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'An environmental guide for selecting wall cladding materials for architects'

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Abstract

In this age of the energy crisis where the level of ecological danger is increasing worryingly, the meaning of sustainability and environmental design in buildings obtain determinant importance in both national and international level. As building technology evolved and structural and cladding functions become separated, the final portrait of the building's character, the durability of the external skin as well the physical properties of external finishes always challenge the architect since he is responsible for illustrating building's public face. The physical qualities and textures of materials used, their environmental impacts during lifecycle from extraction until the end of their use with recycling or disposal, as well as their financial cost, constitute some of the numerous factors which should be taken into consideration in order to choose the most suitable external wall cladding.

More precisely, the choice of wall cladding materials are considered to burden building's envelope aesthetically, environmentally and financially to a different extent, three factors which are been examined holistically in this study. With the occasion of Granville Plus, a nursery school situated in London and created by Anne Thorne Partnership Architects, where various materials have been applied as external wall cladding, a comparative handbook for choosing different materials as external finish for building is been carried out.

The novelty of this study is the edit of an architectural guide where 17 fundamental wall cladding materials are been categorized according to aesthetic criteria and their physical properties in 5 basic categories, and for each one environmental and economical evaluation, examining values like embodied energy, recyclability, lifetime as well as cost throughout the assumed 50 years building's lifetime, are been carried out. The final aim is to set comparative environmental and financial indicators between materials in the disposal of architects in order to have the ability to compare materials with similar physical properties and to choose the most energy and cost effective.

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1. Introduction

1.1. A Global Issue: Climate change - Global warming- Greenhouse effect– Kyoto protocol

During the last decades climate change and the environmental impact of every human activity are taking worrying dimensions at an international level. Rising temperatures, rising sea levels due to the melting of the ice at the North and South Pole, extreme weather conditions including hurricances, thunder and tornados are some of the phenomena that add to evidence verifying the findings of the IPCC[1] . These are resulting in environmental, social and economical impacts on human society.

As it is widely known, global warming is a result of the greenhouse effect which is being reinforced by the increasing level of carbon dioxide (CO_2) in the atmosphere. The contemporary industrialized society in combination with the advance of technology has led to an ongoing energy demand in order to satisfy the quality of modern life we require. The increased need for the use and combustion of fossil fuels like coal, oil etc is leading to this escalation of the CO_2 concentration and other emissions in the atmosphere which could be harmful for the health of the planet and people.

However, numerous attempts are now being made in order to protect the environment. International organizations with environmental concerns like Greenpeace, World Wildlife Foundation (WWF) and others as well as government agencies now show serious concern about environmental issues. The prominent example is Kyoto Protocol which emphasizes the importance of the reduction of carbon dioxide emissions. The UK Government is a signatory to the 1997 Kyoto Conference agreement where most of the world's developed countries agreed to cut the emissions of greenhouse gases by an average of 5,2% on 1990 levels between 2008 and 2012. The UK's target is to reduce CO_2 emissions to a level of 20% less than the 1990 figures by 2010 [2], while the Royal Institute of British Architects (RIBA) has stated that 'members should support the goal of reducing carbon emissions arising from building in construction and use by 30% against 1990 levels by 2010' [3].

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[1] http://www.ipcc.ch/ 22/06/06

[2] Anderson J Shiers D Sinclair M(2002) *Green Guide to specification* BRE UK

[3] Sustainable Homes: *Embodied Energy in Residential property development A Guide for Registered Social Landlords,* The house corporation Sustainable homes

In order to achieve these targets, the Government is promoting energy efficiency in buildings through a number of measures including the Building Regulations, the Energy Efficiency Best Practice Program and the Home Energy Conservation Act. It has also identified the importance of using materials more efficiently to reduce overall energy demand, stating that 'about 10% of national energy consumption is used in the production and transport of construction products and materials embodied energy'[4].

1.2. Environmental Design and Sustainability

In a world with limited resources and serious environmental impacts it is obvious that a more sustainable life style will be more and more important and the act of constructing buildings is no exception. The environmental design of buildings constitutes a compulsory need and the role of the architect should be in accordance with the rules of sustainability. The Brundtland Commission (The world commission on Environment and Development 1987) defined sustainable development as 'development that meets the needs of the present without compromising the ability of the future generations to meet their needs'.[5]

Sustainable development or more precisely 'bioclimatic design' is aiming to insure the ideal indoor conditions according to the proper thermal attitude of the building during winter and summer by diminishing the energy consumption. The design of cooling and heating buildings has passed through several stages, starting from simple natural techniques to complicated systems and it had always one purpose: to improve the indoor conditions of living in spaces where humans work and live. Technological advances have provided systems with high efficiency and performance and have managed to give the solution to the problem of good living but with an additional energy cost. The current awareness of environmental problems as well as the re-examination of alternative technologies and systems, are forcing architects and engineers to consider carbon emissions even at the earliest design stage.

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[4] Sustainable Homes: *Embodied Energy in Residential property development A Guide for Registered Social Landlords*, The house corporation Sustainable homes

[5] Washan P (2005) Msc Dissertation '*Refurbish or redevelop A sustainable comparison for social housing in Brixton*' Environmental Design and Engineering UCL

1.3. Building Envelope

Building envelopes are human prostheses that represent the third skin separating indoor environments from the outside world. Like our first skin which is a living regenerating organ and unlike our second skin, clothing, which seldom outlives the vagaries of fashion cycles; skins of buildings are ideally intended to last the life of the whole building in particular its structure or skeletal system. In traditional building forms employing load bearing masonry, this relationship was axiomatic since the structure was also the skin[6]. As building technology evolved and the structural and cladding functions become separated, the durability of the skin over building's life cycle challenged the architect. This challenge focuses on the design of walls which represent the highest cost components of the building envelope system and are the most visible aspect of the building, its façade[7].

The external envelope is the key factor in portraying the character and design philosophy of the building because this is the building's 'public face'[8]. All the creativity and the intentions of the architect are being projected through the envelope verifying his design principles through the internal layout. It obeys the intentions and the desires of the architect responding to the principle issues of subjective aesthetics as well as functional needs. Perforated by numerous openings or completely closed, introvert or extravert, light weight or heavy are some of the choices that the architect has in mind in selecting components while obeying the morphological and functional principles that he imposes on the layout and the restrictions of the climatic conditions and the surrounding space.

Responding to the external irritant like a living organism, building envelopes represent the skin separating the indoor environment from the outside world. Like a cocoon, its aim is the maintenance of a pleasant and viable internal environment where people work and live protecting it from the outdoor weather conditions that may include intense solar radiation, wind and rain.

Perhaps more than any other decision facing the architect, the choice of the external envelope is subject to the widest range of practical, economic and visual

6 www.canadianarchitect.com
7 www.canadianarchitect.com
8 Anderson J Shiers D Sinclair M(2002) *Green Guide to specification* BRE UK

considerations[9]. The whole external appearance is being defined by the elaboration of the external envelope following the original vision of the architect. Choosing from a variety of materials, different textures and colours, alternations of voids and complete blind walls, the external appearance of the building obtains interest, it intrigues the eye of the people passing by, mirrors the internal functions and decisively influences the environment in which it is integrated.

Furthermore, the morphological elaboration of the external envelope depends on each country, on the mentality given and the techniques used since it reflects its culture and civilization. In addition, climatic conditions and the seismic nature of the ground play a fundamental role in the structure of the building and hence the external envelope. For example, in the case of countries in the Northern hemisphere, like the UK, where solar radiation is limited, the use of light weight structures with glazed external envelopes is recommended in order to take as much advantage as possible of the natural light. On the other hand, countries like Greece where due to the increased seismic activity, regulations exist to reinforce the structures of buildings and external envelopes, meanwhile due to the intensive solar radiation wide openings are being avoided in order to minimize overheating all year round.

1.4. Construction Materials

The choice of construction materials, which comprise the structure of the external envelope of the building, affects the environmental impact of a building since all building materials are processed before they can be incorporated into a building. It is estimated that in the case of industrial countries the percentage of energy associated directly or indirectly with the function and the construction of buildings, is about 50% of the total consumption. 'In the UK it is estimated that the production of building materials is responsible for about one tenth of energy consumption and CO_2 emissions'.[10] These facts constitute the price of the industrial development and of the advance of technology which have contributed to the ensuring of comfort and the

[9] Anderson J Shiers D Sinclair M(2002) *Green Guide to specification* BRE UK

[10] Roaf S Fuentes M Thomas S (2003) *Ecohouse 2 A design guide* — Architectural Press p12

improvement of the quality of life. As it is widely known, this development has influenced the creation of contemporary buildings. The industry has started to produce new construction materials in order to correspond to the need for improvement and suppleness. New products are being discovered contributing to the energy efficiency and durability of buildings aiming at the reduction of heating, cooling and maintaining requirements and resulting in the reduction of energy consumption and CO_2 emissions. Though, the advance of technology doesn't keep up always with the quality of new materials.

Architects are obliged to choose from a variety of materials having in mind the form-physical appearance, the durability and mainly the cost. In fact, when choosing materials several factors have to be weighed and well considered. Nowadays, the decision must be influenced by the ecological behaviour of the construction materials in order to avoid their harmful consequences to the environment. With careful thought at the outset of projects, building design can take a holistic and integrated approach incorporating technical, cost and environmental considerations into the design strategy[11].

1.5. General characteristics of materials

1.5.1. Embodied Energy

Perhaps the most important measure of an object's environmental impact is provided by the concept of embodied energy. 'We define embodied energy as the primary energy used in all different stages of materials processing, from the extraction of raw materials, through manufacture, processing and packaging, transportation at all different stages, installation, and finally demolition and disposal.'[12] The embodied energy is an important measure since it determines the amount of primary energy derived from fossil fuels-coal, oil, gas- and thus the amount of CO_2 released. 'The greater the number of processes a material or set of components have to go through, the higher will be their embodied energy and the number of associated waste products'[13].

[11] Anderson J Shiers D Sinclair M(2002) *Green Guide to specification* BRE UK
[12] Harris C Borer P (1998) *The Whole House Book -Ecological Building Design and Materials* – CAT p 94
[13] Roaf S Fuentes M Thomas S (2003) *Ecohouse 2 A design guide* — Architectural Press p. 48

The combustion of fossil fuels in order to achieve energy production releases a large amount of air pollutants, like CO_2 emissions and other greenhouse gases like CFCs, which are created during some manufacturing processes, and end up in the stratosphere destroying the ozone layer. Thus, embodied energy constitutes the evaluating indicator for the environmental behaviour of materials used (fig 1). As a "rule of thumb", the construction materials with low embodied energy are preferable than those with high embodied energy since the former require small amounts of energy during their life cycle compared to the latter, and in general are associated with lower pollutant emissions.

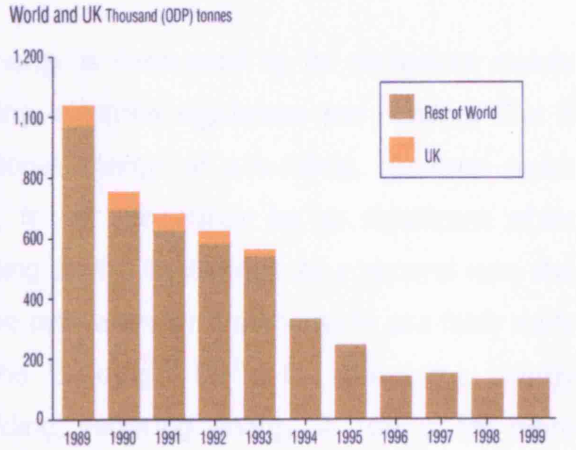


Fig 1: World and UK consumption of CFCs – DEFRA , National Statistics 2002 - Harris C Borer P (1998) *The Whole House Book – Ecological Building Design and Materials* – CAT, p 97

Embodied energy is influenced not only by the productive procedure of each country but through the whole life cycle of each material [see section 1.5.7]. A factor which influences critically the amount of embodied energy is the transportation of materials from their point of extraction to the point of their use (fig 2). For instance, even though wood is a renewable resource with a small amount of embodied energy, in the case of imported timber from the tropical forest of Amazon, it is obvious that large amount of energy is requires for its transportation to Europe.

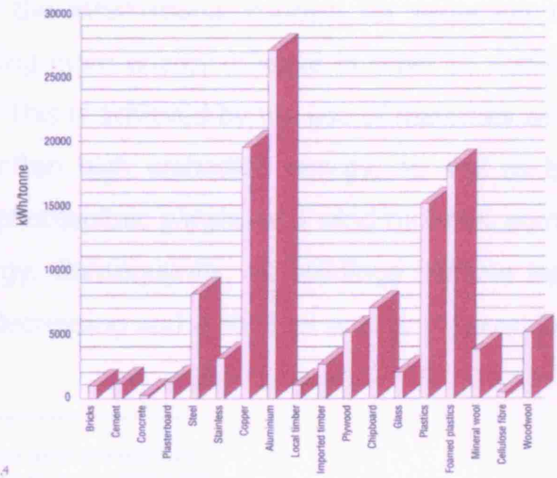


Fig 2: Embodied energy values of basic materials – Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 96

1.5.2. Operational Energy

Throughout the lifetime of a building, energy is consumed by its occupants mainly spent in space, water heating, space cooling, electrical appliances and lighting. This is known as the 'energy in use' or 'operational energy' of a building. However much embodied energy is saved in a building, it will very rarely be as significant when compared to the energy used by the building during its lifetime. As a general rule, the embodied energy of a given building will be overtaken by the energy in use fairly early (the first years of its operation) in the building's life[14]. In minimizing energy consumption over the lifetime of a building, reducing energy in use is far more effective than minimizing the embodied energy of its components.

Operational energy can establish how successful a building is in terms of environmentally 'considerate' design, since it is interlocked with the environmental design strategies followed. It is a significant measure of sustainability that enables straightforward comparisons between alternative building technologies. Though embodied energy of construction materials comprises an important indicator of their environmental impact, the construction industry shows more concern in reinforcing the energy efficiency of buildings. Following the international concern for reduction of energy consumption, buildings are becoming more energy efficient in order to restrict the operational energy in buildings (fig 3). This is achieved by the use of materials with a satisfying thermal behaviour but with often high embodied energy, as well as by using technology such as solar collectors, photovoltaic panels, and wind turbines, some of these also having high embodied energy. Consequently, as buildings become less energy demanding, operational energy is decreasing and embodied energy is becoming more significant.

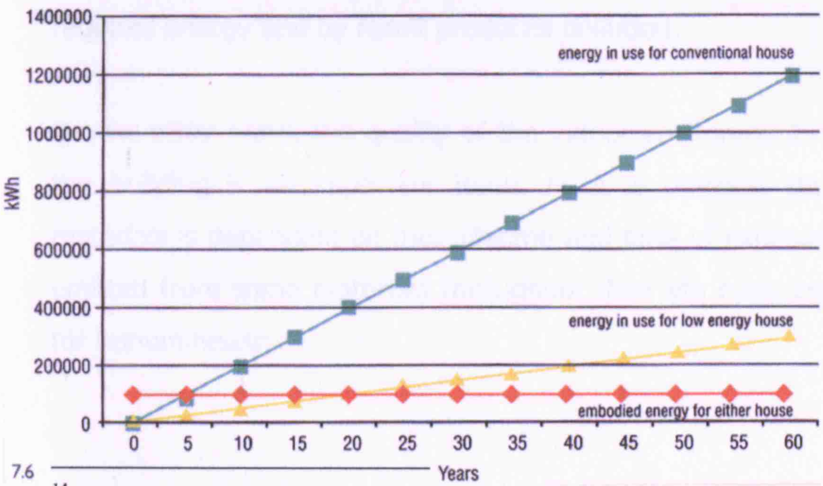


Fig 3: Energy Consumption- 'Sustainable Homes' Hastoe Housing Association - Harris C Borer P (1998) *The Whole House Book – Ecological Building Design and Materials* – CAT, p 96

14 Sustainable Homes: *Embodied Energy in Residential property development A Guide for Registered Social Landlords,* The house corporation Sustainable homes

1.5.3. Life Cycle

In an industry as complex as construction, a vast range of materials, products and techniques are used, many in a number of different applications during the erection of a building or structure[15]. There are numerous stages in the design and construction of buildings which have different impacts on the environment. Thus, in order to evaluate the environmental sequences of construction materials, it is fundamental to understand their Life Cycle. This Life Cycle includes the following stages (fig 4):

- extraction and pre-production
- industrial production/ manufacture
- construction
- in service use
- after use (Reuse/ Recycling/disposal)
- Biodegradation

For the majority of construction materials, the largest proportion of environmental consequences is located between the two first stages, meaning extraction and manufacture. Especially during the second stage, the required amount of energy and water is so high that it results in the creation of a considerably large amount of construction waste and air pollutants, in both local and global environment. At the same time the transportation of construction materials requires energy and by result produces pollution.

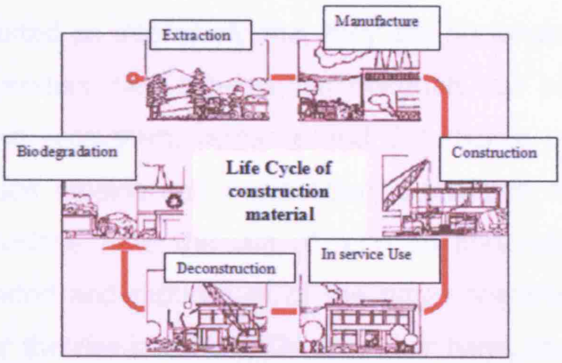


Fig 4: Life cycle of construction materials
Koronaios A Sargentis F (2005) *Construction materials and ecology*, NTUA Athens

On the other hand, the quality of the indoor environment during the in service use of the building is an important issue. As it is obvious, the environmental impact of materials is depending on their lifetime and time of exposure. Toxic substances can be emitted from some materials throughout their life cycle creating possible side effects for human health

[15] CIRIA (1995) *Environmental Impact of Materials Special publication 116*, Volume A-Summary , Construction Industry Research and Information Association, UK

1.5.4. Extraction of raw materials

Important parameters during the life cycle of construction materials are the raw materials. Although the initial sourcing of materials is often a large distance from the installation site, the location and method of extraction can influence the actual environmental impact. The feedstock for a manufacturing process may consist of virgin material, byproducts from construction industries or recycled materials salvaged from construction. Most materials from every category, regardless of the different type, generally require large amounts of energy in order to be extracted and be used as raw materials.

The environmental impact associated with extraction relate to the excavation, via surface quarrying or mining of naturally occurring, non renewable resources which form the basic feedstock for many manufacturing processes. Although many of the resources may be in plentiful supply at present, they are nevertheless finite and non-renewable. Some minerals are being exploited so intensively that they are no longer abundant. Their exploitation in order to produce new construction materials can be responsible for the decay of landscape and ecosystem: nuisance and disturbance to the residents, ecological impact through soil erosion and degradation, demolition of natural habitats and landscapes. On a positive note the use of recycled materials reduces the amount of raw materials needed and reduces all of the other negative consequences associated with extraction of the raw materials. On the other hand, the procedure of production of materials contributes to the waste of a large proportion of wastes.

1.5.5. Production stage

During the production stage, complicated processes and equipment are being employed which are characterized by energy consumption, amount of waste produced, particular feedstock required, by products and pollutants[16]. Furthermore, the degree of handling and processing required on a construction site will vary from material to material. Often, prefabricated units will be delivered to site for assembly and installation. In other cases raw materials may be delivered in bulk for batch mixing on

[16] CIRIA (1995) *Environmental Impact of Materials Special publication 116*, Volume A-Summary , Construction Industry Research and Information Association, UK

site. Nevertheless, the act of structuring the building requires large amounts of energy and produces inevitably CO_2 emissions.

1.5.6. Construction waste – Recycling – Reuse - Disposal

When the cycle of a building's life has been completed, a large amount of construction waste needs to be disposed. Waste disposal leads to environmental degradation and possible human health hazards. Finding a sustainable solution to this problem is becoming an urgent need for the society. 'Construction waste is produced in large quantities – 70 million tonnes annually, or 1.25 tones per person per year. This equates to 24% of all UK waste – more than double the figure for all domestic wastes (fig 5). Of this, 12-15 million tonnes is recycled, but mainly 'downcycled', to low-grade users such as hardcore and landscaping fill.'[17]

Fig 5: Construction Wastes - Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* –CAT, p 99

In cases where non-renewable materials are used, those that have been or can be reused or recycled should be favoured. Straightforward reuse is the best potential option without any extra stage of reprocessing involved in recycling. Timber and tiles, bricks and blocks in a low-cement mortar are usually suitable for reuse and often present better qualities than buying new ones. One exemplar with reused and recycled construction wastes is the British Research Establishment in the UK (fig 6). In this case study an existing building was demolished and a replacement was rebuilt. 'The recycling of the construction materials reached 96%. The applied concrete was a

Fig 6: BRE Building -UK

[17] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT p 99

compound of 100% recycled inactive cement. Also, there were used materials like used bricks and flooring which were recovered from the demolition of other buildings'[18].

The act of recycling is prosperous mainly in the case of materials which have the ability to be recycled, have high embodied energy of production and require little energy during recycling process. Usually materials which originate from natural resource and have only been altered slightly are biodegradable and easily recycled. In the case of those where man has altered them significantly for example using chemical processing, recycling is a tough procedure with a high energy demand and by result it is less profitable to recycle them rather than produce new ones. Though, in the case of non recycled materials, the reuse of construction materials is more preferable than their demolition, with the condition that they retain their initial qualities. In fact the reuse of construction materials can recover up to 95% of the embodied energy of materials which would otherwise be lost through the waste disposal. That is the purpose of the existence of directories on the internet about the offer and the demand of construction materials recovered from the demolitions of buildings, which can be recycled and reused. Consequently, during the design of a building it is necessary to apply measures allowing easy disassembly rather than demolition at the end of its life.

Once these options for minimizing present and future waste creation have been exhausted, then incineration in a high temperature boiler, complying with the latest regulations on emissions control, and preferably with some means of recovering heat from the flue gases, should be considered. However, waste is rarely destroyed completely – just transferred elsewhere[19]. Environmentally speaking, the least preferred option for waste disposal but still the one most commonly used, is landfill. Unsorted waste is simply dumped in the ground and left for future generations to deal with. According to the Environmental Agency, more than half of the 2264 landfill sites in England and Wales are breaching their licenses: 14% are 'nowhere near compliance' and pose a serious risk to health'.[20]

Seldom, materials and products are been used in the construction process without the aid of mechanised transport. Transport and transportation create environmental

[18] The conclusions from the construction of the building are including in the guide: "Demonstration of reuse and recycling- BRE Environmental building, IP 3/97. BRE 1997 "
[19] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 100
[20] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 100

pollution by consuming fuels, creating noise and fumes adding to the energy and financial cost of the product.

1.5.7. Life Cycle Assessment

Life Cycle Assessment (LCA) is the most commonly used tool for evaluating the environmental impacts of construction elements and structures the basis for most environmental schemes. 'Life Cycle Assessment is a process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution; reuse, maintenance; recycling, and final disposal'.[21]

In general, it constitutes an internationally accepted method in order to evaluate the environmental behaviour of buildings and their materials, meaning the direct and indirect environmental burdens associated with a product, process or activity. In addition, it examines a full range of impacts over all phases of a building's useful life time quantifying energy, material usage and environmental releases at each stage of a product's life cycle. Life cycle assessment is a useful comparative tool of the environmental aspects of specific products as it enables the ecological comparison of two or more products made of different raw materials but used for the same purposes.

'Life Cycle Assessment is a technique for assessing the environmental aspects and potential aspects associated with a product or service by : compiling an inventory of relevant inputs and outputs, evaluating the potential environmental impacts associated with those inputs and outputs, interpreting the results of the inventory and impact phases in relation to the objectives of the study'.[22]

One drawback of the LCA method is the tendency to focus on individual elements of construction, rather than on the interaction between them. Furthermore, the difficulties

[21] Guidelines for Life Cycle Assessment :A code of practice, Society for Environmental Toxicology and Chemistry, SETAC, Brussels 1993

[22] BS EN ISO 14040:1997 *Environmental Management– Lifecycle Assessment – Principles and Framework*

associated with the representation of environmental impacts as well as the inevitable subjective value judgment impose some further question on the reliability of these assessments.

In order to make society more sustainable, industry decision–makers must confront the social, economic and environmental implications of sustainable construction. Two current methods of applying weighting factors to these very different issues were produced by BRE:

- The BRE Environmental Assessment Method (BREEAM) weightings are used to evaluate building management actions against best environmental practices, using weighting with environmental impact data to derive UK Ecopoints which measure total environmental impact[23].

  'BREEAM provides independent and practical guidance on minimizing the damaging effects of buildings on global and local environments. It also promotes a healthy, comfortable and productive indoor environment. It recognizes buildings with lower overall environmental impact using a scale of ratings given by licensed assessors using the BRE methodology'.[24]

  'A UK Ecopoint is a single unit measurement of environmental impact. A UK Ecopoint score is a measure of the total environmental impact of a particular product or process expressed in units (ecopoints). It is calculated in relation to impacts on the environment in the UK and therefore applies to UK activities only.'[25] The UK Ecopoint score is covering the following environmental impacts: climate change, fossil fuel depletion, ozone depletion, freight transport, human toxicity to air, human toxicity to water, waste disposal, water extraction, acid deposition, ecotoxicity, eutrophication, summer smog and mineral extraction.

- In addition, BRE has developed the BRE Environmental Profiles in order to set a methodology for construction materials which allow comparisons of materials, elements or buildings that perform the same function. Furthermore, CIRIA[26] has provided a study in order to offer guidance on assessing materials in terms of their environmental

[23] Dickie I Howard N (2000) Digest 446 Assessing environmental impacts of construction Industry consensus, BREEAM and UK Ecopoints , BRE Centre for Sustainable Construction
[24] Dickie I Howard N (2000) Digest 446 Assessing environmental impacts of construction Industry consensus, BREEAM and UK Ecopoints , BRE Centre for Sustainable Construction
[25] Dickie I Howard N (2000) Digest 446 Assessing environmental impacts of construction Industry consensus, BREEAM and UK Ecopoints , BRE Centre for Sustainable Construction
[26] CIRIA (1995) *Environmental Impact of Materials Special publication 116*, Volume A-Summary , Construction Industry Research and Information Association, UK

impact according to their categories: minerals, metals, plastics, timber, paints, coatings and adhesives. The Green Building Handbook as well as the Green Guide to Specification produced by BRE and written by Anderson J, Shiers D and Sinclair M present accurate environmental assessment data in terms of embodied energy, emissions, toxicity, wastes, resource use and recycling properties, rating each construction element on a scale from A to C. The Centre of Sustainable Construction at BRE[27] is currently utilizing the environmental weightings and Ecopoints within its Life Cycle Assessment tools and consultancy including BREEAM, Green Guide specification and the software tool Envest.
Finally, each country in order to provide information concerning the environmental impact and energy use of construction industry is using life cycle assessment tools such as ATHENA (Canada), BEES (Unites States), Envest (UK) and LISA (Australia).

1.6. Aims and Methodology

1.6.1. Aims of the study

The aim of this study is to:

- Develop an understanding of the critical issues of sustainability and environmental design, reinforcing the concept of sustainability and energy efficiency at the level of environmental design but mainly in the design of the building envelope and taking advantage of the general characteristics of construction materials associated with environmental impacts.
- Develop a categorization of basic construction materials according to their external aesthetic properties
- Develop an evaluation about the environmental consequences of a variety of construction materials in terms of their embodied energy, recyclability, disposal and initial cost.
- The final aim is the use of this guide as comparative handbook for choosing different materials as external wall cladding for buildings allowing architects to make an informed choice for lower overall environmental impacts for their buildings.

[27] http://www.bre.co.uk/service.jsp?id=53 25/06/06

1.6.2. Methodology of the study

After the holistic understanding of current sustainable development philosophy and review of existing literature and sustainability assessment tools, the nursery school Granville Plus, a building designed by Anne Thorne Architects Partnership where fundamental wall cladding materials have been applied, is being examined. Later, basic materials used as external cladding of building envelope are categorized based on aesthetic criteria of textures from the architect's point of view in: shining, smooth, assembled with grid, striped and roughcast. Furthermore, after extensive research, the basic characteristics for every material are developed according to aesthetic, economical and environmental criteria. Consequently, issues such as embodied energy, energy required to install, use and maintain a certain material cladding over its lifetime, initial cost as well as maintenance cost are individually presented for each material. In the process, comparative tables are developed showing values of individual environmental and financial performance, setting comparative indicators ready to be weighted and be compared and leading towards the development of the selection guide fully informed.

For the purpose of this study, cumulative life cycle energy use 'per m2' over the assumed 50 years lifetime of the building structure is used. In addition, in the case of some materials having a lifetime is shorter than this a replacement factor has been estimated indicating the number of the replacements necessary over the 50 years lifetime.

Analysis of the results and discussion of the cumulative life cycle energy requirements, environmental impact and economic burden of each different material is been made. Finally, conclusions emerge from the relative weighting of each material allowing the comparison of the environmental behaviour for each material.

2. Case Study

2.1 Granville Plus

In the area of Kilburn Park, a community centre has been refurbished along sustainable principles by Anne Thorne Architect Partnership. Incorporated to this centre, a new building has been developed and now accommodates a nursery school (fig 7). This new building constitutes the imaginable expanding of the old building as a sign of innovation and modernism within an old existing shell. This new establishment is been used during the morning hours as a nursery school, while the old one is used during the afternoon and evening hours as community centre occupying young people and children. Even though both of them have maintained their independency, internal connections make the intercommunication of both spaces and activities feasible.

Fig 7: Aspect of Granville Plus - Entrance

The new building is being characterized by bright and vivid colours in order to constitute a mean of entertainment and pleasant ambience to the young users whereas the old one maintains the firmness of the old structure. Wind turbines, photovoltaic panels and solar thermal panels generate electricity and provide a local source of information on renewable technologies.

Anne Thorne Partnership[28] has an ecological approach to design for community buildings and in general urban environments. Their main concern is the creation of healthy and environmentally sound solutions to building design and materials specifications in order to contribute to a sustainable and environmentally ambience. That is why they have incorporated into their projects low embodied energy materials and construction techniques. Applying organic finishes, non chemical timber treatment, low electromagnetic radiation, ecological paints and making use of native timber

[28] http://www.annethornearchitects.co.uk/content.html 15/05/06

species or FCS certified timber sources they prove actually their environmental concerns[29].

The building has been developed in two stories. The ground floor consists of administrational offices and classrooms for children 2-3 years old and 0-2 years old as well as auxiliary spaces like reception area, conservatory play area and WC (fig 8). The main intention of the building design is the immediate connection with the external environment and that is why folding glass screens, and timber framed doors permit the unification of external and internal space. The first floor mainly accommodates functions of the teaching staff like meeting rooms, offices and staff rooms[30].

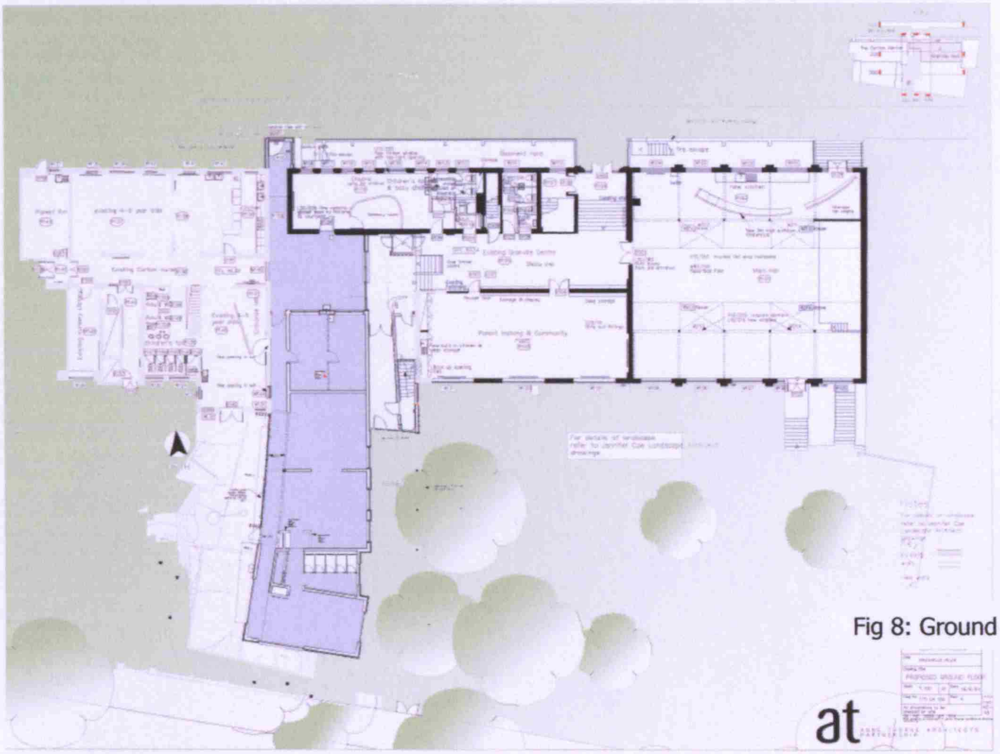


Fig 8: Ground Floor plan

2.2 Typical section of the building – Structural Details

The set out of the external views of the building images the architects concern about environmental friendliness and the achievement of aesthetic interest. Four fundamental construction materials are being used as external cladding of the building: timber, aluminium, clay (ceramic tiles) and glass [see section 1.2.3]. Each internal area, depending on the different use, is been vested externally by different cladding in order to enhance the different use as well as contributing to the creation of an intriguing

[29] http://www.annethornearchitects.co.uk/content.html 15/05/06
[30] Appendix 1

visible result. After all, wall external cladding should be considered an integral part of the overall building design as it contributes to aesthetic, comfort and structural performance.

Nevertheless the variety of materials used as external cladding depending on the need and the use of each interior space, the whole construction of the nursery school Granville Plus is been ruled by standardization of the structural materials used. The structural skeleton is timber framed assembled by vertical (63x38mm) and horizontal battens (25x38mm) which are connected with metallic nails. Thus, they constitute the frame of the building over which the cladding and filling materials are structured (floors, walls, roof)[31].

For the protection of the building against external weather conditions and the maintenance of a viable and pleasant interior environment, insulation of 200mm width has been used with the form of Warmcell (fig 9). Warmcell is made from 100% recycled newsprint and constitutes the environmentally friendly response of UK insulation industry. Loosefill cellulose fibre is thermally superior and highly durable. It is manufactured in the UK reducing the embodied energy attributed to transport. In advanced, the fact that it derives from recycled raw material constitutes Warmcell a sustainable and environmental friendly material. 'Just insulating an average of 45m2 with warmcell saves 685 kg CO2 emissions. In addition, it has no VOCs, no CFC's, and no formaldehyde and does not constitute a waste hazard when disposed of finally'[32].

Warmcell has a thermal conductivity of 0.035 Wm/k which is 12,5% better than traditional insulation materials whose typical k is only 0.040 Wm/k. During the manufacturing process simple non reacting compounds are been used to provide protection against insects, biological and fungal attack and to make it unattractive to vermin whilst it remains harmless to other common building components such as PVC cables and nailing

Fig 9: Warmcell - http://naturalbuildingproductscouk.ntitemp.com/pdfs/warmcel100_insert.pdf#search=%22warmcell%22 Warmcell 100 Natural Building

[31] Appendix 1

[32] http://naturalbuildingproductscouk.ntitemp.com/pdfs/warmcel100_insert.pdf#search=%22warmcell%22 Warmcell 100 Natural Building Technologies 24/07/06

plates. It appears outstanding protection against fire, is non toxic and can be handled without any specialist protective clothing[33].

For the further protection of the building against heat losses and moisture penetration, an extra layer of Bitvent has been used over the layer of Warmcell with a width of 150mm acting like a barrier between exterior and interior. 'Bitvent is made of softwood fibre, taken as waste chips saw dust and off cuts from saw miles located close to the production plant. Basically, the production process converts these waste materials with only the addition of natural bitumen, waste newsprint and water into a board material'[34].

Bitvent (fig 10) has been designed for use as sheathing for timber and steel frame constructions, where it provides a good racking strength and further thermal insulation. It presents excellent thermal conductivity value of 0.05 Wm/k compared to other timber sheathing boards. With the use of Bitvent in accordance with Warmcell as insulation material, a typical timber construction may achieve the requirements of English Building regulations which impose U values of 0.35 Wm/k[35]. Furthermore, the low conductivity reduces the risk through the studs of any cold bridging. The boards are resistant enough to prevent moisture from outside getting in without the need of a breathing membrane[36].

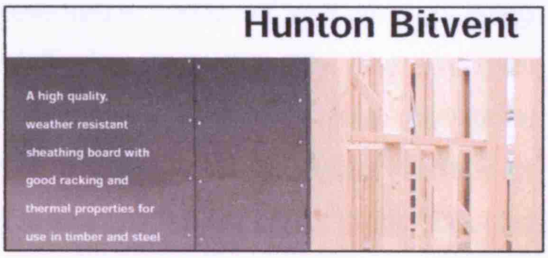


Fig. 10 : Bitvent - http://www.greenspec.co.uk/pdf/bitvent.pdf#search=%22bitvent%22Technologies 24/07/06

For the structure of roof and floors, as reinforcing material for the better rigidness and the stability of the construction, Oriented Strand Boards (OSB) sheathing boards are been used with width of 19mm. Oriented stand boards sheathing (fig 11) is

Fig. 11 : OSB - http://www.osbguide.com Technologies 24/07/06

[33]http://naturalbuildingproductscouk.ntitemp.com/pdfs/warmcel100_insert.pdf#search=%22warmcell%22 Warmcell 100 Natural Building Technologies 24/07/06

[34]http://www.greenspec.co.uk/pdf/bitvent.pdf#search=%22bitvent%22 24/07/06

[35]Regulatory Impact Assessment Part L and Approved Document F, March 2006 Office of the Deputy Prime Minister: London

[36] http://www.greenspec.co.uk/pdf/bitvent.pdf#search=%22bitvent%22 24/07/06

an innovative, affordable and environmentally smart wood based structural panel. It presents the same performance standards as plywood yet is more cost effective. 'It has excellent tolerance and is much less susceptible to the stress related problems of plywood, such as warping and ply separation. Made from wood chips and resins it has exceptional dimensional stability and consistent quality because it is not dependant on the character of an individual log. It is easy to install with pre-marked nailing lines'[37]. Finally it is considered to be environmentally smart because it is manufactured from a wide range of fast growing and relatively smart trees. Besides the production process uses a maximum amount of wood fibres from each tree harvested, making better use of forest resources[38].

Concluding, according to all the above, a representative section of wall which is being met all along the structure, is shown at the following figure (fig 12). The structural skeleton is constituted of vertical timber battens (63x38mm) and horizontal (25x38mm) which are creating a stable structural frame. On the outer surface of vertical batten each external cladding is being structured, either this is timber Douglas fir, or ceramic tiles or aluminium panels. On the inner side of horizontal battens, a layer of bitvent (15mm) is playing the role of protecting barrier against moisture between external and internal environment protecting simultaneously the layer of Warmcell (200mm) which is following in order to provide insulation to the building. Finally, an internal cladding made of OSB (12.5mm) constitutes the base which structures plaster (12.5mm) which is the final finish of the internal spaces all along the building.

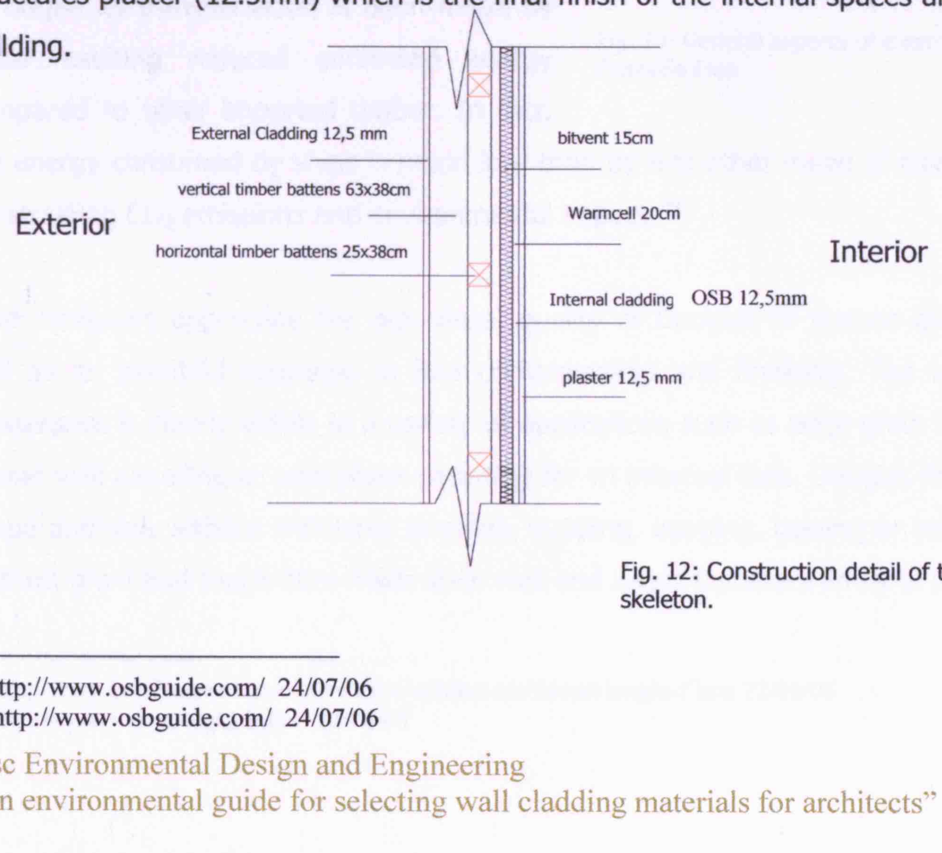


Fig. 12: Construction detail of the timber frame skeleton.

37 http://www.osbguide.com/ 24/07/06
38 http://www.osbguide.com/ 24/07/06

2.3 External Cladding – Materials Used

Following the intentions of Anne Thorne Architects the final external desirable result was the creation of shining external finishes, with intensive cubism elements as a sign of innovation. The formation of different volumes, the use of different materials textures and colours as well as the different external finishes contribute to the creation of an interesting external view proportional to the pleasant internal use. As it is already mentioned four fundamental construction materials are being used as external wall cladding: timber, aluminium, clay (tiles) and glass. The different matching of the views intrigues the eye of the young children playing inside altering their mood and making them feeling more creative and happy.

2.3.1 Timber – Douglas fir

The timber used as external cladding in the case of Granville Plus is Douglas fir type, a species of softwood timber regularly imported from the west coast of North America (fig 13). It has a high reputation as structural timber with a very good service life when suitable installation and maintenance practices are followed. Due to its origin, its transportation is been made by ships resulting reduced embodied energy compared to other imported timber. In fact, the energy consumed by ships is much less than by any other mean of transportation constraining CO_2 emissions and environmental impacts[39].

Fig. 13: General aspects of external cladding in Granville Plus

Most designers appreciate the rich visual quality of Douglas fir texture and grain as well as its beautiful response to fine craftsmanship and finishing. The wood's fine appearance is clearly visible in a variety of applications such as edge-grain veneers for format wall panelling or solid plank panelling for an informal look. Douglas fir retains its shape and size without shrinking, swelling, cupping, warping, bowing or twisting. The uniform grain and tough fibre holds stain well and keeps fasteners firmly in place[40].

[39] http://www.bcadventure.com/adventure/wilderness/forest/douglasf.htm 22/06/06
[40] http://www.wwpa.org/dfir.htm 22/06/06

Douglas fir's light rosy colour is set off by its remarkably straight and handsome grain pattern. It will 'redden' over time when exposed to light but with appropriate paints and external coatings can hold all types of stains and finishes maintaining its initial appearance. It is characterized by exceptional strength, hardness and durability and it is the only redwood type material still available in substantial volumes of clear wood fibre[41]. 'The hardness, texture and attractive coloration of Douglas fir rival those of many hardwoods commonly used in the construction industry'[42].

Fig. 14: Use of Douglas fir as external wall covering

Timber clad walls which will experience moderate to severe weather exposure must make use of cladding manufactured from the highest available grade of timber. All timber will take up or lose moisture in response to changes in environmental conditions and will undergo corresponding dimensional changes. Timber cladding boards are generally produced in widths between 150mm and 200mm. At this point it should be considered that timber cladding should be kept dry and clean from the time it is received on the building site until it is fixed and finished. Furthermore, timber cladding can be left in a natural condition or finished with a preservative, clear, stain or opaque finish. In the specific case of Granville Plus the timber finishes remains neutral with the application of preservative ecological paints which ensure the creation of a healthy ambience. In addition, the selection of the correct fixing nails is important to the performance of a finished wall. Joist between external cladding boards must be carefully designed to avoid ingress of water. In general, timber cladding needs treatment prior to finishing[43].

In general, the use of timber as external cladding of the building, beyond the environmental benefits since it consists environmental friendly material, provides with a warm and friendly external finish with low maintenance requirements. The horizontal

[41] http://www.weyerhaeuser.com/coastalwood/wydouglas/default.asp 22/06/06
[42] http://www.bcadventure.com/adventure/wilderness/forest/douglasf.htm 22/06/06
[43] http://www.oak.arch.utas.edu.au/tbia/article_srch_topic.asp?area=tech&topic=10 04/07/06

assembly of wooden boards disturbs the monotony of the grid created by the ceramic tiles, contributing to a more enjoyable exterior environment.

2.3.2 Ceramic Tiles

Other basic materials used as external cladding are clay products, more specifically ceramic tiles in two different colorations, green-yellow and purple (fig 15). They are made from clay, a natural but finite resource, they are durable and require low maintenance. They are locally manufactured, easy to clean, they produce low or no VOC emissions and they present high resistance to stains and burning. Unfortunately, as a drawback it should considered the fact that they come from a non renewable source and they present high embodied energy due to high temperatures required to fire the tiles. Traditionally, ceramic products have been created using raw materials that require high firing temperatures and energy intensive procedure. The manufacture of clay-based tiles requires firing temperatures of approximately 2200^0 F. Ceramic products can also be produced using glass-melting methods which require temperatures of 2700^0 F or more. In advanced, because of their heavy weight they present high embodied energy for transport. From an environmental point of view, clay mining results negatively on land and water quality.

Fig. 15: General aspects of external cladding in Granville Plus

Following the established tradition of thousand of years, ceramic tiles have been used as flooring material as well as wall panelling in Granville Plus. In the market there are also available some recycled-content tile which are made from light bulbs, ground glass and auto windshields[44]. Recycled content ceramic tiles can contain up to 70% recycled glass, are very durable and often more moisture and stain resistant than traditional tiles. These materials have a relatively low environmental impact since the glass used in this product contains recycled content.

[44]http://www.eere.energy.gov/inventions/pdfs/haun.pdf#search=%22ENERGY%20SAVING%20METHOD%20OF%20MANUFACTURING%22 23/06/06

Although energy requirements for producing ceramic tiles are high, they are durable and are produced in many locations from abundant natural clays. However, choosing a tile locally sourced contributes to the reduction of energy used in transporting this heavy material. Tiles come either glazed (sealed with a smooth finish; highly moisture and stain resistant) or unglazed (somewhat coarser and more porous). Glazed tiles are inert since they are baked onto the tiles at high temperatures but as usual, adhesives should be chosen with care. Ceramic tiles require some specialized tools and knowledge to cut and install; however, they can be laid with simple Portland cement based grout which does not emit vapours and requires very little maintenance as in the case of Granville Plus[45].

Ceramic tiles are available in a wide variety of colours, sizes and textures to choose from. The use of low VOC, water based grout sealant will increase resistance to moisture and staining. Ceramic tiles offer a very hard, scratch and resistant surface.

In general, the external cladding of Granville Plus with ceramic tiles results in the creation of a grid on the building's surface which is repeated and constitutes a discrete assembly which offers harmony and metric tone on the views, and which is interrupted by the use of different materials in order to avoid monotony. The external texture is waxen resulting low maintenance requirements and offering a glossy surface to reject the rain water, and the vivid colours used create a pleasant and friendly environment to the children (fig 16).

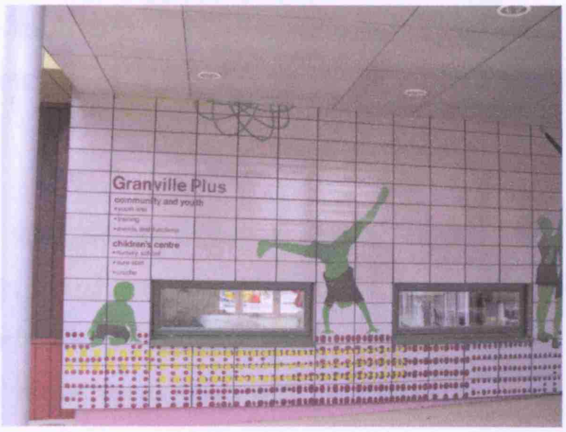


Fig. 16: Use of ceramic tiles

2.3.3 Aluminium Panels

Taking advantage of its physical properties, the architects have chosen aluminium panels for the external cladding part of the building, in order to create an efficient, qualitative, resistant and functional construction (fig 17). Aluminium's strength, weight and versatility make it an ideal building and cladding material. Its shiny and waxen

45 http://greenhomeguide.com/idex.php/knowho w/entry/802/C220 23/06/06

texture appoints it as an interesting and attractive material which has the ability of reflecting the natural light and enlightening the surrounding space, an important element especially in the case of UK where the days with sunshine are limited. Its resistance to corrosion means it is virtually maintenance free, it does not crack and does not absorb moisture.

Aluminium building products, which are used in the construction industry as wall panelling, window frames, weatherproofing layers etc can help keep the interior of buildings cool in summer, warm during winter and snug and dry all the year round. Aluminium cladding sheet is also available with insulation and reflective foil backing, so walls can be weatherproof and energy efficient, as in the case of Granville Plus. In fact, a layer of insulated aluminium sheet is four times more effective than un-insulated wood siding, four inches of brick or ten inches of stone masonry[46].

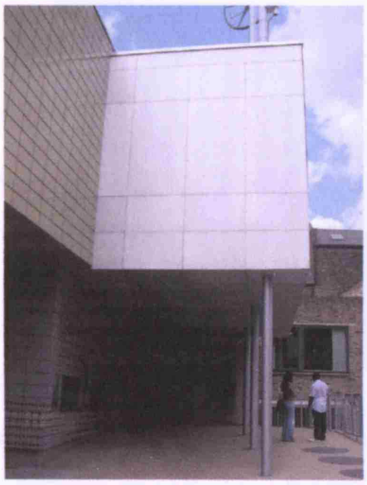


Fig. 17: General aspects of the entrance

Aluminium is easy to form and join and its light weight makes it easy to handle and transport. Furthermore, metallic aluminium in massive form will not burn. Its relatively low melting point (660^0 C) means it will 'vent' early during a severe fire, releasing heat and thereby saving lives and property[47]. It remains unchangeable during all seasons with a long life time (100 years) offering an excellent external appearance.

However, aluminium presents a considerably high embodied energy, around 180-240 MJ/kg, because of the high electricity consumption for the bauxite's extraction. The industry of aluminium mentions that it absorbs 1,4 % of the world energy consumption. In fact, aluminium and its alloys with other metals constitute natural sourced materials since they come from earth's rock. Unfortunately, the process and the production of aluminium have as a result a significant amount of waste which contains heavy metal and toxic substances. In fact, industries in the UK have suffered serious condemnation about the high level of toxic heavy metals releases in the saps[48].

46 www.world-aluminium.org/applications/construction/index.html 04/07/06
47 www.world-aluminium.org/applications/construction/index.html 04/07/06
48 www.world-aluminium.org/applications/construction/index.html 04/07/06

Construction and demolition waste products represent a growing challenge for modern industrial societies. The deposition or incineration of most types of materials can lead to air, water and soil pollution.

Aluminium is easily recycled with no loss of quality and the high cost of its production ensures its unchangeable appearance. It has the ability to be recycled 100% several times ensuring the safety of the environment and public health. Furthermore, because of their metallic nature, aluminium and its alloys have- contrary to solid organic materials or refractories – the ability to maintain their inherent metallic properties during recycling[49].

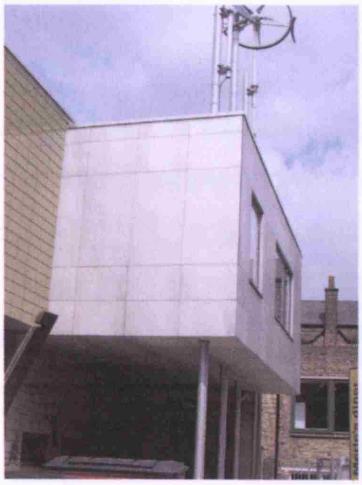


Fig. 18: Use of aluminium sheets as wall cladding

Using recycled material as crude, large amount of energy, around 80-95% can be saved compared with the production of new from bauxite, but it takes time. In the mean time, a large proportion of limited raw material is been saved since bauxite is threatened with disappearance[50].

2.3.4 Double glazed surfaces

In order to achieve an immediate contact with the exterior ambience, and a greater exploitation of the natural light, wide openings with either timber or aluminium frames and double glazed surfaces illustrate the view of Granville Plus (fig 19). These openings allow the entrance of the natural light contributing simultaneously to the reduction of energy consumption required for both artificial light and space heating. Besides, the creation of openings in the envelope of a building creates a more viable and pleasant environment, helping children and users to feel more productive and pleased by interior conditions.

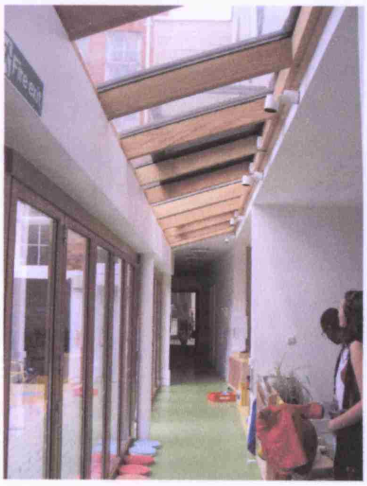


Fig. 19: Internal aspect – use of double glazing surfaces

[49] European aluminium association Environment, Health and Safety – September 2005
[50] www.world-aluminium.org/applications/construction/index.html 04/07/06

In advanced, the use of double glazed windows with reduced U values restrains heat losses and protects the building from the external weather conditions maintaining a pleasant temperature environment. Even though double glazed windows present high embodied energy, their contribution to the thermal behaviour of the building is determinant to the reduction of energy consumption of the building.

Glass is in general used in the openings, but lately has also been used as wall cladding material. It is produced from silica, material which is abundant in the nature and which is not toxic. The only environmental impact associated with glass is the large amounts of energy required during the process of production. Finally, all types of glass constitute recyclable materials, even though recycled glass is considered to be 'second hand' material.

3. Cladding product selection for architects

3.1 Choosing cladding material based on aesthetic, economical and environmental criteria

The process of choosing external wall cladding on a building requires a lot of consideration and reflection, since it constitutes the public face of the building towards the surrounding environment. Its external texture determines the external skin of the building and characterises the ambience. The architect acting as creator of the construction is obliged to weigh all the factors in order to decide about the final appearance of the building. Besides, the variety of different materials, different colorations and textures which are available on the market, complicate the act of choosing and impose as a compulsory necessity the institution of certain objective criteria in order to take decisions.

The primary care of the architect is to settle his aesthetic preferences. Having as yardstick his personal taste, he is obliged to choose the external finishes that he likes. In general, materials could be separated suggestively according to their external appearance and textures, in the following categories:

- Shiny: shiny surfaces made of metallic sheets of aluminium, copper, steel, stainless steel, zinc
- Smooth: smooth surfaces made of glass, polycarbonate
- Assembled surfaces with grid: clay products ceramic tiles and ceramic bricks
- Striped: striped surfaces created by the assembly of wooden boards, Douglas fir, hardwood (kiln dried rough sawn), softwood (kiln dried rough sawn), plywood, fibreboards, chipboards.
- Roughcast: roughcast surfaces created by the assembly of earth sourced materials. Natural stone, fibre cement boards, concrete tiles, aerated concrete panel, and earth raw rammed soil cement.

Simultaneously with the aesthetic criteria, a very important role in the choice of external cladding should be cost evaluation of each material chosen. Cost constitutes a determinant factor in every investment in the construction industry. It isn't sufficient for the material chosen to be physically attractive and in accordance with the aesthetic criteria of the architect, but it should be weighed also from an economical point of view.

In general the total cost of an investment determines if the construction is profitable or not and if the erection of a building is feasible. In fact lifecycle costing techniques are necessary to prioritise interventions and possible choices and to identify the most cost effective solution. In addition, the calculation of the simple payback of the investment in accordance with the total cost provides a cost-benefit framework for assessing potential social and economic benefits of measures considered. In order to evaluate an investment with economical criteria factors like initial cost, lifetime, number of replacements when required, as well as cost of maintenance, should be considered. Costing is an important parameter because it offers a quantitative value which is easy to calculate and which can be used as yardstick for comparing different materials and technologies[51].

In order to be more accurate in our evaluations it is important to include in our estimations a replacement factor which depends on the lifetime of the building (which is assumed to be 50 years) and the lifespan of the material examined, considering also a safety factor[52]. Thus, Replacement Factor = $\frac{\text{Lifetime of the building}}{\text{Lifetime of the material}} + 0,5$

On the other hand, considering all the environmental issues associated with the energy crisis and the aggravation of planet health, the third and most determinant factor in the choice of construction materials should be their environmental impacts. Inevitably every attempt in the construction industry to satisfy the increased demands of contemporary society is participating in the decay of the environment, as a result of the competitive relation between technology and environment. Innovative products created with the use of advanced technological means provide energy efficiency and contribute to the maintenance of a viable and pleasant internal environment, but without always keeping up with satisfying environmental behaviours. That is why all factors should be weighted in a life cycle basis in order to evaluate the contribution of each material to the environment.

More precisely, since all building materials are processed before being incorporated into the building, as well as having in mind their maintenance requirements, the choice of construction element and specially wall cladding materials affects the environment

[51] Boyle G (1996) *Renewable energy: power for a sustainable future*, Oxford University Press Oxford
[52] Anderson J Shiers D Sinclair M(2002) *Green Guide to specification* BRE UK

to a wide extend. Parameters like embodied energy, recyclability, reuse, lifecycle assessments, disposal and wastes, toxicity and emissions releases during in service use resulting possible side effects on human health, are some of the factors which determine the environmental behaviour of materials used. Besides, a simple examination of the embodied energy considering total lifetime and maintenance requirements as well as their effectiveness in the reduction of the building's operational energy, could constitute a comparative indicator between the different materials evaluating their environmental behaviour and finally choosing the one which seems to be the less harmless. An assessment of the environmental consequences could be a yardstick to protect the environment, local and global, as well as the health of habitants and users of buildings.

The aim of this study, as it is already mentioned in the previous chapter [see section 1.6], is the categorization of important wall cladding materials based on their external physical properties, as it can be set by an architect. Since Granville Plus was the reason for the editing of this 'architectural guide', it is assumed that the structural skeleton of the building combined with each cladding material is the same as Granville Plus complied with the UK building regulations[53] and the only thing that is differentiated each time is the external wall cladding. Furthermore, for each construction material an attempt has been made to assess its environmental behaviour indicating the environmental impact arising from each stage of its lifetime. Therefore, research has been carried out in order to present the lifetime, the embodied energy (cradle to gate stage), the energy required during the installation-assembly stage, the energy required for use-maintenance, the potential recyclability or energy required for disposal, the energy required for transportation and the replacement frequency, for every material categorized based on aesthetic criteria.

In this point it should be noticed that several assumptions have been made in order to assemble tables and enhance comparative values between different materials. Hence, embodied energy values, from cradle to gate, have been collected after thorough research on the internet and international bibliography. A table of referenced embodied energies of representative materials deriving from different sources is presented on the appendix 2

[53] Regulatory Impact Assessment Part L and Approved Document F, March 2006 Office of the Deputy Prime Minister: London

According to a research report carried out by Environmental Modelling Laboratory in the Polytechnic University of Catalonia[54] , it is assumed that for the assembly of every type of wall cladding material an energy consumption of 0,22 kWh/kg or $1,12x10^{-3}$ GJ/m^2 is required. Energy consumption and techniques for installation are considered to be similar for all types of wall cladding[55]. In addition, since the embodied energy includes the energy consumption throughout the whole production process from cradle to gate - which is characterized by great energy cost- it is assumed that the energy needed for use or maintenance of all types of wall cladding materials is negligible compared to the values all around their lifecycle[56]. Furthermore, the activity of deconstruction which consists of dismantling the external wall cladding with the aim of making maximum use of the materials by recycling may not require labor and perhaps needs minor energy consumption[57]. For this reason it is assumed that the energy consumption in this stage is negligible.

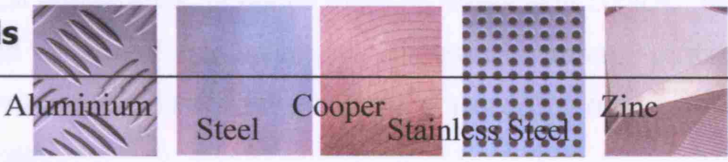
Since this study is aiming in highlighting the environmental performance of basic wall cladding materials, the potential recyclability of each one is been investigated. These figures are variable and depend on the different physical properties of each material and were collected after research on the internet. Indicative values deriving from different sources are been set out in Appendix 3. Furthermore, in order to enhance the importance of recycling, it is essential to investigate the energy required for the final disposal of building material after the end of their use. An energy consumption of 0,155 kWh is assumed per kg of waste deposited in a disposal site or $7,91x10^{-4}$ GJ/m^2 [58]. Also, it is assumed that the transport associated with the different stages of the lifecycle is carried out in cargo trucks which use diesel fuel, and they have an energy demand of 0.00073 kWh km-1 kg-1 (WEC, 1998),[59] value which is applicable to Western Europe and which in same cases differentiates according to the data presented by SCI. A mean journey of 100 km was considered for the transport of materials to the assembly plant; and 100 km for both transport of construction material

[54] http://www.aboutpvc.org/recursos/00131033RECURSO.pdf#search=%22estimate%20energy%20consumption%20PVC%20wooden%20frame%22 09/07/06
[55] http://www.aboutpvc.org/recursos/00131033RECURSO.pdf#search=%22estimate%20energy%20consumption%20PVC%20wooden%20frame%22 09/07/06
[56] http://www.aboutpvc.org/recursos/00131033RECURSO.pdf#search=%22estimate%20energy%20consumption%20PVC%20wooden%20frame%22 09/07/06
[57] http://www.aboutpvc.org/recursos/00131033RECURSO.pdf#search=%22estimate%20energy%20consumption%20PVC%20wooden%20frame%22 09/07/06
[58] http://www.aboutpvc.org/recursos/00131033RECURSO.pdf#search=%22estimate%20energy%20consumption%20PVC%20wooden%20frame%22 09/07/06
[59] http://www.aboutpvc.org/recursos/00131033RECURSO.pdf#search=%22estimate%20energy%20consumption%20PVC%20wooden%20frame%22 09/07/06

to the site of installation and for disposal of the waste materials in a disposal site[60]. A table with basic energy requirements for the transportation of different materials is exposed in Appendix 3.

Finally, after extended research for each material the initial and maintenance cost over the assumed 50 years building's lifetime are recorded in order to have in disposal potential alternatives and find the most cost-effective solution. In terms of initial cost, the purchase of material as well as the labour required for their installation is included whereas maintenance cost includes innovation requirements. All figures are taken from Spon's Architects' and Builders' Price Book where price lists are recorded for 2001. In order to be more accurate in cost estimations, an inflation rate of 12 % has been taken into consideration for these 6 years[61] (from 2001-2006).

3.2 Shiny materials



This category consists of metallic textures materials which have the ability to reflect the natural light, enlightening the surrounding area and to offer to the external envelope a shiny, bright and metallic finish. In advance, they could function like mirror elements reflecting the surrounding area. They constitute materials which interact and depend on the ambience. For this reason, metal cladding attributes to a building which is situated in a densely populated urban space a different sensation than a similar one located in an open green landscape.

This category includes shiny surfaces made of sheets of aluminium, copper, steel, stainless steel and zinc, metals which can be used with the form of panels and could be applied in wall and roof claddings. In fact, during the last decades the industry of all types of metals has gained ground over the use of timber in most applications. These materials are derived from mines, the extraction of which produces significant local pollution. Their environmental impact is located mainly on the energy consumption during their extraction and manufacture. Usually metals are high cost materials requiring an energy intensive manufacturing process. Extraction can accelerate

60 http://www.aboutpvc.org/recursos/00131033RECURSO.pdf#search=%22estimate%20energy%20consumption%20PVC%20wooden%20frame%22 09/07/06

61 Appendix 3

methane release and high temperatures required for smelting process are responsible for large amounts of CO_2 and acid gases. Most of these materials don't cause disorder on human health, with the exception of heavy metals. In this case, when the concentration of heavy metals is rising above certain levels inside the human body, severe damages are noticed in human health[62]. In general most metals are recycled materials, although this process is not without environmental cost; the smelting process requires large energy inputs and generates highly toxic dioxin emissions because of the chlorine found in most metals. That is why it is advisable to minimize the use of metals in constructions and should be used only in small quantities for particular purposes like for jointing and fixing materials.

Their satisfying behaviour against weather conditions and their high structural strength, as well as the minimum energy and cost requirements for maintenance, apart from their appealing physical appearance, enhance them as reasonable choice. In UK, most raw materials needed for metal production are imported in a semi-processed state. Consequently, the environmental and social impacts of extraction and processing constitute inevitable sad reality.

3.2.1 Aluminium

General characteristics of aluminium have been developed in previous section [see section 2.3.5]. In this chapter, the issues related to environment and cost are been examined. The use of aluminium in the construction industry is increasing rapidly. Bauxite, the ore from which aluminium is produced, is in an abundant supply. Most of these supplies are located abroad, like South America, Australia, Norway and Canada. Hence, energy is consumed in transportation over huge distances.

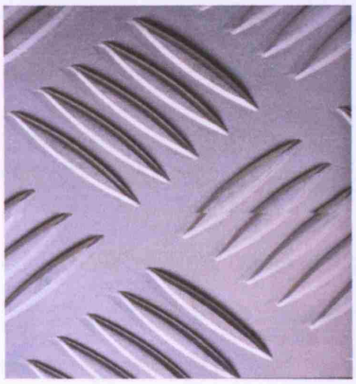


Fig. 20: Aluminium – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

In general aluminium, silver in colour, appears to be long-lived and resistant over time since its normal lifetime is around 100 years (fig 20). In order to keep its appearance attractive, a maintenance program with minimum requirements is needed to be

[62] Koronaios A Sargentis F (2005) *Construction materials and ecology*, NTUA Athens

followed, since the frequency of cleaning will depend on the atmospheric environment as well as on the effect of weathering on aluminium finish and on the ability of the finish to shed dirt and grime. Unfortunately, the production process of aluminium consumes more energy than any other building material. After the relevant literature review it is estimated that the embodied energy for virgin aluminium sheets from cradle to gate is 0,28 GJ/m^2 and for recycled it is reduced in 0,02 GJ/m^2. Mainly, aluminium production involves hydroelectric generated power reducing the large amounts of electricity required. On the other hand, due to its low density compared to other metals, it requires less energy consumption for transportation. Consequently, it is assumed that since the apparent density of aluminium is around 1/3 of other metals, the energy required for its transportation is the 1/3 of that required for the others, meaning around 0,015 GJ/m^2.

As it is already mentioned, the skeleton which structures the wall cladding materials is assumed to be in all cases timber frame with the same properties as Granville Plus. Thus, according to assumptions already explained in previous chapter [see section 3.1], it is estimated that for installing the aluminium sheet cladding, $1,12 \times 10^{-3}$ GJ/m^2 are required, the energy consumed for maintenance is negligible compared to the other amounts of energy consumption throughout their lifecycle, and that for recycling 0,02 GJ/m^2 are required compared to $7,91 \times 10^{-4}$ GJ/m^2 needed for disposal. Aluminium appears to be easily recyclable with no loss of its initial quality, fact that appoints it a solution worth being considered from energy and financial point of view. With lifetime of 100 years exceeding the assumed 50 years of building's lifetime calculation of replacement factor is been appointed as vain and unnecessary.

Fig. 21: Town Hall - Schouwen by Rau & Partners – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

Finally, suggestively research has appointed that the initial cost of buying aluminium panels including purchase of material and labour is around 50,91 £/m^2, the cost for maintenance over 50 years is 67,5 £/m^2 and the overall cost is around 118,41 £/m^2 . It should be noticed that for maintenance requirements only cleaning services with steam and special brushes with frequency of 6 months have been included. According to table

1, even though it seems an expensive solution, the long lifetime as well as the maintenance low requirements reduce the initial cost and appoint it a solution that is worth to be considered.

	Aluminium Sheets (virgin)	Aluminium Sheets (recycled)
Lifetime	100 years	100 years
Density	2579 kg/m3	2579 kg/m3
Width	0,55mm	0,55mm
Embodied energy (Cradle to gate)[63]		
extraction **transport** **production**	199 GJ/ton or 0,28 GJ/m2	14,8 GJ/ton or 0,02 GJ/m2
Transport[64]	0,015 GJ/m2	0,015 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others	negligible compared to the others
Recycling[65]	15,012 GJ/tonne or 0,02 Gj/m2	15,012 GJ/tonne or 0,02 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	0
Total for 25years (recycling incl)	0,32 GJ/m2	0,06 GJ/m2
Total for 25years (disposal incl)	0,29 GJ/m2	0,04 GJ/m2
Total for 50years (recycling incl)	0,32 GJ/m2	0,06 GJ/m2
Total for 50years (disposal incl)	0,29 GJ/m2	0,04 GJ/m2
Cost Estimation[66]		
Capital cost (as material)	9,98£/ m2	9,98£/ m2
Capital cost (incl initial cost+labor)	50,91£/ m2	50,91£/ m2
Capital cost including Replacement factor	50,91£/ m2	50,91£/ m2
Cost for maintainance (once)	1,35£/ m2	1,35£/ m2
Frequency for maintainance	every year	every year
Cost for maintainance over 50 years	67,5£/ m2	67,5£/ m2
Total Cost first year	52,26£/ m2	52,26£/ m2
Total Cost over 50 years	118,41£/ m2	118,41£/ m2

Table 1: Aluminium

3.2.2 Copper

Copper and its alloy bronze - usually tin as the main additive with other elements such as phosphorus, manganese, aluminium, or silicon[67]- appear to be an extremely conductive material. With indefinite lifetime and unique visual characteristics, the use of copper enhances buildings as prestigious and might be perceived as 'premium' material. In the last years, copper is been used as construction material for wall and roof tiling. Its main use though is located in the duct of water system and in wires and

[63] Appendix 2
[64] Appendix 3
[65] Appendix 3
[66] Appendix 4
[67] http://en.wikipedia.org/wiki/Bronze 28/08/06

lately as external cladding material. It is considered to be harmful for human health especially in case where salt of copper are coming through the duct of water system inside the human peptic system and they can cause severe disorder like inflammations and to a large extend sanction of the liver[68].

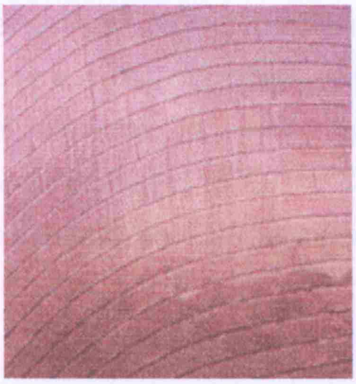


Fig. 22: Cooper – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*,

Bronze in colour (fig 22), copper appears to be very long-lived due to its durability with an estimated lifetime of 200 years, owning a high level of corrosion resistance, characteristics which discourage the use of protective coatings and maintenance requirements. In fact, copper does not require any decoration, cleaning or maintenance. When it is exposed to the outside it protects itself by developing a patina over time, which can reform if damaged, ensuring extreme durability and resistance to corrosion[69].

Fig. 23: Baron vert –Osaka by Philippe Stark – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

Copper ore is quarried or mined in Congo, Zimbabwe, Canada, USA and Chile and during the production process large amounts of sulphur dioxide and other acid gases are been released. The greatest amount of energy is consumed during its production and exploitation. The 9% of its embodied energy concerns transportation. The metallurgy of copper is producing large amount of polluted solid wastes of heavy metals. More specifically, it presents an embodied energy of 0,34 GJ/m^2 and as every other metal cladding it requires for installation $1{,}12x10^{-3}$ GJ/m^2 and for transportation 0,05 GJ/m^2.

An estimated 60-70% of copper is been recycled, fact which can reduce the energy costs of production by up to 80%. The recycling of copper is a well established practice and its extent follows overall consumption patterns. This is due to the relative ease-compared to other materials- of reusing both processing waste and salvaged scrap

[68]Koronaios A Sargentis F (2005) *Construction materials and ecology*, NTUA Athens

[69] Guide to Copper in Architecture www.cda.org.uk/megab2/build/pub-154-guide-to-copper-in-architecture.pdf 05/06/06

from eventual demolition, as well as the incentive of copper's value[70]. In fact there is a well developed market for recycling scrap, and given the cost and energy savings, it is been enhanced as a both economical and environmental friendly option. It is estimated that 0,05 GJ/m^2 are required in order to recycle copper sheets compared to 7,91 x10^{-3} GJ/m^2 required for disposal. As well as in the case of aluminium, the 200 years of lifetime makes the consideration of the replacement factor as vain.

Finally, from economical point of view, it is estimated that the initial cost for copper sheets is around 69,11-91,49 £/m^2 which coincides with the overall cost over 50 years since they are not required any additional costs for maintenance. It seems a solution which should be weighted in accordance with the total lifetime and needs to be confronted as long term investment. All values are gathered in table 2:

	Copper Sheets (virgin)	Copper Sheets (recycled)
Lifetime	200 years	200 years
Density	8890,2 kg/m3	8890,2 kg/m3
Width	0,55mm	0,55mm
Embodied energy (Cradle to gate)[71]		
extraction		
transport		
production	70,6 GJ/tonne or 0,34 GJ/m2	10,59 GJ/tonne or 0,05 GJ/m2
Transport[72]	0,05 GJ/m2	0,05 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	no maintenance requirements	no maintenance requirements
Recycling[73]	10,59 GJ/tonne or 0,05 GJ/m2	10,59 GJ/tonne or 0,05 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	0
Total for 25years (recycling incl)	0,45 GJ/m2	0,15 GJ/m2
Total for 25years (disposal incl)	0,40 GJ/m2	0,10 GJ/m2
Total for 50years (recycling incl)	0,45 GJ/m2	0,15 GJ/m2
Total for 50years (disposal incl)	0,40 GJ/m2	0,10 GJ/m2
Cost Estimation[74]		
Capital cost (as material)	21,99-24,00 £/ m2	21,99-24,00 £/ m2
Capital cost (incl initial cost+labor)	69,11-91,49 £/ m2	69,11-91,49 £/ m2
Capital cost including Replacement factor	69,11-91,49 £/ m2	69,11-91,49 £/ m2
Cost for maintainance (once)	0	0
Frequency for maintainance	0	0
Cost for maintainance over 50 years	0	0
Total Cost first year	69,11-91,49 £/ m2	69,11-91,49 £/ m2
Total Cost over 50 years	69,11-91,49 £/ m2	69,11-91,49 £/ m2

Table 2: Copper

[70] Guide to Copper in Architecture www.cda.org.uk/megab2/build/pub-154-guide-to-copper-in-architecture.pdf 05/06/06

3.2.3 Steel

Fig. 24: Steel – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

The most common metal wide used is steel (fig 24). It became widespread known in the construction industry during the Industrial Revolution and still consists one of the most popular materials. Its physical properties and its facility to be adopted in every architectural scheme, make it very interesting. The steel industry is one of the biggest energy users of all major industries. It can be applied as either structural element for the reinforcement of concrete tiles or as cladding material which can be colored with different coatings. Its durability is responsible for the 75 years of lifetime and offers a zero to minimum requirement for cleaning and maintenance.

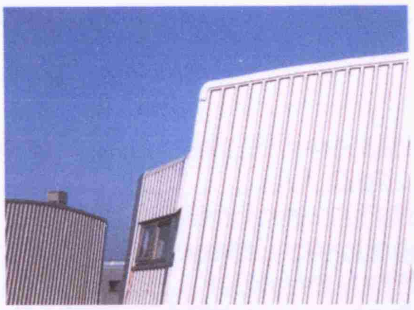


Fig. 25: 't Shaartje – Hoorn by Min 2 bow-kunst – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

The main constituents for the production process are scrap steel, pig iron and metallised ore heated to 1700-1800^0 C[75]. Large amounts of coal and water are used. All the iron ore used in Britain is imported mainly from Brazil, Canada and Australia. For the production of virgin steel sheets 0,10 GJ/m^2 are required compared to 0,03 GJ/m^2 for recycled steel sheets. Its manufacture is creating significant local and global pollution but comparatively to other metals, the energy required is relatively small. During the process of vanning, the combustion's emissions produced contain green house gases and acid rain. During the manufacture process, the installation stage and the recycling of steel release of dioxins is noticed. Furthermore, the energy required for installation, disposal and transportation is assumed to be the same as every other metal, since most of them are imported from abroad and present approximately the same densities, installation and disposal requirements. All energy and financial costs are collected in table 3.

[71] Appendix 2
[72] Appendix 3
[73] Appendix 3
[74] Appendix 4
[75] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 159

The most common environmental advantage of steel is the easy procedure of its recycling, even though the successive colored coats can obstruct the desirable result. Due to the fact of recycling, it is concluded that the production of steel isn't threaten by exhaustion of its supplies since there is long term field of productivity. Even though it is considered to be a recyclable material, with energy demand of 0,03 GJ/m^2, steel is eminently suitable for reuse rather than recycling fact which appears to be less financially attractive than for other metals. Existing steel sections can be reclaimed and repaired relatively easily, especially if they are bolted rather than welded together.

Financially, it appears to be a very profitable solution since it constitutes a very cheap option with an estimated capital and overall cost around 21,55 £/ m^2 with no maintenance requirements.

	steel (virgin)	**steel (recycled)**
Lifetime	75 years	75 years
Density	7849 kg/m2	7849 kg/m2
Width	0,4mm	0,4mm
Embodied energy (Cradle to gate)[76]		
extraction transport production	32 GJ/tonne or 0,10 GJ/m2	10,1 GJ/tonne or 0,32 GJ/m2
Transport[77]	0,05 GJ/m2	0,05 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others	negligible compared to the others
Recycling[78]	10,1 GJ/tonne or 0,03 GJ/m2	10,1 GJ/tonne or 0,03GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	0
Total for 25years (recycling incl)	0,18 GJ/m2	0,11 GJ/m2
Total for 25years (disposal incl)	0,15 GJ/m2	0,08 GJ/m2
Total for 50years (recycling incl)	0,18 GJ/m2	0,11 GJ/m2
Total for 50years (disposal incl)	0,15 GJ/m2	0,08 GJ/m2
Cost Estimation[79]		
Capital cost (as material)	16,77 £/ m2	16,77 £/ m2
Capital cost (incl initial cost+labor)	21,55 £/ m2	21,55 £/ m2
Capital cost including Replacement factor	21,55 £/ m2	21,55 £/ m2
Cost for maintainance (once)	0	0
Frequency for maintainance	0	0
Cost for maintainance over 50 years	0	0
Total Cost first year	21,55 £/ m2	21,55 £/ m2
Total Cost over 50 years	21,55 £/ m2	21,55 £/ m2

Table 3: Steel

[76] Appendix 2
[77] Appendix 3
[78] Appendix 3
[79] Appendix 4

3.2.4 Stainless Steel

In order to protect and prevent steel corrosion, alloys of nickel and chrome, wide known as stainless steel, are commonly used in the construction industry (fig 26). The principle feedstock is recycled steel and no new ore is been used. Externally, stainless steel presents the same physical properties as steel following similar production process.

Its apparent resistance to corrosion and its durability are responsible for the 100 years of lifetime. However, with the use of multiple coatings and tensile loads stainless steel tends to lose gradually its corrosion resistance. Its embodied energy 0,08 GJ/m^2 is significantly lower than that of steel with all the other energy requirements, for installation, recycling, disposal and transportation, remaining the same as those of steel. Because of its high value stainless steel is virtually guaranteed to be continually recycled. It is inert and sterile and is often the most suitable surface for allergy suffers[80].

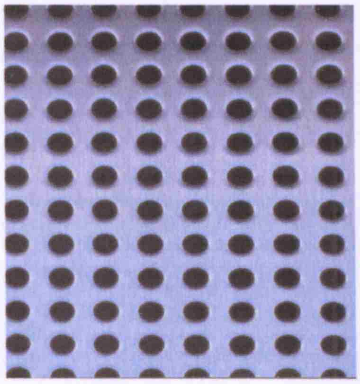


Fig. 26: Stainless Steel – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

Financially, stainless steel appears to be slightly more expensive than regular steel, with overall cost of 34,50-37,69 £/ m^2. In general, having in mind the environmental benefits, due to its low embodied energy, its high recyclability content and zero maintenance requirements stainless steel seems to be a very prosperous solution over regular steel. Detailed energy and cost evaluations are shown in table 4.

Fig. 27: Pathe Arena- Amsterdam by Frits van Dongen, de Architecten Cie– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

[80]Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 159

	stainless steel
Lifetime	100 years
Density	7849 kg/m3
Width	0,55mm
Embodied energy (Cradle to gate)	
extraction	
transport	
production	18,8 GJ/tonne or 0,08 GJ/m2
Transport	0,05 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling	10,1 GJ/tonne or 0,03 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years (recycling incl)	0,16 GJ/m2
Total for 25years (disposal incl)	0,13 GJ/m2
Total for 50years (recycling incl)	0,16 GJ/m2
Total for 50years (disposal incl)	0,13 GJ/m2
Cost Estimation	
Capital cost (as material)	17,61-20,81
Capital cost (incl initial cost+labor)	34,50-37,69
Capital cost including Replacement factor	34,50-37,69
Cost for maintainance (once)	0
Frequency for maintainance	0
Cost for maintainance over 50 years	0
Total Cost first year	34,50-37,69
Total Cost over 50 years	34,50-37,69

Table 4: Stainless Steel

3.2.5 Zinc

Zinc is commonly used for galvanized coatings, for pure zinc roofing, walling sheets and flashing (fig 28). It is also used as pigment in paints and in timber treatment against rot. Modern galvanized techniques use roughly half zinc and half aluminium in order to take advantage of the qualities of both materials. Galvanized coatings will extend the life of steel sheet and nails but the latter are relatively fragile and easily chipped. Compared with aluminium, copper or stainless steel, galvanized steel has a shorter life[81].

Fig. 28: Zinc – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

[81] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 162

Mainly zinc quantities are imported into UK from countries like Australia, Peru and USA. This results large amounts of energy demands in transportation. Silver and reflective, zinc does not present the same durability as other metals already mentioned with a shorter lifetime of 20 years. It is extracted often from the same ore as lead and reserves are estimated to be depleted within decades if the current rate of consumption stays the same. It requires 0,20 GJ/m^2 from cradle to gate while mining of zinc ore releases cadmium, and the enrichment process emits lead, antimony, bismuth and arsenic, mostly in the form of soil and water pollution[82]. Furthermore, the large quantities of wastes are contaminated with heavy metals and could be harmful for the environment.

It is already mentioned in this study that the energy needed for maintenance is negligible compared to the other lifecycle values. Also the energy needed for installation, transportation and disposal is the same as every other metal examined. The recycling of zinc is possible but, whether as an alloy or galvanized coating it can be difficult and expensive[83] . Thus it requires 0,04 GJ/m^2 for recycling whereas the energy needed for disposal is estimated to be around 7,91x10^{-4} GJ/m^2.

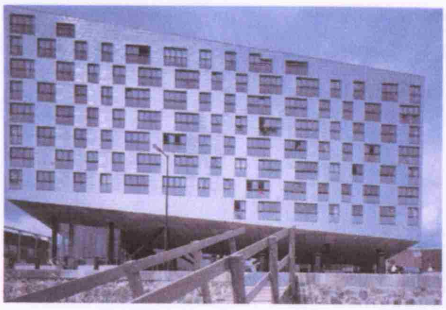


Fig. 29: The Whales- Amsterdam by Frits van Dongen, de Architecten Cie– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

Since its lifetime is around 20 years, it is needed to calculate a replacement factor which depends on the lifetime of the building (which is assumed to be 50 years) and the lifespan of the material, considering also a safety factor (0,5).

Thus: $$\text{Replacement Factor} = \frac{\text{Lifespan of Building}}{\text{Lifespan of Material}} + 0{,}5$$

In the case of zinc the replacement factor is 3, showing that it should be replaced three times over the 50 years lifetime of the building, increasing its total embodied energy as well as financial cost threefold as it is obvious in table 5.

[82] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 162

[83] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 163

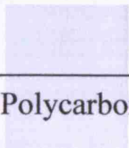
Financially it is estimated that for a sheet of zinc 62,93 £/m^2 including purchase of material and labour as initial cost are required, but with the drawback of the three replacements over the 50 years which increase the total cost of the investment to 188,79 £/m^2.

	zinc
Lifetime	20 years
Density	7176,3 kg/m3
Width	0,55mm
Embodied energy (Cradle to gate)[84] **extraction** **transport** **production**	5,1 GJ/tonne or 0,20 GJ/m2
Transport[85]	0,05 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[86]	0,514845 GJ/tonne or 0,04 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years (recycling incl)	0,29 GJ/m2
Total for 25years (disposal incl)	0,25 GJ/m2
Total for 50years (recycling incl)	0,29 GJ/m2
Total for 50years (disposal incl)	0,25 GJ/m2
Cost Estimation[87]	
Capital cost (as material)	15,81
Capital cost (incl initial cost+labor)	62,93
Capital cost including Replacement factor	188,79
Cost for maintainance (once)	0
Frequency for maintainance	0
Cost for maintainance over 50 years	0
Total Cost first year	62,93
Total Cost over 50 years	188,79

Table 5: Zinc

3.3 Smooth Surfaces


Glass


Polycarbonate

In this category materials are included which reinforce the sensation of transparency and semi- transparency adding to the external surface a smoothness and clarity of the architectural scheme. More precisely glass and polycarbonate are been examined, two

[84] Appendix 2
[85] Appendix 3
[86] Appendix 3
[87] Appendix 4

materials which even though they are coming from very different raw materials are been used as alternatives between transparency and semi – transparency. The revelation of the absolute clearness and the aesthetic of the semi-transparency could represent the tools in the hands of architect for the better exploitation of the natural light, for the use of passive means of heating, for the unification of external and internal space contributing to the dematerialization of the whole construction. Examples worldwide known in which wide glazing surfaces have been applied, verify the demolition of the meaning of building deliberating it from its firm limits, transforming it as lighter and making the users feel that are in mediate connection with the nature.

In general, these materials interact and depend on the surrounding area since they appear to be responsible for the creation of the interior space. They are generally high cost materials with intensive energy requirements during their manufacture process. On the other hand they considered to be energy saving materials diminishing the operational energy by contributing to the passive solar heating of the building and reducing the need for artificial lighting. In fact they allow the passage of daylight and warming to the interior, while at the same time they could trap heat by absorbing most of the infrared radiation. Nevertheless, without the use of specific insulation materials they could generate cold bridges and greenhouse effect to the interior.

3.3.1 Glass

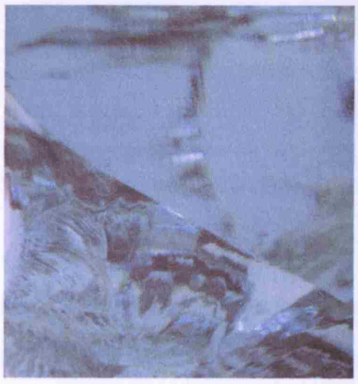


Fig. 30: Glass – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

The main raw material for glass is silica (from sand) mixed with lime and heated to about 1500^0 C[88]. Glass neutral in color since it is transparent (fig 30), is aiming to the contact of interior and exterior environment creating an invisible limit. It can provide a satisfying passage for natural lighting and solar heating to the interior but also it can be a poor insulator since it can enhance heat losses. Glazing industry has made a lot of progress in improving the physical properties of glass and a variety of different types is now available: double glazing surfaces, low e-coating filled with inert

[88] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 154

gas such as argon, may improve thermal and acoustic insulation of glazing surfaces. All these different types and physical properties of glazing surfaces make précising glass' lifetime an indefinite task.

As it is shown in table 6, for its production (cradle to gate) 0,10 GJ/m^2 are required followed by harmful emissions such as chlorides, fluorides and particulate matters[89]. As for every other material in this study, it is assumed that the energy requirements for installation, transportation, maintenance and disposal are the same. Since it is the first everyday material to be recycled on a mass scale, it demands 1,10x10^{-7} GJ/m^2 for recycling. Waste from the production process is normally reused. Even though the potential use of recycled glass could be beneficial in terms of energy cost, its failure to maintain initial properties degrades its quality and it can be used only as low-grade glass or aggregate.

In general, glass is inert, non-polluting and can last indefinitely if it is well protected from impact. It can be wired, toughened or laminated to improve its strength on impact and ensure that it breaks safely[90]. Having in mind the wide range of glazing types, a potential attempt of estimating the cost for such investment is considered to be unfortunate since all the prices are depending on the characteristics of each glazing sheet. A rough estimation shows that 26,80-112 £/m^2 are required for purchasing and labouring glazing surfaces whereas cleaning requirements every 6 months with individual cost each time of 1,35 £/m^2 , increase the total cost over 50 years up to 161,8-247 £/m^2 . Concluding, even though glazing sheet present large amounts of embodied energy and financial cost, their contribution on the creation of a healthy and viable environment and as well as on the thermal behaviour of the building seems to be significant, fact which enhances them to a profitable solution.

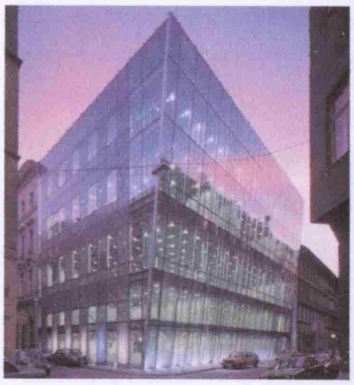


Fig. 31: ING Headquarters-Budapest by Eric Van Egeraat, de Architecten Cie– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

[89] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 154
[90] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 155

	glass
Lifetime	indefinite
Density	2563 kg/m3
Width	4mm
Embodied energy (Cradle to gate)[91]	
extraction	
transport	
production	9,72 GJ/tonne or 0,10 GJ/m2
Transport [92]	5,28 GJ/tonne or 0,05 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[93]	1,08x10-5 GJ/tonne or 1,10x10-7 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years (recycling incl)	0,15 GJ/m2
Total for 25years (disposal incl)	0,15 GJ/m2
Total for 50years (recycling incl)	0,15 GJ/m2
Total for 50years (disposal incl)	0,15 GJ/m2
Cost Estimation[94]	
Capital Cost (as material)	–
Capital Cost (incl initial cost+labor)	26,80-112
Capital Cost including Replacement Factor	26,80-112
Cost for maintainance (once)	1,35
Frequency for maintainance	every 6 months
Cost for maintainance over 50 years	135
Total Cost first year	28,15-113,35
Total Cost over 50 years	161,8-247

Table 6: Glass

3.3.2 Polycarbonate

Semi transparent with opaque appearance (fig 32), excellent toughness, thermal and very good dimensional stability, polycarbonate is one of the most widely used engineering thermoplastics which tend to replace glass in most applications. It is included in the category of thermoplastic polymers since it is produced by recycled synthetic material.

Fig. 32: Polycarbonate– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*

Polycarbonate sheet cladding is a low cost approach to improve the thermal performance of a building, preventing summer heat gains and performing satisfying well during winter reducing heat losses by around 3%. As all the

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thermoplastics products, polycarbonate considered to be waste product from the production of petroleum reducing the accumulation of waste materials[95]. Nonetheless, the industrial exploitation is varying according to the product, but in any case high level of energy consumption is required and almost always volatile combinations are emitted and harmful wastes are produced. Its high embodied energy of 0,51 GJ/m2 from cradle to gate verifies the unfriendly behaviour of polycarbonate. Having in mind that these products are disrupted with difficulty, they can cause long-term pollution to the air, the water and the ground. The combustion of plastics can release significant dangerous emissions variable according to the type of the material.

Fig. 33: Nicolaas Maesschool-Amsterdam by Meyer en Van Schooten, de Architecten Cie– Borch I, Kenning D, (2004) *Skins for building-*

According to table 7, for the recycling of polycarbonate, 0,01 GJ/m^2 are required, an amount by far lower than that required to produce a new one from scratch. Polycarbonate does not present a very durable profile since after 20 years of lifetime it renders to yellow and needs to be replaced. The apparent embodied energy is been also verified by the high total cost of polycarbonate sheets which fluctuates from 315 – 345 £/m^2 , where 60-70 £/m^2 are needed for purchase and labour and 1,35 £/m^2 are needed for cleaning services every 6 months.

	polycarbonate
Lifetime	12-20 years
Density	1200 kg/m3
Width	4mm
Embodied energy (Cradle to gate)[96] **extraction** **transport** **production**	107 GJ/tonne or 0,51 GJ/m2
Transport [97]	5,28 GJ/tonne or 0,05 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[98]	2,334 GJ/tonne or 0,01 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	3
Total for 25years (recycling incl)	0,57 GJ/m2

[95] http:// www.edu/courses/engr498/docs/doc/dfe.material.stage.doc
[96] Appendix 2
[97] Appendix 3
[98] Appendix 3

Total for 25years (disposal incl)	0,56 GJ/m2
Total for 50years (recycling incl)	1,71 GJ/m2
Total for 50years (disposal incl)	1,68 GJ/m2
Cost Estimation[99]	
Capital Cost (as material)	–
Capital Cost (incl initial cost+labor)	60-70
Capital Cost including Replacement Factor	180-210
Cost for maintainance (once)	1,35
Frequency for maintainance	every 6 months
Cost for maintainance over 50 years	135
Total Cost first year	61,35-71,35
Total Cost over 50 years	315-345

Table 7: Polycarbonate

3.4 Surfaces assembled with grid

In this category materials like brick and tiles are included which after their application on the external envelope of a building are creating a repeated assembly and a metric grid. They are materials which come from clay fired in high temperatures and which with their standard sizes attribute to the external appearance of the building harmony.

In earthly tones bricks and in different colours ceramic tiles constitute the 'earthly' response of the construction industry towards wall cladding materials. With rough assembly due to the created grid, and grainy or porous or smooth texture, clay products are the standard choice for external finishes of buildings in most countries like UK. They are used in order to create firm and closed walls, mainly in cases where the architect pursues introversion and isolation of the building from the exterior. Due to their increased density and weight, they contribute to the stability and strength of the building gaining the trust of the users.

When clay is heated in kilns to high temperatures (up to 2000 ^{0}C) it gains very good compressive strength and weather resistance, but with significant environmental impacts due to the energy used and pollution created. Different clay products could be considered as a traditional and easy solution in the external cladding of buildings.

[99] Appendix 4

Furthermore, as earth sourced materials, they could function relatively as thermal mass materials absorbing and emitting solar heat gains.

3.4.1 Ceramic bricks

Fig. 34: Bricks– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

Fired clay bricks (fig 34) considered to be the traditional option for cladding buildings in the UK. Bricks seem to be in accordance with the traditional architectural style of Victorian times which dominates all over England. Brown and red in colour and with porous texture bricks whilst having high embodied energy content are long lasting and durable with an estimated 50-100 lifetime. The average energy used in brick production is around 0,02 GJ/m^2 due to the high energy requirements for firing the bricks in kilns. In fact, for every 100^0 C increase in the firing temperature, another 0,2MJ of energy is used per kilogram of bricks.[100] However, the only bricks that are widely available are vitrified or well- fired bricks, sold for all-purposes use.

Due to their heavy weigh the energy needed for their transportation is around 0,09 GJ/m^2, approximately four times more than their initial embodied energy. That is why locally sourced products are much more preferable. Financially bricks present an average initial cost of 44,78 – 67,52 £/m^2 due to labour requirements. On the other hand, due to their physical appearance they do not require intensive maintenance, which includes cutting out decayed, defective or cracked work and replacing with new common bricks in ganged mortar, and it is variable priced depending on the thickness of the blockwall between 522,55-1808,912 £/m^2 over 50 years. Thus the overall cost increase up to 567,33-1876,432 £/m^2

Made by mass production techniques, even though they cannot be recycled the option of reclaimed bricks seems an environmental relief. Due to the lack of data, in this study an evaluation of reused materials has not been made. Reclaimed bricks though are now available relatively easily and offer financial and environmental advantages. The requirements for installation are minimum since a simple layer of lime mortar is

[100] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 149

enough, when for disposal 7,91x10-4GJ/m^2 are needed. Adding all the figures it seems that the overall embodied energy is 0,11 GJ/m2 .

	ceramic tiles
Lifetime	50-100 years
Density	19922 kg/m3
Width	5mm
Embodied energy (Cradle to gate) [101]	
extraction transport production	2,5 GJ/tonne or 0,02 GJ/m2
Transport[102]	9,21 GJ/tonne or 0,09 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[103]	non recyclable
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years	0,11 GJ/m2
Total for 50years	0,11 GJ/m2
Cost Estimation[104]	£/ m2
Capital cost (as material)	20,23-42,97
Capital Cost (incl initial cost+labor)	44,78-67,52
Capital Cost including Replacement Factor	44,78-67,52
Cost for maintainance (once)	104,51-361,7824
Frequency for maintainance	every 10 years
Cost for maintainance over 50 years	522,55-1808,912
Total Cost per year	149,28-429,31
Total Cost over 50 years	567,33-1876,432

Table 8: Ceramic Bricks

3.4.2 Ceramic tiles

Tiles seem to present similar physical properties as bricks since they are derived from the same raw material following the same production process. They can be in different textures, smooth, porous, striped and in different colours (fig 35) and they can transform the external appearance of a building according to the inspiration of the architect, as in the case of Granville Plus where the playful

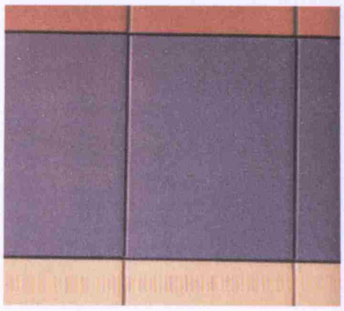

Fig. 35: Tiles– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*

[101] Appendix 2
[102] Appendix 3
[103] Appendix 3
[104] Appendix 4

purpose of the building is been projected on its wall art tiles applied.

Made from clay, a natural but finite resource, tiles are durable with 50-100 years of lifetime and require low maintenance since they do not emit vapours and are easy to be cleaned. Not recyclable, they can be reclaimed and reused in order to reduce embodied energy. If they are locally sourced they contribute to the reduction of energy consumed for their transportation.

As far as energy requirements concerns, all the figures seem to be similar to those mentioned in the brick's section, with an embodied energy of 0,02 GJ/m^2 increased by 0,09 GJ/m^2 due to transportation demands. Economically, tiles seem to have lower initial cost than bricks (39,74-143,81 £/m^2) with assumed the same maintenance cost and an overall cost evaluation of 562,29-1952,722 £/m^2 over 50 years.

	ceramic bricks
Lifetime	25-100 years
Density	2194 kg/m3
Width	16cm
Embodied energy (Cradle to gate) [105]	
extraction	
transport	
production	2,5 GJ/tonne or 0,02 GJ/m2
Transport[106]	9,21 GJ/tonne or 0,09 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[107]	non recyclable
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years	0,11 GJ/m2
Total for 50years	0,11 GJ/m2
Cost Estimation[108]	£/ m2
Capital cost (as material)	15,37-62,23
Capital Cost (incl initial cost+labor)	39,74-143,81
Capital Cost including Replacement Factor	39,74-143,81
Cost for maintainance (once)	104,51-361,7824
Frequency for maintainance	every 10 years
Cost for maintainance over 50 years	522,55-1808,912
Total Cost per year	144,24-505,59
Total Cost over 50 years	562,29-1952,722

Table 9: Ceramic Tiles

[105] Appendix 2
[106] Appendix 3
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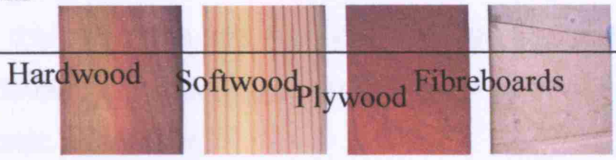
3.5 Striped Surfaces



Striped surfaces can be created with the use of different boards of timber. The application of wooden boards on the external finish of the building constitutes a widespread method for external cladding and could be considered as environmentally friendly option. In earthly colourations timber boards placed either horizontically or vertically, create a stabilised assembly with relief texture and similarity.

In the construction industry timber could be found everywhere. Its versatility, durability, strength in tension, compression and bending, impose it as ideal material for structural support, flooring, cladding, doors and windows. Very appealing in site, it is easily assembled, worked and repaired with inherent durability and easy to maintain. It is considered to be an environmental friendly material, renewable, which requires low level exploitation in order to achieve its final state. Comparatively to other materials like metal or glass, timber presents the lowest accumulated embodied energy. As a renewable resource, its main attributes are that it reduces the amount of CO_2 in the atmosphere until it decays or it burns since it is considered as a 'carbon sink'.

The biggest environmental problem which is associated with timber, in both local and global level, is the unorganised woodcutting. A large amount of forests are destroyed provoking disruption of the ecological balance, derangement of the territory, soil erosion and pollution of the riverbed. Specifically, the ecological problem is located on tropical areas which are considered to contain more sensitive ecosystems. According to a survey of the International Organisation of Tropical Timber, only the 1% of the tropical forests is under inspection for the production of timber. GREENPEACE estimates that the deforestation of the tropical ecosystem is responsible for a large proportion (around 18%) of the world increased temperature due to the greenhouse effect.

Epidemiological surveys have been carried out in working places where people were exposed to dusts deriving from timber exploitation, and have settled an upper limit of exposure. In the mean time, further researches in Scandinavian countries mention that the smoke emitted from the procedure of timber's desiccation can be cancerous and that the employers are in great danger. That is why it is necessary to maintain the fundamental measures for the protection and security of human health. On the other hand, it is estimated that timber is not causing disorder in the health of occupants if it hasn't been processed by toxic substances[109].

The construction and the demolition of buildings are responsible for the creation of million of tonnes of wooden construction waste. Unfortunately a very small amount of those are being reused or recycled, even if the commercial recycling of construction wastes from other sources with aim the synthetic timber has started being established. For the purpose of this study, four types of timber which assemble striped surfaces are been examined: hardwood, softwood, plywood and fibreboards.

3.5.1 Hardwood

About one third of the six million cubic metres of timber produced annually by British forests is hardwood such as ash, beech, birch and oak. There are however two species generally considered suitable for structural purposes: oak and sweet chestnut. These are traditional materials used in timber framed houses in Britain and they are very strong and long lasting[110]. Hardwood (fig 36) are worked on and incorporated into a building while they are in their 'green' unseasoned state. While they dry out many timbers present the tendency to warp or twist, drawback which could be overcome with the use of ties and braces at frequent intervals. Because of their inherent quality and longevity as well as their high financial cost and limited availability, most types of hardwood are likely to be reused.

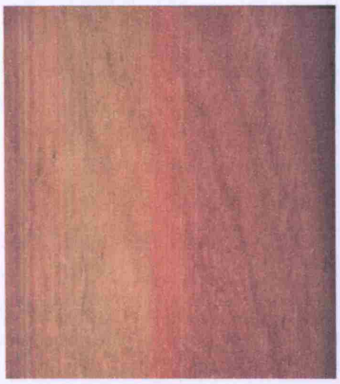


Fig. 36: Hardwood–Skins for building- Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book,*

The use of home grown hardwoods is being promoted in order to reduce the energy required for transporting them from long distances. This purpose as well as the good forest management for a sustainable supply, result the characterization of hardwood as environmental friendly material. More specifically, the apparent lifetime of hardwoods is around 50 years with an initial cost of 40,15-45,81 £/m^2 approximately. As it is

[109] Euthimopoulos I. (2000) *Ecological structure , Inter-scientific Institute Environmental Research*, Ministry of public tasks, Athens

[110] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 112

Fig. 37: Nieuw Terdregge-Rotterdam– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book,*

natural product, its maintenance includes treatment of boarding with 2 coats of proprietary insecticide and fungicide by splay or brush application with a frequency of every 5 years and a cost of 34,7-38,6 £/m^2 over 50 years. This results a total cost of investing in hardwood of 74,85-84,41 £/m^2 over 50 years which seems a rather beneficial solution.

Its embodied energy is estimated to be around 0,044 GJ/m^2 with an additional energy cost for transportation of 0,13 GJ/m^2 in the case of imported timber. It is found that only 8,82x10^{-7} GJ/m^2 are required for recycling any type of timber attributing it as the most easy recycling material. Resulting a total of 0,17 GJ/m^2 over 50 years, hardwood is been appointed as an eco-friendly material.

	hardwood (kiln dried rough sawn)
Lifetime	50 years
Density	720,83 kg/m3
Width	5cm
Embodied energy (Cradle to gate) [111] **extraction transport production**	2,0 GJ/tonne or 0,04 GJ/m2
Transport[112]	6 GJ/tonne or 0,13 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[113]	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years (recycling incl)	0,17 GJ/m2
Total for 25years (disposal incl)	0,17 GJ/m2
Total for 50years (recycling incl)	0,17 GJ/m2
Total for 50years (disposal incl)	0,17 GJ/m2
Cost Estimation[114]	£/ m2
Capital cost (as material)	–
Capital Cost (incl initial cost+labor)	40,15-45,81
Capital Cost including Replacement Factor	40,15-45,81
Cost for maintainance (once)	3,47-3,86
Frequency for maintainance	every 5 years
Cost for maintainance over 50 years	34,7-38,6
Total Cost per year	43,62-49,67
Total Cost over 50 years	74,85-84,41

Table 10: Hardwood

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3.5.2 Softwood

These timbers mostly spruce, pine and fir are used mainly for pallets, packaging and fencing, wall cladding and chipboard production. In most cases where softwoods are applied in the construction industry, are considered to be of poor quality and non structural with the exception of European larch ad Douglas fir (fig 38). Those two appear as excellent framing timbers which are being classified by TRADA as 'semi-durable'. They both are naturally dense, resinous and therefore relatively rot and satisfying insect-resistant[115].

Fig. 38: Softwood– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

Softwoods present a lifetime of 50 years with zero or minimum maintenance requirements. Their energy required from cradle to gate is around 0,03 GJ/m^2 in the case of imported timber with an overall embodied energy of 0,16 GJ/m^2 and 8,82x10^{-7} GJ/m^2 needed for recycling. Their financial cost appears to be lower than hardwoods with a capital cost of 6,85 – 16,69 £/m^2 and considering the same maintenance demands every 5 years the total cost runs into 41,55-55,29 GJ/m^2. These facts appoint it as a profitable solution worth to be considered.

Fig. 39: Den Daalder – Boxtel by Min 2 bow-kunst – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

	softwood (kiln dried rough sawn)
Lifetime	25-50 years
Density	448,5 kg/m3
Width	5cm
Embodied energy (Cradle to gate) [116] **extraction** **transport** **production**	1,6 GJ/tonne or 0,03GJ/m2
Transport[117]	6 GJ/tonne or 0,13 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[118]	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2

[115] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 114
[116] Appendix 2
[117] Appendix 3
[118] Appendix 3

Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years (recycling incl)	0,16 GJ/m2
Total for 25years (disposal incl)	0,16 GJ/m2
Total for 50years (recycling incl)	0,16 GJ/m2
Total for 50years (disposal incl)	0,16 GJ/m2
Cost Estimation[119]	
Capital cost (as material)	1,91-6,62
Capital Cost (incl initial cost+labor)	6,85-16,69
Capital Cost including Replacement Factor	6,85-16,69
Cost for maintainance (once)	3,47-3,86
Frequency for maintainance	every 5 years
Cost for maintainance over 50 years	34,7-38,6
Total Cost per year	10,33-20,55
Total Cost over 50 years	41,55-55,29

Table 11: Softwood

3.5.3 Plywood

Plywood can be categorized as composite board of timber products (fig 40). Made of soaking the whole log and peeling off thin layers or veneers, which are then dried and glued together using formaldehydes or isocyanate resins, plywood sheets are suitable for every external finish cladding use as walls, roofs and floors[120]. There are numerous grades of plywood available on the market as shuttering ply, middle of the range ply, marine ply and finally blockboard or laminboard, differentiating in physical properties, environmental impacts as well as financial cost.

Fig. 40: Plywood– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book,*

Plywood has an apparent lifetime of 40-50 years. Since it consists a product derived from timber, special manufacture process is needed and thus the high embodied energy over lifecycle of 0,25 GJ/m^2 is been justified. The including energy of 0,13 GJ/m^2 is necessary to be taken into consideration for its transportation to the place of installation whereas all the other figures for disposal and recycling are the same as in every timber product. Additionally a capital cost of

Fig. 41: Camperdown House– Australia by Lahz NimmoArchitects – Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book,*

[119] Appendix 4

[120] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 114

16,41-24,09 £/m^2 and overall cost of 51,11-62,69 GJ/m^2 burdens the application of external wall cladding filled with plywood.

	plywood
Lifetime	25-50 years
Density	560,645 kg/m3
Width	5cm
Embodied energy (Cradle to gate) [121]	
extraction	
transport	
production	10,4 GJ/tonne or 0,12 GJ/m2
Transport[122]	6 GJ/tonne or 0,13 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[123]	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years (recycling incl)	0,25 GJ/m2
Total for 25years (disposal incl)	0,25 GJ/m2
Total for 50years (recycling incl)	0,25 GJ/m2
Total for 50years (disposal incl)	0,25 GJ/m2
Cost Estimation[124]	
Capital cost (as material)	10,48-15,61
Capital Cost (incl initial cost+labor)	16,41-24,09
Capital Cost including Replacement Factor	16,41-24,09
Cost for maintainance (once)	3,47-3,86
Frequency for maintainance	every 5 years
Cost for maintainance over 50 years	34,7-38,6
Total Cost per year	19,88-27,95
Total Cost over 50 years	51,11-62,69

Table 12: Plywood

3.5.4 Fibreboards

There are basically two types of fibreboards : the medium density fibreboard which is manufactured with urea-formaldehydes as the bonding agent and the softboard, mediumboard or hardboard which are made of felting wood fibres bonded together into a sheet using heat, pressure and the wood's own resins[125]. The first one seems to be applied in most internal finishes and due to the presence of formaldehydes workers involved in the cutting and shaping of MDF sheets seem to be at particular risk from inhaling dust. For the production of the second (fig 42), no synthetic glues are needed and the use of this type of fibreboard is associated with a very low environmental

[121] Appendix 2
[122] Appendix 3
[123] Appendix 3
[124] Appendix 4
[125] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 114

impact. Smooth, offering high quality finish, structurally resistant and very durable, fibreboards seem that can be reused several times with a lifetime of 40-50 years. If it is burnt, harmful gases such as hydrogen cyanide may be produced and if it is dumped on a landfill site the timber will biodegrade but the constituents of the glues will remain in the ecosystem causing harmful consequences[126].

Fig. 42: Fibreboards– Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT

Needing a special manufacture process, fibreboards have an overall embodied energy of 0,19 GJ/m^2 , where the energy cost of 0,13 GJ/m^2 is required for its transportation due to its heavy weight. For assembly, use, recycling and disposal the figures are the same as in every other timber product. Financially fibreboards seem cost-effective with a capital cost of 17 £/m^2, which is increased by additional maintenance cost taking place every 5 years up to 56 £/m^2.

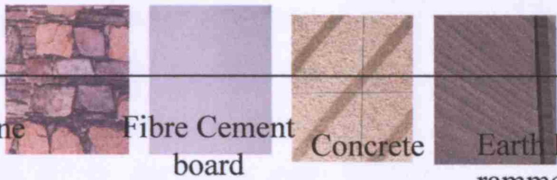
	fibreboards
Lifetime	25-50 years
Density	560,645 kg/m3
Width	5cm
Embodied energy (Cradle to gate) [127]	
extraction **transport** **production**	5,7 GJ/tonne or 0,06 GJ/m2
Transport [128]	6 GJ/tonne or 0,13 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[129]	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years (recycling incl)	0,19 GJ/m2
Total for 25years (disposal incl)	0,19 GJ/m2
Total for 50years (recycling incl)	0,19 GJ/m2
Total for 50years (disposal incl)	0,19 GJ/m2
Cost Estimation[130]	
Capital cost (as material)	–
Capital Cost (incl initial cost+labor)	17
Capital Cost including Replacement Factor	17
Cost for maintainance (once)	3,69

[126] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 122
[127] Appendix 2
[128] Appendix 3
[129] Appendix 3
[130] Appendix 4

Frequency for maintainance	every 5 years
Cost for maintainance over 50 years	36,9
Total Cost per year	22,69
Total Cost over 50 years	56

Table 13: Fibreboards

3.6 Roughcast surfaces



All the following widely used bulk building materials, assembled together in order to form the external walls of a building, create roughcast textures due to their physical properties. In this category materials like natural stone, earth rammed soil, fibre cement boards and concrete blocks are included and examined since their texture and physical appearance offer roughcast sensation. Some of them like natural stone and rammed earth are used in raw state without any further processing. However, the large quantities needed to construct a building together with their high density means that masonry materials are often the greatest contributor to the total embodied energy cost of the building.

The fact that they are non renewable sources in relation with the apparent local and immediate effects of quarrying them should be listed as their greatest ecological impact. Disturbance of natural habitats, creation of noise, dust and vibration are some of the side effects arisen during their production process.

Apart from these, use of these materials contributes to the durability and the strength of the construction as well as the care of the architect to get in touch with the natural and its natural products. Earth materials could be assembled on the exterior of a building offering a warm, traditional and simple appearance reinforcing vernacular architecture. The warm earthly colours and textures make roughcast surfaces as excellent supporting materials as well as appealing external cladding. Their physical properties and warm tones create the illusion that the building as inspired by the architect is been emerged from the ground and it is becoming a piece of that, intergrading it smoothly in the surrounding environment. Furthermore, their capacity of performing as thermal mass materials staying cool and fresh during summer and warm during winter, upgrades it to a material which contributes to the energy efficiency of the building.

3.6.1 Natural stone

One material which constitutes the base of the vernacular architecture in most countries (like Mediterranean's) and still being used is natural stone. Available in different colours, depending on the origin, being pre-cut, polished or staying in natural state, stone is an appealing wall cladding material (fig 43). Its durability and ability to stay unchangeable with the passing of time, do not impose a lot of maintenance requirements since once it is dug out from the ground, it requires cutting and trimming in blocks.

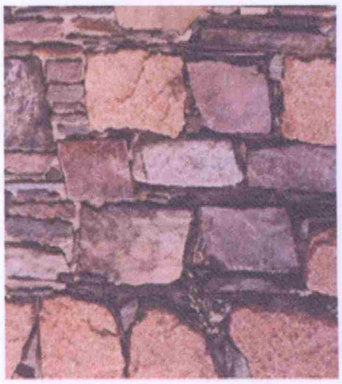


Fig. 43: Natural stone– Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 114

Durable and strong with massive thickness, natural stone shows an indefinite lifetime. Acting as heat storage and buffer against extreme weather conditions, and staying resistant to water penetration stone considered to be an environmental friendly material even though it is not renewable. The apparent environmental impacts are associated with the energy used during its extraction and mainly its transportation to the installation site due to its heavy weight. That is why locally sourced stone has a high energy benefit. More precisely, it is found that 0,44 GJ/m^2 are needed during whole lifecycle for locally sourced stone and 3.39 GJ/m^2 for imported and 0,083 GJ/m^2 and 0,25 GJ/m^2 to transport them respectively to the installation point.

As it is already mentioned, it is assumed that since all cladding materials are applied on a timber frame construction, the energy requirements for installation and disposal are the same as previous already examined materials.

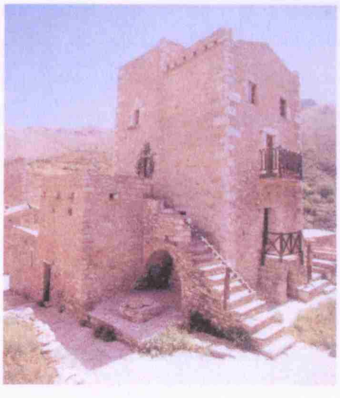


Fig. 44: Traditional house-Greece

Nowadays, buildings with stone in the structural sense are rare. At most, it is used as a cladding, often at the request of the local authority, concerned to replicate the vernacular. Occasionally the cladding is real stone, skilfully laid with fine mortar joints, but more often any 'store' used will be a synthetic, reconstituted product, made of crushed stone mixed with a resin binder or cement[131]. In the case of imported stone, it seems as expensive solution with high capital cost of 58,85-71,11 £/m^2 whereas the use of locally sourced stone can reduce the price to 1/3 meaning to 19,61-23,70 £/m^2. due to the apparent durability of natural stone it is assumed that the maintenance requirements are minimum, mainly cleaning every 10 years. The maintenance demands needed contribute to the total cost by 104,51-361,78 £/m^2 over 50 years. Although the total cost over 50 years fluctuates between 26,06-41,3 for local and 65,3-88,71 for imported£/m^2 it stills remains a very appealing external wall cladding.

	natural stone (local)	natural stone (imported)
Lifetime	indefinite	indefinite
Density	2306 kg/m3	2306 kg/m3
Width	20cm	20cm
Embodied energy (Cradle to gate) [132]		
extraction		
transport		
production	0,79 GJ/tonne or 0,36 GJ/m2	6,8 GJ/tonne or 3,14 GJ/m2
Transport [133]	0,55 GJ/tonne or 0,083 GJ/m2	0,55 GJ/tonne or 0,25 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others	negligible compared to the others
Recycling[134]	non recyclable	non recyclable
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	0
Total for 25years	0,44 GJ/m2	3,39 GJ/m2
Total for 50years	0,44 GJ/m2	3,39 GJ/m2
Cost Estimation[135]		
Capital cost (as material)	41,29-63,49	41,29-63,49
Capital Cost (incl initial cost+labor)	19,61-23,70	58,85-71,11
Capital Cost including Replacement Factor	19,61-23,70	58,85-71,11
Cost for maintainance (once)	1,29-3,52	1,29-3,52
Frequency for maintainance	every 10 years	every 10 years
Cost for maintainance over 50 years	5,45-17,6	5,45-17,6
Total Cost per year	20,9-27,22	60,14-74,63
Total Cost over 50 years	26,06-41,3	65,3-88,71

Table 14: Natural Stone

[131] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 1136
[132] Appendix 2
[133] Appendix 3
[134] Appendix 3
[135] Appendix 4

3.6.2 Concrete Blocks

One of the most wide used materials in the modern society is concrete (fig 45). It can be used as an ideal external cladding, offering a secure and firm wall panelling to the building. Working as thermal mass element it can contribute to the energy efficiency of the building. Its manufacture process requires large amounts of energy and results large amounts of emissions in local and global environment. Grey in colour, concrete is well known for its high durability and strength as structural material. Especially in countries with intensive seismic behaviour concrete reinforced by steel bars constitutes the certain solution for a stable building.

Fig 45: Concrete

Dense concrete blocks are made from cement, sand and aggregates steam-cured under pressure. 'Lightweight concrete blocks use expanded clays and shales such as pumice. Finally, aerated concrete blocks are made of cement, sand and lime with a small amount of aluminium sulphate added'[136]. More specifically, the overall embodied energy of concrete blocks is estimated to be around 2,29 GJ/m^2 (tiles or aerated respectively) while for its transportation 0,21 GJ/m^2 are required. Since it is an industrialised product and due to its high density and weight, the energy cost attributed to concrete are really high. Financially, light weighted and aerated blocks seem to be more expensive than dense blocks. Approximately, a cost evaluation shows that concrete blocks are priced with 49,76 £/m^2 and every 10 years they require cleaning out of existing minor cracks and filling in with cement mortar mixed with bonding agent, increasing the cost by 6,45-17,6 over 50 years. Thus the overall cost runs into 56,21-67,36£/m^2 which seems a profitable solution.

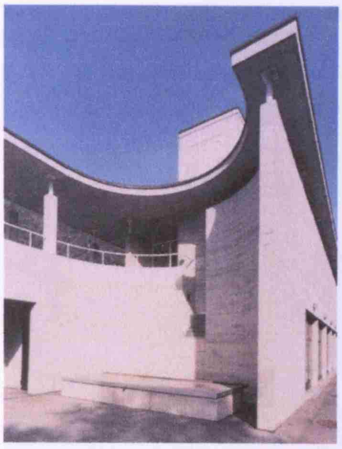


Fig. 46: Gymnasium – Monte Carasso by M.Arnaboldi and G.Mazzi– Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

[136] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 113

	concrete blocks (tiles)	concrete blocks (aerated)
Lifetime	indefinite	indefinite
Density	1922 kg/m3	1922 kg/m3
Width	20 cm	20 cm
Embodied energy (Cradle to gate[137]) **extraction** **transport** **production**	0,81 GJ/tonne 0,31 GJ/m2	5,4 GJ/tonne 2,08 GJ/m2
Transport [138]	0,55 GJ/tonne or 0,21 GJ/m2	0,55 GJ/tonne or 0,21 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others	negligible compared to the others
Recycling[139]	non recyclable	non recyclable
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	0
Total for 25years	0,52 GJ/m2	2,29 GJ/m2
Total for 50years	0,52 GJ/m2	2,29 GJ/m2
Cost Estimation[140]		
Capital cost (as material)	25,21	25,21
Capital Cost (incl initial cost+labor)	49,76	49,76
Capital Cost including Replacement Factor	49,76	49,76
Cost for maintainance (once)	1,29-3,52	1,29-3,52
Frequency for maintainance	every 10 years	every 10 years
Cost for maintainance over 50 years	6,45-17,6	6,45-17,6
Total Cost per year	52,165	52,165
Total Cost over 50 years	56,21-67,36	56,21-67,36

Table 15: Concrete Blocks

3.6.3 Fibre Cement Boards

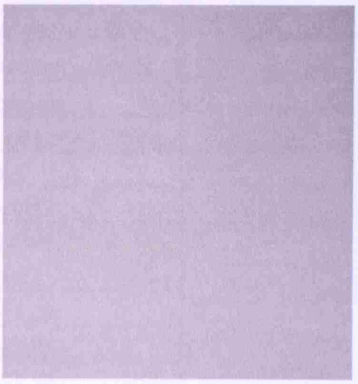


Fig. 47: Fibre Cement Boards- Borch I, Kenning D, (2004) *Skins for building-The architect's material Sample book*, BIS Publishers

Fibre cement is a simple abbreviation for Fibre Reinforced Cement (FRC) used as alternative reinforcing materials to create asbestos-free cement-based building products (fig 47). Fibre cement products are a mixture of cellulose fibre, from plantation-grown Radiata Pine trees, Portland cement, sand, water and small amounts of other chemical additives are used to help the process, or provide products with particular characteristics[141]. As material it appears to be fire resistant, resistant to permanent water and termite damage, and, when installed as directed, resistant to

[137] Appendix 2
[138] Appendix 3
[139] Appendix 3
[140] Appendix 4
[141] Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT, p 113

rotting and warping.

These products are easy to work with and they are practically maintenance-free, making them the ideal choice for professional builders, designers and architects, and the do-it-yourself (handyman) enthusiast. Even though, they require ongoing maintenance by painting in order to keep up with its initial physical properties.

Fibre cement boards could be applied as external cladding in every building. With a high durability of 20-50 years of lifetime, fibre cement boards require low maintenance and present lower overall embodied energy of that of timber or metal, meaning 0,14GJ/m^2. For the transportation of these products, 7,48x10^{-3} GJ/m^2 are needed with no recycling potential. Financially, they appear to have low initial cost (15,77-18,29 £/m^2) and it is assumed to have the same maintenance requirements as concrete increasing the overall cost over 50 years into 27,16- 40,83 £/m^2.

	cement (fibre cement board)
Lifetime	20-50 years
Density	1361 kg/m3
Width	10mm
Embodied energy (Cradle to gate) [142]	
extraction **transport** **production**	9,5 GJ/tonne 0,13 GJ/m2
Transport [143]	0,55 GJ/tonne or 7,48x10-3 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[144]	non recyclable
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	3
Total for 25years	0,14 GJ/m2
Total for 50years	0,42 GJ/m2
Cost Estimation[145]	£/ m2
Capital cost (as material)	15,77-18,29
Capital Cost (incl initial cost+labor)	20,71-23,23
Capital Cost including Replacement Factor	20,71-23,23
Cost for maintainance (once)	1,29-3,52
Frequency for maintainance	every 10 years
Cost for maintainance over 50 years	6,45-17,6
Total Cost per year	22-26,75
Total Cost over 50 years	27,16-40,83

[142] Appendix 2
[143] Appendix 3
[144] Appendix 3
[145] Appendix 4

3.6.4 Earth raw rammed soil

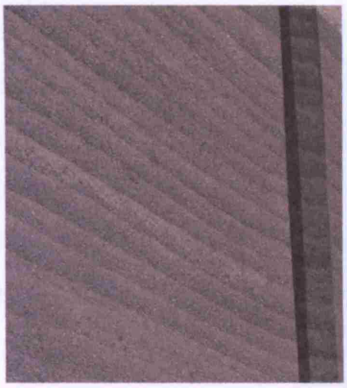


Fig. 48: Earth Raw rammed soil - CAT

First used in Lyons, France in 1562, the term applied to the principle of constructing walls at least 50 cm thick by ramming earth between two parallel frames that are then removed, revealing a completed section of hard earth wall[146]. The colour of rammed earth walls is determined by the earth and aggregate used (fig 48). The ramming process proceeds layer by layer and this can introduce horizontal stratification to the appearance of the walls[147]. The stratification due to ramming can enhance the overall appearance and can be controlled as a feature or eliminated. Aggregates can be exposed and special effects can be created by the addition of different colored material in some layers and elements such as feature stones, alcoves or relief mouldings can be incorporated into rammed earth walls, at a price[148].

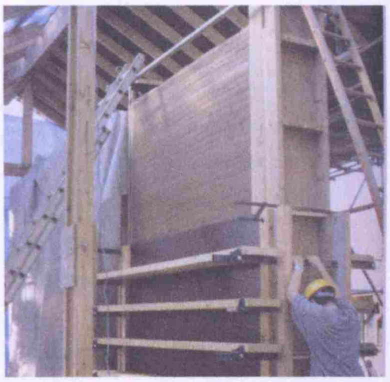


Fig. 49: Earth Raw rammed soil assembly- Harris C Borer P (1998) *The Whole House Book –Ecological Building Design and Materials* – CAT

Rammed earth is very strong in compression and can be used for multi-storey load-bearing construction. Earth walls perform better under earthquake conditions than walls made of separate bricks or blocks. It can function like thermal mass by absorbing or 'slowing down' the passage of heat through it and then releases that heat when the surrounding ambient temperature goes down. In fact, rammed earth behaves as a heavyweight masonry element with a high thermal mass capacity. Rammed earth possesses a generally high durability but all types of rammed earth walls are porous by nature and need protection from driving rain and long term exposure to moisture. It is essential to maintain water protection to the tops and bottoms of walls. Continued exposure to moisture may degrade the internal structure of the earth by reversing the cement stabilisation and allowing the clays to expand[149].

146 http://greenhouse.gov.au/yourhome/technical/fs34c.htm 11/08/06
147 http://greenhouse.gov.au/yourhome/technical/fs34c.htm 11/08/06
148 http://greenhouse.gov.au/yourhome/technical/fs34c.htm 11/08/06
149 http://greenhouse.gov.au/yourhome/technical/fs34c.htm 11/08/06

The embodied energy of rammed earth is low to moderate. With 0,31 GJ/m2 required for production and 0,41 GJ/m2 for transportation, rammed earth is composed of selected aggregates bound with cementitious material and can be thought of as a kind of 'weak concrete' with overall embodied energy of 0,72 GJ/m^2. Although it is a low greenhouse emission product in principle, transport and cement manufacture can add significantly to the overall emissions associated with typical modern rammed earth construction. The most basic kind of traditional rammed earth has very low greenhouse gas emissions but the more highly engineered and processed variant of rammed earth has the potential for significant emissions[150].

Since it presents zero maintenance requirements, earth raw rammed soil appears to be very appealing financially with only 18-33 GJ/m^2 total cost over 50 years.

	Earth raw rammed soil
Lifetime	indefinite
Density	1850 kg/m3
Width	40 cm
Embodied energy (Cradle to gate) [151]	
extraction	
transport	
production	0,42 GJ/tonne 0,31GJ/m2
Transport [152]	0,55 GJ/tonne or 0,41 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others
Recycling[153]	non recyclable
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0
Total for 25years	0,72 GJ/m2
Total for 50years	0,72 GJ/m2
Cost Estimation[154]	
Capital cost (as material)	–
Capital Cost (incl initial cost+labor)	–
Capital Cost including Replacement Factor	–
Cost for maintainance (once)	–
Frequency for maintainance	0
Cost for maintainance over 50 years	0
Total Cost per year	18-33
Total Cost over 50 years	18-33

Table 17: Earth raw rammed soil

150 http://greenhouse.gov.au/yourhome/technical/fs34c.htm 11/08/06
151 Appendix 2
152 Appendix 3
153 Appendix 3
154 Appendix 4

4. Summary of results

4.1 Overall Summary

The particular characteristics of the external appearance of each wall cladding material as well as the subjective taste of the architect makes the comparison between all of them by aesthetic criteria alone impossible and vain. However, their assessment according to their impacts on environmental and financial level is not only feasible but also compulsory in order to choose the most cost effective solution in energy and economical terms[155].

As yardstick the apparent lifetime of each wall cladding material, it is evident that earth materials which are included in the roughcast category present high durability and are long-lasting, with natural stone, concrete blocks and earth raw rammed soil presenting an indefinite lifetime (more than 150 years), as well as several shiny surface materials like copper, steel, aluminium and stainless steel presenting 200, 75 and 100 years lifetime respectively (fig 50). Their physical properties as well as their satisfying resistance to weather conditions contribute to this result. On the other hand, zinc and polycarbonate seem to be the most short-lived options with 20 and 12-20 years lifespan respectively, requiring more frequent replacements and additional financial and energy costs. In advanced, considering that zinc presents low durability and relatively high embodied energy (0,29 GJ/m^2), as well as the fact that polycarbonate is been absorbed by the ecosystem after the end of its life (after 10 years) with difficulty, their selection seems rather non beneficial. All other materials examined in this study present an average life span of 50-100 years.

In an attempt to evaluate their environmental behaviours, embodied energy values are being compared in figure 51. The most energy demanding material seems to be imported stone with 3,39 GJ/m^2, a figure increased by the high energy demand for transportation due to it's high density and weight. Second worst in the overall ranking of wall cladding materials appear concrete products (aerated blocks) with 2,29 GJ/m^2 as well as polycarbonate with 1,68 GJ/m^2 , both deriving from different raw materials which require long lasting and tough manufacturing processes until they are suitable for application in construction. As expected, the most environmental friendly materials with minimum environmental consequences are striped surface materials including

[155] Appendix 4

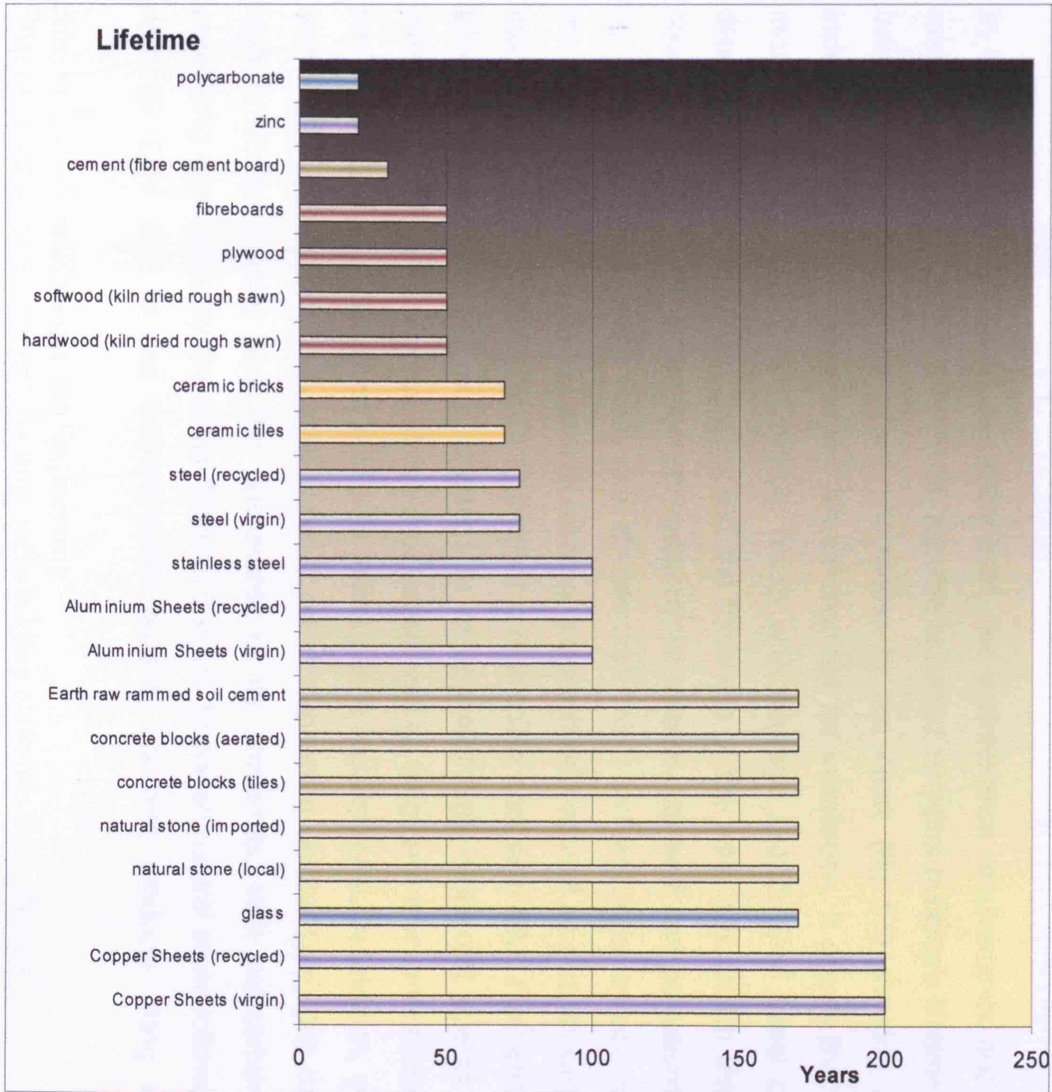


Fig. 50: Lifetime of all materials

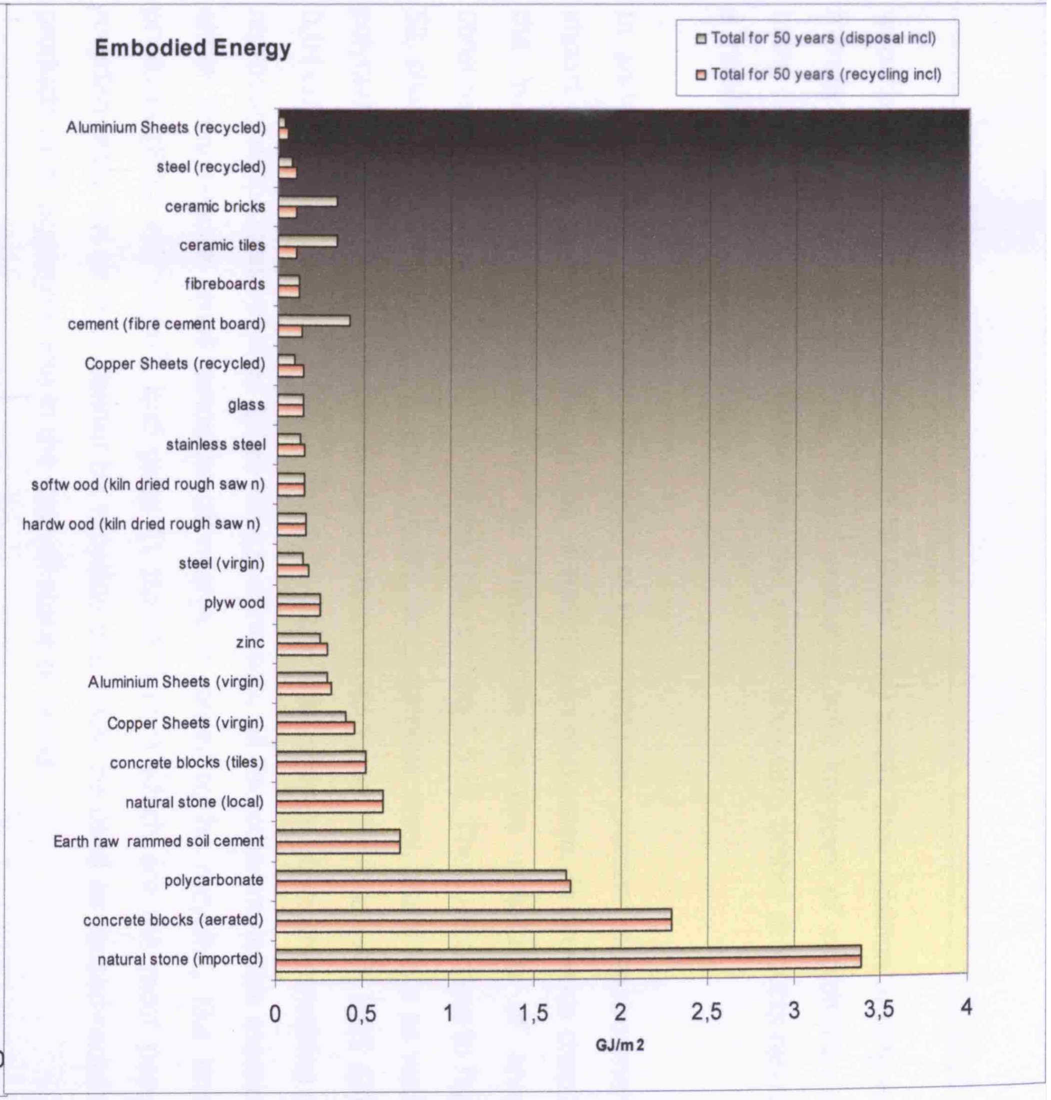


Fig. 51: Embodied Energy of all materials

wood products. With an average of 0,18 GJ/m^2 they justify their position among eco-friendly materials. Deriving from natural resources with low level of exploitation and being normally absorbed by nature after the end of their use, timber products result in a minimum impact to the ecosystem.

In addition, a very important parameter in the evaluation process of environmental impact is the ease and the energy cost of recycling in each case. In previous chapters the importance of recycling and its contribution to the reduction of energy consumption has already been mentioned (see section 1.5.6). Thus, according to figure 52, shiny surface materials including copper, zinc, stainless steel, aluminium as well as polycarbonate require great energy amounts in order to be recycled with 0,05 GJ/m^2 0,04 GJ/m^2 0,03 GJ/m^2 0,02 GJ/m^2 and 0,01 GJ/m^2 respectively, since the smelting and reproduction process requires large energy demands. All the other materials examined either they require small amounts of energy in order to be recycled, like timber products (8,82 x10^{-7}GJ/m^2) and glass (1,10x10^{-7}GJ/m^2) which are the most popular recycled materials or they cannot be recycled and could be used as reused-reclaimed products or as aggregate like in the case of stone or bricks.

In terms of cost evaluation, the initial cost, the maintenance requirements and the overall cost of each cladding material over the assumed 50 years building's lifetime are being investigated and compared. According to the chart (fig 53) showing cost including purchase of material and labour required for installation, it seems that the most expensive solution are ceramic bricks with average 183,55 £/m^2 initial cost, depending on the type, the quality and the thickness of the wall. It is known that in order to achieve better insulation attributes to the interior, brickwall can be assembled by multiple layers of bricks (half, one, double brick thick) increasing the initial cost of the investment. Following the overall ranking, copper sheets as well as smooth surface materials (glass and polycarbonate) present a high initial cost with 80,3 £/m^2 and 65 £/m^2 respectively. Even though copper has an apparent high initial cost due to the intensive manufacture process, it could be considered as long term investment since it has a long lifetime (200 years) and zero maintenance requirements. In addition, glass seems an expensive solution with variable prices depending on the type, due to its high embodied energy and the uniqueness of its properties, with polycarbonate presenting approximately the same financial burden. Imported natural stone follows up with 65 £/m^2 due to the transportation burden, concrete products along with

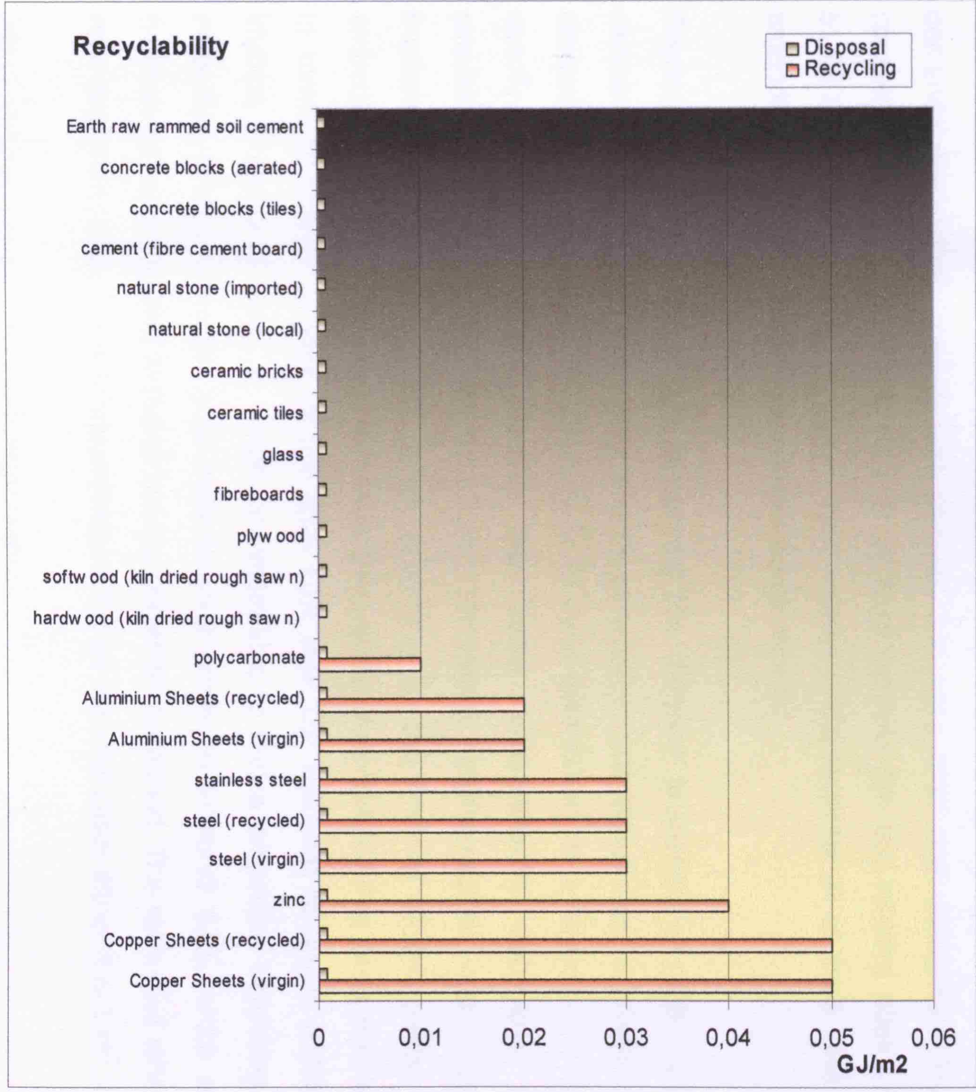


Fig. 52: Recyclability of all materials

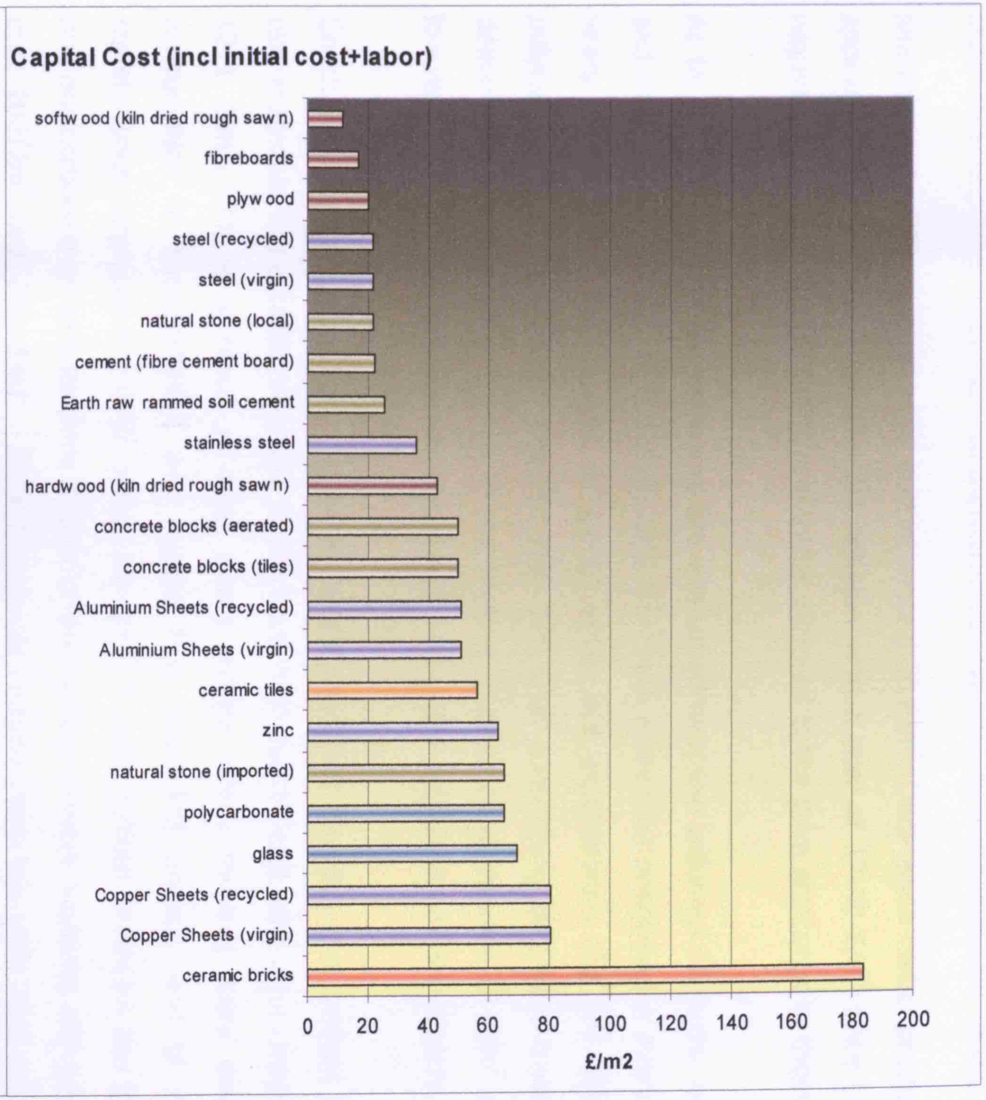


Fig. 53: Capital Cost of all materials

aluminium sheet present an initial cost of around 50 £/m^2. Once again timber products appear to be the most cost-effective solution with a cost of 17-40 £/m^2 since they require a low level of exploitation and this is mirrored to the price attributed to them.

As far as maintenance requirements are concerned over the assumed 50 years, brick and tiles seem to be high priced with 1166 £/m^2 each since their maintenance every 10 years includes also replacement of pieces which are weatherworn (fig 54). Glass, polycarbonate and aluminium proceed with 135 £/m^2 considering only their cleaning demands every 6 months. Lowest in the ranking appears concrete with 12 £/m^2 with low requirements like replacement of cement mortar and application of new plaster.

Concluding the cost comparison of all materials examined (fig 55), it is evident that clay materials like ceramic tiles and bricks have high overall cost with an average of 1221 £/m^2. This is a result of their heavy weight which requires more energy consumption in transportation and overall high embodied energy, and of their maintenance –replacement costs when required. Smooth surface materials like glass and polycarbonate as well as shiny metals follow up as expensive solutions with overall cost 200£/m^2 and 330 £/m^2 . Both categories include materials with high energy demands during their manufacture process increasing their cost evaluation. Finally, concrete and timber products as well as steel possess the last ranking places with 61,78 £/m^2 and 21,55£/m^2 respectively, considering the fact that all of them have low embodied energy and low maintenance requirements.

Bearing in mind all the above concerning the different properties of each material examined, their comparison either in environmental or economical level is feasible and desirable since comparative indicators have been established. In a further attempt to specify which material presents the better environmental behaviour with simultaneously minimum financial cost eliminating environmental and financial burdens, difficulties are been faced. According to the findings of this study, the embodied energy of individual materials throughout their lifecycle has been estimated in terms of GJ/m^2, as well as the total cost over the assumed 50 years building's lifetime in terms of £/m^2. It would be reasonable to find a proportion indicating the embodied energy value for each material over pound in terms of GJ/£, which could function as a comparative indicator among materials examined. This ratio GJ/£ which is referring to a specified unit of measurement for all material cases either it is 1 m^2, 10

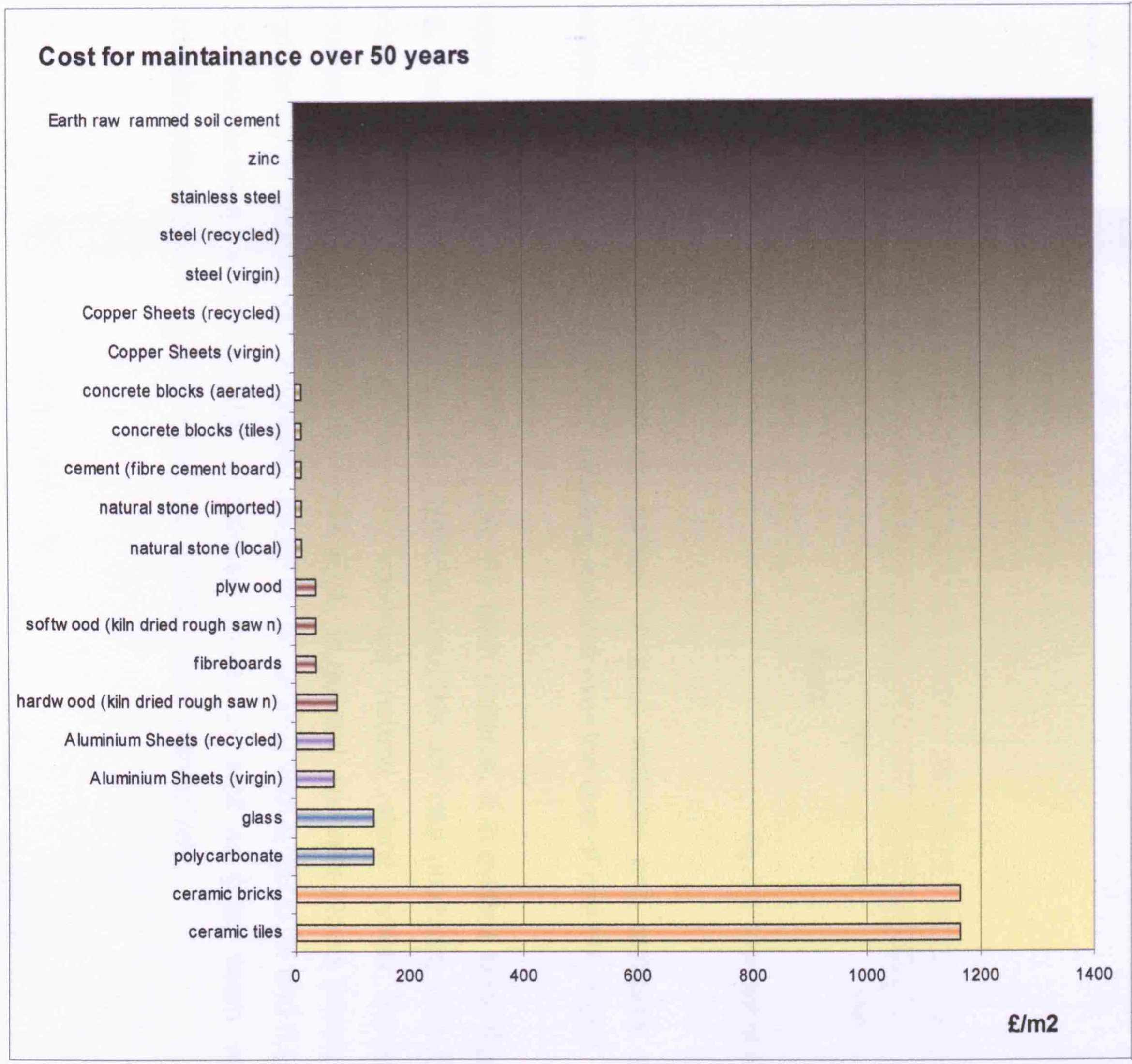


Fig. 54: Cost for maintenance of all materials

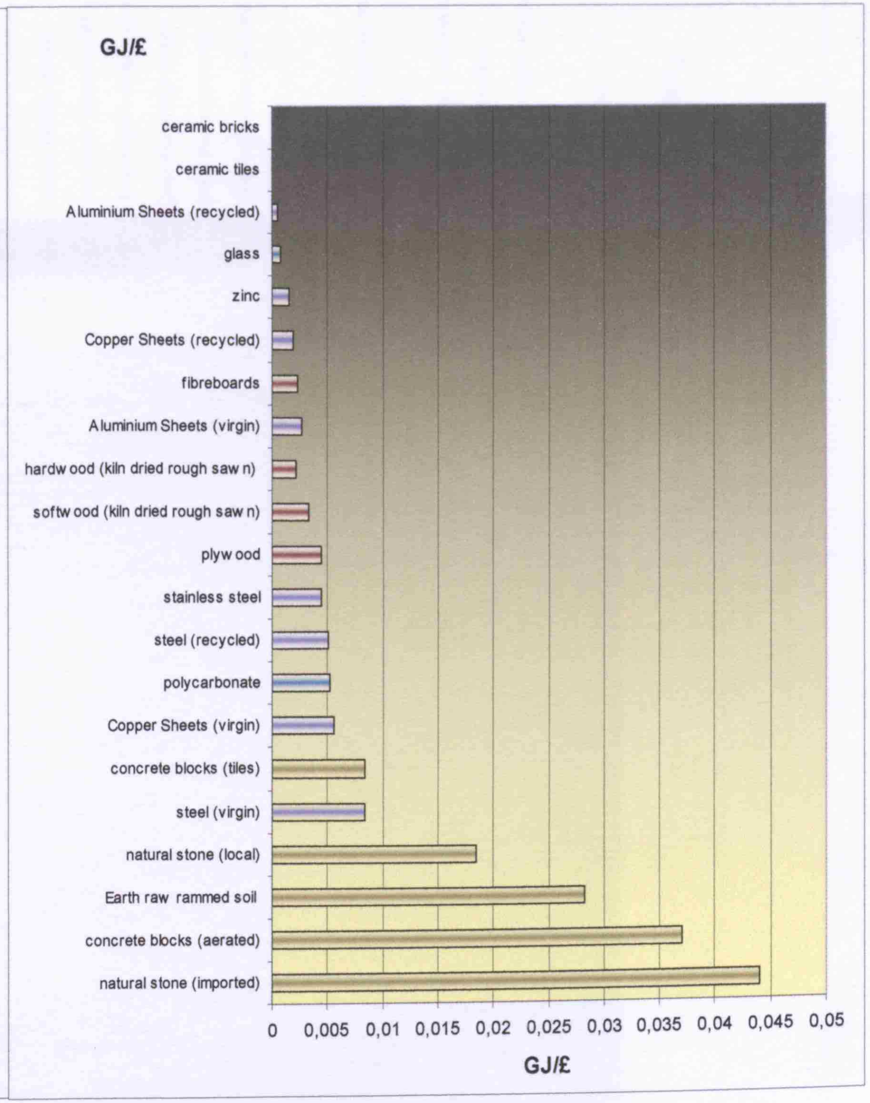


Fig. 56: Embodied Energy per £ of all materials

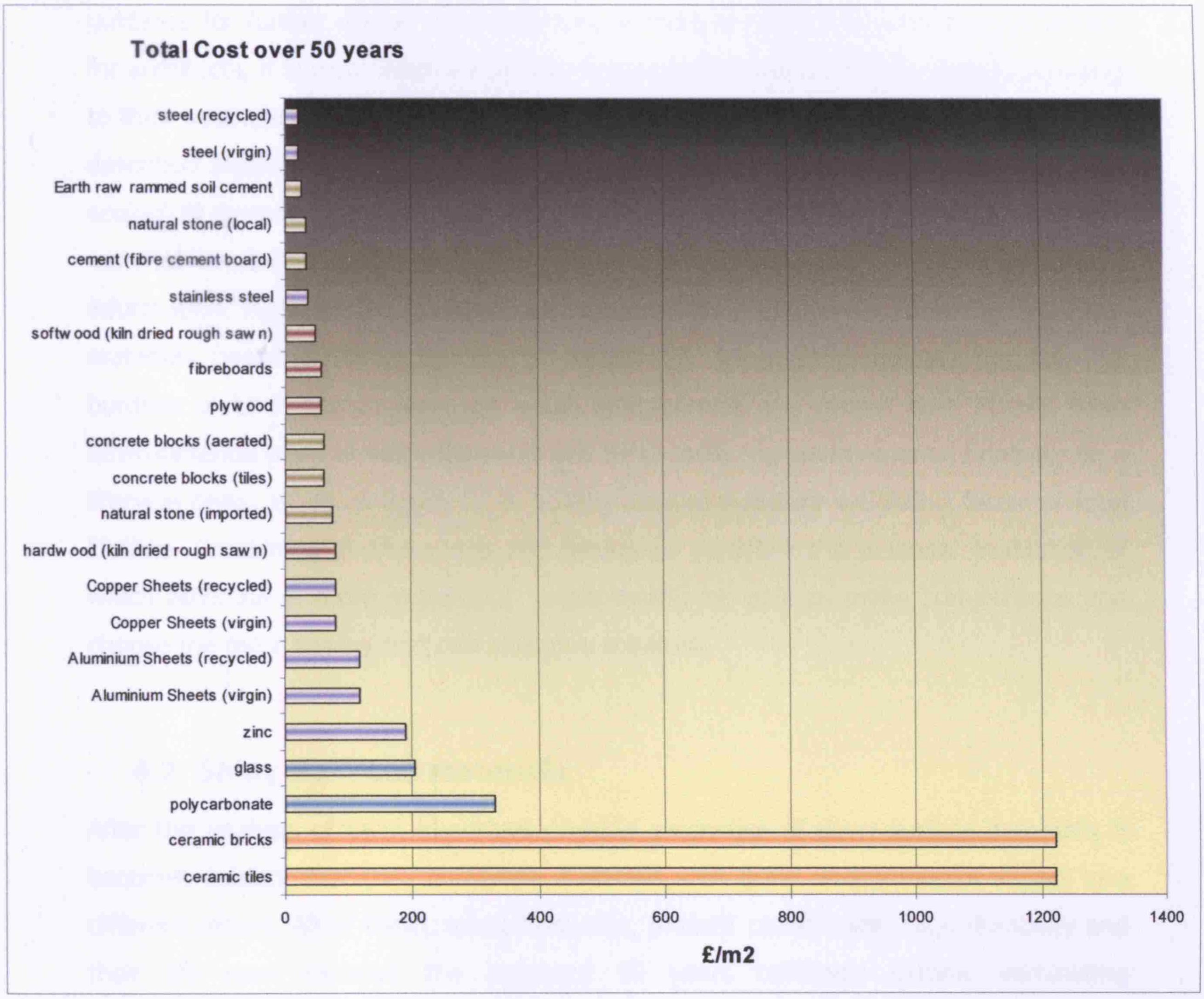


Fig. 55: Total cost of all materials

m^2 or 100 m^2, is independent on surface of each material and indicates the environmental burden of each wall cladding material over the cost of one UK pound.

Hence assuming for instance 1 m^2 surface for each material, it is evident from figure 56, that the most cost and energy beneficial materials are clay products, tiles and bricks with $9x10^{-5}$ GJ/£ contrary to imported natural stone which burdens environmentally and financially with 0,044 GJ/£. In general, concrete blocks (aerated) and earth raw rammed soil are highly placed in the ranking with 0,037 GJ/£ and 0,028 GJ/£ respectively, while recycled aluminium sheets as well as glass seem very profitable solutions with 0,00051 GJ/£ and 0,00073 GJ/£ respectively.

After the analysis of comparative tables among materials examined, it should be given guidance for further use of this handbook. In order to make this guide more practical for architects, it is recommended at first to choose the wall cladding material according to their aesthetic preferences among the 5 set categories. Then, making use of figures described above they would be able to make choices having in mind the financial and ecological impact of their decisions. In an attempt to choose the most profitable material in environmental and financial terms, figure 56 can provide with relative information. Furthermore, in more detailed investigation, in order to choose potential materials based on financial criteria, figures 53, 54 and 56 indicate the financial burdens of each one in terms of initial, maintenance and overall cost. Finally, from environmental point of view, figure 51 and 52 present the environmental behavior on a lifecycle basis, whereas figure 50 is adding a supplementary weighting factor of total lifetime. Combining all the above and having as yardstick the personal evaluation of which attribute is more important, users would be able to make comparisons and choose the most energy and cost effective solutions.

4.2 Shiny Surfaced materials

After the analysis of most important physical properties of shiny surface materials, it becomes evident that they constitute materials with great environmental impact in a different extent. All of them, apart from zinc, present considerably high durability and their life span exceeds the assumed 50 years building's lifetime eliminating replacement requirements. The most durable and long-lived material is copper with 200 years lifetime and zero maintenance requirements due to its physical properties, compared to zinc which needs to be replaced every 20 years. On the other hand, the durability of copper is being followed by intensive energy requirements since it presents the maximum value of embodied energy among all shiny surface materials. Furthermore, the material with the lowest embodied energy in this category is recycled aluminium with 0,06 GJ/m^2, result which certifies the contribution of recycling to the overall environmental performance of materials tested.

Consequently, virgin copper sheets, which are recycled at the end of their use, present the highest embodied energy among shiny surface materials with 0,45 GJ/m^2 whereas virgin copper sheets which are disposed at the end as well as recycled steel sheets follow up with 0,40 GJ/m^2 . From figure 57 it becomes evident that recycling contributes noticeably to the reduction of embodied energy. In the case of aluminium, the use of recycled substance as raw material requires almost 1/5 of the initial energy of producing metal sheets using virgin ore. The same is been observed in the case of copper which requires the greater energy in order to be recycled (0,05 GJ/m^2) but it seems to have a sort of redemption of this extra energy needed for recycling long term. Using recycled copper as raw material embodied energy is being diminished to 1/5 of the initial with the use of virgin cooper, meaning from 0,45 GJ/m^2 to 0,15 GJ/m^2. On the other hand, the easiest recyclable material and the least energy intensive is aluminium with energy required for recycling around 0,02 GJ/m^2 and recycled steel is coming along with 0,08 GJ/m^2.

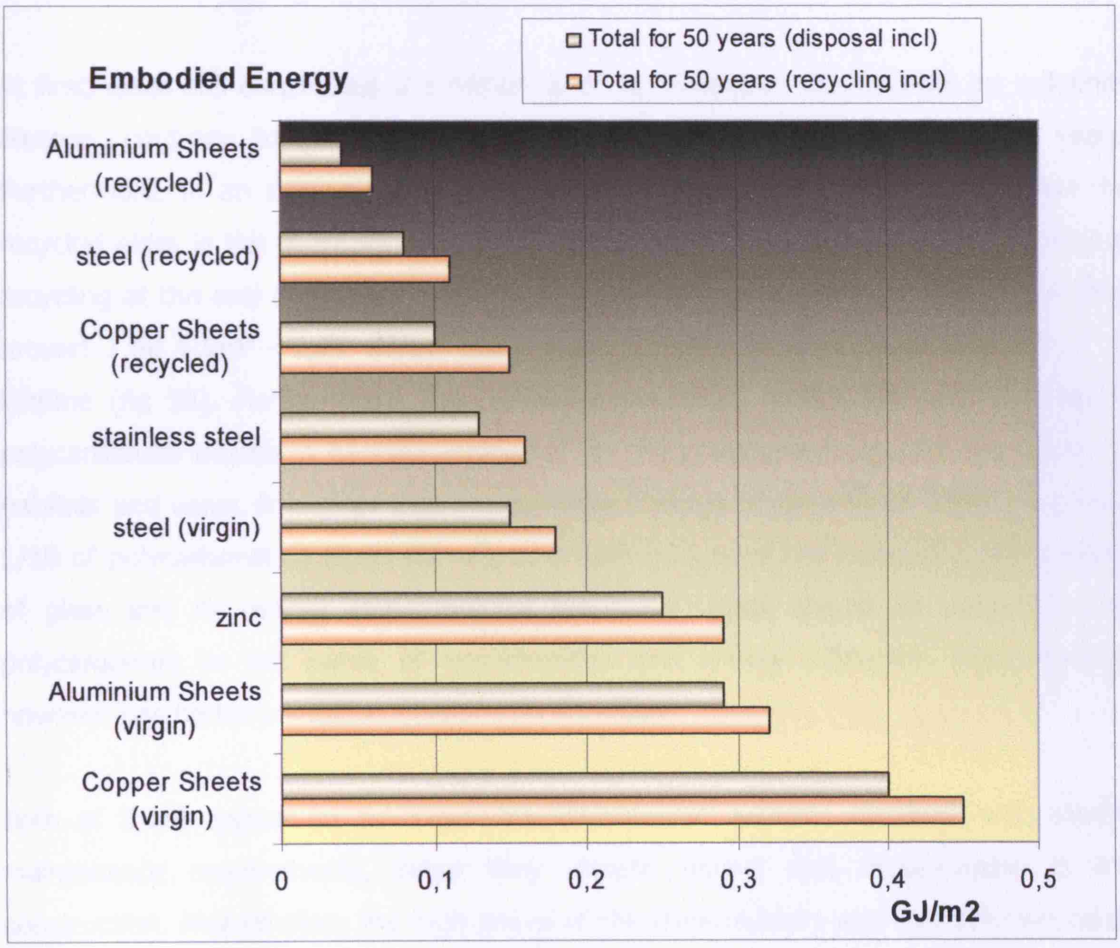


Fig. 57: Chart with embodied energy among shiny surface materials

From financial point of view, the most expensive solution seems to be zinc with an overall cost of 188,79 £/m^2 over 50 years compared to steel which seems to be the cheapest solution with 21,55 £/m^2 . Even though zinc presents a similar capital cost (including labour) to copper at around 65 £/m^2, its short lifetime of 20 years and its replacement demands increase the initial cost appointing it as an expensive solution. Second placed in the price ranking of shiny materials is aluminium with 118 £/m^2 which is the only material in this category which requires cleaning every 6 months raising the total cost over 50 years.

4.3 Smooth Surface

Glass and polycarbonate, the two representative materials which where examined in the category of smooth surface claddings, constitute industrialized products with intensive energy requirements. Both of them are ranked in the highest positions of the unitary table with all materials' embodied energies.

At first, glass still constitutes the certain and most durable solution with an indefinite lifetime, contrary to polycarbonate which has to be replaced every 20 years. Furthermore, in an attempt to compare the two of them, it becomes clear that the recycled glass is the more environmental friendly solution with 0,15 GJ/m^2 (including recycling at the end of its use) whereas polycarbonate presents high energy cost with around 1,68 GJ/m^2 - 1,71 GJ/m^2 either with disposal or recycling at the end of its lifetime (fig 58). Furthermore, the general exploitation, installation and recycling of polycarbonate results in harmful emissions for the environment and for the health of habitats and users. It is clear that the embodied energy of glass (0,15 GJ/m^2) is almost 1/10 of polycarbonate's (1,68 GJ/m^2), and having in mind the external characteristics of glass and its overall environmental behaviour, glass should be preferred over polycarbonate in the name of sustainability and energy efficiency. Polycarbonate however has better insulation qualities for its mass.

Both of them appear to be expensive solutions of external cladding, with similar maintenance requirements, since they remain unique and irreplaceable in the construction. Nevertheless the high prices of the glass industry and the different types of glazing surfaces which are available on the market around 161,8-247 £/m^2 , polycarbonate presents higher total cost over the 50 years with 315-345 £/m^2 due to its limited lifespan and the need for frequent replacement.

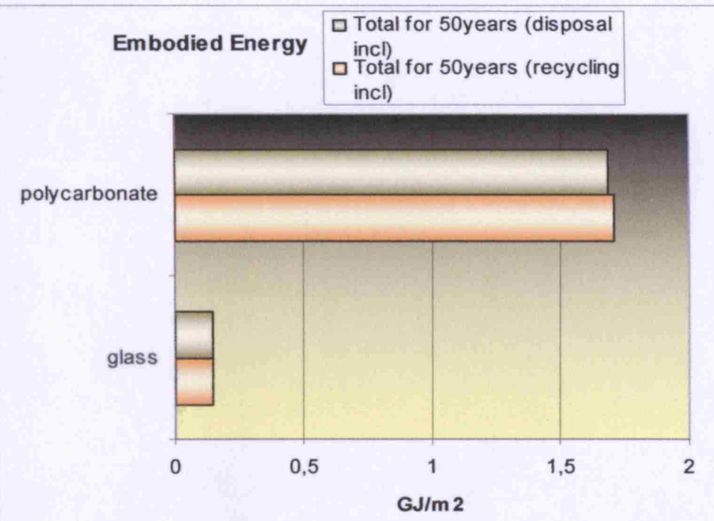


Fig. 58: Chart with embodied energy among smooth surface materials

4.4 Surfaces assembled with grid

Clay products like tiles and bricks seem to be an energy intensive option due to their firing requirements and due to their heavy weight which complicate their transportation. Those two factors contribute to the increase of the energy cost of production and transportation even though they both derive from natural infinite resource (mainly clay).

Apart from that, they present the same environmental impact with total embodied energy of 0,11 GJ/m^2 over 50 years, with no ability to be recycled and with approximately the same initial cost around 570 £/m^2 over 50 years. Their relative low initial cost of 15,37-62,23 £/m^2 is been raised by the maintenance and replacement of pieces which are destroyed over time once every 10 years contributing to the increase of financial cost.

In general they constitute a solution which cost financially and environmentally with no special profit and which continues to be favourable due to the ease of assembly as well as to its place in the traditional architectural style.

4.5 Striped Surfaces

From the analysis so far it becomes evident that the materials in this category, in addition to recycled metals, are the most environmental friendly options with minimum impacts in global and local environment. Even though they present limited lifetime, around 50 years, their low maintenance requirements enhance them as favourable choices. Their covering with protective coatings against moisture and insects every 5 years, postpones their life span without the use of any other advanced means of maintenance.

Compared to other cladding materials, timber products present the lowest figures of embodied energy certifying their energy effectiveness. Plywood since it derives from timber product with additional manufacture process, presents the highest embodied energy of 0,25 GJ/m^2 whereas softwood present the lowest of 0,16 GJ/m^2 (fig 59). Fundamental factor which contributes to the increase of the figure of embodied energy is the importing of timber from overseas. In the case of Douglas fir, which is imported from Canada, the transportation is being made by boats reducing the energy consumption and as result releasing less CO2 emissions compared to other means of transportation. That is why it is important to have as first priority the choice of locally sourced materials or those with minimum environmental impact.

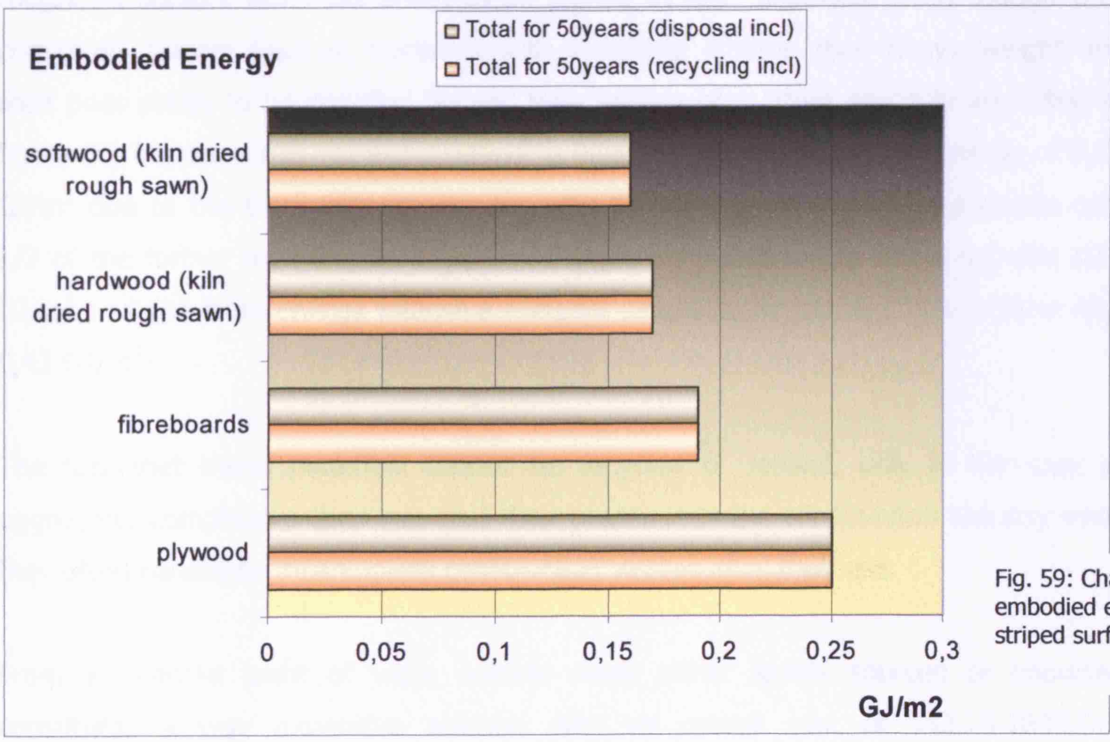


Fig. 59: Chart with embodied energy among striped surface materials

It is important to point out that for all types of timber products the required energy for recycling, disposal and installation has been assumed the same. Observing the table with the embodied energy figures, it is noticed that the choice of recycling or disposal after the end of the use does not constitute a variable element in the case of timber. Further consideration shows that recycling of timber products may not differentiate figures but contributes to the maintenance of the natural balance and to the protection of the ecosystem.

Finally, the ease of their assembly and installation in relation with their environmental behaviour enhance them as favourable choice with low prices and maintenance requirements compared to the other cladding materials. Thus, their prices fluctuate around 60 £/m^2 over 50 years, including recoating once every 5 years for protection against insects and moisture, with hardwood being the most expensive solution with 74,85-84,41 £/m^2 due to its durability and softwood being the cheapest with 41,55-55,29 £/m^2 since it is more abundant in the nature.

4.6 Roughcast surfaces

In the general ranking of wall cladding materials according to their embodied energy, roughcast surface materials seem to be placed in high positions. Even though they constitute natural sourced materials with indefinite lifetime their heavy weight and their poor ability to be recycled burden their energy cost. More precisely according to figure 60, imported natural stone seems to have a very high embodied energy of 3,39 GJ/m^2 due to the transportation burden whereas locally sourced stone presents only 1/7 of the former meaning 0,44 GJ/m^2 . Concrete aerated blocks follow up with 2,29 GJ/m^2 and the least energy intensive material seems to be cement fibre boards with 0,42 GJ/m^2.

The fact that these materials cannot be recycled or reused, only in the case of aggregate, complicates their role and their presence in the construction industry since they often constitute meaningless construction wastes after their use.

From a financial point of view, natural stone either locally sourced or imported constitutes a very expensive solution with an overall cost of 542,16-1832,612 £/m^2,whereas earth raw rammed soil and fibre cement boards seem to be the most beneficial with 18-33 and 27,16-40,83 £/m^2 respectively. The fact that natural stone requires energy to be transported as well as the maintenance cost which include replacement of pieces once every 10 years in case of decay, contributes to the increased price whereas fibre cement boards having low insulation characteristics constitute cheaper but not very effective solutions.

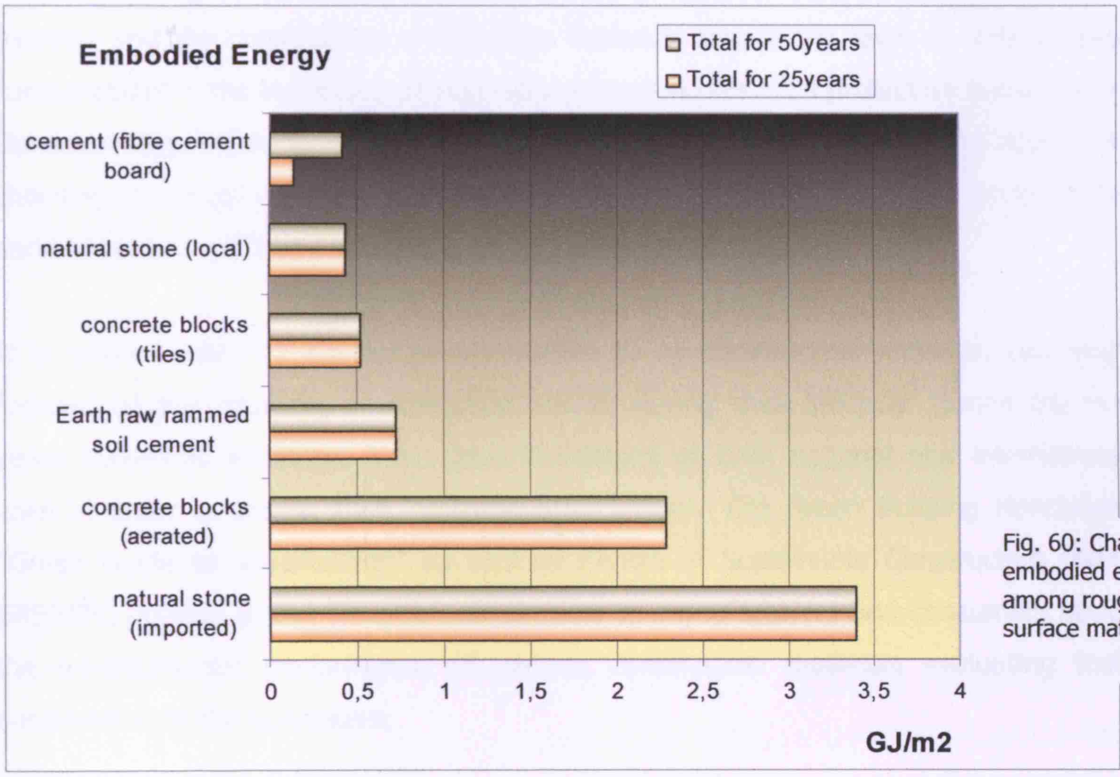


Fig. 60: Chart with embodied energy among roughcast surface materials

5. Conclusions

In this age of the energy crisis where the level of ecological danger is increasing worryingly, the sensitization and mobilization of governmental organisms as well as individual attitude is compulsory and the meaning of sustainability and environmental design obtain determinant importance. Since it is estimated that in the case of industrial countries the percentages of energy associated direct or indirect with the function and the construction of buildings fluctuate around the level of 50% of total consumption[156], the institution of regulations for environmental protection is necessary. Consequently, architects are obliged with their choices, either at the design level or in choosing construction materials, to achieve a minimum burden on natural environment and to human health and to contribute to the energy saving.

It is evident that the environmental burden of all construction materials has been focused on the counting of embodied energy during their lifecycle. During the last years numerous indicators have been developed at both national and international level in order to assess their environmental impact. The Green Building Handbook, "Green Guide to specification" as well as Centre of Sustainable Construction (BRE, BREEAM) provide useful lifecycle assessments to manufacturers and consumers about the environmental performance of various construction materials evaluating their contribution to the ecosystem.

Nowadays, the importance of choosing eco-friendly materials has been proven by the attempts to impose ecological labeling to each construction material from International and Governmental Organisations. Ecological labeling is an encouraging parameter in the wide field of construction materials. Unfortunately, so far, the number is limited and concerns one small part of the total of construction materials. However, according to European Union, ecological labelling is being imposed by regulation. This labelling constitutes a guarantee that these materials own the least environmental impact. Further efforts have been made in order to establish the constitution and the acceptance of international

Fig. 61: European Union ecological label

[156]Boyle G (1996) *Renewable energy: power for a sustainable future,* Oxford University Press Oxford

standards according to which the ecological quality of each product will be testified. So far, in Europe, ecological labelling with different standards and methodology are been provided by European Union (European Ecological Labelling), Germany (blue angel), Scandinavian countries (Scandinavian swan), Austria (Umweitzeichen–Baome), France (NF-Environment) and Spain (Aenor-Medio Ambiente). To this direction all efforts of ISO (International Standard Organization) are leading with starting the publication of standard ISO 14040 of 1996, which defines the basic principles applied for the Life Cycle Analysis[157].

The novelty of this study is the edit of an architectural guide where 17 fundamental wall cladding materials are been categorized according to aesthetic criteria and their physical properties in 5 basic categories and for each one environmental and economical evaluation, examining values like embodied energy, recyclability, lifetime as well as cost throughout the assumed 50 years building's lifetime, are been carried out. The final aim is to set comparative environmental and financial indicators between materials in the disposal of architects in order to have the ability to compare materials with similar physical properties and to choose the most energy and cost effective.

According to the summary of comparisons between the different materials, it is obvious that embodied energy cannot constitute environmental indicator on its own. Factors like overall lifetime, easiness and energy cost of recycling as well as their contribution to the reduction of operational energy, determine the long term redemption and assimilation of the initial embodied energy and the energy - cost effectiveness of each material. For example, the high embodied energy of concrete blocks is equilibrating with the long term lifetime and the minimum maintenance requirements. Similar case is copper sheet which could be considered as long term investment where the high initial cost is been written off during the 200 years of lifetime, contrary to polycarbonate which even though presents a high embodied energy the apparent lifetime does not make it beneficial.

Due to limited time for the elaboration of this study, editing of limited fundamental construction materials among the wide range of those which are available on the market has been achieved. Further study and recording of more materials and the expansion of categories according to aesthetic criteria (ex porous surfaces, grainy

[157] ISO 14040 "Life Cycle Analysis- General Principles and Guidelines"

surfaces etc) would contribute to the enrichment of this guide and would expand the range of choices available. In the meanwhile, since the technology is evaluating in rapid steps and the technology of materials is been improved every day, this guide should be updated and be improved following the contemporary needs.

Further investigation and laboratory research need to be carried out for the complete evaluation of the used construction materials. The process has recently started and for the moment is depending on a plethora of peremptoriness and subjectivism. For that it becomes necessary to establish valid sources of information in order to avoid the use of harmful materials where this is possible.

The sensitization and the protection of environmental issues by taking actions are governmental and individual responsibility. Governments have the obligation to offer the information required about environmental impacts of materials to consumers and to enhance the research and the recording of environmental guides. In advanced, they should take active actions for the institution of ecological parameters in the construction reinforced by potential taxes on harmful materials and applied techniques. As architects and consumers it is important to have in mind that there is a wide range of materials with similar physical properties and textures but with very different environmental behaviors. Equalizing embodied energy values, with lifetime and recyclability the correct choice with minimum ecological cost is not only feasible and desirable but also imperative.

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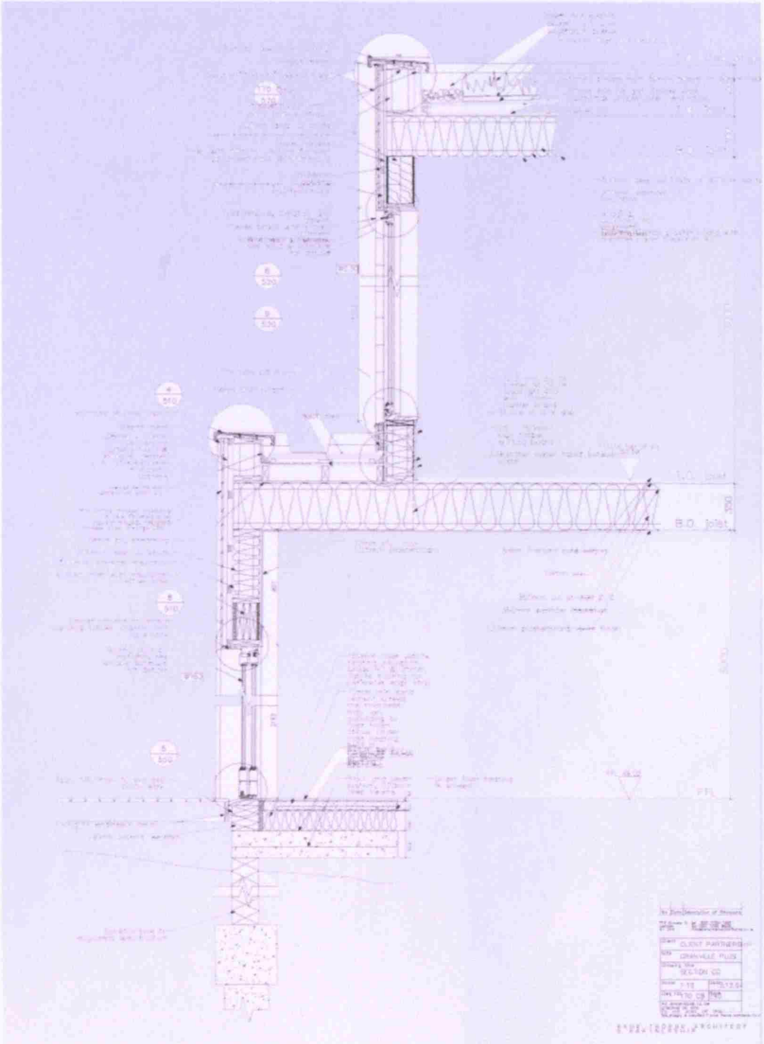
7. Appendices

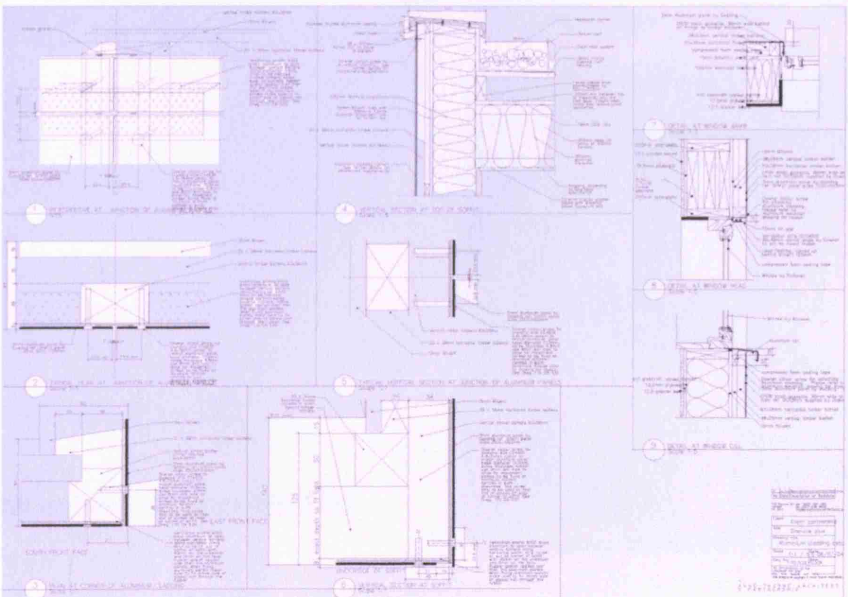
Appendix 1 (Granville Plus - drawings and pictures)

First Floor plan - Source AT Architects

South Elevation – Source AT Architects



Section – Source AT Architects



Construction Details – Source AT Architects

General aspects of Granville Plus

BRE Environmental profile matching with construction characteristic of Granville Plus

BRE

BRE Certification Limited

Approved Environmental Profile

Characterised and Normalised Data for:

1 square metre over 60 Year Life: External Wall: Framed Wall Construction: preserved softwood timber weatherboarding, battens, cavity, 9.2mm waterproof fibre board wall sheathing, preserved softwood studwork, Warmcel insulation (damp sprayed), 12.5mm plasterboard.

Quality of Data for Certified Material (Data for other constituent materials are available from BRE)

Start Date	**1 April 2001**
End Date	**31 March 2002**
Source of Data	**Excel Industries**
Geography	**UK**
Representativeness	**1 Site Representing 100% of Warmcel Production**
LCA Methodology	**BRE Environmental Profiles**
Allocation	**100% to Product**
Date of Data Entry	**30 April 2003**
Boundary	**Cradle to Grave over 60 Year Building Life**
Comments	

Issue	Characterised Data	
Climate Change	**31**	**kg CO2 eq. (100yr)**
Acid Deposition	**0.31**	**kg SO2 eq.**
Ozone Depletion	**0.00000019**	**kg CFC11 eq.**
Pollution to Air: Human Toxicity	**0.38**	**kg tox.**
Pollution to Air: Photochemical Ozone Creation Potential	**0.76**	**kg ethene eq.**
Pollution to Water: Human Toxicity	**0.00004**	**kg tox.**
Pollution to Water: Ecotoxicity	**2900**	**m3 tox.**
Pollution to Water: Eutrophication	**0.046**	**kg PO4 eq.**
Fossil Fuel Depletion	**0.012**	**toe**
Minerals Extraction	**0.096**	**tonnes**
Water Extraction	**32**	**litres**
Waste Disposal	**0.068**	**tonnes**
Transport Pollution & Congestion: Freight	**88**	**tonne.km**
Issue	Normalised Data	
Climate Change	**0.0025**	**12300 kg CO2 eq. (100yr)**
Acid Deposition	**0.0052**	**58.9 kg SO2 eq.**
Ozone Depletion	**0.00000065**	**0.296 kg CFC11 eq.**
Pollution to Air: Human Toxicity	**0.0042**	**90.7 kg tox.**
Pollution to Air: Photochemical Ozone Creation Potential	**0.024**	**32.2 kg ethene eq.**
Pollution to Water: Human Toxicity	**0.0034**	**0.0117 kg tox.**
Pollution to Water: Ecotoxicity	**0.016**	**178000 m3 tox.**
Pollution to Water: Eutrophication	**0.0068**	**8.01 kg PO4 eq.**
Fossil Fuel Depletion	**0.0029**	**4.09 toe**
Minerals Extraction	**0.019**	**5.04 tonnes**
Water Extraction	**0.000076**	**418000 litres**
Waste Disposal	**0.0094**	**7.19 tonnes**
Transport Pollution & Congestion: Freight	**0.021**	**4140 tonne.km**
Primary Energy	**0.43**	*GJ*
[illegible]	0.5	[illegible]

Appendix No: 278e **Valid To:** 07/05/06

Issue No: 1

Signed on behalf of BRE Certificatio _ C K Beedel

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Appendix 2 (Embodied energy)

	Source	Aluminium	Timber	Ceramic	Glass
1	**Timber Building in Australia** http://oak.arch.utas.edu.au/tbia/view_article.asp?articleID=107	435 MJ/kg	15 MJ/kg		
2	**CSIRO Manufacturing and materials technology** http://www.cmit.csiro.au/brochures/tech/embodied/	180 GJ/tonne	10-20 GJ/tonne	25 GJ/tonne	90 GJ/tn
3	**New Zealand embodied energy coefficient** http://www.vuw.ac.nz/cbpr/documents/pdfs/ee-coefficients.pdf#search=%22embodied%20energy%20coefficient%20alphabetical%22	199 MJ/kg (virgin) 14,8 MJ/kg (recyc)	1,6 MJ/tonne	2,5 MJ/kg (brick) 2,5 MJ/kg (tile)	15,9 MJ/kg
4	http://www.greenhouse.gov.au/yourhome/technical/fs34a.htm	170 MJ/kg	3,4 MJ/kg (softwood)	2,5 MJ/kg	12,7 MJ/kg
5	**Sustainable Homes** http://www.sustainablehomes.co.uk/		144 Kwh/tonne	60 Kwh/tonne	528 Kwh/tn
6	http://www.newbuilder.co.uk/	550 - 920 MJ/m2 30-90 MJ/m2 (recycl)		270-430 MJ/m2	
7	**CIRIA (1995*) Environmental Impact of Materials Special publication 116,*** Volume A-Summary , Construction Industry Research and Information Association, UK		195-250 kwh/tonne imported 158 kwh/tn (indigenous)	76 kwh/tn	
8	http://www.canadianarchitect.com/asf/perspectives_sustainibility/measures_of_sustainablity/measures_of_sustainablity_embodied.htm	227 MJ/kg	2,5 MJ/kg	2,5 MJ/kg (brick) 2,5 MJ/kg (tiles)	15,9 MJ/kg
9	www.cda.org.uk/megab2/build/pub-154-guide-to-copper-in-architecture.pdf	115,4 MJ/m2			
10	http://www.greenhouse.gov.au/yourhome/technical/fs31.htm	250 Btu/tn (virgin) 95% energy saved by recyclig			
11	**Sustainability and End User Expectations** http://www.environ.ie/DOEI/DOEIPol.nsf/0/75fb4dee289541c980256f5d0045f6cb/$FILE/TFHC2002_Chapter%206.pdf#search=%22sustainability%20user%20embodied%20energy%22	200 GJ/tn	13 GJ/tn	5,8 GJ/tn	

12	**Msc UCL Dissertation 'Refurbish or redevelop A sustainable comparison for social housig in Brixton - Pratima Washan 2005**				
	CIRIA Environmnental Impact of materials (EE)		7-9 GJ/tn (import)		8,4-29 GJ/tn
	BRE (cradle to gate)			6,8 GJ/tn	
	SCI (including transportation)	200 GJ/tn	13 GJ/tn	11,71 GJ/tn	
13	**The Whole House Book –Ecological Building Design and Materials – Cindy Harris Pat Borer – CAT,**				
	(BRE, CIRIA,BERGE research included)	27000 kwh/tn	2700 kwh/tn	900 kwh/tn	1000 kwh/tn
	energy needed to produce virgin material	134700 BTU/pound	11400 BTU/pound		7800 BTU/pound
	energy needed to recycle material	5000 BTU/pound	8800 BTU/pound		7200 BTU/pound

(Continue)

	Source	Cooper	Steel	Polycarbonate	Concrete
1	**Timber Building in Australia** http://oak.arch.utas.edu.au/tbia/view_article.asp?articleID=107		35 MJ/kg		2 MJ/kg
2	**CSIRO Manufacturing and materials technology** http://www.cmit.csiro.au/brochures/tech/embodied/	115 GJ/tn	40 GJ/tn	110 GJ/tn	2 GJ/tonne
3	**New Zealand embodied energy coefficient** http://www.vuw.ac.nz/cbpr/documents/pdfs/ee-coefficients.pdf#search=%22embodied%20energy%20coefficient%20alphabetical%22	70,6 MJ/kg	32 MJ/kg (virgin) 10,1 MJ/lg (recycl)	70 MJ/kg	0,94-2 MJ/kg
4	http://www.greenhouse.gov.au/yourhome/technical/fs34a.htm	100 MJ/kg	38 MJ/kg		
5	**Sustainable Homes** http://www.sustainablehomes.co.uk/		834 Kwh/tn	2224 Kwh/tn	
6	http://www.newbuilder.co.uk/				
7	**CIRIA (1995) *Environmental Impact of Materials Special publication 116,*** Volume A-Summary , Construction Industry Research and Information Association, UK			1629 kwh/tn	
8	http://www.canadianarchitect.com/asf/perspectives_sustainibility/measures_of_sustainablity/measures_of_sustainablity_embodied.htm	70,6 MJ/kg	32 MJ/kg (virgin)	70 MJ/kg	0,94-2 MJ/kg
9	www.cda.org.uk/megab2/build/pub-154-guide-to-copper-in-architecture.pdf	103,3 MJ/m2	157,2 MJ/m2		
10	http://www.greenhouse.gov.au/yourhome/technical/fs31.htm	15,6 Btu/tn 5% energy saved by recyclig		8,8 Btu/tn 88% energy saved by recyclig	
11	**Sustainability and End User Expectations** http://www.environ.ie/DOEI/DOEIPol.nsf/0/75fb4dee289541c980256f5d0045f6cb/$FILE/TFHC2002_Chapter%206.pdf#search=%22sustainability%20user%20embodied%20energy%22		18,8 GJ/tn		
12	**Msc UCL Dissertation 'Refurbish or redevelop A sustainable**				

	comparison for social housig in Brixton - Pratima Washan 2005				
	CIRIA Environmnental Impact of materials (EE)				
	BRE (cradle to gate)				
	SCI (including transportation)				
13	**The Whole House Book –Ecological Building Design and Materials – Cindy Harris Pat Borer – CAT,**				
	(BRE, CIRIA,BERGE research included)	15000 kwh/tn	8100 kwh/tn	16000 kwh/tn	
	energy needed to produce virgin material	25900 BTU/pound	8300 BTU/pound	49500 BTU/pound	
	energy needed to recycle material	1400-2900 BTU/pound	4400-7500 BTU/pound	1350 BTU/pound	

Appendix 3 (Energy required for recycling and transportation)

Shiny Materials

	Aluminium Sheets (virgin)	Aluminium Sheets (recycled)	Copper Sheets (virgin)	Copper Sheets (recycled)	steel (virgin)	steel (recycled)	stainless steel	zinc
RECYCLING	15,012 GJ/tonne or 0,02 Gj/m2	15,012 GJ/tonne or 0,02 GJ/m2	10,59 GJ/tonne or 0,05 GJ/m2	10,59 GJ/tonne or 0,05 GJ/m2	10,1 GJ/tonne or 0,03 GJ/m2	10,1 GJ/tonne or 0,03GJ/m2	10,1 GJ/tonne or 0,03 GJ/m2	0,514845 GJ/tonne or 0,04 GJ/m2
SOURCE	Denison R (1999) Environmental Life cycle comparisons of recycling and filling and incineration: a review of recent studies, article	Denison R (1999) Environmental Life cycle comparisons of recycling and filling and incineration: a review of recent studies, article	Harris C Borer P (1998) The Whole House Book Ecological Building Design and Materials – CAT	Harris C Borer P (1998) The Whole House Book Ecological Building Design and Materials – CAT	Denison R (1999) Environmental Life cycle comparisons of recycling and filling and incineration: a review of recent studies, article	Denison R (1999) Environmental Life cycle comparisons of recycling and filling and incineration: a review of recent studies, article	assumed the same as steel	it requires 0,49-19,7% of the initial embodied energy Harris C Borer P (1998) The Whole House Book Ecological Building Design and Materials – CAT
TRANSPORTATION	0,015 GJ/m2	0,015 GJ/m2	0,05 GJ/m2	0,05 GJ/m2	0,05 GJ/m2	0,05 GJ/m2	0,05 GJ/m2	0,05 GJ/m2
SOURCE	1/3 lower density than other metals, so assumption of 1/3 energy required compared metals	1/3 lower density than other metals, so assumption of 1/3 energy required compared metals	SCI 1998 UK (Embodied energy values including transportation	SCI 1998 UK (Embodied energy values including transportation	assumed the same as copper	assumed the same as copper	assumed the same as copper	assumed the same as copper

Smooth Surface

	glass	polycarbonate
RECYCLING	1,08x10-5 GJ/tonne or 1,10x10-7 GJ/m2	2,334 GJ/tonne or 0,01 GJ/m2
SOURCE	Denison R (1999) Environmental Life cycle comparisons of recycling and filling and incineration: a review of recent studies, article	Harris C Borer P (1998) The Whole House Book Ecological Building Design and Materials – CAT
TRANSPORTATION	5,28 GJ/tonne or 0,05 GJ/m2	5,28 GJ/tonne or 0,05 GJ/m2
SOURCE	SCI 1998 UK (Embodied energy values including transportation	SCI 1998 UK (Embodied energy values including transportation

Assembled with grid

	ceramic tiles	ceramic bricks
RECYCLING	non recyclable	non recyclable
SOURCE	assumption	assumption
TRANSPORTATION	9,21 GJ/tonne or 0,09 GJ/m2	9,21 GJ/tonne or 0,09 GJ/m2
SOURCE	SCI 1998 UK (Embodied energy values including transportation	SCI 1998 UK (Embodied energy values including transportation

Striped Surface Materials

	hardwood (kiln dried rough sawn)	softwood (kiln dried rough sawn)	plywood	fibreboards
RECYCLING	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2
SOURCE	Denison R (1999) Environmental Life cycle comparisons of recycling and filling and incineration: a review of recent studies, article	Denison R (1999) Environmental Life cycle comparisons of recycling and filling and incineration: a review of recent studies, article	assumed the same as every other timber products	assumed the same as every other timber products
TRANSPORTATION	6 GJ/tonne or 0,13 GJ/m2	6 GJ/tonne or 0,13 GJ/m2	6 GJ/tonne or 0,13 GJ/m2	6 GJ/tonne or 0,13 GJ/m2
SOURCE	SCI 1998 UK (Embodied energy values including transportation (imported timber)	SCI 1998 UK (Embodied energy values including transportation (imported timber)	SCI 1998 UK (Embodied energy values including transportation (imported timber)	SCI 1998 UK (Embodied energy values including transportation (imported timber)

Roughcast Surface materials

	natural stone (local)	natural stone (imported)	cement (fibre cement board)	concrete blocks (tiles)	concrete blocks (aerated)	Earth raw rammed soil
RECYCLING	non recyclable	non recyclable	non recyclable	non recyclable	non recyclable	non recyclable
SOURCE	assumption	assumption	assumption	assumption	assumption	assumption
TRANSPORTATION	0,55 GJ/tonne or 0,083 GJ/m2	0,55 GJ/tonne or 0,25 GJ/m2	0,55 GJ/tonne or 7,48x10-3 GJ/m2	0,55 GJ/tonne or 0,21 GJ/m2	0,55 GJ/tonne or 0,21 GJ/m2	0,55 GJ/tonne or 0,41 GJ/m2
SOURCE	assumed the same as concrete blocks, difference on the density	assumed the same as concrete blocks, difference on the density	assumed the same as concrete blocks, difference on the density	SCI 1998 UK (Embodied energy values including transportation (imported timber)	assumed the same as concrete blocks, difference on the density	assumed the same as concrete blocks, difference on the density

Appendix 4 (Cost Evaluation)

Different type of Material	Capital cost (as material) £/m2		Capital Cost £/m2 (Incl initial cost+labor)		Capital Cost £/m2 incl Replacement Factor	Cost for maintainance £/m2		Frequency for maintenance	Cost for maintainance £/m2 over 50 years	Total £/m2 per 50 years
	2001[1]	2006[2]	2001[1]	2006[2]	2006[2]	2001[1]	2006[2]			2006
Aluminium	6,23	9,98	45,46	50,91	50,91	–	1,35	every year	67,5	118,41
Copper	19,64-21,43	21,99-24,00	61,71-81,69	69,11-91,49	69,11-91,49	0	0	0	0	69,11-91,49
Steel	14,98	16,77	19,24	21,55	21,55	0	0	0	0	21,55
Stainless Steel	15,73-18,58	17,61-20,81	30,80-33,65	34,50-37,69	34,50-37,69	0	0	0	0	34,50-37,69
Zinc	14,12	15,81	56,19	62,93	188,79	0	0	0	0	188,79
Glass	–	–	23,93-100	26,80-112	26,80-112	–	1,35	every 6 months	135	161,8-247
Polycarbonate	–	–	–	60-70	180-210	–	1,35	every 6 months	135	315-345
Ceramic tiles	18,06-38,37	20,23-42,97	39,98-60,29	44,78-67,52	44,78-67,52	93,31-323,02	104,51-361,7824	every 10 years	522,55-1808,912	567,33-1876,432
Ceramic bricks	13,72-55,60	15,37-62,23	35,48-128,40	39,74-143,81	39,74-143,81	93,31-323,02	104,51-361,7824	every 10 years	522,55-1808,912	562,29-1952,722
Hardwood	–	–	35,85-40,90	40,15-45,81	40,15-45,81	3,10-3,45	3,47-3,86	every 5 years	34,7-38,6	74,85-84,41
Softwood	1,79-5,91	1,91-6,62	6,12-14,90	6,85-16,69	6,85-16,69	3,10-3,45	3,47-3,86	every 5 years	34,7-38,6	41,55-55,29
Plywood	9,36-13,94	10,48-15,61	14,65-21,51	16,41-24,09	16,41-24,09	3,10-3,45	3,47-3,86	every 5 years	34,7-38,6	51,11-62,69
Fibreboards	–	–	–	17[3]	17[3]	–	3,69	every 5 years	36,9	56
Natural stone (local)	36,87-56,69	41,29-63,49	52,55-67,19	19,61-23,70	58,85-71,11	93,31-323,02	104,51-361,7824	every 10 years	522,55-1808,912	542,16-1832,612
Natural stone (imported)	36,87-56,69	41,29-63,49	52,55-67,19	58,85-71,11	58,85-71,11	93,31-323,02	104,51-361,7824	every 10 years	522,55-1808,912	581,4-1880,022
Fibre Cement Boards	14,08-16,33	15,77-18,29	18,49-20,74	20,71-23,23	20,71-23,23	1,15-3,14	1,29-3,52	every 10 years	6,45-17,6	27,16-40,83
Concrete blocks	22,51	25,21	44,43	49,76	49,76	1,15-3,14	1,29-3,52	every 10 years	6,45-17,6	56,21-67,36
Earth raw rammed soil	–	–	–	–	–	–	–	0	0	18-33*

[1] Spon's Architects and Builders Price book David Langdon and Everest 2001
[2] Since all the prices are given for 2001, an inflation rate of 12% is been assumed

[3]http://www.webbswood.co. uk/pricelist.htm#plywood
*http://www.formblock.com.au/f_a_q_.htm#How%20much%20does%20it%20cost%20to%20build%20a%20Formblock%20home?

Appendix 5 (Summary)

Shiny Materials

	Aluminium Sheets (virgin)	Aluminium Sheets (recycled)	Copper Sheets (virgin)	Copper Sheets (recycled)	steel (virgin)	steel (recycled)	stainless steel	zinc
Lifetime	100 years	100 years	200 years	200 years	75 years	75 years	100 years	20 years
Density	2579 kg/m3	2579 kg/m3	8890,2 kg/m3	8890,2 kg/m3	7849 kg/m2	7849 kg/m2	7849 kg/m3	7176,3 kg/m3
Width	0,55mm	0,55mm	0,55mm	0,55mm	0,4mm	0,4mm	0,55mm	0,55mm
Embodied energy (Cradle to gate)								
extraction transport production	199 GJ/ton or 0,28 GJ/m2	14,8 GJ/ton or 0,02 GJ/m2	70,6 GJ/tonne or 0,34 GJ/m2	10,59 GJ/tonne or 0,05 GJ/m2	32 GJ/tonne or 0,10 GJ/m2	10,1 GJ/tonne or 0,03 GJ/m2	18,8 GJ/tonne or 0,08 GJ/m2	5,1 GJ/tonne or 0,20 GJ/m2
Transport	0,015 GJ/m2	0,015 GJ/m2	0,05 GJ/m2	0,05 GJ/m2	0,05 GJ/m2	0,05 GJ/m2	0,05 GJ/m2	0,05 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others	negligible compared to the others	no maintenance requirements	no maintenance requirements	negligible compared to the others	negligible compared to the others	negligible compared to the others	negligible compared to the others
Recycling	15,012 GJ/tonne or 0,02 Gj/m2	15,012 GJ/tonne or 0,02 GJ/m2	10,59 GJ/tonne or 0,05 GJ/m2	10,59 GJ/tonne or 0,05 GJ/m2	10,1 GJ/tonne or 0,03 GJ/m2	10,1 GJ/tonne or 0,03GJ/m2	10,1 GJ/tonne or 0,03 GJ/m2	0,514845 GJ/tonne or 0,04 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	0	0	0	0	0	0	0
Total for 25years (recycling incl)	0,32 GJ/m2	0,06 GJ/m2	0,45 GJ/m2	0,15 GJ/m2	0,18 GJ/m2	0,11 GJ/m2	0,16 GJ/m2	0,29 GJ/m2
Total for 25years (disposal incl)	0,29 GJ/m2	0,04 GJ/m2	0,40 GJ/m2	0,10 GJ/m2	0,15 GJ/m2	0,08 GJ/m2	0,13 GJ/m2	0,25 GJ/m2

Total for 50years (recycling incl)	0,32 GJ/m2	0,06 GJ/m2	0,45 GJ/m2	0,15 GJ/m2	0,18 GJ/m2	0,11 GJ/m2	0,16 GJ/m2	0,29 GJ/m2
Total for 50years (disposal incl)	0,29 GJ/m2	0,04 GJ/m2	0,40 GJ/m2	0,10 GJ/m2	0,15 GJ/m2	0,08 GJ/m2	0,13 GJ/m2	0,25 GJ/m2
Cost Estimation	£/ m2							
Capital cost (as material)	9,98	9,98	21,99-24,00	21,99-24,00	16,77	16,77	17,61-20,81	15,81
Capital cost (incl initial cost+labor)	50,91	50,91	69,11-91,49	69,11-91,49	21,55	21,55	34,50-37,69	62,93
Capital cost including Replacement factor	50,91	50,91	69,11-91,49	69,11-91,49	21,55	21,55	34,50-37,69	188,79
Cost for maintainance (once)	1,35	1,35	0	0	0	0	0	0
Frequency for maintainance	every year	every year	0	0	0	0	0	0
Cost for maintainance over 50 years	67,5	67,5	0	0	0	0	0	0
Total Cost first year	52,26	52,26	69,11-91,49	69,11-91,49	21,55	21,55	34,50-37,69	62,93
Total Cost over 50 years	118,41	118,41	69,11-91,49	69,11-91,49	21,55	21,55	34,50-37,69	188,79

Smooth Surface

	glass	polycarbonate
Lifetime	indefinite	12-20 years
Density	2563 kg/m3	1200 kg/m3
Width	4mm	4mm
Embodied energy (Cradle to gate)		
extraction **transport** **production**	9,72 GJ/tonne or 0,10 GJ/m2	107 GJ/tonne or 0,51 GJ/m2
Transport	5,28 GJ/tonne or 0,05 GJ/m2	5,28 GJ/tonne or 0,05 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others	negligible compared to the others
Recycling	1,08x10-5 GJ/tonne or 1,10x10-7 GJ/m2	2,334 GJ/tonne or 0,01 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	3
Total for 25years (recycling incl)	0,15 GJ/m2	0,57 GJ/m2
Total for 25years (disposal incl)	0,15 GJ/m2	0,56 GJ/m2
Total for 50years (recycling incl)	0,15 GJ/m2	1,71 GJ/m2
Total for 50years (disposal incl)	0,15 GJ/m2	1,68 GJ/m2
Cost Estimation		
Capital Cost (as material)	–	–
Capital Cost (incl initial cost+labor)	26,80-112	60-70
Capital Cost including Replacement Factor	26,80-112	180-210
Cost for maintainance (once)	1,35	1,35
Frequency for maintainance	every 6 months	every 6 months
Cost for maintainance over 50 years	135	135
Total Cost first year	28,15-113,35	61,35-71,35
Total Cost over 50 years	161,8-247	315-345

Assembled with grid

	ceramic tiles	ceramic bricks
Lifetime	50-100 years	50-100 years
Density	19922 kg/m3	2194 kg/m3
Width	5mm	16cm
Embodied energy (Cradle to gate) **extraction** **transport** **production**	2,5 GJ/tonne or 0,02 GJ/m2	2,5 GJ/tonne or 0,02 GJ/m2
Transport	9,21 GJ/tonne or 0,09 GJ/m2	9,21 GJ/tonne or 0,09 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others	negligible compared to the others
Recycling	non recyclable	non recyclable
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	0
Total for 25years	0,11 GJ/m2	0,11 GJ/m2
Total for 50years	0,11 GJ/m2	0,11 GJ/m2
Cost Estimation	£/ m2	£/ m2
Capital cost (as material)	20,23-42,97	15,37-62,23
Capital Cost (incl initial cost+labor)	44,78-67,52	39,74-143,81
Capital Cost including Replacement Factor	44,78-67,52	39,74-143,81
Cost for maintainance (once)	104,51-361,7824	104,51-361,7824
Frequency for maintainance	every 10 years	every 10 years
Cost for maintainance over 50 years	522,55-1808,912	522,55-1808,912
Total Cost per year	149,28-429,31	144,24-505,59
Total Cost over 50 years	567,33-1876,432	562,29-1952,722

Striped Surface Materials

	hardwood (kiln dried rough sawn)	softwood (kiln dried rough sawn)	plywood	fibreboards
Lifetime	50 years	50 years	40-50 years	40-50 years
Density	720,83 kg/m3	448,5 kg/m3	560,645 kg/m3	560,645 kg/m3
Width	5cm	5cm	5cm	5cm
Embodied energy (Cradle to gate)				
extraction transport production	2,0 GJ/tonne or 0,04 GJ/m2	1,6 GJ/tonne or 0,03GJ/m2	10,4 GJ/tonne or 0,12 GJ/m2	5,7 GJ/tonne or 0,06 GJ/m2
Transport	6 GJ/tonne or 0,13 GJ/m2	6 GJ/tonne or 0,13 GJ/m2	6 GJ/tonne or 0,13 GJ/m2	6 GJ/tonne or 0,13 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others	negligible compared to the others	negligible compared to the others	negligible compared to the others
Recycling	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2	2,45x10-5 GJ/tonne or 8,82 x10-7 GJ/m2
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	0	0	0
Total for 25years (recycling incl)	0,17 GJ/m2	0,16 GJ/m2	0,25 GJ/m2	0,19 GJ/m2
Total for 25years (disposal incl)	0,17 GJ/m2	0,16 GJ/m2	0,25 GJ/m2	0,19 GJ/m2
Total for 50years (recycling incl)	0,17 GJ/m2	0,16 GJ/m2	0,25 GJ/m2	0,19 GJ/m2
Total for 50years (disposal incl)	0,17 GJ/m2	0,16 GJ/m2	0,25 GJ/m2	0,19 GJ/m2
Cost Estimation	£/ m2			
Capital cost (as material)	–	1,91-6,62	10,48-15,61	–
Capital Cost (incl initial cost+labor)	40,15-45,81	6,85-16,69	16,41-24,09	17
Capital Cost including Replacement Factor	40,15-45,81	6,85-16,69	16,41-24,09	17
Cost for maintainance (once)	3,47-3,86	3,47-3,86	3,47-3,86	3,69
Frequency for maintainance	every 5 years	every 5 years	every 5 years	every 5 years

Cost for maintainance over 50 years	34,7-38,6	34,7-38,6	34,7-38,6	36,9
Total Cost per year	43,62-49,67	10,33-20,55	19,88-27,95	22,69
Total Cost over 50 years	74,85-84,41	41,55-55,29	51,11-62,69	56

Roughcast Surface Materials

	natural stone (local)	**natural stone (imported)**	**cement (fibre cement board)**	**concrete blocks (tiles)**	**concrete blocks (aerated)**	**Earth raw rammed soil**
Lifetime	indefinite	indefinite	20-50 years	indefinite	indefinite	indefinite
Density	2306 kg/m3	2306 kg/m3	1361 kg/m3	1922 kg/m3	1922 kg/m3	1850 kg/m3
Width	20cm	20cm	10mm	20 cm	20 cm	40 cm
Embodied energy (Cradle to gate)						
extraction transport production	0,79 GJ/tonne or 0,36 GJ/m2	6,8 GJ/tonne or 3,14 GJ/m2	9,5 GJ/tonne 0,13 GJ/m2	0,81 GJ/tonne 0,31 GJ/m2	5,4 GJ/tonne 2,08 GJ/m2	0,80 GJ/tonne 0,59GJ/m2
Transport	0,55 GJ/tonne or 0,083 GJ/m2	0,55 GJ/tonne or 0,25 GJ/m2	0,55 GJ/tonne or 7,48x10-3 GJ/m2	0,55 GJ/tonne or 0,21 GJ/m2	0,55 GJ/tonne or 0,21 GJ/m2	0,55 GJ/tonne or 0,41 GJ/m2
Installation-assembly	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2	0,792 GJ/tonne or 1,12x10-3 GJ/m2
Use-50years maintenance	negligible compared to the others	negligible compared to the others	negligible compared to the others	negligible compared to the others	negligible compared to the others	negligible compared to the others
Recycling	non recyclable	non recyclable	non recyclable	non recyclable	non recyclable	non recyclable
Disposal	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2	0,558GJ/tonne or 7,91x10-4 GJ/m2
Replacement factor	0	0	3	0	0	0
Total for 25years	0,44 GJ/m2	3,39 GJ/m2	0,14 GJ/m2	0,52 GJ/m2	2,29 GJ/m2	1 GJ/m2
Total for 50years	0,44 GJ/m2	3,39 GJ/m2	0,42 GJ/m2	0,52 GJ/m2	2,29 GJ/m2	1 GJ/m2
Cost Estimation			£/ m2			

Capital cost (as material)	41,29-63,49	41,29-63,49	15,77-18,29	25,21	25,21	–
Capital Cost (incl initial cost+labor)	19,61-23,70	58,85-71,11	20,71-23,23	49,76	49,76	–
Capital Cost including Replacement Factor	19,61-23,70	58,85-71,11	20,71-23,23	49,76	49,76	–
Cost for maintainance (once)	104,51-361,7824	104,51-361,7824	1,29-3,52	1,29-3,52	1,29-3,52	–
Frequency for maintainance	every 10 years	every 10 years	every 10 years	every 10 years	every 10 years	0
Cost for maintainance over 50 years	522,55-1808,912	522,55-1808,912	6,45-17,6	6,45-17,6	6,45-17,6	0
Total Cost per year	163,36-432,89	163,36-432,89	22-26,75	52,165	52,165	18-33*
Total Cost over 50 years	542,16-1832,612	581,4-1880,022	27,16-40,83	56,21-67,36	56,21-67,36	18-33*