Section Life Cycle Management

Design for Environment

Life Cycle Costing as Part of Design for Environment

Environmental Business Cases

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Abstract

Background. In developing products various requirements have to be integrated including functionality, quality, affordability as well as environmental aspects. Often conflicting requirements have to be fulfilled. Therefore, multi-dimensional decision support approaches are necessary.

Methods. Here, one approach is to relate the conflicting requirements to each other. Life Cycle Costing (LCC) has the potential to support the trade-off between some environmental targets and overall affordability targets by including all monetary flows along the product life cycle (going beyond the well-known costs of ownership by integrating also long-term use and end-of-life costs). Those solutions can be identified that (a) have the highest efficiencies (where do we get most environmental improvements per €) and (b) have the highest affordability for the customer along the life cycle. Furthermore, on-costs in the design phase can be justified in terms of future savings either for the customer or for the recycling of the products. These represent real business cases for environmental actions. Three types of environmental business cases can be differentiated.

Results and Discussion. This paper presents various examples where LCC is integrated into product design. However, there are a number of open issues in the implementation of LCC within real product development including data availability and uncertainty (future costs/savings), level of discounting, accounting and compensation. Various internal case studies done in the last years showed that already few changes in the costs structure can significantly affect the identified future costs.

Recommendation and Outlook. Uncertainties in LCC are higher than in LCA and highest when applied in the stage of product development, i.e. used to support DfE action. As a consequence, the resulting figures can only be seen as directional. Therefore, the use of LCC in Design for Environment cannot be recommended without major restrictions in terms of guidance, experience/training. The linkage between LCC and DfE can either be established via (1) experts supporting design teams or (2) as part of a DfE tool. The DfE tool has to include detailed guidance for interpretation, and its application should be based on a solid training for DfE engineers.

Keywords: Automobile; business case; design for environment; eco-design; environmental efficiency; life cycle assessment; life cycle costing; system boundaries; uncertainty

Introduction

Design-for-Environment is a 'systematic approach to improving environmental performance of products and processes over their entire life....' [1]. Similar terms for integrating environmental aspects into product design and development include eco-design and the environmental part of product stewardship [2]. The majority of these approaches aim to support the trade-off process of product design where various requirements are evaluated. One approach for this trade-off process is to incorporate one dimension (environment) into another dimension (affordability). To do so, benefits and risks of non-economic dimensions have to be transferred into monetary units for savings/revenues and costs using various methods [3]. However, this integration of 'externalties' is very difficult, questionable (in this particular if using survey-based data for willingness-to-pay/accept), purely anthropocentric and due to the macro-economic approach not in line with the usual micro-economic perspective of economic operators (customer, enterprises, business units) who are focusing on direct costs / real cash flow [3,4]. The discussion regarding the integration of external effects into private cost calculations has a long history. In 1918, Pigou had been in favor of taxations (Pigouvian Tax) that are the equivalent of the external costs [5]. Looking at the difficulties in estimating these costs and having this as a general taxation, Coase condemned the Pigou-tax as harmful and proposed voluntary, individual (compensation) negotiations between the party(ies) responsible for the external effect and the party/parties suffering from this effect [6]. However, also this Coase-theorem has been seen as not realistic and understood as preferring richer people [7].

Between these extremes, Life Cycle Costing in Design-for-Environment seems to be a pragmatic way of including all opportunities if they concentrate on real (i.e. not assumed) money flows (cash flows [8] instead of 'virtual eco costs' [9]). Companies using LCC in product development try to integrate beyond their direct costs also the costs of their consumers (cost of ownership: purchasing/leasing, financing costs, constructing/installing, operating, maintaining, taxation, repairing, insurance, etc.) as well as the costs of product disposal or the remaining residual value [8,10,11]. LCC is defined as 'an economic method for evaluating a project or project alternatives over a designated study period' – the study period is reflecting the decision maker perspective [8] or the 'cumulative cost of a product over its life cycle' [12]. The incentive for this voluntary integration of external costs into the cost equation is to improve the competitiveness of products by considering the costs of consumers as well as potential future liabilities or economic risks (cost-free take-back or negative effect of residual values). This approach is pragmatic in terms of:

- Avoiding uncertainties in assessing externalities that are currently not expressed in costs / savings but includes existing costs including current (or announced) taxation.
- Avoiding complicated negotiations (as suggested by Coase) but includes individual product costs of all involved life cycle stakeholder.

However, there are several shortfalls as (a) costs are excluded that are not covered by the direct product life cycle, (b) this approach is still anthropocentric, and (c) seen as only mid-term not really long-term.

The LCC methodology has been well established in the last century leading to several standards as quoted in this paper. Recently, the intensity of discussions about LCC increased again referring for example to the extended producer responsibility and to planned legislation [13]. Currently, a SETAC working group is further developing the LCC methodology [14].

The aim of this paper is to evaluate whether LCC can be used as part of a DfE approach that aligns a decision for an environmentally favorable design with economical aspects. This is necessary as affordability often restricts DfE actions.

1 Method of Environmental Business Cases Type 1,2 and 3

1.1 Environmental business case type 1

The basic requirement for any environmental business cases for environmental design actions is that the DfE action leads along the life cycle to reduced environmental impacts compared to the existing base case taken as reference. The environmental impact or environmental performance can be evaluated by using for example the tool of Life Cycle Assessment. For the purpose of this paper, environmental performance is expressed as the result of the Life Cycle Impact Assessment ([15] ISO 14042). The DfE action shall result in lower indicator results for targeted impact categories. This basic requirement for environmental business cases is expressed in (1):

$$LCIA(x)_{DfE} \overset{!}{<} LCIA\,(x)_{Base} \qquad (1)$$

With LCIA(x) = Life Cycle Impact Assessment result of design (DfE or Base) for impact category x.

Of course there is the issue of environmental trade-offs, i.e. where one environmental impact category shows an improvement of the DfE action whereas other environmental impact categories may show an increase in the environmental impacts (see discussion in a previous paper [16]). This may relax the basic requirement (1) in a way that it does not need to be fulfilled simultaneously for all environmental impacts.

The easiest environmental (and economic) business case are the so-called 'low hanging fruits', i.e. DfE measures that have no on-cost for the producer, neither in design nor in production, but provide clear environmental improvements. This environmental business case type 1 is expressed in (2)

$$C\,(DfE)_D + C\,(DfE)_P \overset{!}{\leq} 0 \qquad (2)$$

$C\,(DfE)_D$ = On-Cost of DfE action in design (net)

$C\,(DfE)_P$ = On-Cost of DfE action in production (net)

1.2 Environmental business case type 2

Unfortunately, the 'low hanging fruits' discussed in Type 1 cases are mostly already implemented. Other DfE actions are often linked to innovations or changes to the existing manufacturing and supply base that might suffer from other uncertainties. However, a first, pragmatic step can be done beyond the classical calculations of business cases by integrating future costs for:

- Purchasing/Leasing, financing costs
- Installation costs
- Energy consumption in use
- Emission taxation in use
- Consumption of auxiliaries in use
- Maintenance, insurance, other taxation
- Residual value (if product life is longer than the considered time in the LCC study) and / or
- Product disposal/recycling.

Consumer costs imply end-user costs as well as costs of manufacturers further down the supply chain [17]. The external costs should be concentrated in a pragmatic approach mainly to real cash flow (see above). Based on this perspective, designers can justify business cases for various additional environmental actions including:

- Improving consumption of energy/auxilaries in use
- Reducing product emissions
- Durability
- Ability for dismantling (serviceability) and/or
- Economical Recyclability/Recoverability,

even if the basic requirement for DfE actions (1) though not the requirement for business cases (2) is fulfilled. This environmental business case type 2 aims at an overall, net cost saving along the life cycle of a product or service. Alternatively, at least a break-even situation has to be gained. This is expressed in (3) and (4):

$$S\,(DfE)_D + S\,(DfE)_P + S\,(DfE)_U + S\,(DfE)_R \overset{!}{\geq} C\,(DfE)_D + C\,(DfE)_P + C\,(DfE)_U + C\,(DfE)_R \qquad (3)$$

or

$$LCC_{DfE} \overset{!}{\leq} LCC_{Base} \qquad (4)$$

$S\,(DfE)_D$ = Savings in product development due to the DfE action
$S\,(DfE)_P$ = Savings in production due to the DfE action (incl. warranty, liabilities, etc.)
$S\,(DfE)_U$ = Savings in use due to the DfE action (including energy, auxiliaries, taxation, maintenance, insurance, residual value (if scope of LCC is shorter than product life), etc.)
$S\,(DfE)_R$ = Savings in recycling / disposal due to the DfE action
$C\,(DfE)_U$ = On-Cost of DfE action in use (e.g. heavier but better recyclable materials in vehicles)
$C\,(DfE)_R$ = On-Cost of DfE action in recycling (e.g. by composites ilo recyclable mono-materials)
LCC_{DfE} = Total Life Cycle Costs of DfE action
LCC_{Base} = Total Life Cycle Costs of Base / existing design

As mentioned before, this approach is a first step beyond the classical calculation of business cases:

$$S\,(DfE)_D + S\,(DfE)_P \overset{!}{>} C\,(DfE)_D + C\,(DfE)_P \qquad (5)$$

An environmental business case is demonstrated for environmentally favorable designs where the resulting savings are higher than potential on-costs and where the design offers superior environmental performance against alternatives.

1.3 Environmental business case type 3

In linking both aspects – costs and environment – a recommendation would be to choose that design alternative linked with minimum costs and maximum environmental benefits. Clearly there are cases where this does not fit together –

even looking at the total life cycle costs. Here, the recommendation can be based on the consideration of environmental efficiencies. This implies that an alternative is chosen that offers the highest environmental improvement per additional cost unit. This makes sense where the base decision / assumption is that an environmental improvement has to be achieved – and the only question is how this can be done. This is obviously a different approach than represented in requirements 2 to 4 where DfE actions are only supported where overall cost savings can be demonstrated (environmental business case types 1 and 2).

The environmental business case type 3 is a situation where the Life Cycle Costs of all DfE alternatives (1 to N) are higher than of the existing base design (6). But where the additional cost per improved unit of targeted environmental performance is for one Alternative (Alternative 1) lower than for all other alternatives (Alternative N; N = 2 to n) (7). These alternatives can include alternatives for the same product, component etc. or benchmarks in different areas (e.g. lightweight design alternatives compared to engine / propulsion changes), industries or Life Cycle sections (e.g. lightweight design alternatives compared to behaviour-related actions). Obviously, it is still important that an environmental improvement can be shown (8).

For

$$LCC_{Alternative1} > LCC_{Base} \qquad (6)$$

two criteria have to be fulfilled to qualify for an environmental business case type 3:

$$EE_1(x) = \frac{LCIA(x)_{Base} - LCIA(x)_{Alternative1}}{LCC_{Alternative1} - LCC_{Base}} \overset{!}{>} \frac{LCIA(x)_{Base} - LCIA(x)_{Alternative\,N}}{LCC_{Alternative\,N} - LCC_{Base}} = EE_N(x) \qquad (7)$$

and

$$EE_1(x) \overset{!}{>} 0 \qquad (8)$$

EE(x) = Environmental efficiency of Life Cycle Impact Assessment Category x

LCC = Life Cycle Cost result of design

Note1: indicate for EE the impact range (i.e. the impact often cannot be reduced down to zero by just adding more money as the linked technologies/costs are limited to a certain improvement potential)

Note2: LCIA and LCC can only be related to each other if both have (a) similar system boundaries and (b) similar reliability. Also for EE the ISO requirements for a comparison have to be fulfilled (same functions, system boundaries).

Obviously, the environmental business case type 3 has only relevance if compliance to defined environmental improvement targets is required, e.g. based on corporate targets and policies. However, the environmental efficiency approach is also important where an environmental business case of type 1 or 2 is identified but different alternative DfE actions exist (in these cases, requirement (8) is not fulfilled, i.e. the environmental efficiency is negative; see examples below). Here, the DfE alternative has to be promoted that provides the highest environmental efficiency (7).

The environmental efficiency is very similar to other concepts as (main differences to EE in brackets):

- Return on Environment (RoE) [18] and Green Productivity (GP) [19]. (RoE and GP are relating the selling price to the LCC – by dividing each other),
- Eco-Efficiency [20,21]. (This method may include a weighting across the environmental impact categories [20] (see [16]), seems to be without discounting of future costs [20] (see chapter 3), does not include end-of-life aspects [21] or implies a normalization of environmental and cost figures (for [20] related to Germany).

1.4 Other new business cases based on LCC

All three types of environmental business cases cover all potential DfE actions. In addition there are Life Cycle Cost business cases that do not necessarily imply environmental improvements (see definition of DfE in the beginning and basic requirement 1) but look for other opportunities where the Life Cycle Costs are reduced. These cannot be described as environmental business cases. Nevertheless, also these may imply a new perspective if they affect for example customer, recycling/recovery or other so far not considered costs. One example is reducing the necessary time for a legally mandatory dismantling. This may not affect directly the environmental performance in a narrow sense (dismantling would have to been done anyway) but is reducing the linked (recycling) costs. Here, LCC is supporting a Design for Disassembly (DfD) approach. The only requirement for these other new business cases is that the company (Type 1) or overall Life Cycle Costs (Type 2) can be reduced (see requirement 4).

Alternatively, if similar to the environmental business case type 3 a certain performance-target has to be achieved even if on-costs occur, requirements 9 and 10 have to be fulfilled.

$$E_1(y) = \frac{Performance(y)_{Base} - Performance(y)_{Alternative1}}{LCC_{Alternative1} - LCC_{Base}} \overset{!}{>} \frac{Performance(x)_{Base} - Performance(x)_{Alternative\,N}}{LCC_{Alternative\,N} - LCC_{Base}} = E_N(y) \qquad (9)$$

$$E_1(y) \overset{!}{>} 0 \qquad (10)$$

$E_1(y)$ to $E_N(y)$: Efficiency of designs (or approaches) 1 to N to improve a certain performance (functionality, comfort, safety, dismantling time, etc.)

Note: DfE actions may also support other performance targets; i.e. approval for DfE actions can be gained either by environmental business cases or by stressing that business cases exist for other product attributes / performance indicators.

In the following, examples are provided demonstrating the support LCC can provide for pushing DfE actions in trade-off decisions between cost and environment. The limits of LCC in terms of uncertainties linked with integrating future costs / savings / revenues in use and recycling phases are discussed.

2 Examples for Environmental Business Cases

LCC calculations are usually performed to show decision makers in corporations and product customers that higher priced products pay-off after a certain use time and turn even into an economic favorable solution after this break-even point ([22,23], etc.). In general, LCC supports DfE actions as long as a product's cost driver and the environmental hot spots are simultaneously and positively affected in the same way. This applies for example to products where energy consumption is the dominating environmental issue (lamps or most mobility carrier); here energy saving action might be supported by LCC if one of the above mentioned environmental business cases is proven.

An example is automotive light-weighting. The example of a closure part for a B-Segment vehicle (Ford Fiesta size; **Table 1**) is detailing for four alternative designs the Life Cycle Costs relative to the base design A (reference design). As all alternative designs have higher direct costs in design and production, the basic requirement for environmental business case type 1 (equation 2) is not fulfilled. The overall Life Cycle Costs of all alternatives are also higher than for the base design, i.e. the requirement for an environmental business case type 2 (equation 3) is not given. This light-weighting example is a case where the basic decision has been made that a weight improvement has to be achieved accepting also on-costs (weight reduction improves fuel economy and the related environmental impacts). Thus the environmental business case type 3 can be applied. Here, not the design 'Closure C' with the lowest weight has been recommended because 'Closure C' does neither offer the lowest Life Cycle Costs nor the highest environmental efficiency. However, a design 'Closure E' with a moderate production cost penalty can be justified, when looking at the overall Life Cycle Costs that are close to the base design 'Closure A'. In addition, this version offers the highest environmental efficiency. For 'Closure E', the basic requirement of an environmental improvement (equation 1) is given for all considered environmental impact categories besides the Acidification Potential. Therefore, the recommendation to support 'Closure E' needs to include a request to improve its Acidification Potential.

The light-weighting example can be generalized to all design actions that affect the life cycle costs of fuel for a vehicle (propulsion system, type of fuel, engine efficiency, weight, aerodynamics, rolling resistance, etc.). **Fig. 1** shows the resulting cost saving in the use phase ($S(DfE)_U$) if design actions improve the vehicle fuel economy by 1 l / 100 km. Following the basic requirement of environmental business cases (see above, equation 1), these design actions are only justified from an LCC perspective if these savings are bigger than any resulting on-costs in other life cycle stages.

Table 1: LCC and LCA results of a defined closure part of a Ford B-Segment vehicle (A to E: different materials and designs)

	Closure A	Closure B	Closure C	Closure D	Closure E
Weight	9.8 kg	5.8 kg	5.44 kg	9.8 kg	7.34 kg
Life cycle costs (% of reference A)	Lowest 100%	Highest 109.5%	Medium 103.8%	Highest 108.9%	Lowest 100.6%
Direct Ford costs (% of total)	65.9%	77.3%	75.4%	65.3%	70.7%
Recycling costs (discounted, Ford) (% of total)	–0.3%	–1.2%	0.8%	1.4%	–0.1%
Use costs (% of total) (discounted, customer)	34.5%	23.9%	23.5%	33.5%	29.3%
Life cycle environmental impact potentials	Medium	Medium	Best	Worst	Medium
Global warming potential GWP [kg CO_2-Equiv.]	180	180	130	237	160
Acidification potential AP [kg SO_2-Equiv.]	0.25	0.08	0.24	0.32	0.26
Eutrification potential EP [kg Phosphate-Equiv.]	0.03	0.04	0.03	0.04	0.03
Photochemical oxidant potential (POCP) [kg Ethene-Equiv.]	0.26	0.16	0.16	0.29	0.20
Environmental-Efficiencies		Poor	Good	Negative	Good
GWP improvement per €	Base	0 kg/€	8.3 kg/€ 5%/€	(–4 kg/€) (–2%/€)	20 kg/€ 12%/€
AP improvement per €	Base	5%/€	1%/€	(–2%/€)	(–4%/€)
EP improvement per €	Base	(–2%/€)	0%/€	(–2%/€)	0%/€
POCP improvement per €	Base	3%/€	6%/€	(–1%/€)	23%/€
Overall recommendation	No solution optimal. For the targeted environmental impacts closure E seems to be best compromise if additional Design for Recycling/Environmental measures are considered and the acidification issue can be addressed.				

Assumptions: 1.1 € / l fuel, discount rate of 5.3%, 150,000 km in use (scenarios for different distances and different fuel/weight ratios are done)
Note: use costs include statistical assumptions about replacing/repair costs due to accidents

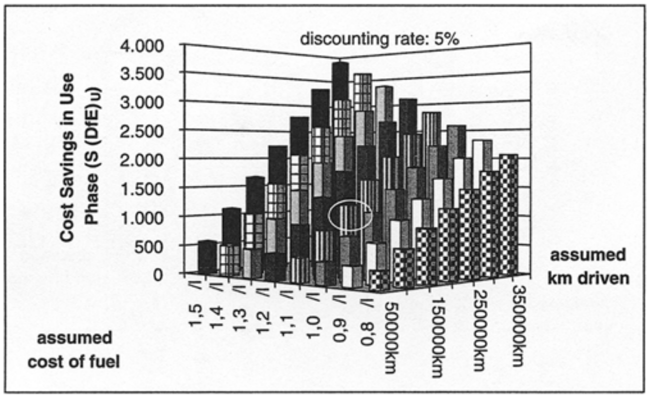


Fig 1: Cost savings for use phase based on design changes reducing fuel consumption of vehicles by 1l/100 km (discounting rate 5%) – highlighted example (white circle): saving of more than € 1200 for the assumption of 1,1 €/l fuel and 150000 km driving distance

It depends on the necessary design and product on-costs whether the fuel economy action is an environmental business case of type 1, 2 or a potential business case of type 3 (if other alternatives are less efficient). **Table 2** is based on Fig. 1 and is linking the cost savings in the use phase with the achieved environmental benefits in terms of reduced global warming potential. The table is providing the environmental efficiencies according to equation 7 (please note the assumptions listed at the bottom of the table). The higher the (positive) environmental efficiency number the better. The negative environmental efficiency numbers indicate an environmental business case type 2 (as in this case requirement 1 is anyway fulfilled; note: environmental efficiencies can be also used to prioritize different alternatives that all comply with the environmental business case type 2 using a slightly modified calculation than in (7)). This example shows that different types of environmental business cases can occur for identical DfE actions – based on different assumptions.

Where DfE actions are not affecting the LCC cost driver, it is difficult to suggest an environmental business case. Automotive DfE actions, that mainly affect the end-of-life phase, impact less than a percent of the overall LCC (including fuel cost, insurance, maintenance, etc.). Reducing the dismantling time by various measures by 10 minutes just improve the end-of-life costs by €1 to € 3 (depending on assumptions as labor rate, discounting factor, etc.), i.e. potential on-costs of these measures have to stay well below this figure. This can be in line with the lower environmental importance of the end-of-life phase for vehicles. However, some actions improve also the assembly or other vehicle attributes and thus already may be supported by other business cases (see chapter 1.4).

3 Uncertainties in Calculating Environmental Business Cases

A general issue with LCC calculations is the definition of the assumed discounting rate for future costs. A discounting rate is generally introduced in economic sciences to express future costs or revenues in terms of its present value (net present value NPV [12]). The reasons for having a discounting include:

- Productivity of capital including also alternative investment opportunities (opportunity costs) or considerations about minimum profitability of any investment (requirements for return-on-investment)
- Uncertainties whether assumed costs or revenues will really take place as assumed, whether the individual (or even society/human kind) will still exist when the assumed future event will occur, etc.
- (Finance) market mechanisms and future economic situation (reduced interest rates to support financing)
- Time preferences of the person/company/society taking into account even intergenerational aspects if very long-term investments are to be discounted (includes ethical considerations).

Concentrating on the design stage based LCC that exclude externalties, the discounting issue is usually not a question of intergenerational equity [25–27] – as long as we do not speak about very long-term investments like buildings, etc. but about a time scale where usually the customers life is longer than the useful life of the product. Also the 'social' discounting rate, i.e. 'the interest rate at which society is willing to lend money for public projects' [28,24], is not the relevant interest rate for most design decisions – at least in the private sector. The discount rate can be then based on official interest and inflation rates (issues: time-specific changes and country-specific differences, i.e. for global products additional variations exist), on the 'rate of return on the best available use of funds' [8] or on legally binding values for LCC ('difference between the interest rate and the

Table 2: Global Warming related environmental efficiencies of fuel economy actions (depending on assumed driving distance and fuel costs; see also Fig. 1) [kg CO2 eq/€] – negative values: environmental business case type 2

	50,000 km	100,000 km	150,000 km	200,000 km	250,000 km	300,000 km	350,000 km
0,80 €/l	1,91	6,58	35,18	–29,99	–14,20	–10,51	–8,87
0,90 €/l	2,02	8,02	914,69	–16,48	–10,23	–8,17	–7,14
1,00 €/l	2,14	10,28	–38,11	–11,36	–8,00	–6,68	–5,97
1,10 €/l	2,27	14,29	–18,67	–8,67	–6,56	–5,65	–5,13
1,20 €/l	2,42	23,45	–12,36	–7,01	–5,56	–4,89	–4,50
1,30 €/l	2,59	65,34	–9,24	–5,88	–4,83	–4,31	–4,01
1,40 €/l	2,79	–83,15	–7,38	–5,07	–4,27	–3,86	–3,61
1,50 €/l	3,02	–25,41	–6,14	–4,45	–3,82	–3,49	–3,29

Assumptions: € 1000 on-costs for DfE Action resulting in 1l/100 km better fuel economy, only the change in the environmental performance of the use phase is considered (1 l/100 km less) taking into consideration the CO_2-eq emissions of tailpipe and fuel (gasoline) production, 5 % discounting rate. Note: € 1000 is an arbitrary example.

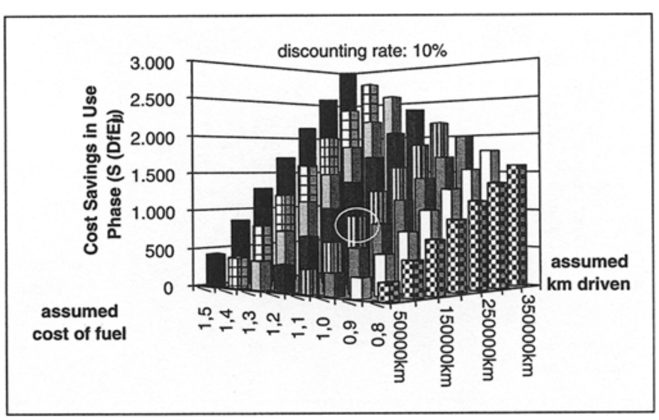
expected average annual inflation', e.g. '5%' [13,29]). The discount rate should reflect the investor's time value of money [8]. However, it is questionable whether all costs along the life cycle should be discounted by the same factor if applied in product development for the purpose of considering also the consumer's perspective. Theoretically, the discounting rate is a question of:

- The companies demands for profitability as well as the companies interest and inflation rates (relevant for $C(DfE)_D$, $C(DfE)_P$).
- The assumed consumer's specific interest and inflation rate. These rates are different for the various regions of the world where the product will be placed. In addition, this interest rate will be time dependent [30] (relevant for the resulting price of the product and the costs during usage).
- The discounting assumptions for those financially responsible for the end-of-life operation.

These rates have to be used to decide whether the higher product price can be justified by the reduced costs during the future use. Please note that this implies the use of different discounting rates for the different costs tracked in LCC.

The calculations leading to **Fig. 2** and 3 are analogous to the cost savings $S(DfE)_U$ calculated for Fig. 1. However, the discounting rates are 0% respectively 10%. By changing the discounting rates (by +/- 100%) the resulting cost savings $S(DfE)_U$ are changed by –26% to +33% (elasticity). This proves the influence of discounting rates. As a consequence, the assumed interest rates have to be clearly noted in any LCC study. However, the same example shows that there are elements/assumptions that effect the LCC result (here in terms of $S(DfE)_U$): The elasticity of the driving distance in this example is even higher (+50% for changing the driving distance by 100%). Similar is true for the assumed costs of fuel. ASTM illustrates a similar case for buildings where changes in fuel prices have a stronger impact than changes in interest rates [8].

In a study of the US Department of Energy [31] a case has been identified where the absolute values differed significantly by changing discounting rates, however, the resulting cost ranking of the alternatives remained similar as long as the time profile of all alternatives are similar. But for the environmental business cases mentioned before, particular



consumption of vehicles by 1l/100 km (discounting rate 0%) – highlighted example (white circle): saving of more than € 1600 for the assumption of 1,1 €/l fuel and 150000 km driving distance

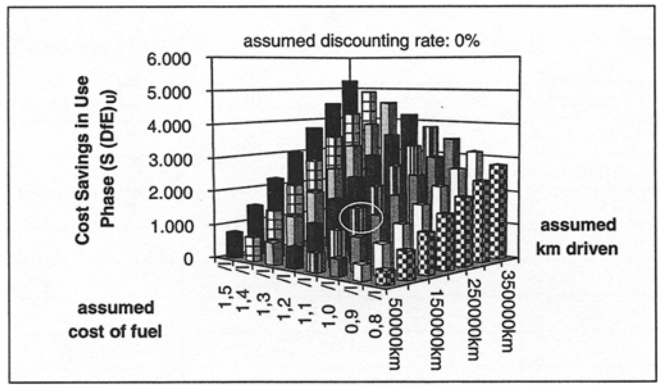


Fig 3: Cost savings for use phase based on design changes reducing fuel consumption of vehicles by 1l/100 km (discounting rate 10%) – highlighted example (white circle): saving of more than € 900 for the assumption of 1,1 €/l fuel and 150000 km driving distance

focus will typically be on alternatives with different time profiles of costs.

The most efficient way for environmental product improvement is to innovate already in the design phase of new products – rather than going for a change later in the life cycle. Unfortunately, the use of LCC in design implies higher uncertainties than applying LCC after the design phase. The earlier in the life cycle the higher the additional uncertainties in applying LCC as more data are based on assumptions rather than measured facts (**Table 3**). This is a fundamental issue for applying LCC in product development – more than being a general issue of LCC itself. As for other tools, prospective LCCs are highly uncertain whereas historical cases reflected by LCC are pretty accurate. Where the market dynamics are significantly strong, the uncertainty for LCC is much higher than for other tools looking e.g. at environmental aspects (such as Life Cycle Assessment). The following influences increase the uncertainties of future costs but not necessarily the uncertainty of future environmental performance:

- Changes in taxation, wages, fringe benefits, etc.
- Chosen discounting rates (see above)
- Changes in market access, number and kind of competitors
- Local and temporal Market price changes that are not technology driven but driven by scarcity/surplus or marketing/image/trends, etc.

Unfortunately, the earlier mentioned extension of LCC beyond the cost of ownership to include also the end-of-life phase is in particular a source of uncertainties. This is mainly an issue for long-lasting products (white goods, mobility products, buildings, etc.). Products with short cycles (packaging, some food, etc.) provide less prediction uncertainties.

Table 4 shows how the assumed directional disposal costs of a vehicle (as internally calculated) are changed if the current market situation would change, e.g. after 15 years or more. The highest uncertainty derives from revenues, interest rates and disposal costs. The impact of the interest rate is higher than for the lightweight example (Fig. 1 compared to Fig. 2 and Fig. 3). The reason is that the influence of an interest rate is increasing with the discounting time.

Table 3: Uncertainties for different LCC elements along the life cycle for products with long development and use phases

Information about Costs (right) being in LC Stage (down)	Product Price	Taxation	Operation Cost (energy)	Maintenance / Warranty Costs	Insurance costs	Residual Value	End-of-Life Cost / Revenues	Uncertainty
Product Development Kick-off	Cost Target / Marketing Price Assumption	Current Legislation forecast	Engineering Target (e.g. for fuel economy) / energy cost forecast	Target	Target (insurance classes) / Insurance forecast	Target	Unknown / Target / Derived from Predecessor	Highest
Product Development (design & verification)	Cost tracking (control model / average) / Marketing price assumption	Current Legislation forecast	Cost tracking (control model / average) / energy price assumption	Engineering actions	Engineering actions (insurance classes) / Insurance forecast	Forecasting tools	Based on material data tracking / DfD/R assumptions / current EOL forecast	High
Start Production	See above / costs for late changes	Current Legislation forecast	See above	Engineering actions	Engineering actions (insurance classes) / Insurance forecast	Forecasting tools	Based on tear-down data / current EOL forecast	Medium
1st Market Launch	Market data	Current Legislation	Market data (but limited to that year)	See above	See above	Forecasting tools	See above	Medium
Full Market Penetration	Market data	Current Legislation	Market data	Market data	Market data	Market data available after several years	See above	Low
First Products to be Disposed	Market data	Current Legislation	Market data	Market data	Market data	Market data	Based on first invoices	Lowest
Uncertainty	Lowest	Low	Medium	Medium	Medium	Medium	Highest	

The issue with most uncertainties listed for the examples of lightweight and disposal is that the probability (i.e. risk level) is unknown or can not easily be quantified without adding additional assumptions / uncertainties. Therefore, uncertainties of LCC can often only be addressed by sensitivity / scenario analysis, etc. Only where historical data are available and allow an extrapolation in future probability analysis may this be possible as suggested [10]. The main issue is then to see what environmental business case can be supported – based on the broad range of potential results. There remains much of subjectivity what result range might be most relevant.

Table 4: Change of assumed directional disposal costs

Assumption	Relative Disposal costs
Original value based on current market situation	100%
No revenues will be obtained in future (15 years +)	181%
Doubled revenues from scrap in 15 years+ compared to today	–256%
Half revenues for scrap in 15 years+ compared to today	278%
50% less time for dismantling needed due to better dismantling efficiency	90%
Doubled dismantling time	120%
Cost-free thermoplastic disposal	56%
Doubled costs for thermoplastic disposal	144%
Reduced interest rate (by 50%)	157%

4 Conclusions

LCC could be applied as part of the DfE tool box by examining all DfE actions for economical aspects. LCC has the potential to support DfE actions, as LCC is providing additional cost transparency beyond the direct development and production cost. LCC can provide decision support for DfE actions best representing one of the three environmental business cases.

However, significant limitations are identified looking at the general uncertainties of LCC but in particular those effective for LCC applied in the design phase, ie. where DfE is applied. In particular, the uncertainties in LCC are high when disposal/ recycling costs are included. The application of LCC in product development is linked to even more uncertainties than LCAs as not only future technological changes have a strong effect on the results, but specific additional influences (in particular the interest rate and market dynamics that are not 'just' technology change driven). By combining LCC and LCA, results linked with different levels of uncertainties lead to an additional issue in the interpretation of the environmental busi-

Table 5: Uncertainty classes of different types of LCC and environmental business cases

Relatively Low Uncertainty	Relatively Medium Uncertainty	Relatively High Uncertainty
Historical use of LCC (after first products reached end-of-life phase)	Descriptive use of LCC for products introduced in the market	Prospective use of LCC done in the design stage
Products with short technical life (few months)	Products in between	Products with long technical life (>5 years)
Products with minor changes from product version/variant to another	Products in between	Products with major changes to the predecessors or products with radical innovations
Static situation in the life cycle (technologies, infrastructure, market, legislation, etc.)	Life cycle situations in between	Short innovation cycles in the Life Cycle (technologies, infrastructure, market, legislation, etc.)
Environmental business case type 1	Environmental business case type 2	Environmental business case type 3

ness case Type 3, respectively the environmental efficiency. The type of product (including the whole life cycle) is determining also the level of uncertainties (Table 5).

Looking at the opportunities (pushing DfE) and shortfalls (uncertainty) the following conclusions can be drawn:

- The application of LCC within the design stage (DfE) cannot be recommended in all cases, in particular if too many uncertainties are included.
- Any environmental business case has to quantify the potential range of results and has to provide a rationale for the assumed results that backs up the environmental business case.
- Any environmental business case done within the design stage (DfE) shall only be accepted if a big improvement for LCC and in particular for the environmental efficiency (EE). The minimum required improvement cannot be recommended from a general perspective.
- Applying LCC in product development needs experiences to enable an interpretation of results. LCC cannot be recommended as a DfE tool suitable for engineers without excessive and dedicated training and guidance (in particular rules for checking uncertainties and interpretation of result ranges) and/or strong software tools that provide both, the accepted data sets as well as the guidance and capability for uncertainty assessment / interpretation.
- Basically, LCC is an expert tool to be used by financial or life cycle experts.

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