss rate per m^3 ($W / m^3.^{\circ}K$)	Temperature difference ($^{\circ}C$)	Rate of ventilation heat loss (W)	Rate of fabric heat loss (W)	Overall heat loss rate (kW)
Wall 1	60	0.34 [e]	12	244.8	776.4	1.0
Wall 2	60	0.34 [e]	12	244.8	624.8	0.9
Wall 3	60	0.34 e	10	204.0	448.0	0.7
Wall 4	60	0.34 e	12	244.8	105.0	0.3
Wall 5	60	0.34 e	12	244.8	105.0	0.3
Wall 6	60	0.34 e	12	244.8	106.4	0.4
Wall 7	60	0.34 e	12	244.8	102.6	0.3
Wall 8	60	0.34 e	11	224.4	96.3	0.3

Table E.2: Ventilation Losses through the External Walls for All Wall Types

Notes: [e] Designing for an average dwelling in a sheltered position

	Overall heat loss rate (kW)	Seasonal heat loss (GJ)	Seasonal gains (GJ)	Net seasonal requirements (GJ)	House efficiency factor [i]	Gross energy requirements (GJ)	
						Seasonal	Over 500 years [j]
Wall 1	1.0	18.7	3.3	15.4	1.1	16.9	8463.0
Wall 2	0.9	15.9	3.3	12.6	1.1	13.9	6937.4
Wall 3	0.7	11.9	3.3	8.6	1.1	9.5	4747.0
Wall 4	0.3	6.4	3.3	3.1	1.1	3.4	1705.7
Wall 5	0.3	6.4	3.3	3.1	1.1	3.4	1705.7
Wall 6	0.4	6.4	3.3	3.1	1.1	3.4	1720.3
Wall 7	0.3	6.4	3.3	3.1	1.1	3.4	1682.0
Wall 8	0.3	5.9	3.3	2.6	1.1	2.8	1412.3

Table E.3: Energy Required to Heat Room for All Wall Types

Notes: [i] electricity fuelled storage radiators / warm air or under-floor heating

[j] assuming the requirements remains constant over the 500 years

APPENDIX F: METHODOLOGY USED TO DEVELOP LIFE-CYCLE COSTINGS

F.1 INTRODUCTION

The following appendix shows how the life-cycle costings were developed. The basic prices for the works, which are shown in Tables F.1 to F.3, were obtained from *Spon's Architects' and Builders' Price Book* (Davis, Langdon and Everest, 2003). The book is divided into two sections, one for major works (where the value of the works exceeds £ 40,000) and a second for minor works. The prices for the initial cost of construction were taken from the major work section and the prices for the maintenance and demolition works were taken from the minor work section.

Appendix F.2 gives an example of a life-cycle costing calculation for a brickwork / blockwork cavity wall. This involved calculating the initial cost of construction, the total cost of any maintenance required, and the cost of disposal and demolition of the wall at the end of its life, and adding them together to determine the whole-life cost. These costs of the wall at 60 years are summarised in Table F.6.

Appendix F.3 shows the process that was used to extrapolate the whole-life costings to 500 years. This was to allow comparisons to be made with the L.C.A. data.

Description:		**Price**
70 mm thick expanded polystyrene external cladding; F.R.P. reinforcing coat; glass fibre reinforcing mesh; one coat of primer; mechanical fixings using P.V.C. intermediate tracks and T-splines		£ 56.60 / m^2
Facing bricks; PC £ 250.00 / 1000; in gauged Mortar (1:1:6)	Half brick thick (102 mm)	£ 33.05 / m^2
	One brick thick (215 mm)	£ 61.14 / m^2
	One and a half bricks thick (327.5 mm)	£ 87.99 / m^2
Galvanised steel twisted wall ties; 75mm cavity; three wall ties per m^2		£ 1.23 / m^2
50mm thick cavity insulation; fixed with adhesive to brick or block		£ 14.62 / m^2
Timber studwork; 63 mm × 50 mm softwood timber studs and 19 mm plywood		£ 19.92 / m^2
140 mm thick lightweight aerated concrete blocks; in gauged mortar (1:1:6)		£ 20.25 / m^2
12mm thick gypsum plasterboard to B.S. 1230; fixed with nails; joints filled with filler and joint tape to receive decoration; skimmed with one coat of plaster		£ 18.08 / m^2
Two coats emulsion paint; plaster / plasterboard walls		£ 2.19 / m^2

Table F.1: Basic Prices for New Works

(Major Works Section in *Spon's Architects' and Builders' Price Book*

(Davis, Langdon and Everest, 2003))

Description:		**Price**
Remove existing external insulation and replace with similar product		£ 84.73 / m^2
Repointing in gauged mortar (1:1:6) to match existing; brickwork walls		£ 11.90 / m^2
Repair defective brickwork, re-use existing bricks with gauged mortar (1:1:6)		£ 22.16 / m^2
Cut out decayed, defective or cracked brickwork and replace with new facing bricks; PC £ 250.00 / 1000; in gauged mortar (1:1:6);	Half brick thick (102 mm)	£ 99.81 / m^2
	One brick thick (215 mm)	£ 180.89 / m^2
	One and a half bricks thick (328 mm)	£ 256.81 / m^2
Galvanised steel twisted wall ties; 75mm cavity; three wall ties per m^2		£. 1.55 / m^2
Remove existing cavity insulation and replace with similar product		£ 24.68 / m^2
Remove and replace existing 140 mm thick lightweight aerated concrete blockwork wall		£ 86.38 / m^2
Remove existing timber studwork and replace with similar product		£ 46.96 / m^2
Remove and replace existing gypsum plasterboard		£ 26.51 / m^2
Repaint plaster / plasterboard walls with two coats emulsion paint		£ 2.99 / m^2

Table F.2: Basic Prices Basic prices for Alteration Works

(Minor Works Section in *Spon's Architects' and Builders' Price Book*

(Davis, Langdon and Everest, 2003))

Description:		**Price**
Demolition		
Rendered insulation, 215 mm thick solid brickwork with plaster on internal face		£ 15.37 / m^2
Rendered insulation, 328 mm thick solid brickwork with plaster on internal face		£ 20.91 / m^2
Rendered insulation, Inner and outer skins of 102.5 mm thick brickwork, cavity insulation, and plaster		£ 17.72 / m^2
215 mm thick solid brickwork with plaster on internal face		£ 13.27 / m^2
328 mm thick solid brickwork with plaster on internal face		£ 18.81 / m^2
Inner and outer skins of 102.5 mm thick brickwork, cavity insulation, and plaster		£ 15.62 / m^2
102.5 mm thick skin of brickwork, cavity insulation, 140mm thick skin of aerated blockwork with plaster on internal face		£ 14.32 / m^2
102.5 mm thick skin of brickwork, cavity insulation, timber studwork with plaster on internal face		£ 14.32 / m^2
Disposal:		
Groundwork		
Off site disposal; to include trip not exceeding 13 km (using lorries); including Landfill Tax	Inactive or inert waste	£ 16.00 / m^3
	All other taxable waste	£ 34.00 / m^3

Table F.3: Basic Prices Basic prices for Demolition and Disposal

(Minor Works Section in *Spon's Architects' and Builders' Price Book*

(Davis, Langdon and Everest, 2003))

F.2 EXAMPLE OF THE DEVELOPMENT OF THE WHOLE-LIFE COSTINGS FOR A BRICKWORK / BLOCKWORK CAVITY WALL

• INITIAL COST OF CONSTRUCTION

Materials	Basic price (£ / m^2)	Quantity (m^2)	Price (£ / m^2)
102 mm thick facing bricks; PC £ 250.00 / 1000; in gauged mortar (1:1:6)	33.05	1	33.05
Galvanised steel twisted wall ties; 75mm cavity; three wall ties per m^2	1.23	1	1.23
140 mm thick lightweight aerated concrete blocks; in gauged mortar (1:1:6)	20.25	1	20.25
12mm thick gypsum plasterboard to B.S. 1230; fixed with nails; joints filled with filler and joint tape to receive decoration; skimmed with one coat of plaster	18.08	1	18.08
Two coats emulsion paint; plaster / plasterboard walls	2.19	1	2.19
Total			**£ 74.80 / m^2**

• MAINTENANCE

Table F.4 shows an extract from Table 5.8 which gives details of the maintenance requirements of clay brickwork masonry cavity walls. These were determined from an analysis of condition survey data. The data in the table are for a good maintenance regime only and refer to the requirements of the outer brickwork leaf only.

Design life	Maintenance activity (brickwork outer leaf only)		
	Number of times wall repointed within period	Area of brickwork repaired within period	Area of brickwork replaced within period
60 years	1	10 %	5 %

Table F.4: Maintenance Requirements of Brickwork Outer Leaf in External Cavity Walls

The example assumes that the inner leaf would only require half of the maintenance of the outer leaf and that it would not be repointed. In addition, it was assumed that the wall ties and cavity insulation would only be replaced when the inner or outer leaves were maintained. As in Table D.6, the plasterboard was assumed to need replacing at 60 year intervals and the inner face of the wall would be repainted every 5 years.

Maintenance activity	Basic price (£ / m^2)	Quantity (m^2)	Replacement interval (years)	Frequency	Price (£ / m^2)
Repointing in gauged mortar (1:1:6) to match existing; brickwork walls	11.90	1	-	1	11.90
Repair defective brickwork, re-use existing bricks with gauged mortar (1:1:6)	22.16	0.05	-	1	1.11
Cut out decayed, defective or cracked brickwork and replace with new 102 mm thick facing bricks; PC £ 250.00 / 1000; in gauged mortar (1:1:6)	99.81	0.1	-	1	9.98
Galvanised steel twisted wall ties; 75mm cavity; three wall ties per m2	1.55	0.15	-	1	0.23
Remove existing cavity insulation and replace with similar product	24.68	0.15	-	1	3.70
Remove and replace existing 140 mm thick lightweight aerated concrete blockwork wall	86.38	0.075	-	1	6.48
Remove and replace existing gypsum plasterboard	26.51	1	60	0	0
Repaint plaster / plasterboard walls with two coats emulsion paint	2.99	1	5	11	32.89
Total					**£ 66.29 / m^2**

Table F.5: The Cost of the Maintaining a Brickwork / Blockwork Cavity Wall to 60 years

- **DEMOLITION**

102.5 mm thick skin of brickwork, 140mm thick skin of aerated blockwork with plaster on internal face £ 14.32 / m^2

- **DISPOSAL**

Off site disposal; to include trip not exceeding 13 km (using lorries); including Landfill Tax

Classification	Basic price (£ / m^3)	Material	Quantity of materials over 60 years (m^3)	Price (£ / m^2)
Inactive or inert waste	16.00	102 mm thick brickwork	0.192	3.07
		Wall ties	0.002	0.03
		140 mm thick blockwork	0.186	2.98
		12mm thick plasterboard	0.048	0.77
All other taxable waste	34.00	Emulsion paint	0.005	0.17
Total				**£ 7.02 / m^2**

- **WHOLE-LIFE COST AT 60 YEARS**

Initial cost of construction	£ 74.80 / m^2
Cost of maintenance over 60 years	£ 66.29 / m^2
Cost of demolition	£ 14.32 / m^2
Cost of disposal	£ 7.02 / m^2
Total	**£ 162.43 / m^2**

Table F.6: Whole-Life-Cost of a Brickwork / Blockwork Cavity Wall with a 60 Year Life

F.3 EXTRAPOLATING THE WHOLE-LIFE COSTING DATA

F.3.1 WHOLE-LIFE COST OF A BRICKWORK / BLOCKWORK CAVITY WALL AT 150 YEARS

- **MAINTENANCE**

Table F.7 shows the maintenance requirements for cavity walls at 150 years for a good maintenance regime at Table F.8 shows the cost of this maintenance.

Design life	Maintenance activity (brickwork outer leaf only)		
	Number of times wall repointed within period	Area of brickwork repaired within period	Area of brickwork replaced within period
60 years	2	40 %	25 %

Table F.7: Maintenance Requirements of Brickwork Outer Leaf in External Cavity Walls

Maintenance activity	Basic price (£ / m^2)	Quantity (m^2)	Replacement interval (years)	Frequency	Price (£ / m^2)
Repointing in gauged mortar (1:1:6) to match existing; brickwork walls	11.90	1	-	2	23.80
Repair defective brickwork, re-use existing bricks with gauged mortar (1:1:6)	22.16	0.25	-	1	5.54
Cut out decayed, defective or cracked brickwork and replace with new 102 mm thick facing bricks; PC £ 250.00 / 1000; in gauged mortar (1:1:6)	99.81	0.40	-	1	39.92
Galvanised steel twisted wall ties; 75mm cavity; three wall ties per m2	1.55	0.65	-	1	1.00
Remove existing cavity insulation and replace with similar product	24.68	0.65	-	1	16.04
Remove and replace existing 140 mm thick lightweight aerated concrete blockwork wall	86.38	0.325	-	1	28.07
Remove and replace existing gypsum plasterboard	26.51	1	60	150 / 60 = 2	53.02
Repaint plaster / plasterboard walls with two coats emulsion paint	2.99	1	5	150 / 5 = 30	89.70
Total					**£ 257.09 / m^2**

Table F.8: The Cost of the Maintaining a Brickwork / Blockwork Cavity Wall to 150 years

- **DISPOSAL**

Off site disposal; to include trip not exceeding 13 km (using lorries); including Landfill Tax

Classification	Basic price (£ / m^3)	Material	Quantity of materials over 150 years (m^3)	Price (£ / m^2)
Inactive or inert waste	16.00	102 mm thick brickwork	0.275	4.40
		Wall ties	0.009	0.14
		140 mm thick blockwork	0.236	3.36
		12mm thick plasterboard	0.144	2.31
All other taxable waste	34.00	Emulsion paint	0.125	0.43
Total				**£ 10.64 / m^2**

- **WHOLE-LIFE COST AT 150 YEARS**

Initial cost of construction	£ 74.80 / m^2
Cost of maintenance over 150 years	£ 257.09 / m^2
Cost of demolition	£ 14.32 / m^2
Cost of disposal	£ 10.64 / m^2
Total	**£ 356.85 / m^2**

Table F.9: Whole-Life-Cost of a Brickwork / Blockwork Cavity Wall with a 150 Year Life

F.3.2 EXTRAPOLATING THE WHOLE-LIFE COSTING DATA TO 500-YEARS

The whole-life cost of a brickwork / blockwork clay brickwork masonry cavity wall at 150 years were determined as £ 356.85 / m^2. At this age, the wall had reached the end of its life and it was assumed to have been demolished. In order for the data to be extrapolated to 500 years, it is assumed that the wall would be rebuilt and demolished at 150 year intervals – at 150 years, 300 years and 450 years. The whole-life cost extrapolated to 500 years is shown in Table F.10.

Initial cost of construction	£ 74.80 / m^2
Cost of maintenance over 150 years and cost of demolition and disposal at 150 years.	£ 282.05 / m^2
Cost of construction at 150 years	£ 74.80 / m^2
Cost of maintenance over 150 years and cost of demolition and disposal at 300 years.	£ 282.05 / m^2
Cost of construction at 300 years	£ 74.80 / m^2
Cost of maintenance over 150 years and cost of demolition and disposal at 450 years.	£ 282.05 / m^2
Cost of construction at 450 years	£ 74.80 / m^2
Cost of maintenance over 50 years and cost of demolition and disposal at 500 years.	£ 87.63 / m^2
Total	**£ 1232.98 / m^2**

Table F.10: Whole-Life-Cost of a Brickwork / Blockwork Cavity Wall Extrapolated to 500 Years

APPENDIX G: CALCULATION FOR COMPARISONS WITH BUILDING RESEARCH ESTABLISHMENT DATA

G.1 INTRODUCTION

As part of the project, comparisons were made between the B.R.E.'s life-cycle data and the corresponding data developed for this project. The B.R.E.'s life-cycle costing data were obtained from their *Envest II* software package and their life-cycle assessment data were taken from *Envest II* and the *Green Guide to Specification.*

The whole-life L.C.A. data were developed using the methodology described in Appendix B. The 3 sets of replacement rates for the construction materials used in this analysis are shown in Table G.1.

Construction Material	Replacement rate based on:		
	Analysis of conditional survey data	B.R.E.'s *Green Guide to Specification*	B.R.E.'s *Envest II* Environmental software pace
Brickwork outer leaf	150+	60	80
Cavity insulation	150+	60	80
Blockwork inner leaf	150+	60	80
Mortar	71	60	80
Plasterboard	60	60	60
Paint	5	5	5

Table G.1: Replacement Rates for the Construction Materials

The replacement rates in Table G.1 were converted to the corresponding mass of construction materials which would be used to maintain the walls at the different ages –

see Table G.2. The maximum age, 150 years was chosen to suit the maximum lifespan for cavity walls which was derived from the analysis of the conditional survey data.

A summary of the results for climate change environmental impact are shown in Tables G.2 to G.4. As described more fully in Appendix B.1, because of issues concerning the confidentiality of the data, only the results for the climate change impact category will be shown in the tables although the full comparison involved the data from all 13 impact categories. The final environmental profile which lists the overall impact for each of the thirteen categories is shown in Table G.5.

Replacement rate based on:	Lifespan (Years)	Construction Material						
		Brickwork outer leaf	Replacement of brickwork mortar	Cavity insulation	Blockwork inner leaf	Replacement of blockwork mortar	Plasterboard	Paint
Analysis of conditional survey data	60	4 %	0 %	0 %	2 %	0 %	100 %	1200 %
	100	7 %	25 %	7 %	3.5 %	0 %	100 %	2000 %
	150	25 %	50 %	25 %	12.5 %	0 %	200 %	3000 %
B.R.E.'s *Green Guide to Specification*	60	150 %	150 %	150 %	150 %	150 %	150 %	1250 %
	100	150 %	150 %	150 %	150 %	150 %	150 %	2050 %
	150	250 %	250 %	250 %	250 %	250 %	250 %	3050 %
B.R.E.'s *Envest II* Environmental software package	60	0 %	0 %	0 %	0 %	0 %	100 %	1200 %
	100	100 %	100 %	100 %	100 %	100 %	100 %	2000 %
	150	100 %	100 %	100 %	100 %	100 %	200 %	3000 %

Table G.2: Increase in Mass of the Construction Materials Due to Maintenance at Various Ages

Materials		Installed mass / m^2 (kg)	Climate change per tonne of materials (kg CO_2 eq. (100 yrs))	Impact on climate change from the installed mass of materials / m^2 (kg CO_2 eq. (100 yrs))
102.5 mm brickwork		165.26	240	39.66
Brickwork mortar (1 : 1 : 6)	Cement (13.25 % by mass)	5.81	1100	6.39
	Lime (5 % by mass)	2.22	245	0.54
	Sand (81.25 % by mass)	37.93	4.1	0.16
Cavity insulation		-	-	4.5
140mm aerated blockwork		65.49	240	15.72
Blockwork mortar (1 : 1 : 6)	Cement (13.25 % by mass)	2.19	1100	2.41
	Lime (5 % by mass)	0.84	245	0.21
	Sand (81.25 % by mass)	14.33	4.1	0.06
Plasterboard (per face)		18.13	150	2.72
Paint (per face)		0.36	4.50	0.43
Transport to site		-	-	12.00
Total				**84.80**

Table G.3: The Initial Environmental Impact from a Brickwork / Blockwork External Cavity Wall

Materials		Impact on climate change from the installed mass of materials / m^2 (kg CO_2 eq. (100 yrs))	Environmental impact of maintenance					
			As a percentage of installed mass			Impact on climate change from mass of materials / m^2 (kg CO_2 eq. (100 yrs))		
			At 60 years	At 100 years	At 150 years	At 60 years	At 100 years	At 150 years
102.5 mm brickwork		39.66	4 %	7 %	25 %	1.59	2.78	9.92
Brickwork mortar (1 : 1 : 6)	Cement	6.39	0 %	25 %	50 %	0.00	1.60	3.20
	Lime	0.54	0 %	25 %	50 %	0.00	0.14	0.27
	Sand	0.16	0 %	25 %	50 %	0.00	0.04	0.08
Cavity insulation		4.5	4 %	7 %	25 %	0.18	0.32	1.13
140mm aerated blockwork		15.72	2 %	3.5 %	12.5 %	0.31	0.55	1.97
Blockwork mortar (1 : 1 : 6)	Cement	2.41	0 %	0 %	0 %	0.00	0.00	0.00
	Lime	0.21	0 %	0 %	0 %	0.00	0.00	0.00
	Sand	0.06	0 %	0 %	0 %	0.00	0.00	0.00
Plasterboard (per face)		2.72	100 %	100 %	200 %	2.72	2.72	5.44
Paint (per face)		0.43	1200 %	2000 %	3000 %	5.16	8.60	12.90
End of life disposal		-				-	-	0.0
Total						**9.97**	**16.74**	**34.90**

Table G.4: The Increase in Climate Change from a Brickwork / Blockwork External Cavity Wall Based on the Replacement Rates Derived from an Analysis of the Conditional Survey Data

Materials		Impact on climate change from the installed mass of materials / m^2 (kg CO_2 eq. (100 yrs))	Environmental impact of maintenance					
			As a percentage of installed mass			Impact on climate change from mass of materials / m^2 (kg CO_2 eq. (100 yrs))		
			At 60 years	At 100 years	At 150 years	At 60 years	At 100 years	At 150 years
102.5 mm brickwork		39.66	150 %	150 %	250 %	59.49	59.49	99.15
Brickwork mortar (1 : 1 : 6)	Cement	6.39	150 %	150 %	250 %	9.59	9.59	15.98
	Lime	0.54	150 %	150 %	250 %	0.81	0.81	1.35
	Sand	0.16	150 %	150 %	250 %	0.24	0.24	0.40
Cavity insulation		4.5	150 %	150 %	250 %	6.75	6.75	11.25
140mm aerated blockwork		15.72	150 %	150 %	250 %	23.58	23.58	39.30
Blockwork mortar (1 : 1 : 6)	Cement	2.41	150 %	150 %	250 %	3.62	3.62	6.03
	Lime	0.21	150 %	150 %	250 %	0.32	0.32	0.53
	Sand	0.06	150 %	150 %	250 %	0.09	0.09	0.15
Plasterboard (per face)		2.72	150 %	150 %	250 %	4.08	4.08	6.80
Paint (per face)		0.43	1250 %	2050 %	3050 %	5.38	8.82	13.12
End of life disposal		-				-	-	0.0
Total						**113.93**	**117.37**	**194.04**

Table G.5: The Increase in Climate Change from a Brickwork / Blockwork External Cavity Wall Based on the Replacement Rates Derived from the B.R.E.'s *Green Guide to Specification*

Materials		Impact on climate change from the installed mass of materials / m^2 (kg CO_2 eq. (100 yrs))	Environmental impact of maintenance					
			As a percentage of installed mass			Impact on climate change from mass of materials / m^2 (kg CO_2 eq. (100 yrs))		
			At 60 years	At 100 years	At 150 years	At 60 years	At 100 years	At 150 years
102.5 mm brickwork		39.66	0 %	100 %	100 %	0.00	39.66	39.66
Brickwork mortar (1 : 1 : 6)	Cement	6.39	0 %	100 %	100 %	0.00	6.39	6.39
	Lime	0.54	0 %	100 %	100 %	0.00	0.54	0.54
	Sand	0.16	0 %	100 %	100 %	0.00	0.16	0.16
Cavity insulation		4.5	0 %	100 %	100 %	0.00	4.5	4.5
140mm aerated blockwork		15.72	0 %	100 %	100 %	0.00	15.72	15.72
Blockwork mortar (1 : 1 : 6)	Cement	2.41	0 %	100 %	100 %	0.00	2.41	2.41
	Lime	0.21	0 %	100 %	100 %	0.00	0.21	0.21
	Sand	0.06	0 %	100 %	100 %	0.00	0.06	0.06
Plasterboard (per face)		2.72	100 %	100 %	200 %	2.72	2.72	5.44
Paint (per face)		0.43	1200 %	2000 %	3000 %	5.16	8.60	12.90
End of life disposal		-				-	-	0.0
Total						**7.89**	**80.97**	**87.99**

Table G.6: The Increase in Climate Change from a Brickwork / Blockwork External Cavity Wall Based on the Replacement Rates Derived from the B.R.E.'s *Envest II* Environmental software package

Replacement rate based on:	Impact on climate change environmental impact category / m^2 (kg CO_2 eq. (100 yrs))			
	Installed	At 60 years	At 100 years	At 150 years (including end of life disposal)
Analysis of conditional survey data	**84.80**	**94.77**	**101.54**	**119.70**
B.R.E.'s *Green Guide to Specification*	**84.80**	**198.73**	**202.17**	**278.84**
B.R.E.'s *Envest II* Environmental software package	**84.80**	**92.69**	**165.77**	**172.79**

Table G.7: Summary of Impact on Climate Change Environmental Impact Category at Various Ages for a Brickwork / Blockwork External Cavity Wall

Impact category		Units	Installed	At 60 years	At 100 years	At 150 years
Climate change		kg CO_2eq. (100years)	85	95	102	120
Acid deposition		kg SO_2 eq.	0.40	0.53	0.57	0.72
Ozone depletion		kg CFC-11 eq.	0	0	0	0
Pollution to air:	Human toxicity	kg tox.	0.52	0.63	0.70	0.87
	Low-level Ozone Creation	kg ethene eq.	0.010	0.08	0.07	0.09
Fossil fuel depletion and extraction		t.o.e.	0.00001736	0.00001742	0.00001750	0.00001759
Pollution to water:	Human toxicity	kg tox.	120.041	135.222	138.227	147.325
	Eco-toxicity	m^3 tox.	0.029	0.037	0.042	0.053
	Eutrophication	kg PO_4 eq.	0.021	0.030	0.031	0.039
Minerals extraction		tonnes	0.300	0.350	0.425	0.554
Water extraction		litres	482	509	556	626
Waste disposal		tonnes	0.012	0.019	0.024	0.033
Transport pollution and congestion: Freight		tonne.km	26	62	65	87

Table G.8: Summary of Environmental Impact for a Brickwork / Blockwork External Cavity Wall at Various Ages Based on Maintenance Data Derived from an Analysis of Conditional Survey Data

Impact category		Units	Installed	At 60 years	At 100 years	At 150 years
Climate change		kg CO_2eq. (100years)	85	199	202	279
Acid deposition		kg SO_2 eq.	0.40	1.15	1.17	1.63
Ozone depletion		kg CFC-11 eq.	0	0	0	0
Pollution to air:	Human toxicity	kg tox.	0.52	1.41	1.43	2.01
	Low-level Ozone Creation	kg ethene eq.	0.010	0.10	0.13	0.19
Fossil fuel depletion and extraction		t.o.e.	0.00001736	0.00004356	0.00004366	0.00006114
Pollution to water:	Human toxicity	kg tox.	120.041	322.829	322.829	451.960
	Eco-toxicity	m^3 tox.	0.029	0.082	0.082	0.115
	Eutrophication	kg PO_4 eq.	0.021	0.063	0.065	0.092
Minerals extraction		tonnes	0.300	0.802	0.802	1.123
Water extraction		litres	482	1231	1245	1746
Waste disposal		tonnes	0.012	0.038	0.041	0.057
Transport pollution and congestion: Freight		tonne.km	26	112	118	166

Table G.9: Summary of Environmental Impact for a Brickwork / Blockwork External Cavity Wall at Various Ages Based on Maintenance Data Derived from the B.R.E.'s *Green Guide to Specification*

Impact category		Units	Installed	At 60 years	At 100 years	At 150 years
Climate change		kg CO_2eq. (100years)	85	93	166	173
Acid deposition		kg SO_2 eq.	0.4	0.52	0.96	1.03
Ozone depletion		kg CFC-11 eq.	0	0	0	0
Pollution to air:	Human toxicity	kg tox.	0.52	0.62	1.17	1.23
	Low-level Ozone Creation	kg ethene eq.	0.01	0.08	0.13	0.18
Fossil fuel depletion and extraction		t.o.e.	0.00001736	0.00001752	0.00003498	0.00003510
Pollution to water:	Human toxicity	kg tox.	120.041	138.221	262.808	271.898
	Eco-toxicity	m^3 tox.	0.029	0.037	0.068	0.072
	Eutrophication	kg PO_4 eq.	0.021	0.030	0.055	0.060
Minerals extraction		tonnes	0.3	0.341	0.652	0.673
Water extraction		litres	482	506	1004	1023
Waste disposal		tonnes	0.012	0.019	0.035	0.039
Transport pollution and congestion: Freight		tonne.km	26	66	105	128

Table G.10: Summary of Environmental Impact for a Brickwork / Blockwork External Cavity Wall at Various Ages Based on Maintenance Data Derived from the B.R.E.'s *Envest II* Environmental software package

Replacement rate based on:	Installed (Eco-points)	60-years (Eco-points)	100-years (Eco-points)	150years (Eco-points)
Analysis of conditional survey data	0.64	0.82	0.91	1.14
B.R.E.'s *Green Guide to Specification*	0.64	1.74	1.77	2.47
B.R.E.'s *Envest II* Environmental software package	0.64	0.81	1.47	1.58

Table G.11: Summary of the Whole-Life Environmental Impact at Various Ages for a Brickwork / Blockwork External Cavity Wall

APPENDIX H: COMPARISON OF ESTIMATES FOR THE CONTRIBUTION OF BUILDING ELEMENTS TO IMPACT OF A TYPICAL BUILDING

H.1 ESTIMATE OF CONTRIBUTION OF BUILDING ELEMENTS TO IMPACT OF A TYPICAL BUILDING

The following appendix shows how the contributions of the different buildings elements to the whole-life environmental impact of a building were determined at various ages. This was done to allow comparisons with similar data published by the B.R.E. in their *Green Guide to Specification* [Anderson, Shiers and Sinclair, 2002].

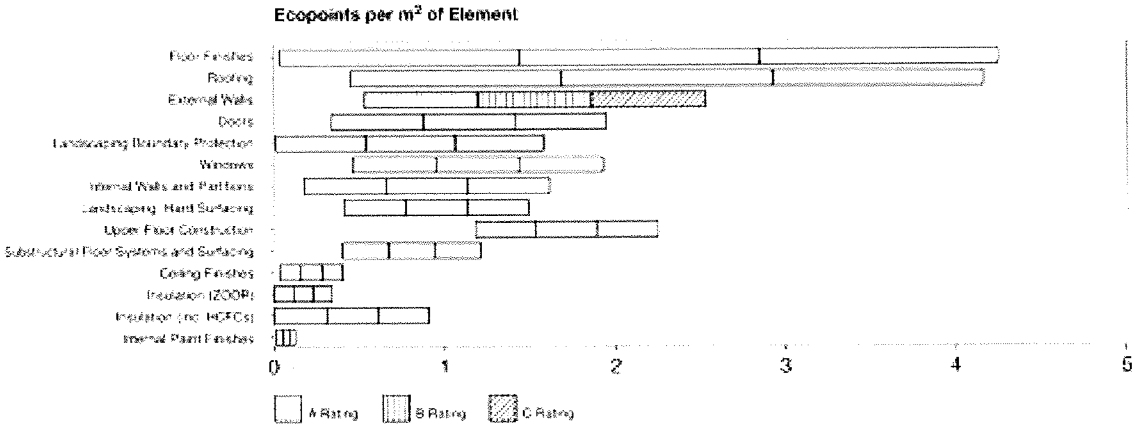
Tables H.1 and H.2 show the replacement intervals and environmental impacts for the different building elements that were used in the estimation exercise. Both of the initial ranges were taken from *The Green Guide to Specification.*

The figures specified as being used for the comparison in Table H.1 were the mode (most frequently occurring) ages in the range.

Building element:	Replacement intervals for the building elements:	
	Age range specified in *Green Guide to Specification* (years)	Age used in comparison exercise (years)
Floor finishes	5 – 20	5
Upper floors	-	60
Substructure	-	60
Floor surfacing	-	30
External walls	25 – 60	60
Roof	15 – 60	30
Ground floor	5 – 20	60
Windows	25 – 35	30
Superstructure	5 – 20	60
Internal walls	15 – 20	15
Ceiling finishes	25 – 40	30
Paint	-	5

Table H.1: Replacement Intervals for the Building Elements

In Table H.2, the impact values used in the comparison were based on an analysis of the distribution of the ratings within the range of values for external walls shown in Figure H.1.



Summary Rating A B C ranges for different elements.

Figure H.1: Range of Summary Ratings for Different Building Elements (Anderson, Shiers and Sinclair, 2002)

The environmental impacts for each of the building elements were based on the average value of the summary rating. This was not determined by simply obtaining the middle value of the summary rating range shown in Figure H.1, as it was felt that this would not accurately reflect the individual performance of all of the individual wall elements in the external wall category and would instead be effectively based on the two elements with the largest and least environmental impacts within the range only.. For instance, the environmental impact for floor finishes ranges between 0.07 eco-points / m^2 and 4.29 eco-points / m^2, therefore, the *A* summary rating would range between 0.07 and 1.477 eco-points / m^2, a *B* rating between 1.478 and 2.883 eco-points / m^2, and a *C* rating between 2.884 and 4.29 eco-points / m^2. Consequently, the mean value for each of the three ranges would be 0.774, 2.181 and 3.587 eco-points / m^2 respectively. *The Green Guide to Specification* notes that 17 of the floor finishes have an *A* summary, 2 a *B* summary rating and 4 a *C* summary rating. The final value used in the comparison were then determined as follows:

$$\frac{(17 \times 0.774) + (2 \times 2.181) + (4 \times 3.587)}{(17 + 2 + 4)} = 1.38 \text{ eco-points / m}^2$$

Building element	Summary rating range - see Figure H.1 (eco-points / m^2)		Distribution of individual elements within summary rating range			Impact used in comparison (eco-points / m^2)
	Lower limit	Upper limit	*A*	*B*	*C*	
Floor finishes	0.07	4.29	17	2	4	1.38
Upper floors	1.19	2.25	2	6	2	1.72
Substructure						-
Floor surfacing	0.4	1.21	3	1	4	0.84
External walls	0.56	2.56	27	22	4	1.27
Roof	0.46	4.19	24	4	11	1.91
Ground floor						1.75
Windows	0.49	1.96	2	4	2	1.23
Superstructure						-
Internal walls	0.19	1.63	11	9	6	0.82
Ceiling finishes	0.04	0.4	6	12	2	0.20
Paint	0.02	0.125	5	3	2	0.06

Table H.2: Environmental Impacts for the Building Elements

The total environmental impacts for the different building elements were based on the following four buildings types which were taken from the Green Guide to Specification – see Figure H.2:

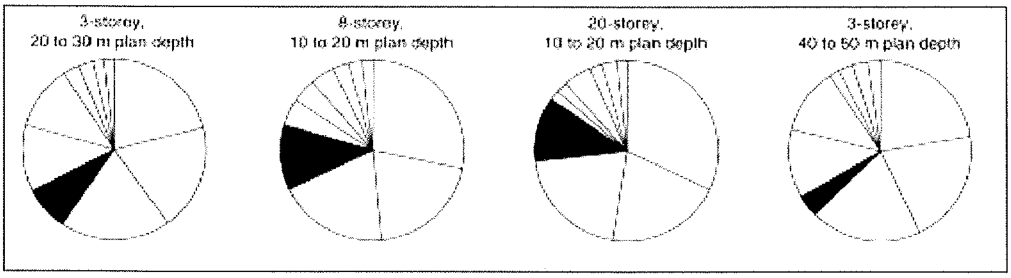


Figure H.2: The Four Generic Buildings used in the Green Guide to Specification (Anderson, Shiers and Sinclair, 2002)

The details of the four buildings are:

- **Building 1** – a three-storey building (3 m storey height) with a plan area of 25 m × 15 m and a glazing to external wall ratio of 30 %.
- **Building 2** – an eight-storey building (3 m storey height) with a plan area of 15 m × 15 m and a glazing to external wall ratio of 30 %.
- **Building 3** – a twenty-storey building (3 m storey height) with a plan area of 15 m × 15 m and a glazing to external wall ratio of 30 %.
- **Building 4** – a three-storey building (3 m storey height) with a plan area of 45 m × 15 m and a glazing to external wall ratio of 30 %.

The mean value of the four buildings was then ascertained for each element to determine the contribution of the elements for a *typical* building – see Table H.3.

Building element	Impact over the life of the building (eco-points)				
	Building 1	Building 2	Building 3	Building 4	Average value
Floor finishes	1558	2493	6232	2804	3272
Upper floors	1290	2709	7353	2322	3419
Substructure	968	1548	3870	1742	2032
Floor surfacing	944	1510	3774	1698	1982
External walls	640	1281	3202	961	1521
Roof	716	430	430	1290	716
Ground floor	645	387	387	1161	645
Windows	265	529	1323	397	628
Superstructure	138	221	552	248	290
Internal walls	92	147	368	166	193
Ceiling finishes	221	353	882	397	463
Paint	31	62	156	47	74
Total	7507	11670	28530	13232	15235

Table H.3: Contribution of Building Elements to the Whole-Life Impact of a *Typical* Building

H.2 COMPARISON OF ESTIMATES FOR THE CONTRIBUTION OF BUILDING ELEMENTS TO IMPACT OF A TYPICAL BUILDING

Once the contribution of the different elements had been estimated for the whole-life impacts at 60 years, the impacts were determined at 100 years, 150 years, 300 years and 500 years, to allow comparisons to be made with similar data derived from this project. It was decided to separately analyse the impact data for an *average* solid and an *average* cavity wall so that useful comparisons could also be drawn between them – see Table H.4 and H.5 respectively. It was also decided to use the impact data for an average standard of maintenance in Table 6.5.

	From Table 6.5, environmental impact (eco-points / m^2)				
	At 60-years	100 years	150 years	300 years	500 years
Wall 1	0.91	0.95	1.12	1.66	2.69
Wall 2	1.29	1.36	1.59	2.3	3.93
Wall 4	1.3	1.46	1.75	2.52	3.36
Wall 5	1.68	1.85	2.17	3.04	4.11
Average	1.30	1.41	1.66	2.38	3.52

Table H.4: *Average* Environmental Impact for a
Solid Clay Brickwork Masonry Wall at Various Ages

	From Table 6.5, environmental impact (eco-points / m^2)			
	At 60-years	100 years	150 years	500 years
Wall 3	0.93	0.98	1.19	4.21
Wall 6	1.32	1.47	1.79	6.22
Wall 7	1.18	1.24	2.01	6.71
Wall 8	0.71	0.89	-	4.08
Average	1.04	1.15	1.66	5.31

Table H.5: *Average* Environmental Impact for a
Clay Brickwork Masonry Cavity Wall at Various Ages

The impacts based on the B.R.E.'s methodology in Tables H.3. were converted to the relevant ages by simply dividing the age by the appropriate replacement interval in Table H.1 and then multiplying the result by the impact data in Table H.2.

The final results from these analyse are shown in Table H.6.

Building element		Environmental impacts (eco-points / m^2)				
		At 60-years	100 years	150 years	300 years	500 years
Floor finishes		3272	5726	8452	16632	27538
Upper floors		3419	6837	10256	20511	30767
Substructure		2032	4064	6095	12191	18286
Floor surfacing		1982	3963	5945	10899	16843
External walls	Impacts from the *Green Guide to Specification*	1521	3042	4563	9126	13689
	Average impact for a solid wall	1521	1688	1987	2849	4213
	Average impact for a cavity wall	1245	1377	1987	-	6356
Roof		716	1433	2149	3941	6090
Ground floor		645	1290	1935	3870	5805
Windows		628	1257	1885	3456	5342
Superstructure		290	507	797	1521	2463
Internal walls		193	338	531	1014	1642
Ceiling finishes		463	926	1389	2547	3936
Paint		74	130	192	377	625

Table H.6: Contribution of Different Building Elements to the Whole-Life Impact of a Building

APPENDIX I: COMPARISON OF ENVIRONMENTAL PERFORMANCE OF AN EXISTING BUILDING AND A REPLACEMENT BUILDING

I.1 INTRODUCTION

An analysis was completed to compare the environmental performance of an existing building. A building was chosen which did not comply with the current statutory requirements for the performance of buildings but whose age was between 60 and 80 year lifespans that the B.R.E. use in their *Green Guide* series and *Envest II* L.C.A. packages respectively. It was compared with an upgraded version of the building which met the current requirements for the thermal performance of buildings and a replacement building. The design and layout of the new building was based on a new row of terraced housing which were recently built in Leeds.

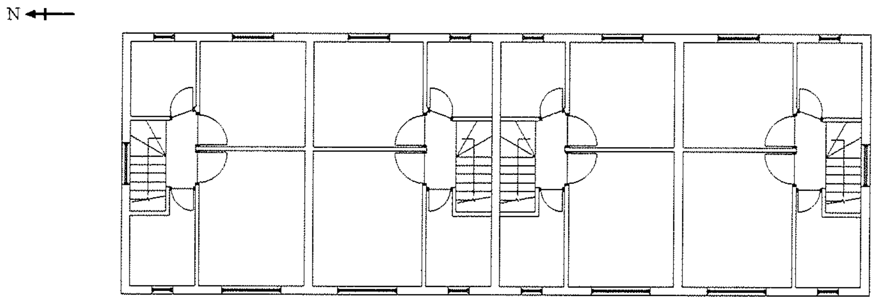
The existing building consisted of four terrace houses. There were four similar buildings in the same street. The houses have 215mm thick solid brickwork external walls with thin lime mortar joints and, consequently, do not comply with the current requirements for the thermal performance of external walls. There has not been any maintenance carried out on the brickwork of the building as a whole since it was built but all of the original doors and windows have been replaced with new PVC-U double-glazed units. In addition, the northern end-terrace house, which was the only one which could be surveyed internally, the loft had been insulated with glass wool insulation although, when it was analysed, it was only half the thickness required for the roof to comply with the current requirements for the thermal performance of roofs.

In the analysis, only the energy required to heat the building was determined rather than the operational energy of the building. This was because it was considered that, apart from the energy required to heat the building, the other operational energies, i.e. lighting, cooking, etc. would be constant irrespective of whether the building was upgraded, etc.

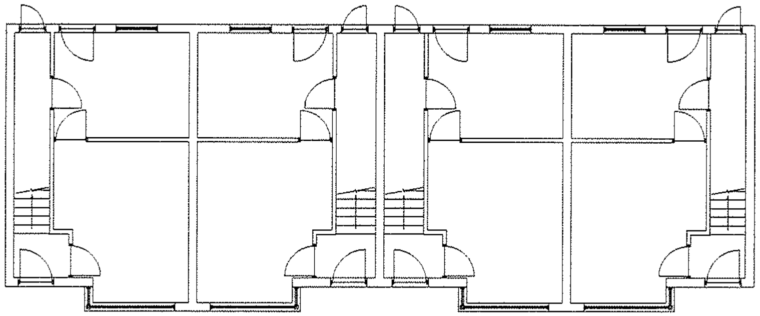
The embodied energy of the construction materials in the existing building were not considered in this analysis. This was because, as the architect Quinlan Terry stated (see Paragraph 2.2) *'the fossil fuel emissions that were produced during the construction of the existing homes are already in the atmosphere'.* It was decided, therefore, that because the existing buildings was still fulfilling its basic function – providing shelter – and it was only being demolished to improve its thermal performance that the embodied energy of the construction materials should not be considered.

It was also decided to only consider the maintenance requirements of the brickwork in the analysis. This was because the other elements, i.e. the windows, boiler, carpets, etc., would need to be replaced at similar ages irrespective of the building they were installed in. In addition to the external walling, the only other major element which would also have a different replacement interval between the two buildings was the roof. The existing building had slate tiles and the new roof had concrete tiles and, whereas the replacement interval for slate tiles is 50 years, it is only 20 years for concrete tiles. Despite an extensive search, no information could be found about the environmental impacts of slates tiles, however, so the replacement of these items could not be considered in the analysis.

The analysis was based on a lifespan of 100 years which was chosen because it was the maximum lifespan for a brickwork / timber cavity wall used in the life-cycle analysis in this thesis – see Table 6.3. A survey was conducted on the existing building to confirm that it is capable of continuing to survive until at least this age. The maintenance requirements of the walls were based on those for an average standard of maintenance given in Table 5.8 and 5.9.

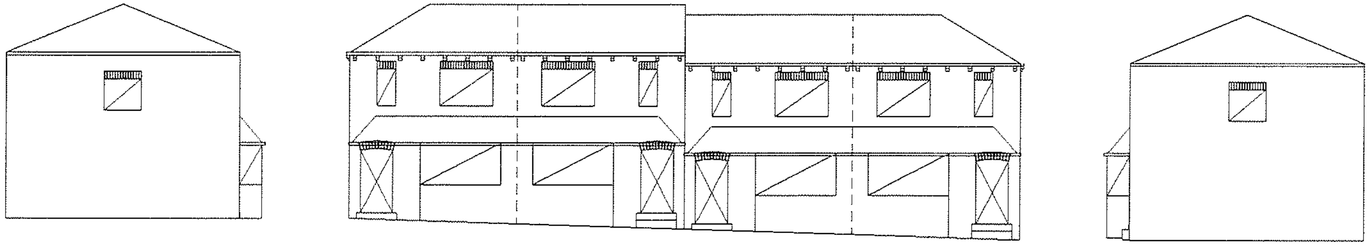


First Floor Plan



Ground Floor Plan

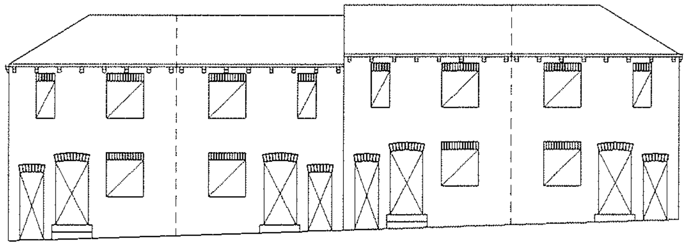
Figure I.1: Plan on Existing Building



Side elevation

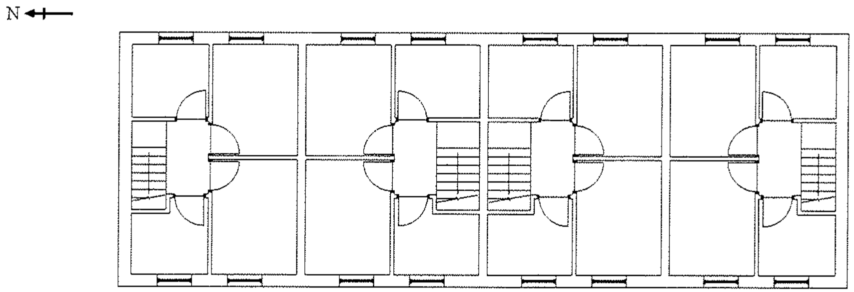
Front elevation

Side elevation

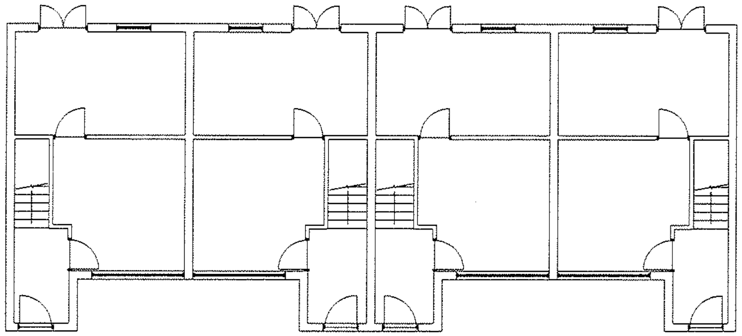


Rear elevation

Figure I.2: Elevations on Existing Building



First floor plan



Ground floor plan

Figure I.3: Plan on Replacement Building

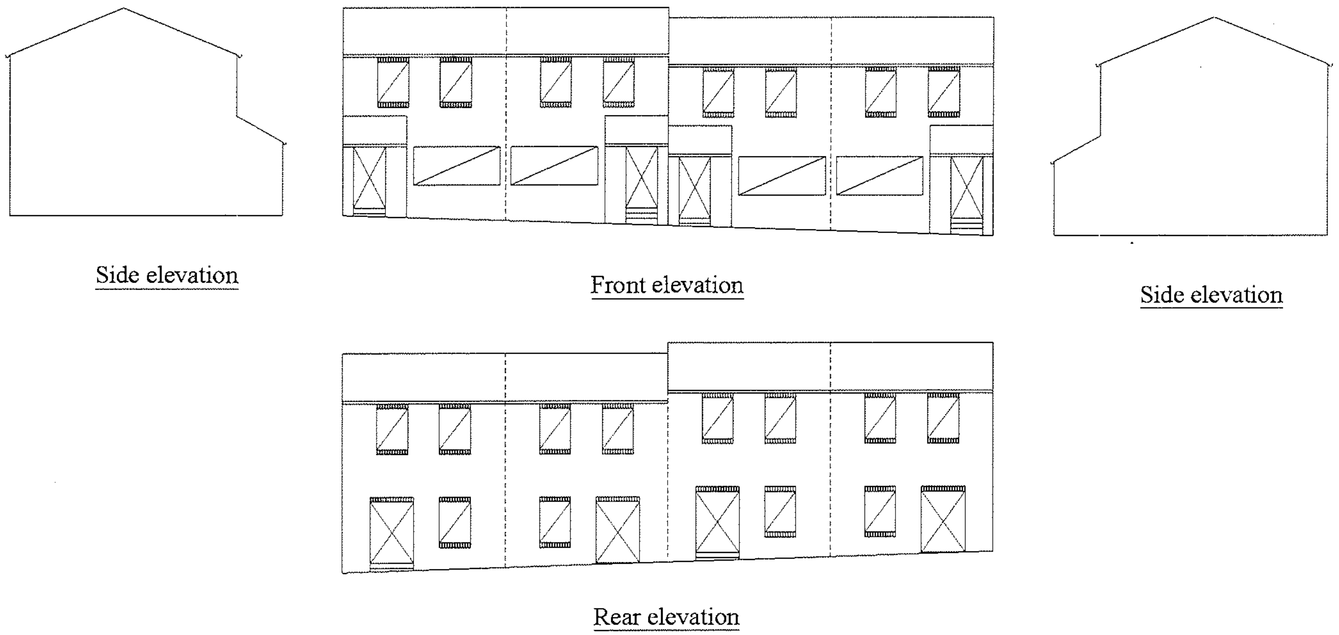


Figure I.4: Elevations on Replacement Building

I.2 EMBODIED ENERGIES OF THE CONSTRUCTION MATERIALS

Roofing elements

Timber truss rafters, insulation, roof tiles and accessories	0.38 eco – points / m^2
Attic insulation	0.04 eco – points / m^2

External elements

Brickwork / timber insulated external cavity wall	0.77 eco – points / m^2
Cement render	0.49 eco – points / m^2
External insulation and accessories	0.11 eco – points / m^2
PVC-U double-glazed units	2.45 eco – points / m^2
450 mm x 300 mm deep strip footing foundation provided beneath perimeter and party walls only	1.32 eco-points / m run

Internal elements

Load-bearing aerated blockwork partitions, plasterboard	0.16 eco – points / m^2
Solid dense blockwork party wall, plasterboard	0.51 eco – points / m^2
Plasterboard ceiling on battens, 2 coats of emulsion paint	0.10 eco – points / m^2
Doors and frame	0.15 eco-points / door
2 coats of paint	0.08 eco-points / m^2

Ground and Upper floors

Pre-cast concrete beams and block floor	1.00 eco – points / m^2
Insulation	0.20 eco-points /m^2
Timber joists, chipboard sheets	0.43 eco – points / m^2
Wool carpet on sponge rubber underlay	1.73 eco – points / m^2

I.2.1 ENVIRONMENTAL IMPACT OF THE UPGRADED BUILDING

Quantity of construction materials

Area of ceiling (attic)	26.1 m^2
Area of external brickwork leaf (excluding windows)	205.8 m^2

Total environmental impact

Attic insulation	0.04 x 26.1 m^2	=	1.0 eco – points
Cement render	0.49 x 205.8 m^2	=	100.8 eco – points
External insulation and accessories	0.11 x 205.8 m^2	=	22.6 eco – points
	Total	=	**124.4** eco-points

I.2.2 ENVIRONMENTAL IMPACT OF THE REPLACEMENT BUILDING

Quantities of construction materials

Area of roof	140.0 m^2
Area of outer brickwork leaf (excluding windows)	218.7 m^2
Area of glazing (including double-glazed doors to rear of property)	30.8 m^2
Foundations (length)	78.2 m
Area of partitions	181.8 m^2
Party walls	108.3 m^2
Ceilings	52.2 m^2
Internal and external doors	7 No.
Paint (walls only)	361.8 m^2
Area of ground floor	26.1 m^2
Area of upper floor	26.1 m^2

Total environmental impact

Roofing elements

Timber truss rafters, roof tiles, etc.	0.38 x 140.0 m^2	=	53.2 eco – points

External elements

Brickwork / timber external cavity wall	0.77 x 218.7 m^2	=	168.4 eco – points
PVC-U double-glazed units	2.45 x 30.8 m^2	=	75.5 eco – points
450 mm x 300 mm deep strip footings	1.32 x 78.2 m	=	103.2 eco – points

Internal elements

Partitions, plasterboard	0.16 x 181.8 m^2	=	29.1 eco – points
Blockwork party wall, plasterboard	0.51 x 108.3 m^2	=	55.2 eco – points
Ceiling, 2 coats of paint	0.10 x 52.2 m^2	=	5.2 eco – points
Doors	0.15 x 7	=	1.1 eco – points
2 coats of paint	0.08 x 361.8 m^2	=	28.9 eco – points

Ground and Upper floors

Pre-cast concrete beams and block floor	1.00 x 52.2 m^2	=	52.2 eco – points
Insulation (ground floor only)	0.20 x 26.1 m^2	=	5.2 eco – points
Timber joists, chipboard sheets	0.43 x 52.2 m^2	=	22.4 eco – points
Wool carpet on sponge rubber underlay	1.73 x 52.2 m^2	=	90.3 eco – points
	Total	=	**689.9** eco-points

I.3 MAINTENANCE REQUIREMENTS OF THE BUILDINGS

As previously discussed in Paragraph I.1, the only maintenance requirements that were considered in this analysis were those for the external walls. The wall types that were considered in this analysis were identical to Walls 1, 4 and 8 in the earlier part of this thesis.

The maintenance requirements used in this analysis were based on an average standard of maintenance given in Tables 5.8 and 5.9. The maintenance figures were taken directly from Table 6.5. The requirements for the existing building that were used in the analysis were those for between 60 years and 150 years. It was decided that, although this was outside the actual age range being considered in this analysis, they were very similar. In addition, there was an allowance in Table 6.5 for a minimal amount of maintenance being carried out before 60 years, whereas there has been no maintenance on the real building. Therefore, the figures in Table 6.5 are conservative and will probably overestimate the actual future maintenance requirements of the existing building.

Maintenance requirements over lifespan of building

The existing building	(Wall 1)	0.23 eco – points / m^2
The upgraded existing building	(Wall 4)	0.45 eco – points / m^2
The replacement building	(Wall 8)	0.41 eco – points / m^2

Environmental impact from maintenance

The existing building $0.23 \times 205.8\ m^2 = 47.3$ eco – points
The upgraded existing building $0.45 \times 205.8\ m^2 = 92.6$ eco – points
The replacement building $0.41 \times 218.7\ m^2 = 89.7$ eco – points

I.4 ENERGY REQUIRED TO HEAT THE BUILDINGS

The *u*-values for the external walls were taken from Appendix E.1 and the values for the other elements were taken from Appendix A of *Approved Document L1: The Building Regulations 2000* [Office of the Deputy Prime Minister (2002)].

The operational energies of the buildings were determined using the same methodology and assumptions as that in Appendix E.

***U*-values of construction materials**

Roof

The existing building Tables A.6 and A.8)	0.40 W / $m^2.^\circ K$
The upgraded existing building	0.25 W / $m^2.^\circ K$
The replacement building	0.25 W / $m^2.^\circ K$

External wall

The existing building	(Wall 1)	2.59 W / $m^2.^\circ K$
The upgraded existing building	(Wall 4)	0.35 W / $m^2.^\circ K$
The replacement building	(Wall 8)	0.35 W / $m^2.^\circ K$

PVC-U double glazed windows (Table A.1)	2.0 W / $m^2.^\circ K$
External wooden front entrance door	3.0 W / $m^2.^\circ K$

Areas of building elements

Existing building

Roof	163.8 m^2
External leaf of brickwork	205.8 m^2
Glazing	43.7 m^2

Replacement building

Roof	140.0 m^2
External leaf of brickwork	218.7 m^2
Glazing	30.8 m^2

Existing building

Heat loss – fabric loss

Mean internal temperature, (based on insulation standard 2A, i.e heating provided from 0600 - 0900 and 1700 – 2300 and no additional insulation)	17.5 $^{\circ}$C
Mean external temperature	5.5 $^{\circ}$C

Temperature difference = 17.5 °C - 5.5 °C = 12 $^{\circ}$C

Rate of fabric heat loss,

= ((0.40 x 163.8) + (2.59 x 205.8) + (2 x 43.7) + (3.0 x 1.8)) x 12 $^{\circ}$C = 8296.1 W

Heat loss - ventilation loss

Internal volume of building	527.3 m^3
Ventilation heat loss rate per m^3	0.34 $W/m^3.^{\circ}K / m^3$
Temperature difference	12 $^{\circ}$C

Rate of ventilation heat loss,

= 527.3 m^3 × 0.34 $W / m^3.^{\circ}K / m^3$ × 12 $^{\circ}$C = 2151.4 W

Rate of fabric heat loss (from above calculation) 8296.1 W

Total heat loss = 2151.4 W + 8196.1 W = 10,347.5 W = 10.3 kW

Heat gain – solar gain

Area of glazing orientated north	1.1 m^2
Area of glazing orientated east	20.0 m^2
Area of glazing orientated south	1.1 m^2
Area of glazing orientated west	21.5 m^2

Solar gain through window orientated north	0.25 GJ / m^2 / season [†]
Solar gain through window orientated east	0.41 GJ / m^2 / season [†]
Solar gain through window orientated south	0.68 GJ / m^2 / season [†]
Solar gain through window orientated west	0.41 GJ / m^2 / season [†]

[†] *Standard figures from Mitchell's Environment and Services [Burberry, P. 1997])*

Solar gain,
= (1.1 × 0.25) + (20.0 × 0.41) +(1.1 × 0.68) +(21.5 × 0.41) = 17.6 GJ / season

Heat gain - occupants

Assuming the occupants are out during day = 0.6 GJ / person / season [†]
[†] *a standard figure from Mitchell's Environment and Services [Burberry, 1997])*
Assuming that there are three people per house,
total seasonal gain = 7.2 GJ / season

Total seasonal gains = 17.6 GJ + 7.2 GJ = 24.8 GJ / season

Total energy requirements for the building

Total heat loss 10.3 Kw
Seasonal heat loss = 10.3 Kw × 18.3 = 188.5 GJ [††]
[††] *a standard conversion factor, 1 kW = 18 GJ*
Total seasonal gains (from above calculation) 24.8 GJ
Net seasonal requirements = 188.5 GJ – 24.8 GJ = 163.7 GJ
House efficiency factor (based on electricity fuelled 1.1 [†]
storage radiators / warm air or under-floor heating)
[†] *a standard figure from Mitchell's Environment and Services [Burberry, 1997]*

Gross energy requirements = 163.7 GJ × 1.1 = 180.1 GJ / season

Energy required over 100 years = 180.1 GJ / season × 100 = 18010 GJ

Using a similar methodology,

Energy required to heat upgraded existing building 6848.7 GJ

Energy required to heat replacement building 6663.7 GJ

Based on the energy required to heat the building being derived from electricity,

From Paragraph 3.10.4 1 eco – point = 320 kWh of electricity
From <http://www.deh.gov.au > 1 GJ = 278 kWh

Energy required to heat the existing building,
= (18,010 × 278) / 320 Kwh = 15,643.6 eco - points

Similarly,

Energy required to heat upgraded existing building = 5949.8 eco - points

Energy required to heat replacement building = 5789.1 eco-points

	Embodied energy of the construction materials	Energy required to maintain the building (over 100 years)	Energy required to heat building (over 100 years)	Total (at 100 years)
	(eco-points)	(eco-points)	(eco-points)	(eco-points)
The existing building	0	47	15644	15691
The upgraded existing building	124	93	5950	6167
Existing building demolished and replaced with new building	690	90	5789	6569

Table I.1: Summary Table