Economic and environmental target-setting for innovative building products and systems – using high performance pigments as an example

Mr David Churcher BSc(Hons) MBA
Sustainable Construction Group, BSRIA
david.churcher@bsria.co.uk

Abstract

Where an innovative product or system is intended to replace one already available then an appropriately designed set of life cycle costing and life cycle assessment studies can determine the overall levels of improvement which the new product or system must deliver. These are the economic and environmental targets that have to be met or exceeded in order to show an overall lifecycle benefit.

This paper illustrates the principle of economic and environmental performance targeting, using examples based on the EU Framework 7 project “Nanopigmy”. This project is developing advanced nano-material pigments to produce innovative construction materials, where the life-cycle benefit is a reduction in energy consumption during building occupation.

Keywords life cycle costing, life cycle assessment, performance targeting, innovative materials

1.0 Introduction

Life cycle costing (LCC) and life cycle assessment (LCA) are techniques used to determine the economic and environmental impacts of products, systems or entire buildings/developments. There are agreed international standards setting out how these techniques are to be applied [1] [2].

Innovative design solutions are often proposed by building services consultants or contractors, but in many cases the final decision whether to adopt innovative or traditional products or systems comes down to up-front cost, security of supply, or existence of warranties. While these are important considerations they do not give the full picture. Other information about the through-life performance of the products or systems should also be taken into account. Not doing so can put innovations at a disadvantage, since many innovative designs, products or systems require additional up-front investment in return for savings or lower impacts when they are in-use.

This paper describes how economic and environmental target-setting can help specifiers determine whether a given product or system substitution would be beneficial. The same techniques can help product and system manufacturers determine whether their proposed innovations deliver sufficient improvements to be of interest to their customers.

2.0 Overview of innovations used to illustrate the principle of target-setting

2.1 The Nanopigmy project

The principle of target-setting for economic performance and environmental impacts is illustrated with some prospective innovations that are being investigated by the Nanopigmy European Community research project [3] – see acknowledgement.

The Nanopigmy project is a Framework 7 project that involves eight partners from five European countries. The project concerns the development of innovative high-performance pigments that can deliver physical properties to a material or product beyond just their colour. BSRIA is one of the two UK partners in the project and is leading the work package concerned with testing the life cycle cost and the life cycle assessment of the pigments and the sample innovative materials. The Nanopigmy project is working on five different pigment formulations, but this paper refers to just two of these as examples of product or material innovation that would affect the work of a building services design consultant.

2.2 Innovation 1 – thermal storage using a phase change material

This innovation adds a thermal storage component to the pigment. This is designed to store heat as the internal temperature in a room rises while it is being occupied on a warm or hot day and to release it back to the room as the internal temperature drops during the night.

The impact of this change is to reduce the cooling requirement of a building that uses the altered pigment as part of the internal decoration of a building. This pigment is being tested in the internal paint used to decorate the interior of a building.

2.3 Innovation 2 – improved infra-red reflectance

This innovation alters the composition of the pigment to increase its infra-red reflectance. The basic pigment is an ultramarine blue, which in its natural state has low infra-red reflectance. This pigment is being tested in the external cement render used to cover the exterior walls of a building.

Increasing infra-red reflectance should reduce the amount of solar energy absorbed by the external wall of a building. The impact of this change is to reduce the amount of heat conducted through the external wall. This is expected to reduce the heat transmitted to the interior of the building and therefore to reduce the cooling requirement of the building.

2.4 Life cycle impacts of the innovative pigments and materials

The two pigment and material innovations are expected to have both positive and negative effects on the life cycle costs and environmental impacts of a building.

The positive effects, as outlined above, are expected to be related to a reduction in the cooling load of a building during the summer months when air-conditioning or comfort cooling would be used to maintain a comfortable internal environment. These reduced cooling loads translate into reduced energy consumption for cooling and hence reduced energy costs for the building and reduced environmental impact including reduced primary energy demand.

The negative effects are expected to be related to the complexities of producing the innovative pigments and the initial costs of the altered materials. The production processes may be more complex which bring greater environmental impact. There may also be additional manufacturing costs which mean the altered materials would be more expensive to purchase than traditional materials. These additional environmental impacts and costs would recur whenever the materials needed to be replaced or reapplied.

In addition to the above, there may also be positive or negative effects from the innovative pigments depending on whether the life expectancy of the altered materials is greater or less than the traditional materials. Over a long life cycle study period, a change in life expectancy could materially increase or reduce the number of replacements or reapplications of the materials.

3.0 Modelling the traditional solutions for economic and environmental impact

Demonstrating improved economic or environmental performance because of some production, design or installation innovation requires the comparison between two sets of models – one set representing the traditional solution as a Base Case and the other set representing the innovative alternative. The comparisons between the results from the Base Case and the alternatives then indicate whether the innovations deliver economic and/or environmental benefit.

3.1 Base case geometric model and specifications

A simple example building has been created as the test-bed for the traditional and altered materials. To keep the analysis as simple as possible, this has been designed as a single-storey rectangular building, intended to be used as office space. External and internal isometric sketches of the test building are shown in Figure 1.

The outline specifications of the building elements and materials are shown in Table 1. The specification only includes those parts of the building that would be affected by the impact of the innovative pigments. As these are focused on reducing the energy demand of the building, then the specification is restricted to the structure and envelope, internal partitions and the building services.

There would, of course, be many more elements required in an actual building, including lighting, fixtures and fittings, furniture. But it is reasonable to assume that these are independent from the choice of traditional or innovative wall paint or cement render. On that basis, these items can be excluded from the modelling and analysis as they will make the same contribution across all the models.

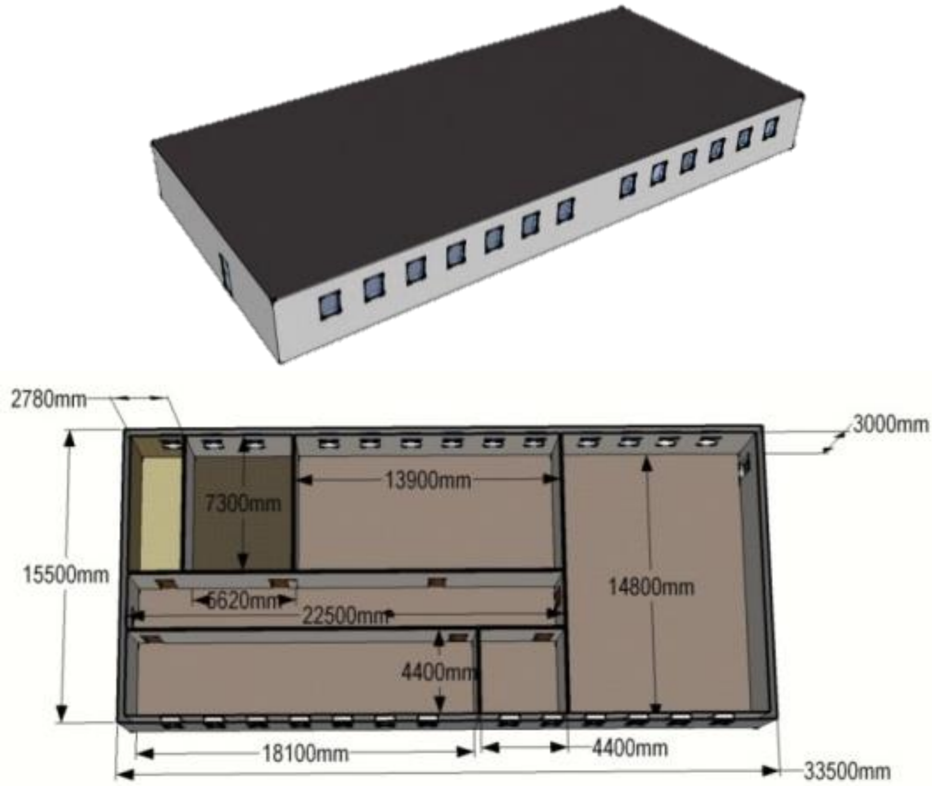

Figure 1 – The test building used for energy, cost and environmental modelling

Element	Outline specification
Ground floor	Suspended concrete beam and block construction with vapour barrier, insulation and screed
External wall	Blockwork cavity wall with insulation, external cement render, internal plasterboard and internal paint
Internal wall	Insulated timber stud partition wall faced with plaster board and internal paint
Roof	Concrete beam and block, external insulation and mastic asphalt, internal plasterboard and paint
Windows	Double glazed with aluminium frame
Doors	Internal – wood, external – wood/glass
Building services	Heating and cooling system

Table 1 – Outline material specification for the test building

The building geometry and specification were captured in the Base Case model, which represented a design using traditional materials. For the purposes of comparison, two alternative models were used. One replaced the traditional internal paint with the paint incorporating phase change materials. The second model replaced the traditional cement render with the render incorporating the infra-red reflective pigment.

3.2 Energy model

As the direct change being tested by the use of the altered materials was to the energy consumption within the building, the next step was to model the energy consumption of the Base Case building using the traditional materials. This was calculated using standard thermal modelling software.

The results of the energy calculations are given in Table 2.

	Annual load (kWh/m^2)	Building area (m^2)	Annual load (kWh)
Heating energy consumption	31.48	519.25	16 348
Cooling energy consumption	20.74	519.25	10 770

Table 2 – Calculated energy consumption for the Base Case building

3.3 Life cycle cost model

The life cycle cost (LCC) model for the Base Case building was developed using BSRIA's in-house LCC calculator in accordance with ISO 15686-5:2008.

Calculation of life cycle costs requires that global variables are set for the study period (the number of years over which the cost is calculated) and for the real discount rate (the annual percentage beyond inflation by which future values of cost and benefit are discounted to arrive at present values).

The study period for this LCC calculation was set at 100 years. In an analysis that covers an entire building, it is usual to take the structural design life as the starting point for the study period. But because a life cycle assessment (LCA) was also being carried out to determine the environmental impacts of the building, and the calculation of global warming potential (GWP) within an LCA is usually done over a period of 100 years, then it was decided to use the same time-frame as the study period for the LCC calculation.

The real discount rate for this LCC calculation was set at 6% per year. A discount rate is partly dependent on the financial stability of the project funder. This means that public sector organisations usually have discount rates that are lower than private sector organisations, and that for the private sector there will be a relationship between the appropriate discount rate and the organisation's credit rating. In the UK, the standard discount rate for the public sector is 3.5% per year. Discount rates for the private sector typically vary between 4% and 10% but can be higher. The choice of 6% for this calculation was consistent with a moderately secure private organisation.

The actual calculation of the LCC for the Base Case required that each item of cost or benefit was estimated and that the timing of each life cycle activity, such as initial installation, maintenance, repair, energy use, was identified. Cost estimates were derived from standard industry price books and timings of element or material replacements were based on industry standard life expectancy information.

Net present value (NPV) formulae were then used to calculate each separate element of the LCC.

The summary LCC calculation is shown in Table 3.

Category of cost	NPV (£)	Notes
Initial construction costs	£173 881	
Maintenance costs, including end-of-life replacement	£52 250	
Operating costs	£7 578 £19 507	Gas for heating at 2.79p/kWh Electricity for cooling at 10.9p/kWh
TOTAL LCC	£253 216	

Table 3 – Summary of LCC for the Base Case building

3.3 Life cycle assessment model

The life cycle assessment (LCA) model for the Base Case building was developed using commercial LCA software and commercial life cycle inventory databases.

In LCA all the resources, inputs, wastes/emissions and outputs associated with the system being analysed are identified. For example, the raw materials, the energy and transport requirements, the levels of recycling. The LCA process combines the appropriate inventory of environmental burdens for each item. These burdens are then allocated to different environmental impact categories according to agreed rules. The results for each category are then combined to prepare the overall impact assessment.

The study period for the LCA was set at 100 years, to align with the category analysis for GWP. This meant that the quantities of materials and components used in the model had to be adjusted to allow for the appropriate number of repeat installations or applications. For example, the life expectancy of the paint on the internal walls of the building was taken as 5 years in the office areas and 1 year in the toilet areas. So as well as the quantity of material needed during initial construction, the wall paint in the office areas was included another 19 times for the repainting.

Discounting has not normally been applied to environmental impacts [4], so there is no equivalent calculation in LCA to the NPV calculations in LCC.

The cradle-to-grave environmental impacts for the Base Case building have been calculated using two methodologies, IPCC 2007 [5] for GWP, and ReCiPe [6] for end-point categories. These are shown in Table 4. CML 2001 [7] was also used in the Nanopigmy project for other mid-point impact categories but this has been excluded from this paper.

Impact category	Environmental impact	Unit
IPCC 2007		
GWP	1 280 000	kg CO_2 eq
ReCiPe		
Single score impact assessment	144 000	Ecopoints

Table 4 – Summary of LCA for the Base Case building

4.0 Defining meaningful improvements in life cycle performance

Neither life cycle cost nor life cycle assessment are exact calculations. Both involve a degree of approximation and the end-results of LCC and LCA analyses should be quoted with an estimated margin of error. This section summarises how these margins of error arise and gives typical figures for the Nanopigmy analyses, which then dictate how much reduction is needed in either LCC or LCA to represent a significant improvement.

4.1 Required improvement in life cycle cost

The accepted rule of thumb is that life cycle costs can have an inherent margin of error that is as much as ±25% when a design or scheme is at feasibility or concept stage, down to ±5% when a design or scheme has been developed in detail [8].

The margin of error cannot realistically be reduced below ±5% for a number of reasons:

- Present-day costs of components, materials or systems are often based on averages across multiple projects, or estimates received from contractors, installers or manufacturers
- Life expectancy of components and materials is usually only quoted to the nearest year, and is often based on expert opinion or the statistical analysis of component failure records
- The discount rate applied to the whole analysis is usually only fixed to the nearest integer value, or perhaps the nearest 0.5 percentage point.

In this paper, it is assumed that the cost estimates are as accurate as they can be. This means that any improvement to a material or component needs to result in at least a 5% reduction in the life cycle cost in order to be judged to be making an improvement to the economic assessment.

4.2 Required improvement in life cycle assessment

In life cycle assessment, the precision of the analysis is linked to a number of different factors, including:

- The completeness of the data collection for the analysed system (i.e. what proportion of the total resources, products and wastes in the system are represented in the assessment model)
- The representativeness of the life cycle inventory data measured in terms of:
    - Geography (is a product or process from a particular country represented by an inventory for the same country, or a regional average, or a global average)
    - Technology (is a product incorporating certain processes or technologies represented by an inventory containing the same processes or technologies, or is there a degree of substitution)
    - Timeliness (is a product manufactured in a certain year represented by an inventory from the same year).

The above factors mean that the precision of an LCA can vary considerably. For the purposes of this paper a 5% reduction in environmental impact has been taken as the minimum change required to demonstrate an improvement.

5.0 Targets for improvements for the innovative pigments

5.1 Target for improvement in life cycle cost

The life cycle cost improvements required from the innovative pigments, and therefore the altered materials, were focused on the cost of energy for cooling. Table 3 shows that the electricity used for cooling has a Net Present Value of £19 507. In order to deliver a 5% reduction in the overall life cycle cost of £253 216, then a saving in cooling NPV of £12 661 is needed. This is a 65% reduction in the cost of cooling, which therefore requires a 65% reduction in the amount of energy used each year for cooling.

This level of performance improvement is a minimum since no account has been taken of any increased purchase cost for the altered material(s) incorporating the innovative pigment.

5.2 Sources of life cycle cost improvement

5.2.1 PCM heat storage

The PCM being used for the Nanopigmy project is a product with a melting point of 21˚C and a heat storage capacity of 125 kJ/kg. The quantity of heat storage over the study period of the LCC analysis is given in Figure 2.

$$Heat\ storage = D \times Y \times A \times Cv \times PC \times I \times SC$$

Where
D = number of cooling days per year
Y = number of years in the study period
A = painted internal surface area (m^2)
Cv = rate of paint application ($\mathrm{kg/m}^2$)
PC = pigment concentration in paint (kg/kg)
I = intensity of PCM in the pigment (kg/kg)
SC = storage capacity of the PCM (kJ/kg)

Figure 2 – Calculation of life cycle heat storage of PCM paint

All the data required for Figure 2 have been obtained from the Nanopigmy project and from the example building, with the exception of the number of cooling days per year. The basis of this figure is explained below. All data are summarised in Table 5.

Data item	Value	Notes
D	100	See text
Y	100	Study period is 100 years
A	450+266+519=1235	Walls + ceiling
Cv	0.3	Figure from paint manufacturer
PC	0.1	Figure from paint manufacturer
I	0.44	Figure from pigment researcher
SC	125	Figure from PCM manufacturer

Table 5 – Data items for the Alternative building

The number of cooling days was estimated to account for the location of the building and for the internal temperature specified for the cooling calculations. The location of the building was taken to be an average location in England. Standard tables of cooling degree days suggested that cooling is typically required from the beginning of

May to the end of September [9]. This gave an approximation of 100 cooling days per year.

Putting the data from Table 5 into the equation in Figure 2 gave the life cycle heat storage of the PCM paint as 20 600 MJ, which was equivalent to 5 720 kWh.

This was a 0.53% reduction in cooling energy, rather than the 65% reduction needed to give a material reduction in life cycle costing. Therefore the PCM paint needed to store 120 times as much energy as the proposed formulation. The amount of energy stored could have been increased by:

- Increasing the rate of paint application, by applying more coats of paint to the internal walls, although this would have increased the cost of the (re)painting
- Increasing the pigment concentration in the paint, although there were practical limits to this and it would also have increased the cost of the paint
- Increasing the heat storage of the paint by using a different PCM.

It was not thought likely that any combination of the above measures could have increased the heat storage of the paint sufficiently to meet the target.

5.2.2 Infra-red reflectance

The second innovation applied to the pigments was to increase the infra-red reflectance and thereby reduce the solar energy transmitted into the building through surface absorption. The reflectance of the standard render was estimated at 30% and two alternative cases were modelled with infra-red reflectance increased to 50% and to 70%. The impacts of these three levels of solar reflectance on the heating and cooling loads for the Base Case building are to be calculated using thermal modelling software.

At the time of writing this modelling has not been completed. In the meantime, it has been assumed that the modified pigment reduces the cooling load by 25% or 45%, and increases the heating load by 5% or 10% depending on the increase in solar reflectance. These altered heating and cooling loads were then incorporated into the life cycle cost model. The resulting changes in life cycle cost are shown in Table 6.

	Standard pigment	Modified pigment 1	Modified pigment 2
Infra-red reflectance (%)	30%	50%	70%
Annual heating load (kWh)	16 348	17 165	17 983
Annual cooling load (kWh)	10 770	8 078	5 924
Life cycle heating cost (£ over 100 years at 6% discount rate)	£7 578	£7 958	£8 337
Life cycle cooling cost (£ over 100 years at 6% discount rate)	£19 507	£14 632	£10 732
Total reduction in heating and cooling life cycle cost (£ over 100 years at 6% discount rate)	NA	£4 495	£8 016
Reduction in LCC for a 5% decrease in total LCC (from section 5.1)	NA	£12 661	£12 661

Table 6 – Summary of LCC for altered infra-red reflectance in external render

As can be seen from Table 6, the net effect of these assumed impacts of the changes to infra-red reflectance of the external render is to give a reduction in overall life cycle cost of £4 495 (if reflectance increases from 30% to 50%) and a reduction in life cycle cost of £8 016 (if reflectance increases from 30% to 70%).

Neither of these improvements is sufficient to give the overall 5% reduction in life cycle cost. The relationship between increase in infra-red reflectance and reduction in life cycle cost is not quite a straight line, and may not continue to be an almost straight line if the reflectance in increased nearer to 100%. But if this relationship did hold, then it can be seen that the reflectance would need to increase to >90% to deliver the 5% life cycle cost reduction.

5.3 Life cycle assessment improvements required from the pigments

For the two methods used in this paper the 5% reduction in the life cycle assessment of the Base Case building equated to either a reduction in GWP of 64 000 kg CO_2 eq or a reduction in overall impact of 7 200 Ecopoints. As the complexities of LCA calculation made it difficult to identify only the impact of the paint or render, then the approach was to model some different improvement scenarios and see how these compared with these overall reduction targets.

In common with the LCC improvement discussed above, this level of performance improvement is a minimum since no account has been taken of any increased impacts from the production of the altered material(s) incorporating the innovative pigment.

5.4 Sources of life-cycle impact improvement

5.4.1 PCM heat storage in internal paint

The energy requirement of the Base Case building was reduced by the same amount as calculated in section 5.2.1. This change was fed into the Base Case LCA and the environmental impacts were recalculated. These are shown in Table 7.

Impact category	**Environmental impact**	**Unit**	**Change from Base Case**
IPCC 2007			
GWP	1 280 000	Kg CO_2 eq	-0.3%
ReCiPe			
Single score impact assessment	143 500	Ecopoints	-0.3%

Table 7 – Summary of LCA for Alternative with interior paint

This improvement in LCA is only one sixteenth of that needed to meet the threshold of meaningful improvement. The amount of energy stored could be improved by increasing the concentration of the pigment in the paint, by increasing the amount of paint applied to the walls, or by changing the different PCM. The impact of the second of these options was investigated further, and this is described in section 5.3.2.

5.4.2 Increasing the amount of paint applied to the walls

Section 5.3.1 shows that substituting the two coats of standard paint with two coats of paint incorporating PCM has a very limited impact on the LCA. The question was raised whether increasing the quantity of paint applied to the walls would improve the results. An LCA on a scenario using four coats of paint instead of the standard two was carried out and the results are shown in Table 8.

Impact category	**Environmental impact**	**Unit**	**Change from Base Case**
IPCC 2007			
GWP	1 290 000	kg CO_2 eq	+0.3%
ReCiPe			
Single score impact assessment	145 700	Ecopoints	+1.2%

Table 8 – Summary of LCA for Alternative with interior paint

Table 8 shows that increasing the quantity of paint used, in order to boost the energy reduction effect of the PCM in the paint, actually increased the environmental impacts. This clearly shows that the benefit of increased energy storage and corresponding reduction in cooling load is more than offset by the life cycle impacts of the additional paint.

5.4.3 Increasing the infra-red reflectance of the external render

The energy requirement of the Base Case building was reduced by the same amount as shown in section 5.2.2. This change was fed into the Base Case LCA and the environmental impacts were recalculated. The results are shown in Table 9.

	Standard pigment	Modified pigment 1	Modified pigment 2
Infra-red reflectance (%)	30%	50%	70%
Heating load (kWh/y)	16 348	17 165	17 983
Cooling load (kWh/y)	10 770	8 078	5 924
Global warming potential 100 years (kg CO_2 eq)	1 280 000	1 148 881 (-10.25%)	1 055 455 (-17.5%)
Single score impact assessment (Ecopoints)	144 000	131 052 (-9.0%)	121 826 (-15.4%)

Table 9 – Summary of LCA for altered infra-red reflectance in external render

Both of the modified pigments reduce environmental impact by more than 5% for both of the calculation methodologies. Interpolating between the results from the Standard pigment and the first Modified pigment shows that a 5% reduction in GWP could be achieved if the infra-red reflectance was increased from 30% to 40%. A 5% reduction in Ecopoints could be achieved if the reflectance was increased from 30% to 41%.

6.0 Conclusions

This paper has shown that the principal of performance targeting can be applied to both the economic and the environmental assessment of prospective product or material innovations. The technique can also be used to demonstrate the likelihood of meaningful improvements in either life cycle cost or life cycle assessment being achieved through a given innovation.

The modified paint, using pigment with PCM, does not meet either the LCC or the LCA thresholds for building-wide improvement on its own. Further, the performance of the modified paint is so far below that required to deliver the minimum 5% improvements in LCC or LCA that there is little prospect of the pigment properties being improved to meet these thresholds.

The modified render, using pigment with higher infra-red reflectance, does not give the 5% improvement in LCC but might achieve this level if a much improved pigment could be formulated. On the other hand, the modified render easily meets the target for improvement in LCA.

These conclusions could be used by specifiers or designers wishing to test the effects of a range of potential innovations on a particular project. The conclusions could also be used by product manufacturers as part of their R&D programmes.

References

1 *ISO 15686-5:2008, Buildings and constructed assets -- Service-life planning -- Part 5: Life-cycle costing, ISO, 2008*

2 *ISO 14040, Environmental management -- Life cycle assessment -- Principles and framework, ISO, 2006*

3 *Nanopigmy web site Home page,* viewed *22 October 2013, www.nanopigmy.eu*

4 *Hellweg S, Hofstetter T B, Hungerbuhler K, Discounting and the Environment: Should current impacts be weighted differently than impacts harming future generations?, International Journal of Life Cycle Assessment, Vol 8, Issue 1 pages 8-18, 2003*

5 *Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avert K B, Tignor M, Miller H L (eds), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2007*

6 *ReCiPe web site, Home page,* viewed 15 November 2013, *www.lcia-recipe.net*

7 *Frischknecht R, Jungbluth N, Althaus H J, Doka G, Dones R, Hischier R, Hellweg S, Humbert S, Margni M, Nemecek T, Spielmann M, Implementation of Life Cycle Impact Assessment Methods: Data v2.0. ecoinvent report No. 3, Swiss centre for Life Cycle Inventories, Dübendorf, 2007*

8 *Churcher D, Whole Life Costing – BG5/2008, BSRIA, Bracknell, 2008*

9 *Vesma web site, Degree day data web page*, viewed 7 November 2013, *http://www.vesma.com/ddd/std-year.htm*

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