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DESIGN OF FUNCTIONAL UNITS FOR PRODUCTS BY A TOTAL COST ACCOUNTING APPROACH

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by

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VINNOVA´s foreword

VINNOVA´s mission is to promote sustainable growth by funding problem-oriented research and developing effective innovation systems. Product realisation and the services associated with it represent a critical success factor in the attempt to achieve sustainable growth. This often requires entirely new and system-oriented, but above all multidisciplinary, approaches that entail collaboration between different technologies and fields of expertise.

The results presented in this publication have been co-funded by the VINNOVA programme Efficient Product Realisation together with industrial funding. The programme started in 2003 and projects will continue throughout 2008. Some 30 research projects are funded by the programme.

The programme has five prioritised areas:

- New business logics and functional sales
- Design and innovation processes
- Capacity for change and organisational development
- Sustainable utilisation of resources
- Industrial IT including simulation and modelling

There is a need for practical assessment tools in product realisation, in order to achieve minimum environmental impact. The project results presented here is one step on the way to tools that can be used for increased environmental awareness when designing products.

VINNOVA in February 2007

Margareta Groth
Programme manager
Efficient Product Realisation

The author´s foreword

This report presents the result of the VINNOVA funded pilot project "Material selection and component design by total cost" (project number P24291-1). The project was performed as a joint study with the following participants, which also partly contributed to the funding of the project:

Anna Henstedt and Per Johansson, Scania CV

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Dennis Taylor, Bodycote CMK Karlskoga

Peter Eriksson, Chalmers Technical University Lindholmen

Gunnar Ruding, Swedish Environmental Engineering Society SEES

William Hogland and Marcia Marques, University of Kalmar

Bo Carlsson, University of Kalmar and the Swedish National Testing and Research Institute

The main authors to the different chapters of the report are acknowledged in the beginning of each chapter.

Bo Carlsson
Project Leader

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Summary

In establishing a more holistic approach to design of functional units of products, a total cost accounting approach may favourably be adopted. The selection of the most appropriate design alternative for a functional unit of a product is based upon a suitability assessment taking into account:

- the required functional capability and reliability, environmental friendliness and sustainability of the considered design alternative of the functional unit, and
- the total cost of the design alternative of the functional unit determined by the sum of production cost, cost associated with initial non-ideal function or performance, maintenance cost, cost of probable failures, end-of-life cost, cost associated with probable ecological damage and development cost

Suitable methods are presently lacking on how to take into account environmental concerns in the early stages of product design in favour of functional quality aspects and cost effectiveness in the short term perspective. The total cost accounting approach adopted in this project offers this possibility. In this report practical tools from Material Lifetime Technology and Industrial Ecology are presented that enable most of the essential factors for the design of functional units of products to be assessed quantitatively in accordance with the total cost accounting approach. The important point is, however, not to obtain an exact value of the total cost, but, to obtain a measure and an understanding of the relative importance of the various factors contributing to the total cost, and be able to make comparisons in the cost characteristics between different design alternatives of the functional unit.

The results of three case studies, in which the total cost accounting approach is adopted for the purpose of product design, are also presented.

In the first case study a sputtered nickel based solar absorber coating is compared with an old electrochemically produced coating for the application of solar domestic hot water production. The results from a suitability analysis show that the sputtered coating seems more favourable to the electrochemical coating in all respects.

The biggest contribution to the difference in total cost between the two absorber coatings is obtained for the cost of probable failures in a case when the solar absorber is installed in a solar collector of bad design and points to the importance of choosing a collector box of a proper design as regards ventilation. The second biggest contribution to the difference in total cost is obtained for the cost of initial non-ideal performance, which illustrates the

importance of having a solar absorber surface with optical properties as close as possible to ideal. Main contributions to the difference in the cost for probable environmental damage are associated with differences in functional capability and thus reduced capability to use solar energy for domestic hot water production.

In the second case study the suitability of different construction materials for the exterior part of a back door to a private car is analysed, namely, carbon steel, aluminium, SMC and a hybrid system GMT/aluminium. From a manufacturer point of view and considering only the production cost for the installed part of the back door, steel is the best alternative. From a user point of view taking into account also cost for non-ideal performance in the form of increased fuel consumption due to excess mass and the two composite materials, particular the GMT/Al material, and aluminium are the most favourable compared. From a total cost point of view the same conclusions can be drawn.

Cost for failures may arise due to crash damage and differences in repair ability make the SMC and the steel alternatives more favourable to the others in that respect but this effect on the total cost is small. Costs for probable failures due to insufficient material durability are more difficult to foresee at least for the GMT/Al alternative. It is therefore recommended to perform a more thorough evaluation of durability. The direct End-of-Life costs are small for the different design alternatives and those contribute very little to the total relative cost. However when considering the requirement on the use of recyclable materials it can be understood that the composite materials are not ideal from an end-of-life perspective. Metallic materials have better end-of-life properties but if the overall efficiency of the recycling process is taken into account there are doubts especially about the suitability aluminium.

The difference in cost for possible environmental damage of the four design alternatives is dominated by the contribution from the service phase and the extra fuel consumption needed to transport the mass of the backdoor around. As a consequence the steel alternative is the most unfavourable whereas the other design alternatives have essentially the same qualities.

In the third case study O-rings for sealing of a turbojet engine are analysed in particular regarding long-term performance. Of most importance is the maintenance cost set in relation to the expected cost for probable failures. As the cost of probable failures is high in this case, the analysis shows that it is economically highly motivated to develop routines for lifetime control of the sealants. By assessing the extent of degradation of the sealants when replaced with new ones during regular overhaul, this kind of information can be used to minimize the interval of maintenance. As shown this can be done without increasing the probability for failure of engine failure but decreasing the maintenance cost considerably.

Important for lifetime control to be successful is, however, access of reliable data on properties of unaged materials. This requires that such data is determined regularly on the same quality of material that is actually installed in the product of interest. Although the material order number will stay the same for many years, this is not a guarantee for that the chemical composition and the material properties are exactly the same.

Knowledge transfer is particular important in connection with suitability analysis based on total cost accounting. In the report a special chapter is devoted on knowledge transfer from the end-of-pipe into so called ecodesign. New tools are needed to promote local, regional and global environmental progress. Environmental pollution assessments through characterisation and monitoring of pollutants load over time and space in soil, water and air can be complemented by toxicity tests and in the near future, by assessment of ecosystems integrity. Such comprehensive assessment and causal chain analysis allow the construction of an indicator-based system that, in turn, supports the production sector in prioritizing investments towards sustainability.

The approach requires new team of experts that includes those with basic education in environmental engineering and management, with complementary/practical experience in natural science and those with basic education in natural science with complementary practical experiences/ education in environmental engineering and management. The hybrid background is necessary if the target is an effective integration of knowledge for development of practical applications.

The transfer of knowledge must be clear for correct interpretation in order to be understood by respective ends of the transfer system. Besides better total cost estimation, an effective implementation of knowledge transfer is likely to improve regulatory compliance, reduce pollution, eliminate waste generation, and even enhance the employee's awareness and bring cultural changes in the companies.

1 Introduction

Bo Carlsson, University of Kalmar, SP Swedish National Testing and Research Institute

1.1 The need of a holistic approach in product design and recovery

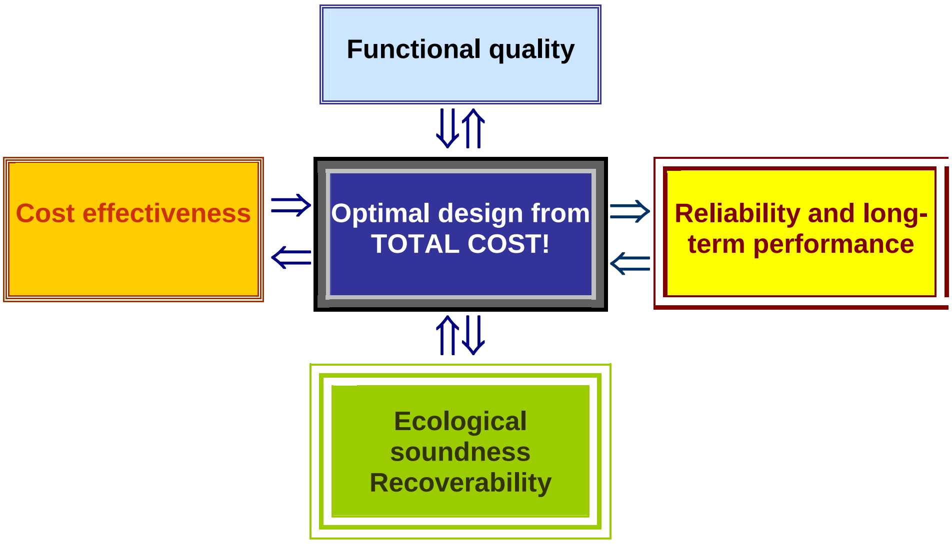
Today specialization and international competition are forcing the industry to improve the tools and methods for the design of products so as to meet requirements set by purchasers and consumers from a larger, more extensive and diversified market.

Today's increasing concern for the environment increases the pressure on companies to develop products for minimum environmental impact during all phases of the product's life cycle complemented by the overall need to ensure that all development is sustainable.

As technical systems and products are becoming more complex, advanced methods are required for forecasting the performance of products in both the short-term and the long-term perspective. In order to minimize cost, it has become more and more important in the early stages of the product development process to identify potential causes of failures in functional capability of the product and of all kinds of environmental damage, which may be caused by the product during its expected life cycle.

Requirements for functional capability, service reliability, service life, life-cycle cost and environmental impact must therefore all be considered from a holistic viewpoint in the very first phases of design work.

Figure 1. Factors dictating the optimal design of a product from a total cost point of view



1.2 Basis for a total cost accounting approach to product design

A total cost accounting approach may favourably be adopted in product design to rank a series of design alternatives for a functional unit of the product by making use of a suggested model originally described in [1]. The total cost for each alternative is estimated by compiling the contributions from all the various factors that may be of importance for the suitability of the design alternative considered. However, the point of departure is not a particular functional unit and its life cycle but the intended function of the unit over time.

For a fixed service time, τ_s , the total cost (C_T) associated with maintaining the specific function defined for the functional unit is estimated from

$$C_T = C_P + C_{NIP} + C_M + C_F + C_{EoL} + C_E + C_D \qquad (1)$$

where
C_P = Production cost
C_{NIP} = Cost associated with initial non-ideal function or performance
C_M = Maintenance cost
C_F = Cost of probable failures and damage
C_{EoL} = End of life cost

[1] A Holistic Approach to Materials Selection in Component Design; B. Carlsson, Y. Virtanen, J. O. Nøkleby, and R. Sandström: Nordtest Report 476, www.nordtest.org

C_E = Environmental cost associated with probable ecological damage
C_D = Development cost.

The production cost, C_P, shall be estimated for the installed functional unit in the product.

The cost associated with initial non-ideal function or performance, C_{NIP} , shall be defined relative to some reference functional unit. It shall be possible to relate to a decrease in the product or system performance and associate it with increased service costs, for e.g. energy, excess weight, material consumption, etc.

The maintenance cost, C_M , includes all the different kinds of active measures taken to maintain the specific function defined for the functional unit during the fixed service time. Those may thus sometimes include replacing the functional unit regularly with a new one during the fixed service time, if the service life of this unit is less than the fixed service time.

The cost of probable failures or decrease in functional performance, C_F , may be expressed as a sum of contribution from the most critical failure or damage modes, i.e.

$$C_F = \sum_{i=1}^{N} (C_{F,i} \cdot F_i (\tau_s)) \qquad (2)$$

where
$C_{F,i}$ = Cost of failure by mode i
$F_i (\tau_s)$ = Probability of (or population fraction) failing by mode i during the fixed service time τ_s.

$F_i (\tau_s)$ is a function of both environmental stress and properties of the functional unit. The service life of the different individuals of the functional unit of the product may vary due to the fact that the different individuals are exposed to varying service stress conditions. But, it may also vary due to varying properties of the individuals. To estimate the probability $F_i (\tau_s)$ would require the distribution in stress level for the different individuals of the functional unit is known and also the distribution in the properties of the functional unit between its individuals.

The end-of-life cost, C_{EoL} , is the cost that arises when the fixed service time has passed. The whole product may then either be re-used or dissembled. The different functional units of it may thus either be re-used or dissembled and their materials recycled or disposed as waste. The End-of-life cost of a functional unit may therefore be positive or negative dependent on the value of the functional unit after the fixed service time has passed.

Costs dictated by environmental considerations may be of two categories: direct costs and indirect costs associated with probable ecological damage. Direct costs comprise contributions from e.g. use of cleaner materials in the functional unit and use of special equipment during production to reduce environmental impact, the cost of planned maintenance in the service phase and the cost of equipment required for the end of life phase of the functional unit. Those costs are therefore parts of the production cost (C_P), maintenance cost (C_M) and end-of-life cost (C_{EoL}), respectively.

The indirect environmental cost associated with probable ecological damage (C_E) may be estimated by applying a similar approach as used to express the cost of probable failures, i.e.

$$C_E = \sum_{j=1}^{M} C_{E,j} \cdot F_j(\tau_s) \qquad (3)$$

where
$C_{E,j}$ = Cost of possible environmental damage j
$F_j(\tau_s)$ = Probability for environmental damage j to occur during the fixed service time τ_s.

By applying the above equations, the design alternative for a functional unit with the lowest total cost would be possible to identify at least from a theoretical view point. However, as will be expounded in the next subchapter a lot of practical tools are available for realizing such an analysis also in practice.

2 Suitability analysis and total cost estimates for a functional unit of a product

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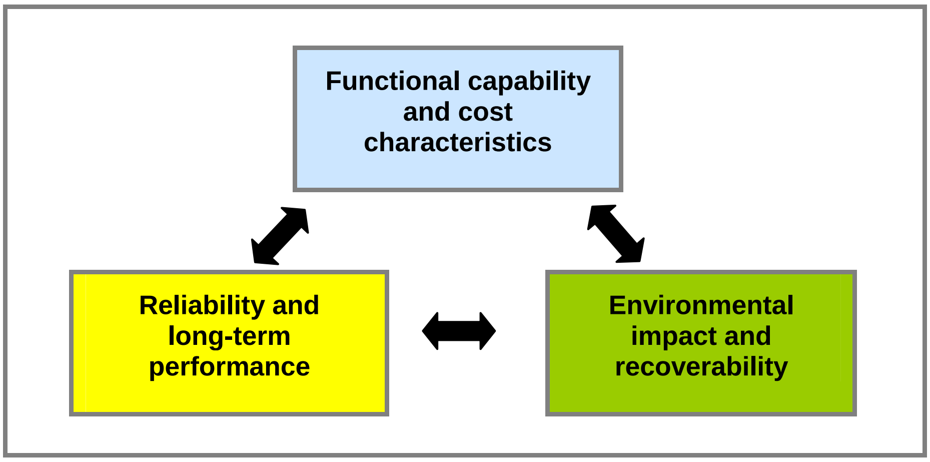
To apply the total cost accounting approach requires the conduction of a systematic suitability analysis of potential design alternatives of a functional unit of a product by making use of methodologies from materials lifetime technology and industrial ecology.

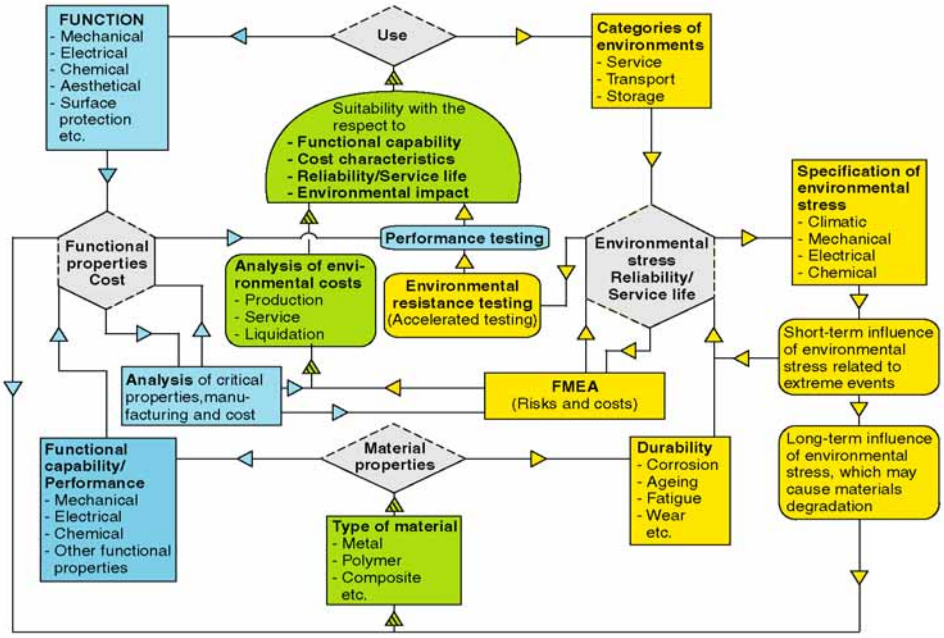
The suitability analysis comprises three different kinds of analysis related to functional capability, reliability and long-term performance, end-of-life system and environmental impact; see Figure 2.

Figure 2. Three different kinds of analysis are needed in the evaluation of the suitability and total cost of a specific design alternative for a functional unit



The overall working scheme to be employed is quite complex and may be illustrated schematically as shown in Figure 3**.** It is composed of a number of steps of which some are closely interrelated to each other and therefore requires an iterative way of working with the suitability assessment.

Figure 3. Overall working scheme for suitability assessment of a functional product unit

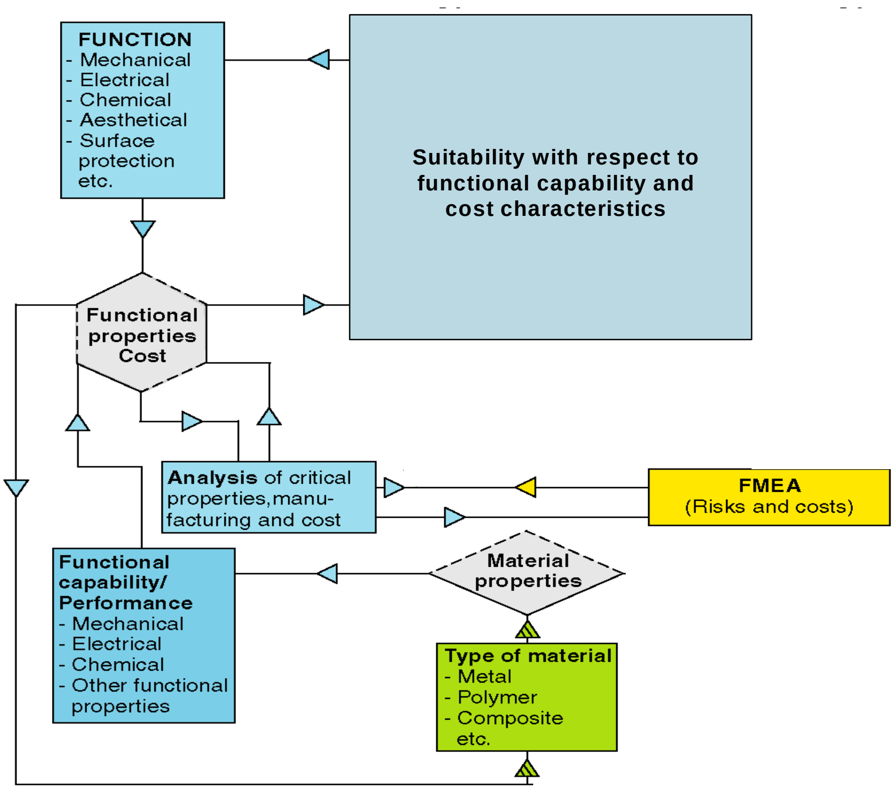


The suitability analysis is not only aimed at identifying the design alternative with the lowest cost but also to obtain a checklist of potential risks and critical materials or functional unit properties and costs for the different design alternatives. With the suitability analysis is achieved a framework for compiling and integrating all data on available materials and functional unit properties, environmental stress characteristics of application, functional unit reliability and materials degradation related to different design alternatives of it , environmental problems and ecological risks associated with the production, use and end-of-life of the different design alternatives of the unit, and cost characteristics for production, for use and for end-of-life. The database resulting from a suitability analysis therefore will be of great value also in future product development.

2.1 Function requirements, capability and cost characteristics

The suitability analysis starts by considering a design alternative for a functional unit with respect to functional capability and associated cost characteristics as is schematically shown in Figure 4.

Figure 4. The suitability of a design alternative for a functional unit is analysed in terms of functional capability and cost characteristics (Production cost for installed unit, Cost for initial non-ideal performance e.g. excess weight, Costs of failure or loss in functional performance). The analysis starts with a function specification. The different steps in the analysis are more fully specified in Table 1 and the result of the analysis is documented as shown in Table 2



In Table 1 the different steps involved in the performance analysis are more fully explained. In Table 2 an example is given on how the results of the analysis of performance and associated cost characteristics may be documented.

2.1.1 Function specification

The first activity is specifying in general terms the function of the functional unit from an end-user and product function point of view.

Table 1. Specific steps in the analysis of functional capability and associated costs of a design alternative for a functional unit in a product; see also Figure 4 and Table 2

1. Specification of the function of the unit from a product or an end-user point of view
2. Requirements on functional properties of the unit following that specification
3. Choice of the most suitable design concepts and material/materials for the unit
4. Identifying design alternatives, which best fit the requirements on functional capability
5. Analysis of the performance characteristics of most promising design alternatives with respect to production cost and cost for initial non-ideal performance
6. Assessment of the severity of different failure modes for the functional unit – Contribution to Function-FMEA (Failure modes and effect analysis)
7. Choice of the most suitable test methods to assess the performance of the functional unit and associated material properties
8. Assessment of the suitability of the design alternatives with respect to cost characteristics when meeting the requirement on satisfactory functional capability

Table 2. Examples of how the results from a suitability analysis of different design alternatives for a functional unit may be documented in case of function requirements, functional capability and associated costs

Specification of end-user and product requirements on functional unit

Function and general requirements	**General requirements for long-term performance during design service time**	**In-use conditions and severity of environmental stress in general terms**
Requirement 1 Requirement 2 etc		

Function, production cost and cost associated with initial non-ideal performance

Critical functional properties	**Test method for deter-mining functional properties**	**Requirement for functional capability and long-term performance**
Property 1 Property 2 etc		
Suitable design alternatives	**Functional capability and material properties**	**Production cost (C_P), Costs associated with initial non-ideal performance (C_{NIP})**
Alt. 1 Alt. 2 etc		

In the function specification for a functional unit the following items should be included for example:

1. A verbal description of the purpose and the function of the unit for the intended application.
2. The planned service life of the unit.

3 The geometric limits on the unit.
4 A list of other parts that it should be joined to.
5 The climatic range (temperature, humidity) that the unit will be operating in.
6 The chemical environment that the unit will be exposed to during service.
7 The mechanical loading and its cycles that the unit will experience.

Items 5 to 7 will be further discussed in 2.2.

It is good practice to follow certain basic principles in this process:

a) The function specification should be general in nature. Any references to specific manufacturing processes, joining techniques or material types should be avoided. It might easily directly or indirectly limit the solution to a limited area, which might represent a non-optimum and non-competitive solution.
b) Direct conditions on material properties should be avoided for the same reason as under a).
c) One should ensure that all specifications, which later lead to requirements on functional properties, are included.
d) The target for optimisation should be specified. In this report the focus will be on cost minimisation taking trade off for energy consumption and other ecological aspects into account.
e) The specification should be quantitative wherever possible.

A common mistake is to provide an incomplete specification, which is satisfied for many design alternatives even some that are not suitable for the application in question. To spend a significant amount of time at this initial stage of the process typically pays off manifold in the later stages.

2.1.2 Transfer of function specification to requirements on functional properties

In this step the function specification is transferred to requirements on functional properties for the unit and associated requirements on material properties. Three main types of properties are generally considered here.

a) *Manufacturing properties*
Properties that are controlling during the manufacturing of the unit such as forming, working, joining and heat treatment.
b) *Use properties*
Properties that are relevant during the use of the unit, such as mechanical strength, electric and optical properties of the unit and sometimes chemical stability of its materials; see also subchapter 2.2.

c) *Availability*
These “properties” include material and manufacturing prices as well as availability of possible design alternatives for the functional unit, product forms and manufacturing processes. They are not genuine functional properties but can in practice be handled as such.

The importance of the function of the unit from an end-user and product function point of view needs to be taken into consideration when formulating the performance requirements in terms of functional properties. It may also be important to understand the consequences of different failures to define general requirements for performance, as failure is defined as occurring below that performance level at which satisfactory function cannot be guaranteed. Thus, if the performance requirement is not fulfilled, the particular design alternative for the functional unit is regarded as having failed. Performance requirements can be formulated on the basis of optical properties/performance, mechanical strength, aesthetic values or other criteria related to the unit or its materials. For failure modes characterised by a gradual deterioration in performance, the consequences of failure may not be that important shortly after the service life requirement is no longer met. However, for catastrophic types of failure modes, the intended functional capability of the component may be completely lost.

2.1.3 Identification of possible design alternatives with respect to functional capability

Requirements with respect to the function of the unit and to the associated material properties define what types of design alternatives that can come into question. It should be clarified that restrictions in what design alternatives that are possible to use may be dictated by the expected kind of environmental stress that the unit may be exposed to and in restrictions due to unacceptable environmental impact. How these considerations will be taken care of will be described later. However, it is important to point out that the suitability analysis should be used in an iterative way so that all aspects can be taken into account simultaneously. The suitability analysis may indicate that for a certain design alternative of a functional unit, for example, a corrosion protection coating needs to be applied, the dimension of the unit needs to be changed, thermal insulation must be introduced or encapsulation be used to protect the functional unit. Such measures will all of course change conditions that might be of importance also for the suitability of other materials in the functional unit and maybe also for other functional units of the product.

The pre-selection procedure aims at identifying types of possible design alternatives for the functional unit. The next phase of work is then to try to find possible design alternatives that fulfil all the requirements with respect to functional capability. Handbooks, databases or data directly from suppliers may be used for this purpose. Previous experience with the same or similar design alternatives may be important.

2.1.4 Analysis of the performance characteristics of most promising design alternatives with respect to production cost and cost associated with initial non-ideal performance

The production cost of each design alternative of the functional unit that fulfils the requirements with respect to functional properties should be estimated. It is not just the prices of materials and manufacturing that are of interest but the total production cost for the installed unit in the product, which means the price of the article plus cost for installing the article in the product including also such measures as surface treatment. Manufacturing and installation costs are very product and product volume specific, and the total production cost for one installed unit may vary from one product to another although the same unit is used in both and the two products are just small modifications of each other.

For the design alternative it is not only of interest to know the total production cost of installed unit and whether this design alternative of the unit fulfils the requirements on functional capability. High quality performance in terms of functional capability may sometimes be beneficial from the product function point of view. Cost so to say associated with initial non-ideal performance should therefore be estimated and taken into account when calculating the total cost of a design alternative.

Non-ideal initial performance may be associated with reflection losses of a window glass pane reducing the energy performance of a window glazing system and thus increasing the energy demand for a house in terms of fossil fuel, natural gas or electricity consumption. Another example of non-ideal performance is overweight of automotive components, which will cause unnecessary high consumption of fuel. In both these cases, the non-ideal initial function will result in an increased energy consumption that can be translated into cost. When calculating and comparing the initial non-ideal performance cost in functional capability of different design alternatives, it is important to select one reference unit and an appropriate model for calculation of those costs.

2.1.5 Assessment of the severity of different failure modes for the functional unit

Costs associated with non-ideal performance appearing during service due to ageing effects of materials should be included in the cost of probable failures; see equation (1). It is therefore discussed more fully in subchapter

2.2. However as part of the performance analysis, when analysing the critical properties, manufacturing of the unit and costs, the severity of potential unit failures needs to be taken into account. This will be a part of a Function-FMEA to be performed and which is described in subchapter 2.2.2. Based on a fault-tree analysis, the costs of different failure modes and damage modes resulting in reduced performance should be estimated.

2.1.6 Choice of the most suitable test methods to assess the performance of the functional unit and associated material properties

For assessing the performance of the functional unit and its materials, relevant test methods and requirements for qualification of the functional unit with respect to performance are needed. Standard methods are preferred. They should be well defined and their results easy to use in the verification of a specific requirement on functionality or quality. Performance tests are not only required in the initial qualification of a unit and its materials, but, also in connection with environmental resistance testing to check if performance changes which might occur during testing are acceptable; see subchapter 2.2. Identification of relevant performance tests is one part of the performance analysis and should be documented; see Table 2.

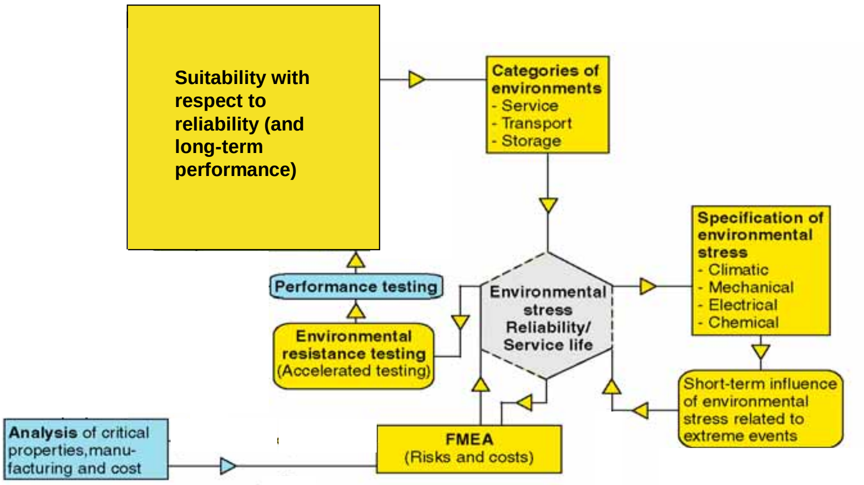
2.1.7 Assessment of the suitability of a design alternative with respect to cost characteristics

The final step in the performance analysis is to compare the cost characteristics of the different design alternatives of the functional unit under consideration. Such an evaluation, however, requires also information on other cost terms appearing in equation (1) and will therefore be discussed separately in subchapter 2.4.

2.2 Reliability and long-term performance, cost of probable failures and maintenance

The next phase of work is considering the expected reliability, long-term performance and associated costs for the different design alternatives selected for analysis as is schematically shown in Figure 5 and Figure 6**.**

Figure 5. The suitability with respect to reliability and environmental resistance against extreme events of environmental stress is assessed by methods from environmental resistance engineering. In estimating risks for failure or performance loss a worst case approach is adopted. The analysis requires as a rule tailor-made environmental resistance tests to be performed. The different steps in the analysis are more fully specified in Table 3a and the result of the analysis is documented as shown in Table 4



For the analysis of reliability and long-term performance, it is important to distinguish between failures and performance losses caused by damage initiated by:

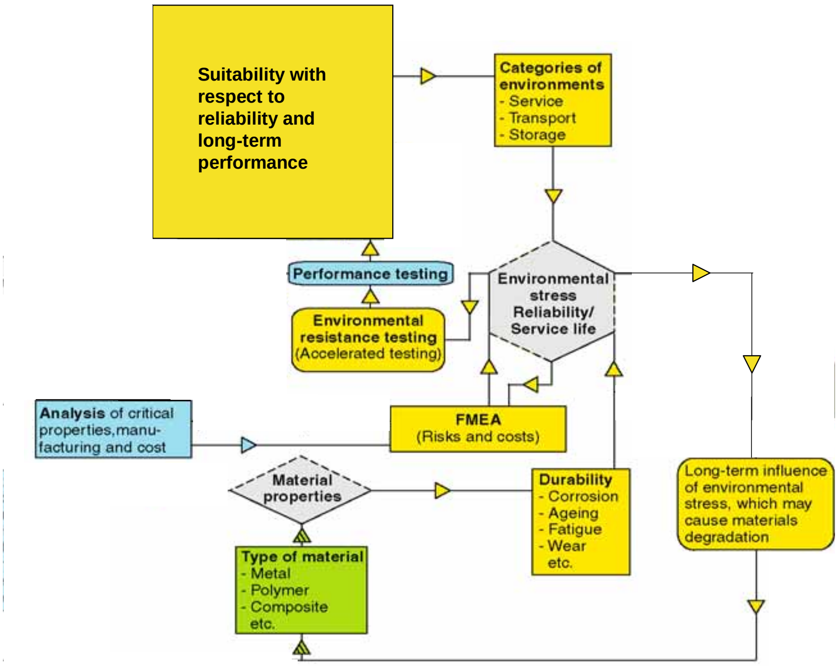
a) short-term effect of environmental stress, the latter representing events of maximum environmental loads on the functional unit and the whole product, see Figure 5 and Table 3a, and

b) long-term effect of environmental stress, the latter causing materials degradation, which may result in a gradual decrease of the performance and the environmental resistance of the functional unit, see Figure 6 and Table 3b.

In the first case catastrophic types of failure dominate, whereas in the second case both gradual and catastrophic types of failures may occur.

In Table 4 an example is given on how the results of the analysis may be documented.

Figure 6. The suitability with respect to long-term performance is analysed by considering the effect of possible physical and chemical degradation and damage mechanisms. Results from accelerated life testing for service life prediction may be needed for the analysis. The possibility to regularly replace the component with a new one to reduce the risk of failure should be considered in the analysis. The cost for maintenance is estimated. The different steps in the analysis are more fully specified in Table 3b and the result of the analysis may be documented as shown in Table 4



2.2.1 Prediction of environmental stress profile and specification of expected severity of different stress factors

The types of environmental stress factors and their severity in the different phases of the product life cycle must be known in order to identify potential failure/damage modes and assess durability. For this assessment a handbook prepared by the Swedish Environmental Engineering Society is recommended for further reading [2].

Environmental conditions representing a worst case may be selected for specification of the environmental stress a product must resist. Alternatively, conditions may be specified from measurements of environmental stress under some typical in-use conditions and selecting data from the most representative case.

[2] Environmental Engineering Handbook, SEES Swedish Environmental Engineering Society, 1997. Handbook can be ordered from www.sees.se

Table 3a. Specific steps in the analysis of reliability and environmental resistance against extreme events of environmental stress and associated costs for a specific design for a functional unit; see Figure 5 and Table 4

1. Identifying type of environments for functional unit in different phases of product life cycle
2. Specification of environmental load profile for the unit and expected severity of different stress factors
3a. Identifying potential failure/damage modes for the specific design alternative for the functional unit which may be initiated by short-term influence from environmental stress related to extreme events
4a. Assessment of most critical failure/damage modes by use of a Function - FMEA analysis to estimate risks of the potential failure modes identified in 3a
5a. Analysis of cost of failures/damage, probability for failures/damage to occur. Decision on what environmental resistance tests are needed to perform for verification
6a. Environmental resistance testing to assess reliability with respect to environmental stress related to the most critical extreme events
7a. Assessment of the suitability of different design alternatives with respect to their expected service reliability and associated cost of probable failures and maintenance when taking into account also long-term performance aspects

Table 3b. Specific steps in the analysis of reliability and environmental resistance against long-term effects of environmental stress and associated costs for a specific design alternative for a functional unit; see also Figure 6 and Table 4. Steps 1 and 2 are shown in Table 3a

3b. First identifying potential failure/damage modes of the specific design alternative for the functional unit, which may result from degradation in material properties due to long-term influence of environmental stress. Then identifying corresponding potential degradation mechanisms which may lead to the failure/damage modes and finely specifying of the severity of the degradation factors for identified mechanisms (corrosion, ageing, …)
4b. Assessment of most critical failure/damage modes/degradation mechanisms by use of a Function - FMEA analysis to estimate risks of the potential failure modes identified in 3b
5b. Analysis of cost of failures/damage, probability for failures/damage to occur, and possibilities for replacement of functional unit during maintenance. Decision on what accelerated environmental resistance tests are needed to perform for verification
6b. Accelerated life testing to assess the expected service long-term performance/reliability during the design service life of the unit
7b. Assessment of the suitability of different design alternatives in respect of their expected service reliability and associated cost of failures and maintenance when taking into account also short-term performance aspects

Table 4. Examples of how the results from a suitability analysis of a design alternative for a functional unit may be documented in case of short-term reliability and long-term performance.

Reliability and long-term performance, cost of possible failures and of maintenance

Design alternative	**Estimated cost of probable failures and damage (C_F)**	**Need and estimated cost of maintenance (C_M)**			
Failure/Damage mode	**Critical factors of environmental stress and severity of stress**	**Estimated risk of failure/damage mode from FMEA, Figure 8**			
		S	P_O	P_D	RPN
Failure type 1					
Damage mode 1					
Damage mode 2					
Failure/Damage mode	**Suitable environmental resistance tests and service environmental stress conditions**	**Probability of failing during the fixed service time, $F_i(\tau_s)$ in eq. (2)**			
Failure type 1					
Damage mode 1					
Damage mode 2					
Failure/Damage mode	**Cost of failure/damage mode, $C_{F,I}$ in eq. (2)**	**Cost of probable failures and damage, ($C_{F,i} \cdot F_i(\tau_s)$) in eq. (2)**			
Failure type 1					
Damage mode 1					
Damage mode 2					

IEC 60721[3], for classification of environmental conditions, may be used as the starting point. The basic idea behind this environmental classification is to create a general reference frame for specifying products and for classification of environmental loads on products. IEC 60721 is aimed at assessing the requirements in respect of environmental resistance of products and at the establishment of an environmental life cycle profile for a product.

IEC 60721, specifies the severity of the single environmental factors to which the product may be exposed, as maximum values. The severity generally represents conditions that will be exceeded with only 1 % probability. The classification does not give any information on duration or statistical distribution of the stress factor. The standard therefore can be used as an aid mainly in determining environmental resistance against short-term environmental influence of extreme events, but not in cases where

[3] IEC 60721, Classification of Environmental Conditions, International Electrotechnical Commission, P.O. Box 131, CH - 1211 GENEVA 20, Switzerland, www.iec.ch

degradation of materials occurs gradually, reducing the environmental resistance of a product.

In the initial phase of durability assessment, however, the most important issue is to identify first the most critical conditions and environmental stress factors which may contribute to failure/damage of a design alternative of the unit and degradation of its materials. Based on this knowledge potential failure/damage modes are identified and associated with those also critical material damage/degradation mechanisms.

2.2.2 Potential failure modes and associated risk of failures

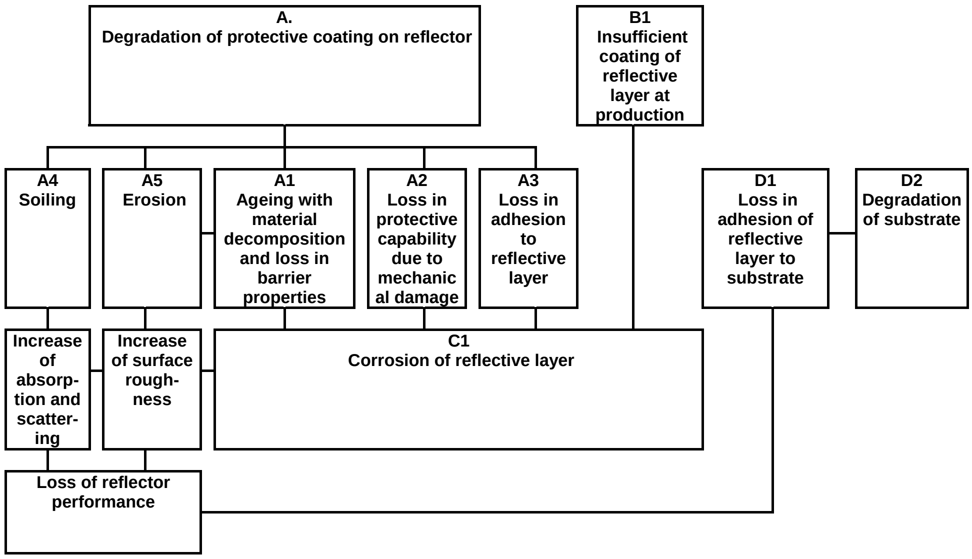
After failures being defined in terms of minimum performance levels (see 2.1.2) potential failure modes for the design alternative considered of the functional unit should be identified.

As a rule there exist many kinds of failure modes for a particular product unit and the different damage modes and material degradation mechanisms, which may lead to the same kind of failure, may sometimes be quite numerous.

Fault tree analysis is a tool, which provides a graphical and logical structure relating failure to various damage modes and underlying chemical or physical degradation mechanisms. Such a representation of failure modes and associated degradation mechanisms is shown in Figure 7 for booster reflectors used to increase the solar gain of flat plate solar collectors.

The objective of the analysis is to identify potential failure/damage modes, degradation mechanisms or mechanisms which may lead to material degradation and the development of damages, and associated critical factors of environmental stress or degradation factors.

Figure 7. Representation of failure: Loss of optical performance and associated damage and degradation mechanisms for booster reflectors[4]; see also Table 4



2.2.3 Risk analysis by Functional – FMEA

The risk or risk number associated with a potential failure/damage mode and degradation mechanism identified can be estimated by use of the methodology of FMEA (Failure Modes and Effect Analysis) and FMECA(Failure Modes, Effects and Criticality Analysis); see for example IEC Standard, Publ. NO.812[5] and the textbook by Britsman, Lönnqvist, and Ottosson[6] for a review on the use of FMEA methodology in product and process design and concerning FMECA the standard ECSS-Q-30-02A[7].

The estimated risk number is taken as the point of departure to judge whether a particular failure mode or damage mode is important and needs to be further evaluated. The estimated risk number may also be used to rate what kind of testing that is needed for qualification of a particular functional product unit or the complete product.

[4] Assessment of durability and service lifetime of some static solar energy materials; B. Carlsson, S. Brunold, A. Gombert, and M. Heck; Proceedings from the conference Eurosun 2004, Freiburg, June 2004
[5] IEC Standard, Publ. NO.812, 1985, ”Analysis Techniques for System Reliability - Procedure for Failure Mode and Effect Analysis (FMEA)
[6] Failure Mode and Effect Analysis, Instruction manual from Volvo Car Corporation in Britsman C., Lönnqvist, Å., Ottosson S.O., Failure Mode and Effect Analysis, Ord&Form AB, 1993, ISBN 91-7548-317-3 (Swedish)
[7] Standard ECSS-30-02A from ESA Publication Division ESTEC, P.O.Box 299, 2200 AG Noordwijk, The Netherlands

The risk number associated with a particular failure mode or damage mode is estimated by use of the following factors: Severity **(S),** Probability of occurrence **(P_O)** and Probability of escaping detection **(P_D).** The risk number **RPN** is the product of all these factors, namely: **RPN = S· P_O · P_D**

The first factor, **Severity**, is a measure on the consequences of a particular failure from safety and economic viewpoints, when looking at the functional unit as part of a product or system. For rating Severity a scale with ten degrees may be used; see Figure 8.

The second factor, **Probability of occurrence**, is a measure on how probable it is that failure according to the particular mode will occur during the design service life of the functional unit. A 10-point scale may also be used here: see Figure 8. The third factor, **Probability of escaping detection,** takes into account how probable it is to detect and avoid failure. Again, a 10-point scale is appropriate; see Figure 8.

Figure 8. Rating numbers for Severity (S), Probability of occurrence (P_O) and Probability of discovery (P_D) in FMEA or FMECA analysis

Severity	RPN
No effect on product	1
Minor effect on product but no effect on product function	2-3
Risk of failure in product function	4-6
Certain failure in product functioning	7-9
Failure that may affect personal safety	10

Probability of escaping detection	RPN
Failure that always is noted. Probability for detection > 99.99%	1
Normal probability of detection 99.7%	2-4
Certain probability of detection >95%	5-7
Low probability of detection >90%	8-9
Failures will not be found - cannot be tested	10

Probability of occurrence	RPN
Unlikely that failure will occur	1
Very low probability for failure to occur	2-3
Low probability for failure	4-5
Moderate probability for failure to occur	6-7
High probability for failure to occur	8-9
Very high probability for failure to occur	10

The risk assessment may be documented as shown in Table 4. In Table 5 the result of a risk assessment based on the failure/damage mode representation shown in Figure 7 is illustrated.

Table 5. Risk assessment on different damage modes for booster reflectors illustrated in Figure 7

Failure/Damage mode / Degradation process	Estmated risk number associated with damage mode (based on FMEA/FMECA)
A1 Degradation of the protective layer - Ageing with material decomposition	80
A2 Degradation of the protective layer- Loss in protective capability due to mechanical damage	40
A3 Degradation of the protective layer - Loss in adhesion to reflective layer	64
A4 Surface soiling	56
A5 Surface erosion	50
B1 Insufficient coating of reflective layer at production	70
C1 Corrosion of the reflecting layer (Result of mechanisms A1-A3, B1)	112
D1 Loss of adhesion of reflector from substrate	70
D2 Degradation of the substrate	32

Risk assessments of potential failure modes and damage modes must take into account how relevant durability and life data found in the literature are for the studied design alternative and its materials. The risk assessment should preferably be performed by a group of experts representing different fields of competence in product design.

How reasonable it is to set the design service life of the functional unit at the same level as that of the product may also be questioned during the risk assessment. During maintenance or repair work the functional unit may be replaced or repaired, which may in some cases considerably lower the requirement on service life of the unit.

It should be pointed out that the risk assessment made at the initial stage of service life prediction may mainly be qualitative in nature. The main purpose is to limit the scope of the service life evaluation to be able to focus on the most important failure modes and damage modes. The rating numbers are to be used as an aid to reduce the number of critical failure modes to be taken into account in the subsequent evaluation of the service life of the studied design alternative of the unit.

2.2.4 Analysis of cost characteristics related to reliability and long-term performance

The FMEA analysis described in 2.2.3 is the first step in trying to estimate and rate the risk of a particular failure/damage and associated degradation mechanisms. The result of the FMEA analysis is a risk number, but ideally this risk number should be expressed in terms of a cost for probable failures or loss in functional capability. To do so, the severity factor needs to be translated into cost and the probability for occurrence factor expressed as a probability value.

In cases of failures with low severity ranking, the failure of the unit has no or minor influence on the product functioning, the cost of failure would be equal to the cost of replacing the functional unit with a new one when regular service is performed. In cases of unit failures where there is a risk of also product failure to occur, the cost of failure is composed of the cost for replacing not only the functional unit under consideration but also of other functional units which might fail as a consequence of the first failure. To the cost of failure should also be added the cost associated with the loss of income for services where the product no longer can be used because of repair work. For failures which might effect personal security and result in injuries such consequences must also be translated into cost terms and added to the cost of this failure. It is clear that in cases like that, it is important also to try to estimate the effect that such a failure might have on sales volume due to bad PR. The cost of failure should be estimated and documented as shown in Table 4.

To be able to estimate the cost of probable failures or loss in functional capability, the probability of each failure identified (see $F_i(\tau_s)$ in equation (2)) needs to be estimated. The different classes for the probability for occurrence, P_O, in Figure 8 may be taken as a point of departure for defining a useful scale for this purpose, which is illustrated in Table 6.

Table 6. Class for probability of failure to occur and suggested range of the parameter $F_i(\tau_s)$ appearing in equation (2)

Class for probability of failure to occur	**Rating number of probability for occurrence, P_O**	**Probability of a specific failure i to occur, $F_i(\tau_s)$**
Unlikely failure will occur	1	$\leq 10^{-4}$
Very low probability for failure	2-3	$10^{-4} \leq F_i(\tau_s) < 10^{-3}$
Low probability for failure to occur	4-5	$10^{-3} \leq F_i(\tau_s) < 10^{-2}$
Certain probability for failure to occur	6-7	$10^{-2} \leq F_i(\tau_s) < 5 \cdot 10^{-2}$
High probability for failure to occur	8-9	$5 \cdot 10^{-2} \leq F_i(\tau_s) < 0.5$
Most probable for failure to occur	10	$0.5 \leq F_i(\tau_s) < 1$

To estimate probabilities for failures requires a deep insight and experience in reliability engineering related to the specific design alternative of the functional unit under study. If such knowledge is lacking a conservative approach is recommended, thus overestimating a risk rather than underestimating it. The first preliminary attempt to estimate probabilities for failures should, however, serve as a base for decision on what critical environmental resistance tests are needed for verification of the reliability and long-term performance of a particular design alternative of the functional unit. After tests have been performed as discussed in 2.2.5, the precision in the predicted probabilities for the most critical failures and damage modes is able to improve. The probability for a specific failure should be documented as shown in Table 4 and used to estimate the cost of probable failures and of loss in functional capability during the assumed service time.

When the cost of probable failures exceeds the cost for replacing the unit with a new one, it is quite obvious that the unit should be replaced in sufficient time before failure occurring. In general, catastrophic types of failures may have a large impact on product reputation as regards reliability and safety and therefore have to be avoided unless the consequences of failure on the product function are low. Functional units with a service life shorter than the expected service time of the product therefore need to be replaced at intervals chosen short enough to guarantee a low probability of failure in function. However, there is a relation between cost for maintenance comprising cost for replacement of the component and cost for probable failures of the component. The sum of the two should of course be as low as possible. The cost of maintenance should be estimated and documented as shown in Table 4.

There are cases where it is not economically reasonable to replace a unit with a new one because of a gradual deterioration in performance of the functional unit occurring. In such cases it may, however, be possible directly to translate this deterioration in economic terms. In chapter 3 on the selection of solar absorber surfaces for collectors in domestic hot water systems, such an example is described.

When comparing one new design alternative for a functional unit and one traditional design alternative in terms of cost of probable failures it may be wise to introduce a safety factor for the former when estimating the expected probability for failure. Due to limited knowledge of the durability of new materials or materials combinations it may be difficult to foresee or estimate the effects of all kinds of failure/degradation modes that might contribute to failure and deterioration in the functional capability of the unit. To estimate probabilities of failures, reliability acceptance testing and accelerated life testing are generally required to verify the resistance to at least the most critical failure and damage modes identified at the FMEA analysis.

2.2.5 Reliability acceptance testing and accelerated life testing

The environmental resistance of a specific design alternative of a functional unit of a product or even the whole product may be verified with the aid of the severity determined by use of IEC 60721, or by use of measured severity of stress for factors which may contribute to failure and damage. There are a huge number of available standard environmental resistance tests that can be used for that purpose. It, however, falls outside the scope of this report to go into the details on what methods which are available and what methods that can be recommended for use in specific application areas. The reader is referred to some general handbooks, reports or standards as exemplified in the footnote below[8].

For verification of the environmental resistance with respect to long-term influence of environmental stress leading to gradual material degradation and subsequent failure, accelerated life testing may be adopted. Appropriate accelerated tests to be used for qualification testing have in case to be tailor-made if they are truly to reflect the particular environmental service conditions, but at an enhanced level of stress. This requires that the test should be able to reproduce the same kind of degradation pattern as observed under real service conditions. The main difficulty after identifying an appropriate accelerated test is, however, to estimate the relationship between testing time and service time for a functional unit in a particular application. The design service life of the component or product has to be converted into an acceptable failure time for the design alternative of the functional unit in the accelerated test[9].

In the suitability analysis of a design alternative of a functional unit with respect to reliability and long-term performance, the combined stress and failure/damage mode analysis, described in 2.2.3, forms the basis also for identifying suitable environmental resistance tests; see e.g. the example given in Table 7 related to evaluation of the long-term performance of booster reflectors.

[8] SEES Handbook in Environmental Engineering, www.sees.se , IEC 60068-2, Nordtest Technical Report 476 www.nordtest.org , www.iso.ch www.iec.ch

[9] see e.g. Nordtest Technical Report 476, www.nordtest.org, or Appendix A of the SEES Handbook in Environmental Engineering, www.sees.se

Table 7. Some recommended accelerated environmental resistance tests for verification of long-term performance of booster reflectors in Task 27 of the IEA Solar Heating and Cooling Program

Damage/degradation mechanisms	Test methods
Degradation of the protective layer	Constant load condensation tests with UV irradiation Constant load temperature test with UV irradiation exposure Artificial weathering test with acid rain (SP-method 2710)
Corrosion of the reflecting layer	Cyclic corrosion test according ISO 21207 method A with and without salt spray exposure involving also a phase with exposure to high humidity air with corrosion promoting pollutants followed by a phase of drying
Adhesion losses	Cyclic condensation and cyclic high humidity tests

In assessing reliability with respect to environmental stress related to the most critical extreme events, the severity of tests used generally should represent conditions that will be exceeded with only 1 % probability (following IEC 60721). If the studied design alternative of the functional unit passes such a test, thus, the probability for the specific failure, which might occur, $F_i(\tau_s)$ should be less than 1%.

In assessing the expected long-term performance of the studied design alternative during the assumed service time of the unit the situation is more complex. Main reason for that is that testing at enhanced levels of environmental stress, compared with the in-service situation, needs to be used in the environmental resistance tests so that testing times can be kept reasonably short.

To be able to assess the in-service long-term performance requires firstly that the predominating degradation mechanisms of the materials of the unit need to be modelled, which generally are very difficult. The rate of degradation in performance may then be quantitatively expressed in terms of environmental stress factors and the material dependent parameters of the assumed model. The material dependent parameters of the model are then determined by way of accelerated testing. By inserting the expected in-service stress conditions into the model the expected long-term performance after the assumed service time of the studied design alternative of the unit may finely be estimated[10].

Consequently, there may be a high uncertainty in the assessment of the long-term performance of a functional unit by way of accelerated life

[10] see e.g. reference in footnote 9

testing. However, for many cases more simplified qualification test procedures with respect to long-term performance may favourably be used. For a suitability analysis aimed at ranking different design alternatives of a functional unit it may in many cases be enough to have a test, which tells you if during the assumed service time it is most probable for failure to occur ($0.5 \leq F_i(\tau_s) < 1$), high probability for failure to occur ($5 \cdot 10^{-2} \leq F_i(\tau_s) < 0.5$) or a certain probability or low probability for failure to occur ($10^{-3} \leq F_i(\tau_s) < 5 \cdot 10^{-2}$; see Table 6.

It will be the estimated cost for probable failures that will indicate how suitable a specific design alternative will be in relation to the others with respect to reliability and long-term performance. As has been mentioned before, if it is most probable that failure of the unit occurs, it may be most favourable to replace the unit regularly with a new one during the assumed service time. Moreover, if there is a certain probability or low probability for failure you do not need to take this failure into account further unless the cost of failure is very high. It is mainly when the test results indicate the probability of failure is high it may be necessary to extend the study on durability towards accelerated life testing described above, in order to decrease the uncertainty in the predicted long-term performance.

2.2.6 Assessment of the suitability of a design alternative with respect to cost characteristics

The final step in the reliability analysis is to compare the cost characteristics of the different design alternatives of the functional unit. Such an evaluation, however, requires also information on other cost terms appearing in equation (1) and will therefore be discussed separately in subchapter 2.4.

2.3 Environmental costs and ecological risks

The third phase of work in the suitability analysis considers the expected environmental impact and recoverability of the design alternative of the functional unit as schematically shown in Figure 9.

Figure 9. The suitability with respect to environmental impact and recoverability is analysed in terms of expected costs for probable environmental damage using Lifecycle Impact Assessment with EPS and the Ecoindicator method. From suitable end-of-life systems the end-of-life cost is estimated. The result of the analysis is documented as shown in Table 8

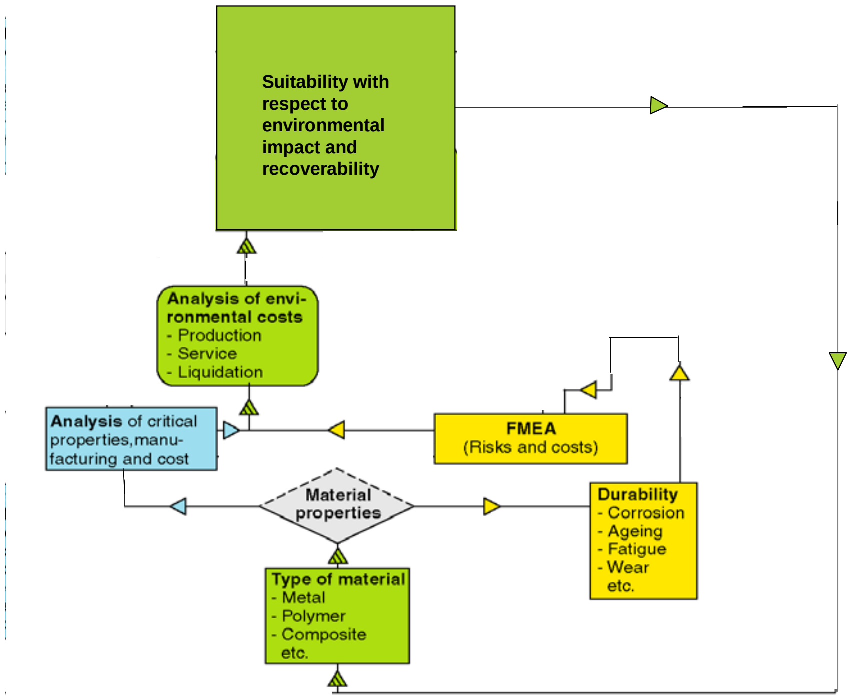


Figure 10. Evaluation of the different kinds of environmental costs for a functional unit of a product

Ecodesign and assessment of **direct costs for those measures** that are needed to keep the environmental impact at a tolerable level ⇒	**Production cost, Maintenance cost, End-of-life cost**
⇓	
Optimisation of the **end-of-life system** for the studied design alternative of the functional unit with respect to reuse, recycling and disposal of the materials of the functional unit and estimation of the end-of-life cost ⇒	**End-of-life cost**
⇓	
Assessment of the **ecological risks** associated with the production, use and decommissioning of the design alternative of the functional unit by making use of life cycle impact assessment cost estimates ⇒	**Environmental cost associated with probable ecological damage**

The analysis may be structured into three major steps as are shown in Figure 10 and the results of the analysis documented as exemplified in Table 8.

Table 8. Example on how the results from a suitability analysis of a design alternative for a functional unit of a product may be documented regarding risks for environmental damage, optimization of the end-of-life system and associated costs.

Ecodesign, end-of life system , ecological risks and associated costs

<table>
<tr><th>Design alternative</th><th>Environmental problem during production, service and end-of-life</th><th>Ecodesign measures and additional costs</th></tr>
<tr><td></td><td>Problem 1
Problem 2</td><td></td></tr>
<tr><th colspan="2">End-of-life system</th><th>Estimated end-of-life cost</th></tr>
<tr><td colspan="2">Case 1
Case 2</td><td>Case 1
Case 2

Average</td></tr>
<tr><th>Environmental impact and ecological risks</th><th>Estimated cost associated with probable ecological damage
$C_{E,j} = P_j \cdot W_E \cdot$(EPS-value)</th><th>Corresponding Eco-indicator 95 and 99 values</th></tr>
<tr><td>Normal use
Functional failure 1 (Table 4)
Functional failure 2 (Table 4)</td><td>

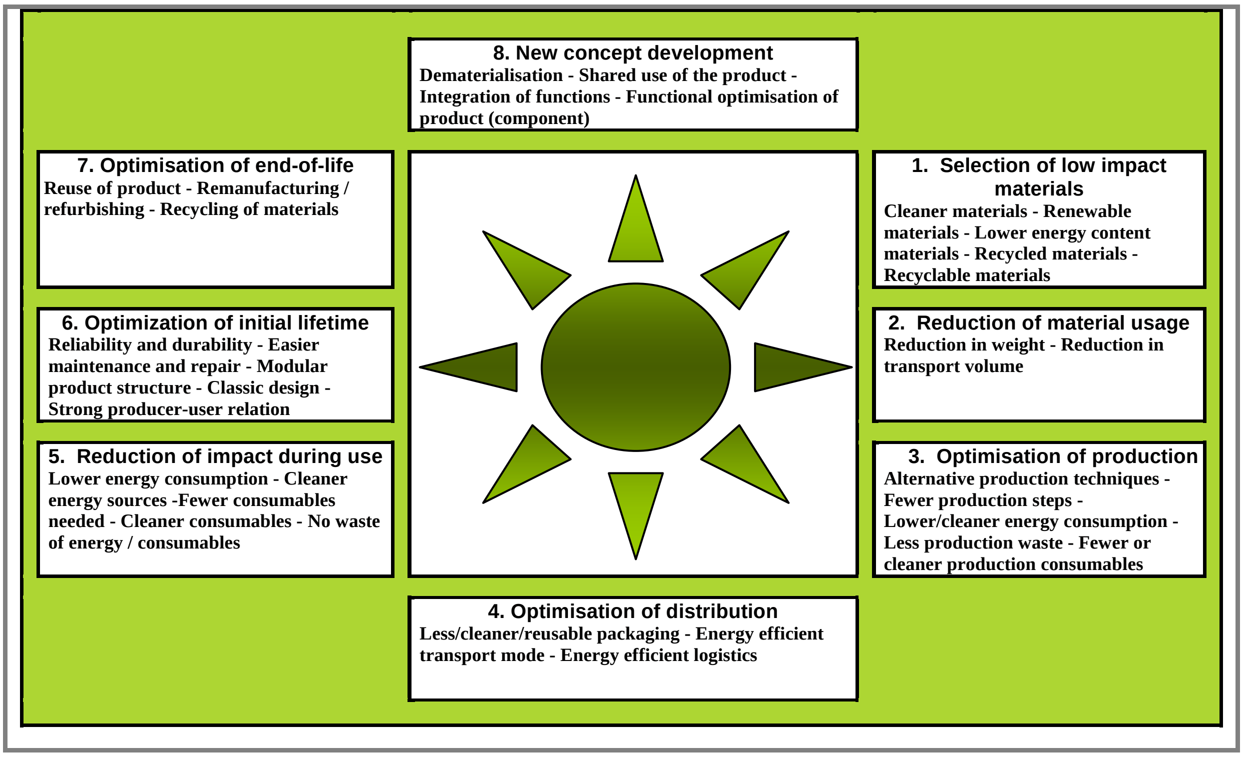
Total</td><td>

Total</td></tr>
</table>

2.3.1 Minimal environmental impact and ecodesign

Ecodesign strategies have been formulated in order to accomplish minimum environmental impact of a product during its development, use and end-of-life phase.

Figure 11. Principle scheme for the ecodesign strategy wheel proposed by Van Hemel[11]



The principle strategies for ecodesign may be represented by the so-called ecodesign strategy wheel illustrated schematically in ***Figure 11***. The strategies 1 and 2 relate to the material level, whereas the strategies 3, 4 and 5 concern the product structure. The strategies 6 and 7 concern measures, which can be taken on the production system level. Those strategies may also have a great impact on the suitability of different design alternatives for a functional unit of the product. Strategy 8 is the new concept development stage where the product concept as a whole is questioned.

The ecodesign strategy wheel thus summarises all the various measures that can be taken to reduce the environmental impact of a product, and therefore may be used as a framework when setting the overall environmental policy priorities of a company into practice.

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[11] Tools for setting realizable priorities at strategic level in Design for Environment; G.G. van Hemel , Proceedings International Conference on Engineering Design, Heurista Prague (1995), p.1040

Strategy 1 is most often the starting point in ecodesign and in the material selection process for design of functional units of products. At that stage, considerations should be paid to the alternative use of:

• Cleaner materials	Due to their toxicity, some materials and additives have become prohibited or probably will be prohibited in the near future; some materials may cause depletion of the ozone layer and therefore should be avoided; some hydrocarbons may cause summer smog, while the use of many surface treatment methods and non-ferrous metals such as chromium, nickel, copper, and zinc, are presently questioned due to their environmental impact.
• Renewable materials	The use of finite materials should be avoided wherever possible.
• Lower energy content materials	The use of high-energy content materials may be questioned if the material is not recyclable.
• Recycled materials	Recycled materials should be used whenever possible instead of virgin materials.
• Recyclable materials	Materials should be selected that can be recycled to give a high quality material. The use of many different materials in a product should be avoided if the product is difficult to dismantle.

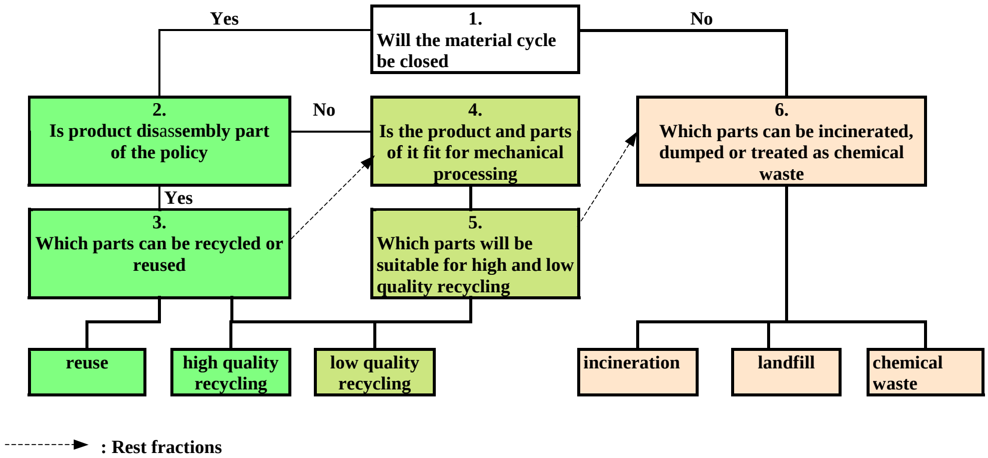
Reduction in material use, strategy 2, should be considered during the material selection process, which means that alternatives reducing the product mass and volume should be chosen because those are favourable from an environmental point of view.

By applying the ecodesign wheel approach, environmental problems associated with the use of a specific design alternative for a functional unit of the product may first be identified and listed as suggested in ***Table 8***. In this table also measures to solve or reduce the risks associated with the particular problem should be considered. This may be in the form of a new design alternative for the functional unit under study, which suitability consequently also needs to be assessed. The additional cost for reducing the environmental problem will appear in the estimated production cost for the new design alternative. Actions that can be taken in the service phase of the product to prevent or minimise the risk of unacceptable harm to the environment are numerous. Economic considerations will determine what measures are justified. To estimate the end-of-life cost, the end-of-life system should first be defined as schematically shown in Figure 12 and described in 2.3.2.

2.3.2 Possibilities for reuse and recycling to optimise end-of-life system[12]

Nowadays, developments in legislation on manufacturers' responsibilities and the increased level of environmental awareness force management to implement strategic considerations on how to optimise the end-of-life system of their products.

Figure 12. Flow chart with general guidelines to determine the end-of life destinations for the materials of a component in a product [13]



The first step in designing an end-of-life system is to determine the end destination of the different units or parts of the product, as schematically illustrated in Figure 12. Product parts can have different end-of-life destinations, depending on how they degrade with time and on how easy it is to dismantle parts from the product.

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[12] This section is a very brief review based on the following main references: (a) Handbook of Recycling Techniques, A. A. Nijkerk, (1995);NOH/353293/0710, Dutch National Research Programme for Recycling of Waste Substances (NOH/NOVEM), Den Haag, Netherlands, ISBN 90-9007664-6; (b) Konstruieren recyclinggerechter technischer Produkte (Designing Techniques for Ease of Recycling), VDI 2243, VD1-Verlag (1993)., Dusseldorf, Germany ; (c) De Eco-indicator 95, Handleiding voor ontwerpers (The Eco-indicator 95; manual for product developers), M. Goedkoop, NOH report 95 10(1995), Utrecht, Netherlands, ISBN 90-72130-78-2 (also available in English)

[13] Handbook of Recycling Techniques, A. A. Nijkerk, (1995). NOH/353293/0710, Dutch National Research Programme for Recycling of Waste Substances (NOH/NOVEM), Den Haag, Netherlands, ISBN 90-9007664-6

Disassembly is done for two reasons. Firstly, it is important to obtain the highest quality of secondary materials possible. Second, hazardous substances must be isolated so they do not contaminate other materials or exert too great an influence on the environmental impact of the whole product or on the financial return.

It is considered economically attractive to disassemble products by hand when the disassembly costs of useful parts (for reuse or recycling) are lower than the end-of-life costs. The decision whether or not to disassemble should be taken on the basis of rough estimation of the entire product. When the choice is made to disassemble the product, end-of-life destinations can be determined in more detail.

Parts may be reused when the technical service life of the product is longer than the economic life. Furthermore, it is important that there is a market for these parts - a current market or a possible future market. The value of secondary parts depends strongly on their application; if this is at the same level as in the original application, reasonable prices (20-60 percent of the original price) can be obtained. The price generally falls rapidly for lower grade applications.

Components or functional units not removed in the disassembly process usually end up in a combined form on mechanical processing lines. Some material may be suited for high quality cycling, some for low quality cycling and the rest have to be sent for incineration or landfill.

When a choice has to be made between incineration and landfill, the heat of combustion must be considered. The best solution for plastic parts, which cannot be reused or recycled, is therefore generally considered to be incineration.

If the product is not stripped of its toxic components, the entire product has to be treated as chemical waste. This will involve certain costs.

A number of design rules can be formulated to optimise a product or a component according to the end-of-life system but it falls outside the scope of this report to present a more detailed review of the field; the reader is referred to e.g. the handbook on recycling by Nijkerk[14].

2.3.3 End-of-life cost

The direct end-of-life cost of a design alternative of a functional unit of a product may be calculated on the basis of price quotations from service providers in the field of logistics, reuse and recycling/ processing. Data must

[14] See footnote 9

be gathered on rates charged for waste and incineration, while the value of the secondary materials must also be known.

In cases when the technical service life of a product is longer than its economic life, the whole product together with its different functional unites may be reused. To estimate the end-of-life cost for a specific design alternative of a functional unit after the economic life of the product has passed, the market price for the specific design alternative of the functional unit as a second hand spare part can be used or estimated. In such cases the end-of-life cost may often become even negative.

When adopting the total cost accounting approach, a specific service time shall be chosen as a base for the suitability analysis to be performed. The value of the secondary part of a specific design alternative of the functional unit depends thus strongly on how this service time is set. Probable failures, which may sometimes occur during the expected service time, will often lead to a certain fracture of the individuals of the functional unit considered can not be reused. When calculating the end-of-life cost of this fraction the different possibilities for recycling, for incineration or for disposal as waste as e.g. for landfill, should all be considered. If the service time is set longer than the expected technical service life of the specific design alternative of the functional unit there should not be any possibilities for direct reuse unless the functional requirements on the functional unit are redefined.

For complex products, it is important to know which parts of the product must be separated and which parts should be eligible for mechanical processing. In life cycle cost analysis, the direct end-of-life cost generally amount only to a minor fraction (1 to 7 percent) of the total cost. In the total cost accounting approach it may amount to a higher fraction dependent on how the assumed service time is defined.

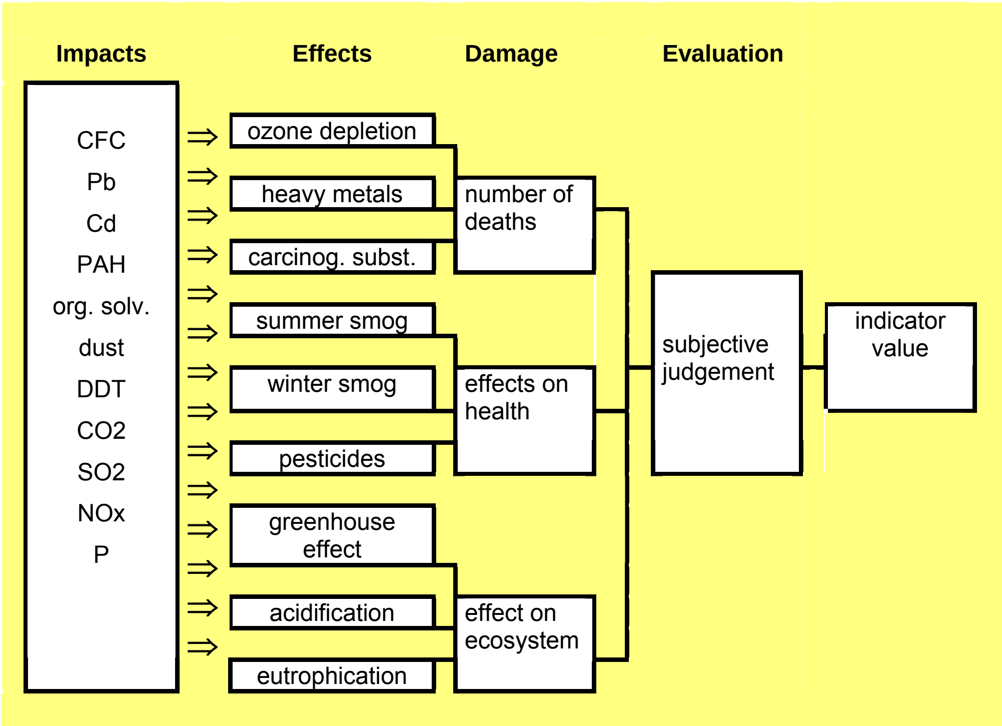
2.3.4 Estimation of environmental impact, ecological risks and associated costs for probable ecological damage

Life Cycle Assessment (LCA) may constitute the point of departure for estimating the ecological risks and associated probable costs for ecological damage that can be attributed to the use of a specific design alternative of a functional unit of a product.

After defining the functional unit in accordance with the LCA rules, the analysis continuous with an inventory of the material and energy exchange between the environment and the functional unit during its complete life cycle, encompassing extracting and processing raw materials, manufacturing, transportation and distribution, use, re-use, maintenance, recycling and final disposal. As a result of this inventory the different kinds of environmental impacts that can be associated with the functional unit may be assessed. From the result of the impact assessment, the effect of all the various impacts in terms of ozone depletion, heavy metal, carcinogenic substances, etc. are estimated as schematically shown in Figure 13.

Different systems are presently in use to facilitate the conversion of the various environmental effects into just one figure. It may be possible to make use of some of them for the purpose of comparing the environmental friendliness of different design alternatives of a functional unit of a product. One such system is the eco-indicator method[15], the principles of which are schematically illustrated in Figure 13. Another system is the EPS (Environmental Priority System)[16], see Figure 14, which is a system that was originally designed to express the environmental impact in cost terms.

Figure 13. Principle of the eco-indicator 95 method to assess environmental effect of a product life cycle[12]



There are many commercial LCA software tools available that can be applied to estimate environmental impact of a design alternative of a functional unit of a product; see e.g. Table 9. Data on environmental

[15] Goedkoop, M.J., Demmers, M., and M.X. Collignon, The Eco-indicator 95, Manual for Designers; NOH report 9524 (update 11/96), 1995, ISBN 90-72130-78-2. See also http://www.io.tudelft.nl/research/dfs

[16] Steen, Bengt, EPS-Default Valuation of Environmental Impacts from Emission and Use of Resources Version 1996. AFR-REPORT 111, Swedish Environmental Research Institute, IVL, Göteborg.

properties, eco - indicator and EPS values for some standard materials are for example available from sources such as the Idemat software tool, based on the SimaPro format[17]

Figure 14. Principle of the Environmental Priority System (EPS) to assess environmental effect of a product life cycle in terms of cost[13]

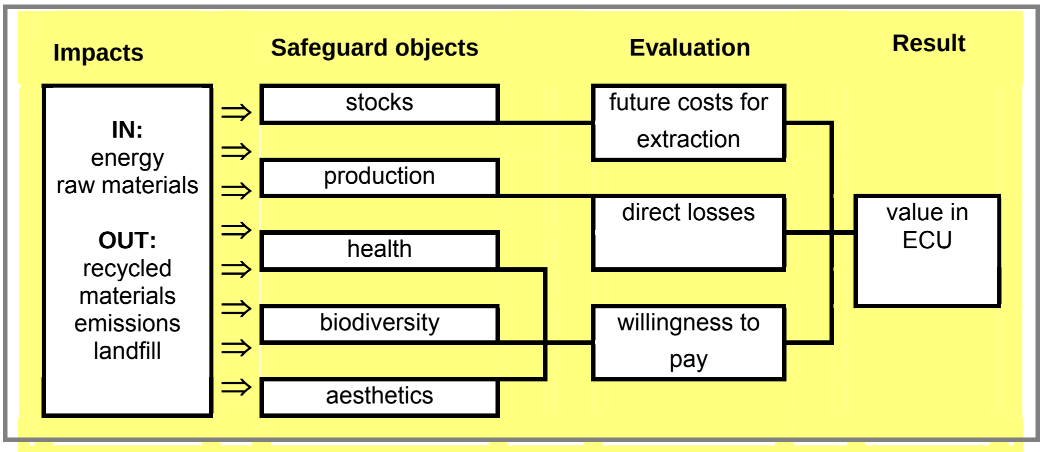


Table 9. Examples of European LCA tools

Tool	Vendor
Boustead	Boustead, UK
GaBi	IPTS, Germany
KCL-ECO	KCL, Finland
LCAiT	Chalmers Industriteknik, Sweden
PEMS	PIRA, UK
PIA	BMI/TME, The Netherlands
SimaPro	Pre' Consulting, The Netherlands
TEAM□	Ecobalance, UK
TEMIS	Oko-Institute, Germany

For the purpose of the total cost accounting approach for suitability analysis presented in this report, the use of the EPS indicator ELU, environmental load unit, is recommended, mainly because it is based on general opinions about the willingness to pay for some safeguard objects and thus related to cost in a way; see Figure 14. How much a specific company is prepared to pay for the same safeguards objects may vary from one company to another. It is thus up to the individual companies to determine how much estimated EPS cost values should be taking into account relative to other types of cost.

[17] www.io.tudelft.nl/research/dfs/service/idemat; see also www.pre.nl

In total cost accounting, therefore, the environmental cost associated with probable ecological damages, C_E , may be expressed as

$$C_E = W_E \cdot (\text{EPS -value}) \quad (4)$$

where W_E is a weighting factor set by the company itself and dictated by the company's environmental policy.

It is important, in the inventory and environmental impact assessment phase of the LCA analysis, also to take into account possible environmental impacts caused by functional unit or product failures, as well as those associated with initial non-ideal performance or functionality.

If a design alternative of a functional unit fails this may give rise to an additional cost due to failure in function, but the failure may also result in environmental damage for which an additional environmental cost may be estimated using, for example, the EPS approach. Additional cost due to failure in function and in repair and environmental clean-up work shortly after the failure has occurred should be included in the cost of failure for a studied design alternative; see equation (1). The cost for the associated probable environmental damage should be estimated as shown in equation (3). The normal case, i.e. when no unexpected failure occurs, represent the case when the probability for failure/damage $P_j = 1$. The probability for the various possible kinds of failure, which might happen and result in environmental damages, may be estimated with the same kind of methods presented and discussed in subchapter 2.3.

In cases when cost for initial non-ideal performance has to be taken into account it should be remembered that non-ideal performance also results in increased environmental impact. Excess weight of automotive parts results in extra fuel consumption giving rise to an extra environmental load. Non-ideal optical performance of a window pane decreases the energy performance of a house and as a consequence of that extra energy has to be supplied, which will increase the environmental load generated for the heating of the house.

The available indicators for environmental impact deviate from each other in that they emphasize the importance of the factors for environmental impact differently. It is therefore recommended to use more than one indicator when presenting the results of an environmental impact study of a product, functional units of it or a material. In Table 8 it is therefore recommended to give values also for Ecoindicator 95 and Ecoindicator 99 although there conversion into cost terms is not evident or possible to achieve.

2.4 Design alternative of functional unit with the lowest total cost

Using equation (1), the result of the complete suitability analysis for a specific design alternative for a functional unit might be represented by a single total cost estimate in which ideally all important aspects of the design of the functional unit are taken into account. The design alternative with the lowest total cost should accordingly be the most appropriate choice for the functional unit.

The results from the suitability analysis of the different design alternatives for the functional unit considered may be documented as exemplified in ***Table 10*** to allow for a comparison of the pros and cons of the different alternatives in a very condensed way. Although it may not be possible to estimate a cost for all terms contributing to the total cost, the result of the exercise may, nevertheless form a good base for obtaining the most appropriate design of the functional unit considered.

From the available data from the suitability analysis, the final choice of design alternative should preferably be performed by a group of experts representing the different fields of expertise needed for the suitability analysis. The information missing can therefore be estimated roughly by expert judgements and at the same time also the relevancy or accuracy of all data obtained in the suitability analysis can also be assessed jointly by the different experts. From a practical point of view, as well as from economic point of view, a suitability assessment study has to be limited in its scope and focused on the most critical aspects associated with the design process of the functional unit. As the final step in the suitability assessment study the development cost for the different design alternatives should be estimated. In that cost should be included the extra cost needed for additional verification of some critical properties related to the use of some of the design alternatives identified during the course of the suitability analysis.

Thus, practical tools from Material Lifetime Technology and Industrial Ecology have been identified that enable most of the essential factors for the design of functional units of products to be assessed quantitatively in accordance with the total cost accounting approach. The different factors, or rather terms, contribute each to the total cost associated with maintaining the prescribed function of a unit of the product for a fixed service time. However, the important point is not to obtain an exact value of the total cost, but, to

- obtain a measure and an understanding of the relative importance of the various factors contributing to the total cost, and

- be able to make comparisons in the cost characteristics between different design alternatives of the functional unit.

Table 10. Example on how the results from a suitability analysis of different design alternatives a functional unit may be summarized (C_P = Production cost, C_{NIP} = Cost associated with initial non-ideal function or performance, C_M = Maintenance cost, C_F = Cost of probable failures and damage, C_{EoL} = End of life cost, C_E = Environmental cost associated with probable ecological damage, C_D = Development cost).

Total cost estimates

Design alternative	C_P	C_{NIP}	C_M	C_F	C_{EoL}	C_E	C_D	C_{Tot}
Alternative 1								
Alternative 2								
Difference in cost between alternative 1 and 2								

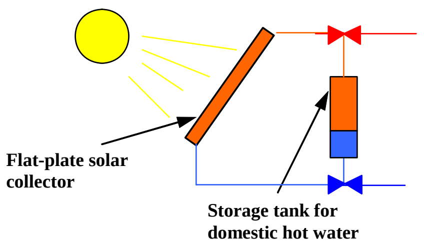
3 Suitability assessment by total cost for selection of solar absorber surfaces

Bo Carlsson, University of Kalmar, SP Swedish National Testing and Research Institute

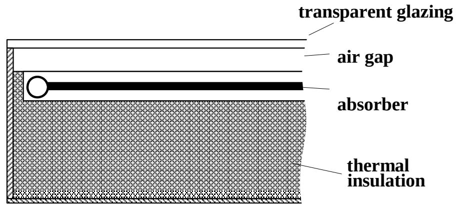
3.1 Solar absorber surfaces for use in flat plate solar collectors for domestic hot water production

Renewable energy technologies, such as solar heating, often place special requirements on the long-term performance of the energy producing systems. Because of the relatively low energy price for today's conventional energy sources, most of today's solar domestic hot water systems, need to function for a long time period, at least 25 years, without significant decrease in their energy efficiency. Besides that, the low power density of the solar irradiation, maximum 1 kW/m^2, place additional requirements on the solar heating system with respect to design and cost effectiveness. As environmental concern is the most important incitement for installing a solar heating system today, the design concept chosen for the solar heating system must also be sustainable in nature. Thus, the solar energy has to be collected with a rather simple, durable and environmental friendly device. The device shall also have a relative large area for solar collection and designed so that heat losses from it can be kept low. In Figure 15 a typical design of a single glazed flat plate solar collector often used for solar domestic hot water production is shown.

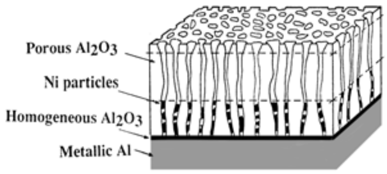
Figure 15. Schematic drawings a solar domestic hot water system with a single glazed flat plate solar collector that is equipped with a solar absorber with a selective absorber coating of anodized aluminium pigmented with small metallic nickel particles



Principle sketch of a solar domestic hot water system. In the example discussed in this chapter the solar domestic hot water system is assumed to have a system efficiency of 50 %. This means that within 25 years the amount of solar energy collected and utilised should be 10 000 kWh/m² . At an energy price of 0,60 SEK/kWh this corresponds to 6000 SEK/m².



Schematic cross section of a single glazed flat plate solar collector

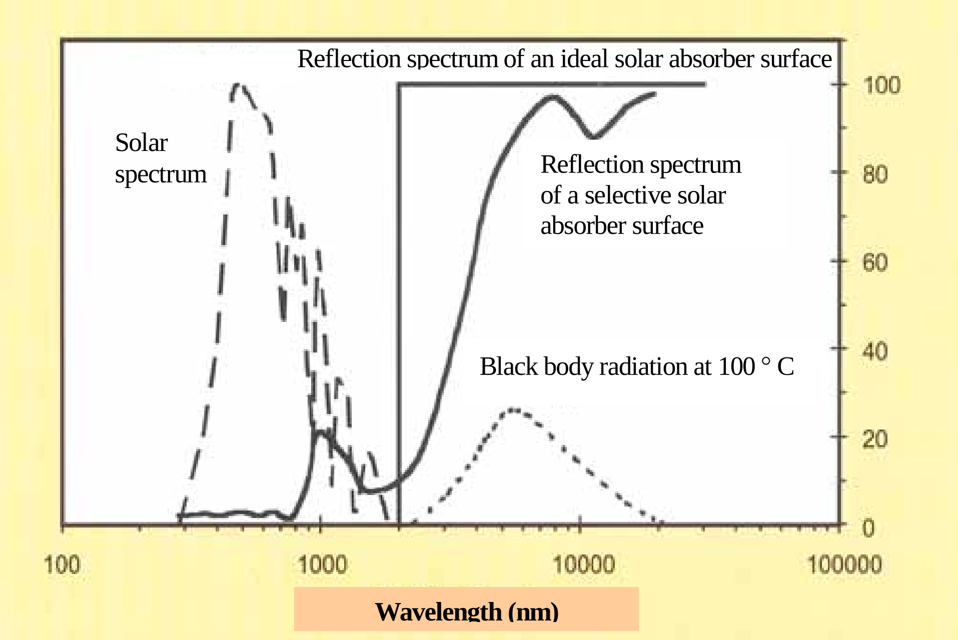


Cross section of a selective solar absorber coating of anodised aluminium pigmented with small metallic nickel particles. The substrate of the coating is an aluminium/ copper laminate.

The solar irradiation is absorbed by an absorber with a front surface often in the form of a coating. The absorber is designed as a flat-plate heat exchanger, where the heat gained is transferred to a fluid for transport to a thermal storage unit. The absorber is insulated to reduce thermal losses. The glazing, acting as a convection barrier, is used for insulating the front surface. The materials properties, particularly the optical properties of the absorber coating and the glazing, contribute essentially to the efficiency of the solar collector and the overall performance of the solar domestic hot water system.

The most important functional unit in the collector is the solar absorber. The front surface of the absorber should absorb as much as possible of the incident solar radiation with intensity maximum in the spectral wavelength range from 0.3 µm to 3 µm; see Figure 16. Moreover, it should not lose energy by thermal radiation meaning that its reflection in the infrared wavelength region from 3 µm to 20 µm should be high. An optimised solar absorber surface, exhibiting a high absorption, low reflection, in the solar range and a low emittance, high reflection, in the thermal range, is called a spectrally selective solar absorber surface.

Figure 16. Reflectance spectrum of a selective solar absorber coating, the spectrum of solar irradiation, and the spectral appearance of the black body radiation at 100 °C



Selective solar absorber surfaces are typically prepared by depositing a coating, which absorbs the solar irradiation and transmits the thermal radiation, to an IR–reflecting metal substrate or metal coating. Porous anodised aluminium has, as shown in Figure 15, long been used as a substrate material for selective solar absorbers. The pores of the alumina are partly filled with small metallic nickel particles produced by electro deposition. The empty upper part of the porous alumina forms the anti-reflective layer.

A wide variety of coatings have been developed in the last few decades. Coatings produced with modern vapour deposition technologies are considered of special interest as the production can be made cleaner without large quantities of chemical waste and the production conditions made easier to control when compared with the electrochemically produced coatings. Some sputtered coatings have been commercially available now for more than five years.

One such sputtered selective solar absorber surface will in this chapter be compared with the electrochemically produced nickel pigmented anodized aluminium absorber coating described in Figure 15. The sputtered coating consists mainly of two layers on a substrate of aluminium, one absorbing base layer next to the substrate and on that one antireflective top layer. The base layer is composed of a mixture of nanosize grains of metallic nickel and of nickel oxide. In the upper part of the base layer the amount of metallic nickel is gradually decreasing and in the front surface only nickel oxide is present[18].

You may ask how favourable the sputtered nickel based absorber coating is when compared with the old electrochemically produced. A suitability analysis with a total cost based comparison between the two alternatives will nicely illustrate the pros and cons of the two kinds of solar absorber coatings. The analysis will partly be based on the results from a case study on accelerated life testing of solar absorbers performed in Task 10 of the IEA Solar Heating and Cooling Program[19]

3.2 Suitability analysis of the two design alternatives

3.2.1 Function requirements, capability and cost characteristics

In Table 12 the general requirements as regards function, long-term performance, and severity of environmental stress under in-service conditions are listed.

To be of economic interest, the requirement on long-term optical performance of the solar absorber coating has been set at level corresponding to a maximal loss of 5 % in system performance after a service time of 25 years in accordance with the IEA Task 10 group recommendation. In-service environmental severities given are very general in this stage of the analysis, but point to the importance of having a solar absorber coating resistant to high humidity loads in case of loss in rain tightness of the collector box.

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[18] Industrial sputtered solar absorber surface, E. Wäckelgård and G. Hultmark, Solar Energy and Solar Cells (1998) 165-170

[19] Accelerated Life Testing of Solar Energy Materials – Case study of some selective solar absorber coating materials for DHW systems, B. Carlsson, U. Frei, M. Köhl, and K. Möller; International Energy Agency Solar Heating and Cooling Programme Task X Solar Materials Research and Development, SP Report 1994:13, ISBN 91-7848-472-3

Table 12. Function specification for the solar absorber surface

Specification of end-user and product requirements on functional unit

Function and general requirements	General requirements for long-term performance during design service time	In-use conditions and severity of environmental stress
-Efficiently convert solar radiation into thermal energy -Reduce heat losses in the form of thermal radiation	-Loss in optical performance should not result in reduction of the solar system energy performance (solar fraction) with more than 5%, in relative sense, during a design service time of 25 years	*-Behind glazing in contact with air.* - Casing of collector exchange air with the ambient, meaning that airborne pollutants will enter collector. - If the collector is not rain tight humidity level of air in the collector may become high - Maximum temperature 200 °C

In Table 13 the general requirements on function have been transformed into specific requirements related the relevant optical properties of solar absorptance (α) and thermal emittance (ε). Based on an analysis performed by the IEA Task 10 group, the general requirements on long-term optical performance may also be transformed into a material specific requirement through the function $PC = - \Delta\alpha + 0.25\Delta\varepsilon$.

From the optical property data presented in Table 13 on the two different design alternatives of absorber coatings it can be seen that the sputtered coating has a higher optical performance than the electrochemically produced in that the solar absorptance is higher and the thermal emittance is lower.

In Table 13 some cost characteristics for the two kinds of absorber coatings are also shown. In case of production cost, C_P, the two coatings can be considered equal although the production of the sputtered coating requires a more advanced technique. However, due to the benefits of larger scale of production, better control and more rational handling of the production, the price of the sputtered coating can be kept at the same level as the electrochemically produced coating[20].

[20] Private communication with Sunstrip AB, www.sunstrip.com, and Jan-Olof Dalenbäck, Chalmers Technical University, Gothenburg, Sweden

Table 13. Functional properties and cost characteristics for the two solar absorber coatings considered

Function, production cost and cost associated with initial non-ideal performance

Critical functional properties	**Test method for deter-mining functional properties**	**Requirement for functional capability and long-term performance**
-Solar absorptance (α) -Thermal emittance (ε) -Adhesion ad (ad)	ISO CD 12592.2 ISO CD 12592.2 ISO 4624	*Functional capability* $\alpha > 0.92$ $\varepsilon < 0.15$ ad >0.5 MPa *Long-term performance* $- \Delta\alpha + 0.25\ \Delta\varepsilon \leq 0.05$
Suitable design alternatives	**Functional capability and material properties***	**Production cost (C_P)**, Costs associated with initial non-ideal performance (C_{NIP})**
Electrochemically produced coating	$\alpha = 0.935$; $\varepsilon = 0.15$; ad >> 0.5 MPa	C_P = 240 SEK/m^2 ; C_{NIP} = 615 SEK/ m^2
Sputtered coating	α= 0.95; $\varepsilon = 0.12$; ad > 0.15 MPa	C_P = 240 SEK/m^2 ; C_{NIP} = 480 SEK/ m^2

** Optical data for the electrochemical produced coating refer to the IEA Task 10 study (see footnote) and for the sputtered coating to measurements made in a round robin test performed by the IEA group Materials for Solar Thermal Collectors*[21]
*** The price, excluding VAT, for a complete flat plate solar collector with a selective solar absorber should be in the order of 1000 SEK/ m^2 at least for a large scale solar system* [x].

A cost for initial non-ideal performance arise in this particular case due to non-ideal optical performance of the absorber coatings, $\alpha = 1$ and $\varepsilon = 0$ ideally. To transfer the meaning of this non-ideal performance into cost terms, the simple model as described in Figure 15 was used. The solar domestic hot water system is assumed to have a system efficiency of 50 %, which means that within 25 years the amount of solar energy collected and utilised should be 10 000 kWh/m². At an energy price of 0,60 SEK/kWh this corresponds to 6000 SEK/m². Loss in solar system performance can in this case be related to loss in optical performance of the absorber coating through the function PC = $- \Delta\alpha + 0.25\ \Delta\varepsilon$, as the value of the PC function corresponds to the relative loss in solar system performance. Relative the ideal case of $\alpha = 1$ and $\varepsilon = 0$, a value of the PC function can thus be calculated and the initial non-ideal optical performance translated into cost based on the assumed amount of solar energy collected and utilized and the assumed energy price.

[21] "Round robin on accelerated life testing of solar absorber surface durability", S.Brunold, U. Frei, B. Carlsson, K. Möller, M. Köhl; Solar Energy Materials & Solar Cells, **61** (2000)239

3.2.2 Reliability and long-term performance, cost of probable failures and maintenance

In the analysis of the reliability and long-term performance in this case only the long-term performance aspect will be considered. The failure to be taken into account is the development of an unacceptable loss in the optical performance of the coatings.

The long-term stability of the electrochemically produced nickel pigmented anodized aluminium coating was thoroughly studied by the IEA Task 10 group. Mainly three degradation mechanisms were identified that could lead to an unacceptable loss in optical performance of the absorber coating, namely

1. high temperature oxidation, which is mainly operative under stagnation conditions of solar collector at high levels of solar irradiation and thus when no heat is withdrawn from the collector,
2. electrochemical corrosion of metallic nickel which may result from exposure to high humidity and airborne pollutants under starting-up and under non-operating conditions of the solar collector when the outdoor humidity level is high, and
3. hydration of aluminium oxide from the action of condensed water or moister on the absorber surface during periods when the humidity in the collector is very high.

To get a first idea on the relative importance of the different degradation mechanisms a FMEA/ /FMECA analysis may be carried out as has been described in the previous chapter. The result of such an initial risk analysis based on the experience gained in the IEA Task 10 study is shown in Table 14 for the case when the electrochemically coating is assumed to be installed in a non-airtight solar collector with uncontrolled ventilation of air meaning that the humidity level in the solar collector may reach very high levels and condensation appear on the absorber coating[22].

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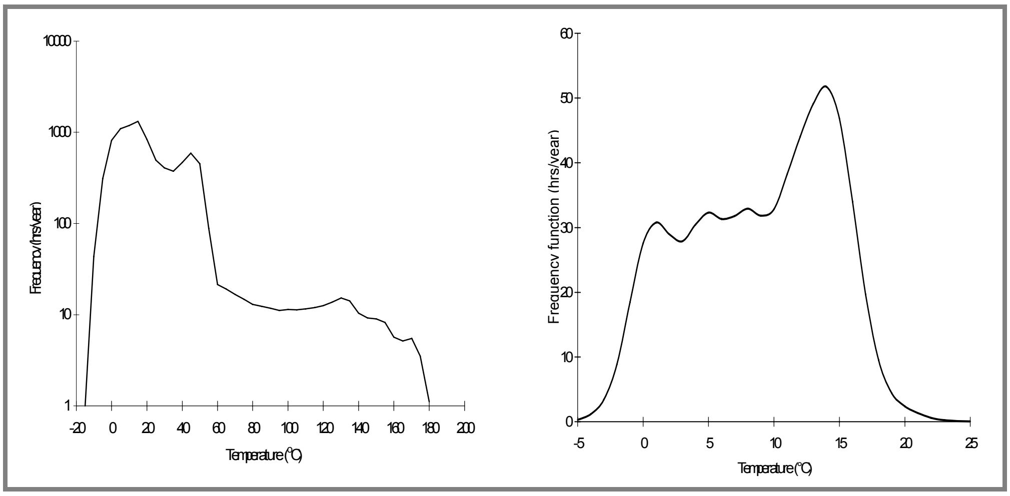
[22] Initial Risk Analysis and Potential Failure Modes, B. Carlsson, *Performance and Durability Assessment of Optical Materials for Solar Thermal Systems,* Editors M. Köhl, B. Carlsson, G. Jorgensen, and A. W. Czanderna, (Elsevier 2004)

Figure 17. Results from measurement of microclimate for absorber in the non-airtight solar collector of IEA Task 10 study; Left diagram: Absorber temperature frequency function for one year. For one month of the year the collector is under stagnant conditions; Right diagram: Absorber temperature frequency function when RH ≥ 99% of that year.
Metallic mass loss due to corrosion of zinc was determined to 0.3 g/m^2, year



The purpose of the initial risk analysis is to identify the most important degradation mechanisms, which importance needs to be further assessed by way of accelerated life testing. In the IEA Task 10 study a program for accelerated life testing was conducted, which results are given in the middle section of Table 14 in case of the electrochemical coating in the non-airtight solar collector. Constant load high temperature exposure tests in the range of 200-500 °C were used to assess the thermal stability of the coating. To convert the test results into an expected service life with PC < 0.05, temperatures were used that had been measured on the absorber in a non-airtight solar collector exposed under typical domestic solar hot water system conditions for one year; see Figure 17. Exposure tests at constant high air humidity of 95 % RH, constant temperature at 20 °C, and in the presence of sulphur dioxide (1 ppm) were used to assess the stability against atmospheric corrosion. Besides that exposure tests under constant condensation ranging from 30-60 °C were used to assess the resistance to condensed water for the absorber coatings. Measured data on environmental stress from the collector exposure were also used in those two cases to convert the test results into an expected service life with PC < 0.05; see Figure 17.

Table 14. Detailed results from the estimation of cost for probable failures in the case of the electrochemically produced solar absorber coating installed in a non-airtight solar collector with uncontrolled ventilation of air

<table>
<tr><td colspan="2">Failure
Unacceptable loss in optical performance related to
PC = - Δα + 0.25 Δε < 0.05 and adhesion >0.5 MPa</td><td colspan="4">Estimated risk of failure/damage mode from FMEA/FMECA</td></tr>
<tr><td>Damage mode</td><td>Critical factors of environmental stress and severity of stress</td><td>S</td><td>P_O</td><td>P_D</td><td>RPN</td></tr>
<tr><td>1. High temperature oxidation of metallic nickel, which results mainly in a decrease in the solar absorptance</td><td>High temperature under stagnation conditions of solar collector at high levels of solar irradiation (no withdrawal of heat from the collector)</td><td>7</td><td>2</td><td>8</td><td>112</td></tr>
<tr><td>2. Electrochemical corrosion of metallic nickel, which also results mainly in a decrease in the solar absorptance</td><td>High atmospheric corrosivity due to high humidity and airborne pollutants under starting-up and under non-operating conditions of the solar collector when the outdoor humidity level is high</td><td>7</td><td>8[2]</td><td>5[1]</td><td>287</td></tr>
<tr><td>3. Hydatization of aluminium oxide, which results in an increase in the thermal emittance</td><td>Condensed water, temperature under conditions involving condensation of water on the absorber surface</td><td>7</td><td>9[2]</td><td>4[1]</td><td>252</td></tr>
<tr><td colspan="6">[1] P_D value resulted from possible failure of glazing;
[2] The high value can be explained by the fact that a non-air tight solar collector with uncontrolled ventilation of air is assumed to be used</td></tr>
<tr><td>Damage mode</td><td>Suitable environmental resistance tests and service environmental stress conditions</td><td colspan="4">Probability of failing during the fixed service time, $F_i(\tau_S)$ in eq. (2)</td></tr>
<tr><td>1. High temperature oxidation of metallic nickel</td><td>Constant load high temperature exposure tests in the range of 200-500 °C* .</td><td colspan="4">Negligible. Service life with PC<0.05 was estimated to >10^5 years by accelerated life testing.</td></tr>
<tr><td>2. Electrochemical corrosion of metallic nickel</td><td>Exposure tests at constant high air humidity 95 %RH, constant temperature 20 °C, and in the presence of sulphur dioxide 1 ppm*.</td><td colspan="4">Service life with PC<0.05 was estimated to 12 years by accelerated life testing. This corresponds to an average loss of 5 % during the total service time of 25 years. F_2 (25) may thus be set at 0.05.</td></tr>
<tr><td>3. Hydration of aluminium oxide</td><td>Exposure tests under constant condensation (sample surface cooled 5 °C below surrounding air which is kept at 95 % RH and temperature conditions ranging from 30-60 °C*.</td><td colspan="4">Service life with PC<0.05 was estimated to 9 years by accelerated life testing. This corresponds to an average loss in system efficiency of 7 % during the total service time of 25 years. F_3 (25) may thus be set at 0.07.</td></tr>
<tr><td>Failure/Damage mode</td><td>Cost of failure/damage mode, $C_{F,I}$ in eq. (2)</td><td colspan="4">Cost of probable failures and damage, ($C_{F,I} \cdot F_i(\tau_S)$) in eq. (2)</td></tr>
<tr><td>Damage mode 1</td><td>6000 SEK for PC = 1</td><td colspan="4">Negligible</td></tr>
<tr><td>Damage mode 2</td><td>6000 SEK for PC = 1</td><td colspan="4">a) 310 SEK</td></tr>
<tr><td>Damage mode 3</td><td>6000 SEK for PC = 1</td><td colspan="4">a) 420 SEK</td></tr>
</table>

* For stress specification measured temperature data was used; see Figure 17

The conclusion from the result of the accelerated high temperature tests was that the thermal stability was quite satisfactory, as shown in Table 14. In case of resistance to corrosion, the service life with PC<0.05 could be estimated to 12 years. This then corresponds to an average loss of 5 % during the total service time of 25 years. The probability of failure $F_i(\tau_s)$, as appears in equation (2), can therefore be introduced in the following way. If failure is redefined to the situation when the optical performance is completely lost F_2 (25 years) may accordingly be set at 0.05. The case taking into account the resistance to condensed water can be treated similarly. From the accelerated life tests results, the service life with PC<0.05 was estimated to 9 years and this corresponds to an average loss in system efficiency of 7 % during the total service time of 25 years. The probability for failure F_3 (25years) may thus be set at 0.07 in this case. As indicated in the lowest section of Table 14, the costs for probable failures related to the two dominating damage modes thereafter could be calculated.

The corresponding costs for probable failures for the absorber with the sputtered coating and for the absorber with the electrochemically produced coating but when installed in an airtight solar collector was made in analogy with what is shown in Table 14 and the results are presented in Table 15.

For the absorber with electrochemically produced coating installed in an airtight solar collector with controlled ventilation of air, the results from the study of the IEA Task 10 group could also be used as base for the estimation of the cost for probable failures. In this case it was assumed that the corrosion of metallic nickel is the only degradation mechanism needed to be taken into account when estimating the cost of probable failures. From the results of a study carried out on samples of the electrochemically produced absorber taken from solar domestic hot water systems that had been in use for more ten years this assumption seemed reasonable to make; see footnote[23].

[23] Comparison between predicted and actually observed in-service degradation of a nickel-pigmented anodised aluminium absorber coating for solar DHW systems" B. Carlsson, K .Möller, U. Frei, S. Brunold, M .Kohl,; Solar Energy Materials and Solar Cells 6 (2000)223

Table 15. Cost of probable failures estimated for the two kinds of solar absorber coatings analysed with respect to their suitability for use in solar domestic hot water production

Reliability and long-term performance, cost of probable failures and of maintenance

Design alternative	Estimated cost of probable failures and damage (C_F)	Need and estimated cost of maintenance (C_M)
Electrochemical produced coating	**730 SEK/m²** in the case of a non- airtight solar collector with uncontrolled ventilation **120 SEK/m²** in the case of an air tight solar collector with controlled ventilation	No need for maintenance in the form of replacing the selective solar absorber during the assumed service time
Sputtered coating	**36 SEK/m²** in the case of a no airtight solar collector with uncontrolled ventilation **12 SEK/m²** in the case of an air tight solar collector with controlled ventilation	No need for maintenance in the form of replacing the selective solar absorber during the assumed service time

For the sputtered solar absorber, accelerated life test results from the round robin test performed by the IEA Working group on materials for solar thermal collectors were used [24]. It should however be pointed out that the sample tested in this case was the sputtered coating but on a substrate of stainless steel instead of on aluminium as planned. The durability of the sputtered coating on stainless might be better compared with that of the sputtered coating on stainless steel, because of the higher corrosion resistance of stainless steel. However, the dominating degradation mechanism is assumed to be the corrosion of the metallic nickel particles and how important the corrosion of the substrate is for the durability of the absorber coating is therefore presently hard to tell.

3.2.3 Environmental costs and ecological risks

As has been mentioned, environmental concern was the driving force in the development of the sputtered nickel based absorber coating to replace the old electrochemically produced nickel pigmented anodized aluminium absorber coating for reasons summarized in Table 16.

[24] Round robin on accelerated life testing of solar absorber surface durability, by S.Brunold, U. Frei, B. Carlsson, K. Möller, M. Köhl and published in Solar Energy Materials & Solar Cells, **61** (2000)239

Table 16. Ecodesign considerations related to the electrochemical produced coating

Design alternative	Environmental problem during production, service and end-of-life	Ecodesign measures and additional costs
Absorber with electrochemicall y produced coating	Waste water from electrochemical production of nickel pigmented anodised aluminium has to be taken care of by sufficient cleaning.	Changing the production process from electrochemical coating to coating by sputtering technique can solve the problem. The production cost can essentially be kept at the same level through more rational handling and better control of the coating process

When comparing the two design alternatives for solar absorber coating with respect to recoverability, the situation is very much the same for the two. The aluminium in the two absorbers can be recovered by recycling through the assistance of the manufacturer of the aluminium used[25]. The scrap price for the absorber is about the same as the cost for dismantling and transport. The direct end-of-life cost can therefore be set at zero for the absorber coatings considered; Table 17

Table 17. End-of-life system for the two kinds of solar absorbers

End-of-life system	Estimated end-of-life cost
The absorber can be recycled. Scrap price is in about the same order as the cost for dismantling and transport.	Direct end-of-life cost can roughly be set at zero.

In case of the indirect environmental costs or cost for probable environmental damage, LCA Impact assessment can be used to get a rough indication of the difference that exists between the two kinds of absorber coatings.

Considering first the manufacturing of the electrochemically produced nickel pigmented anodized aluminium coating some data from the Swiss database ETH-ESU from 1996 can be used [26]. According to this database, the environmental impact expressed by the EPS ecoindicator amounts to 6 ELU/ m^2 solar collector area; as shown in Table 18. The corresponding figure for the sputtered coating was estimated to be around 4 ELU/m^2 solar collector area; this estimate arrived at by making use also of some information from the same database regarding the electricity need for the sputtering process.

From the data presented in Table 18, it can be concluded that the importance of the environmental impact contribution from the manufacturing of the

[25] Private communication Sunstrip AB, www.sunstrip.com
[26] see e.g. SIMA PRO 6 LCA software, www.pre.nl/simapro

absorbers to the total environmental impact of the solar absorbers including also the service phase is relatively small. This becomes evident when taking into account the supply of extra energy, which is needed for two reasons. Firstly, extra energy is needed to compensate for the difference in initial non-ideal optical performance between the two absorber coatings. Secondly extra energy is needed to compensate for the in-service degradation in performance of the absorber coating which will occur; see Table 18. When calculating the extra energy contribution it was assumed that this will be in the form of electricity. It can be concluded that the most important contribution determining the difference in the total environmental impact between the two kinds of solar absorber coatings originates from loss in the capability of the solar absorbers to produce hot water. This is, not unexpectedly, consistent with the fact that replacing conventional energy sources with solar energy should result in a considerable reduction in the environmental impact associated with the conventional way of producing domestic hot water.

Table 18. Ecological risks and associated costs for the two design alternatives of solar absorbers (Data from SimaPro 6 LCA software, www.pre.nl/simapro)

Environmental impact and ecological risks	Estimated cost associated with probable ecological damage $C_{E,i} = P_i \cdot W_E \cdot$(EPS-value)		Corresponding values for Eco-indicator 99 H/A	
Design alternative: Absorber with electrochemically produced coating				
1. During manufacturing	6 ELU		0.8 Pt	
2.Effect of supplying extra electric energy to compensate for non-ideal initial optical properties*	127 ELU		8.9 Pt	
3. Effect of supplying extra electric energy to compensate for degradation in optical properties during service*	*non-airtight case* 162 ELU	*airtight case* 25 ELU	*non-airtight case* 11 Pt	*airtight case* 1.8 Pt
Total	295 ELU	158 ELU	20.7 Pt	11.5 Pt
Design alternative: Absorber with sputtered coating				
1.During manufacturing	4 ELU (rough estimate)		0.6 Pt	
2.Effect of supplying extra electric energy to compensate for non-ideal initial optical properties*	99 ELU		7.0 Pt	
3. Effect of supplying extra electric energy to compensate for degradation in optical properties during service*	*non-airtight case* 7 ELU	*airtight case* 2 ELU	*non-airtight case* 0.5 Pt	*airtight case* 0.14
Total	110 ELU	105 ELU	8.1 Pt	7.7 Pt
Difference between the two alternatives in total	184 ELU	52 ELU		

* The data for electric energy has been taken from the Swiss ETH-ESU database (see footnote x) and represent mean Western European conditions, 10 kWh has been set equal to 1.24 ELU

3.3 Conclusions from the suitability analysis of the solar absorber surfaces

The results of the suitability analysis of the two solar absorber coatings are summarized in Table 19 and as expected the sputtered coating seems more favourable to the electrochemical coating in all respects.

From the results the following general conclusions can be drawn:

1 The biggest contribution to the difference in total cost between the two kinds of absorber coatings is obtained for the cost of probable failures C_F in that case when the solar absorber is assumed to be installed in a non-airtight solar collector with uncontrolled ventilation of air. This points to the importance of choosing a collector box of a proper design as regards ventilation so that the humidity and corrosivity loads on the solar absorber can be kept and maintained low during the entire period of service.

2 The second biggest contribution to the difference in total cost is obtained for the cost of initial non-ideal performance, which illustrates the importance of having a solar absorber surface with optical properties as close as possible to the ideal situation.

Table 19. Summery of the results from the suitability analysis of the two kinds of solar absorber coatings. (a) refers to the case when the solar absorber is installed in a non-airtight solar collector with uncontrolled ventilation of air and (b) refers to the case when the solar absorber is installed in an airtight solar collector with controlled ventilation of air. The service time is 25 years. The price of energy has been set equal to 0.60 SEK/kWh. (C_P = Production cost, C_{NIP} = Cost associated with initial non-ideal function or performance, C_M = Maintenance cost, C_F = Cost of probable failures and damage, C_{EoL} = End of life cost, C_E = Environmental cost associated with probable ecological damage, C_D = Development cost)

Total cost estimates (SEK/m^2)

Design alternative	C_P	C_{NIP}	C_M	C_F		C_{EoL}	C_E (ELU)		C_D	C_{Tot}	
Electrochemically sputtered coating	240	615	0	730 (a)	120 (b)	0	294 (a)	157 (b)	-		
Sputtered coating	240	480	0	36 (a)	12 (b)	0	110 (a)	105 (b)	-		
Difference in cost between the electrochemically and sputtered coating	0	135	0	694 (a)	108 (b)	0	184 (a)	52 (b)		829* (2485)** (a)	243* (711)** (b)

*Excluding $\mathbf{C_E}$ ** Including $\mathbf{C_E}$ under the assumption that 1 ELU = 9 SEK

3 The contribution to the difference in total cost with respect long-term performance in the case of installing the solar absorber in an airtight solar collector is considerably lower when compared with the situation when a non-airtight solar collector is used. However, durability may despite that be an important aspect and efforts made to improve durability should be taken with the same priority as improving the initial optical performance.

4 Main contributions to the difference in the cost for probable environmental damage between the two kinds of solar absorbers are associated with differences in functional capability and thus reduced capability to use solar energy for the intended function of domestic hot water production. If the EPS indicator ELU is converted into cost, Euro as originally meant, the cost for probable environmental damage will be of the same order of magnitude as the total cost excluding this cost even if the weighting factor W_E in equation (4) (see 2.3.4) is as low as around 50 %.

5 Although the main purpose of the suitability analysis in this case was to compare two kinds of solar absorber coatings, the result of the analysis clearly illustrates the environmental benefit of replacing energy from conventional energy sources with solar energy. If this is taken into account the reduction in the cost of probable environmental damage by producing domestic hot water is in the order of 1000 ELU/ m^2 solar collector area.

The results of the suitability analysis of the two solar absorbers well illustrate the benefits of the total cost accounting approach in the design of functional units for products.

That the analysis could be made at such a high quantitative level in this case is thanks to the comprehensive research conducted on selective solar absorbers within the framework of the IEA Solar Heating and Cooling Program. However, as has been mentioned the important point is not to obtain an exact value of the total cost, but, to obtain an understanding of the relative importance of the various factors contributing to the total cost. This means that is most often only the order of magnitude of the different terms contributing to the total cost that may be needed in the evaluation of the best design alternative of a functional unit of a product in the early stages of design work.

4 Selecting construction material for the exterior part of a private car back door

Bo Carlsson, University of Kalmar, SP Swedish National Testing and Research Institute

4.1 Developments towards a more environmental friendly private car

To meet requirements from harder environmental legislation great efforts are presently made by the automotive industry to increase the environmental quality of their products. The life cycles of automobiles are, however, long and complicated, which require the adoption of many diverse design approaches during development. Manufacturers are adopting strategies such as Design for Disassembly, Design for Recycling and the use of engine technologies which reduce fuel consumption, improve heat efficiency and reduce emissions.

4.1.1 Reduction of fuel consumption

To reduce fuel consumption of a private car various possibilities exist as exemplified in Table 20. The roughly estimated potentials for the different possibilities given in the table may despite the complexity involved nevertheless serve the purpose for comparing the options that exist.

Reducing mass contributes significantly to improved fuel economy. Light metals and plastics are therefore used to replace low alloy steel for parts of the car chassis, aluminium is used in motor blocks and plastics are used in bumpers. To get a quantitative idea on how large this effect would be we may consider a private car with a lifetime of 15 years and which is used 20 000 km/year. Using the data from Table 20 yields a total reduction in fuel consumption of 9 litre /kg for this time period. It should, however, be pointed out that reducing the mass of one part of construction also has the effect that the mass of other constructions parts may be reduced because the requirement on mechanical strength would decrease. To take into account also this fact the reduction in fuel consumption might be even doubled[27].

[27] Private communication Hans Reich, Chalmers Lindholmen School of Engineering

Improved air dynamics, reduction in rolling friction and better transmission might reduce fuel consumption by 6 %, whereas the estimated potential for reducing fuel consumption by increasing motor efficiency and electric efficiency amounts to nearly 20 %. The effect of using an internal starter generator is estimated to a 5 % reduction in fuel consumption.

Table 20. Different possibilities and estimated potentials for reducing fuel consumption of a private car (Initial mass of private car = 1500 kg and initial fuel consumption 1 litre/10 km)

Possibility	**Estimated potential for reducing fuel consumption** (litre/10 km)
Reduction in mass with 33 %	- 0.15
Reduction in wind drag	- 0.015
Reduction in rolling friction	- 0.035
Reduction in transmission losses	- 0.010
Increased motor efficiency (20 %)	- 0.15
Increased electric efficiency (servo, AC etc)	- 0.040
Internal starter generator (ISG)	- 0.050

In this chapter the possibility to replace low alloy steel with low weight materials in parts of the car chassis will be discussed. But, this is not only an issue of reducing mass. Other aspects need to be taken into account to identify the most suitable design alternative out of many. One critical aspect that specially needs to be taken into account is the requirement on minimum extent of recyclable materials in private cars; see Table 21a and 21b.

Table 21a. Requirements on reusability and recoverability of parts of a private car (SFS 1997:788)

Minimum extent (weight %)	**Year**
85	2002
95	2015

Table 21b. Requirements on the re usability of parts and recyclability of materials in private cars (SFS 1997:788)

Minimum extent on the use of reusable parts and of recyclable materials (weight %)	**Year**
80	2006
85	2015

As shown in Table 21b the year 2015 requirement means that in mass terms the outcome of the following end-of-life treatment processes: (a) pre-treatment (draining of fluids, emptying the climate unit, removal of batteries etc), (b) removal of reusable parts, and (c) recycling of materials shall amount to a minimum of 85 %. The requirement given in Table 21a means that if also energy recovery is added to the processes (a), (b) and (c), the outcome shall amount to a minimum of 95 %.

The disadvantage with many low weight materials is that they can not be considered as truly recyclable and to illustrate this conflict in the material selection process the total cost accounting approach has been employed. The analysis has been focused on the choice of construction material for the exterior part of a private car back door.

4.1.2 Suitable construction materials for the exterior part of a private car back door

Four possible construction materials for the back door case were selected for the analysis as shown in Table 22.

Table 22. Some possible design alternatives for the exterior part of a back door to a private car

Design alternatives	Material specification	Mass (kg)
Reference	Low alloy steel	19
Alternative 1	Aluminium (Al)	11
Alternative 2	SMC (25 % glass fibre, 50 % sodium silicate, 12 % polyester, 13 % styrene)	13
Alternative 3	GMT/Al multilayer system (10 % Al and 90 % GMT (70 % PP and 30 % glass fibre)	12

The construction material of low alloy steel was chosen as the reference. Aluminium is a low weight alternative to steel, which has its main advantage in allowing a 40 % mass reduction compared to low alloy steel. For the two plastic materials the mass reduction is in the order of 30 - 35 %. The composition of the SMC material is considered to be representative for the automotive application considered although the main reason for selecting this composition was that data from Life Cycle Analysis were available in the SimaPro 6.0 software[28] . Of the same reason the composition of the GMT material was fixed to that given in Table 22. The GMT/Al material is a two layer material with the aluminium layer placed so

[28] SigmaPro 6.0 LCA soft ware ; see www.pre.nl

that it becomes the exterior surface of the back door to facilitate the application of an organic coating system on it.

4.2 Suitability analysis of the four design alternatives

For the suitability analysis, the service time was set at 15 years, which corresponds roughly to the median service life of a private car in Sweden[29]. It was further assumed that the car is used 20 000 km/year during this time period.

4.2.1 The importance of production volume on the manufacturing cost

The first term appearing in the total cost as expressed by equation (1) is the production cost for the installed functional unit in the product. In Table 23 some cost characteristics related to the manufacturing of the four design alternatives are shown.

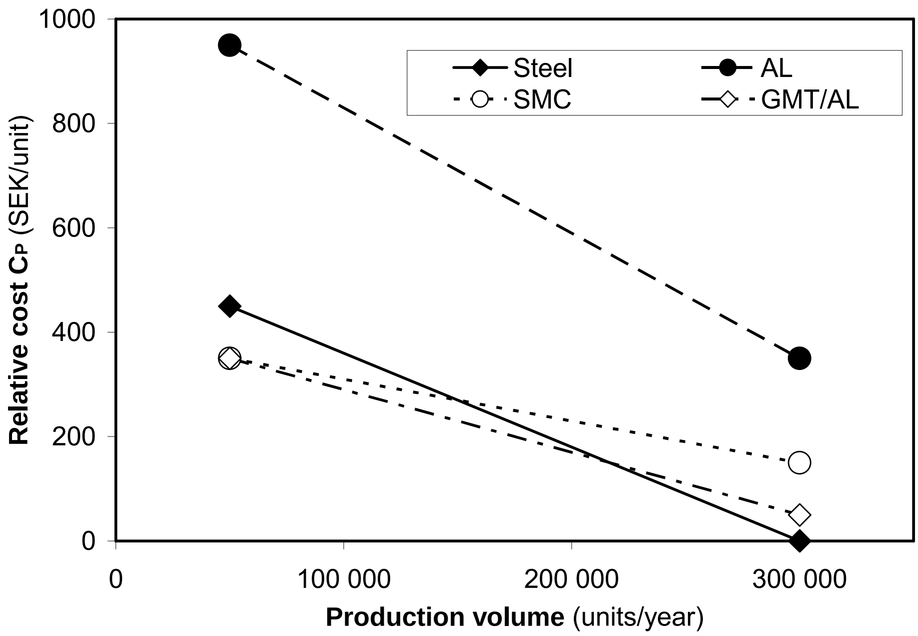
Table 23. Some cost characteristics of the exterior part of a back door to a private car if made of different materials

Cost characteristics	Steel	Al	SMC	GMT/Al
Cost at a production volume of 300 000 units/year (SEK)	650	1000	800	700
Cost at a production volume of 50 000 units/year (SEK)	1100	1600	1000	1000
Investment cost for forming tool (MSEK)	100	140	45	65

The manufacturing cost is highly dependent on the production volume as is also illustrated in Figure 17**.** The main cause to the different dependencies on production volume is varying investment costs for the forming tools. Aluminium is the most sensitive alternative in that respect. At a production volume higher than around 200 000 units/year, steel becomes the design alternative having the lowest cost. At production volumes less than about 150 000 units/year the two plastic design alternatives are the most favourable in terms of production cost.

[29] See www.bilsweden.se

Figure 18. The dependence of production volume on the manufacturing cost for the four design alternatives of the exterior private car back door specified in Table 22



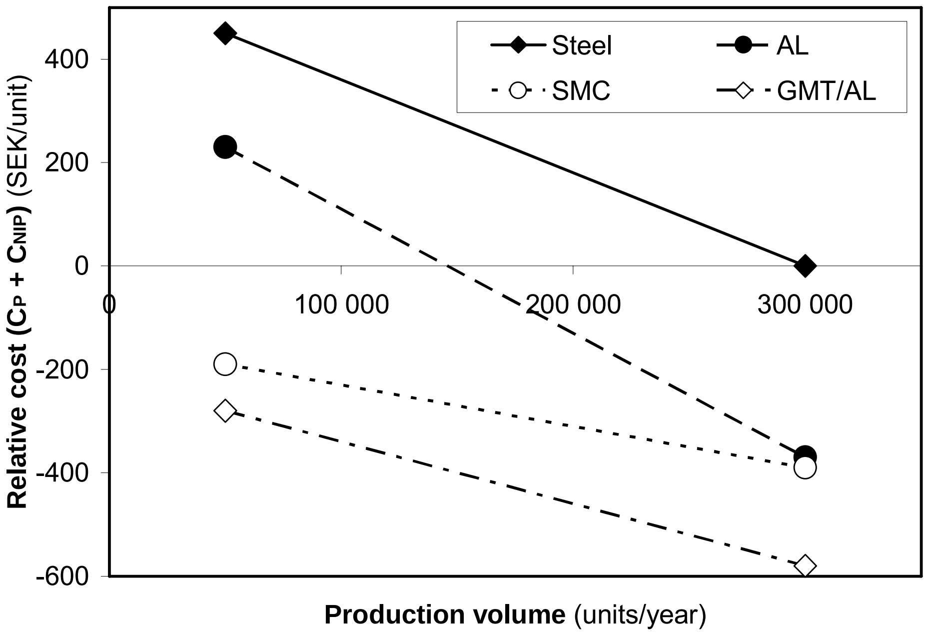
In the suitability analysis relative costs are of prime interest. In the production cost should therefore also be included the relative cost of the four design alternatives for surface coating and installing the functional unit in the product. However, for the preliminary suitability analysis performed it was assumed that the cost of surface coating and cost for installation roughly are the same for the four design alternatives. It should, however, be pointed out that surface coating of the SMC alternative is generally considered to result in larger amounts of scrap due to greater difficulties in obtaining acceptable results in the surface treatment. This fact is, however, considered to be of minor importance in the comparison of the four design alternatives.

4.2.2 Cost for increased fuel consumption due to difference in mass of the four design alternatives

Cost for excess mass of a part of the car, belongs to the category of cost for initial non-ideal performance, C_{NIP}, in equation (1) and can be calculated as a relative cost with respect to the steel door case at a production volume corresponding to 300 000 units/year.

In the case considered with a service time of 15 years, it was assumed that the car is used 20 000 km/year, which as was shown previously, results in a total extra fuel consumption of 9 litre/kg excess mass. With a price of petrol corresponding to 10 SEK/litre, the cost for the extra fuel consumption due to excess mass will be 90 SEK/kg. The relative C_{NIP} costs for the four design alternatives were accordingly calculated and in Figure 19 the results expressed as the sum of the production cost and the cost for excess mass are plotted versus production volume.

Figure 19. Relative sums of costs for production and for excess mass of the different design alternatives for the private car back door. Reference for the relative costs is the steel backdoor at a production volume of 300 000 units/year



As can be seen the relative $C_P + C_{NIP}$ costs for the GMT/Al and the SMC alternatives are negative and so even for the aluminium alternative for production volumes higher than 150 000 units/year. The relative cost for the GMT/Al alternative is the lowest. At a production volume of 300 000 units/year the negative value of the relative sum of costs for this alternative is even of the same order as the production cost for the steel alternative.

The decrease in fuel consumption by use of design alternatives with lower mass may, however, be much higher. As pointed out previously, the mass of also other construction elements may be reduced if a backdoor with lower mass is used. This may double the effect of reducing the mass of the backdoor. Besides that, the price of petrol will increase significantly during the considered service time of 15 years for sure. The effect of using an alternative with a lower mass may thus be at least three to four times higher than is reflected in the plots shown in Figure 19**.** For our preliminary analysis we did not want to overestimate the effect of mass and therefore the data presented in Figure 19 was used in the proceeding analysis.

4.2.3 Cost for probable failures and requirement for long-term performance

The next terms to be considered in the total cost are the cost for maintenance C_M and the cost for probable failures C_F.

From maintenance point of view there seemed not to exist any notable differences between the four design alternatives and in terms of relative cost, thus, the contribution from maintenance has no significance on the relative total cost.

Cost for failures may arise due to crash damage and due to insufficient material durability.

To estimate the cost of probable failures for crash damage, an analysis was made based on the following assumptions. A rule of thumb is that 10 % of all private cars in Sweden are involved in accidents which require repair of the car chassis. Following this rule of thumb, it seemed very reasonable to assume that 2 % of the private car backdoors have to be repaired because of crash damage[30].

Considering the four design alternatives studied there are, however, differences in repair ability. With both the SMC and the steel alternatives some of the crash damaged doors should be possible to restore completely by repair work whereas this seems not a reasonable option in case of the aluminium and GMT/Al alternatives. Accordingly, it was assumed that 2 % of the backdoors with crash damage have to be replaced all with a new backdoor if aluminium and the GMT/Al are used. For the SMC and the steel alternatives it was assumed that 1% of the doors could be repaired but the rest of the doors with crash damage have to be replaced by a new door also in those cases. Taking into account also differences in the price between the different design alternatives and reasonable costs for repair work, the costs presented in Table 24 were arrived at.

Table 24. Estimated relative costs for repair of a probable crash damage The cost for replacing a crash damaged steel door with a new one was set at 6000 SEK. For repair of a crash damaged door when possible in case of steel and SMC the cost was set at 4000 SEK/door

Design alternative	**Estimated relative cost for repair of probable crash damage** (SEK) (300 000 units/year)	(50 000 units/year)
Steel	0	5
Al	30	40
SMC	0	5
GMT/Al	20	30

[30] Private communication Ove Pettersson, Insurance Company IF, Sweden

As seen from the table the relative costs for repair of probable crash damage become small. The higher values for Al and GMT/Al are, as mentioned, a consequence of the fact that during repair the complete door is always replaced by a new one, while this in case of SMC and steel only happens in half of the cases.

Costs for probable failures due to insufficient material durability are more difficult to foresee for at least the GMT/Al alternative because experience from the use of this material in car chassis is limited. When using the steel and the aluminium alternatives corrosion may develop from defects caused by stone chips and repainting may therefore be required in some cases. However this has not been considered to give rise to an important contribution to the cost of probable failures in the present analysis. This is considered to be true also for SMC alternative as the durability of this material is better than that of steel.

In general it is sometimes recommended to introduce a safety factor for a new material as the unexplored GMT/Al alternative when trying to estimate the expected probability for failure. However in the present study it is recommended to perform a more thorough evaluation of durability as described in Chapter 2. Due to limited knowledge of the durability of new materials it may be difficult to foresee or estimate the effects of all kinds of failure/degradation modes that may contribute to the deterioration of the performance of this design alternative.

The worst scenario, which in the present case may happen, would be that the back door has to be replaced with a new one in which a more traditional construction material is used. The cost for replacing a door with a new steel door was previously set to 6 000 SEK/door. The difference in cost, i.e. C_P + + C_{NIP} + C_F , between that of the GMT/Al and that of Aluminium or SMC is in the order of 200 SEK. The probability for failure due to insufficient material durability of the GMT alternative must therefore be less than 5 %, for the GMT/Al alternative to be the most favourable.

4.2.4 End-of-life costs and possibilities for recycling

A service time of 15 years is a very long time and after this time period the back door will most probably end up as shredder scrap. The direct End-of-Life costs for this case are shown in Table 25 for the four design alternatives.

Table 25. End-of-life cost for the different design alternatives as schredder scrap (Data from Stena Gothard in Kalmar)

Case	C_{EoL} (SEK)	Relative C_{EoL} (SEK)	Remark
Steel	-13,3	0	Shredding and recycling of steel
Aluminium	-16,5	- 3,2	Shredding and recycling of aluminium
SMC	+10,4	+ 23,7	Shredding and incineration of organic parts
GMT/Al	- 1,9	+ 15,2	Shredding and recycling of Al (and PP)

As seen from the table the End-of-Life cost (or income) is small for the different design alternatives and contributes thus very little to the total cost.

An aspect that is not reflected in the End-of-Life cost is whether the different design alternatives is qualified with respect to future requirements on minimum extent of recyclable materials, i.e. 85 %.

If only the construction materials are considered the following can be concluded:

- With SMC no recycling can come into question but the material can be taken care of by incineration. The amount of ash will be high; however, as only 25 % of the material is combustible meaning more than 75 % of the material probably have to be disposed as land-fill.
- With GMT/Al recycling of aluminium is possible, i.e. 10 %. The PP part of the rest, a little more than 60 %, would at least in principle be recyclable but the most likely end-of-life treatment would be incineration. The glass fibre, more than 25 %, will probably end up as landfill.

As can be understood the composite materials are not ideal from an end-of-life perspective. However if the metallic materials are considered their end-of-life properties are better. But, if the overall efficiency of the recycling process is taken into account there are doubts especially about the suitability of aluminium, as the overall efficiency will be lower than 100 % due to oxide formation during the recycling process.

4.2.5 Costs for probable environmental damage

Using standard values for the EPS environmental impact indicator contained in the SimaPro 6.0 LCA software[31] it was possible to get approximate

[31] www.pre.nl

environmental impact numbers of relevance for the four design alternatives studied as shown in Table 26.

Table 26. EPS Environmental impact indicator values for the different design alternatives estimated from standard LCA data contained in the SimaPro 6.0 software (EPS_{mat} is the environmental impact from the manufacturing of the materials including also the contribution from the end-of-life phase, $EPS_{service}$ is the environmental impact from the service phase, EPS_{tot} is the sum of the two)

Case	EPS_{mat}	$EPS_{service}$	EPS_{tot}
Steel [a)]	11 ELU	85 ELU	96 ELU
Aluminium [b)]	10ELU	49 ELU	59 ELU
SMC [c)]	6 ELU	58 ELU	64 ELU
GMT/Al [d)]	8 ELU	54 ELU	62 ELU

[a)] Low alloy steel with 80% recycling (Estimated from data by BUWAL 132 (1990))
[b)] Aluminium with 90% recycling (Data from ETH-ESU 1996)
[c)] SMC with incineration and landfill during end-of-life (Data from IDEMAT 2001)
[d)] DMT/AL with 90% recycling of Aluminium and PP (Data from SPIN glass (1992) and PWMI report 3PE/PP)

As can be seen the contribution from the service phase is the dominating one for all alternatives. It should, however, be pointed out that the only environmental impact during the service phase that has been taking into account is caused by the fuel consumption needed to transport the mass of the backdoor around. Other kinds of environmental impact during the service phase are considered the same for the four design alternatives. The amount of fuel needed for the transport of mass was estimated as has previously been described in 4.2.2.

It should, however, be mentioned that EPS_{mat} includes only the environmental impact of the materials themselves and not the environmental impact of processing them into the specific construction part of the door. The contribution of processing to the environmental load is estimated to be in the order of 2-3 ELU and constitutes thus only a minor part of the total environmental impact. As the relative environmental load to that of steel is of interest for each design alternative, this means that the effect of processing may thus be of practically no significance in comparing the different design alternatives with respect to their environmental qualities.

Table 27. Relative total EPS values for the four design alternatives in relation to the steel backdoor alternative

Case	ΔEPS_{tot}	$9 \cdot \Delta EPS_{tot}$
Steel	0	0
Aluminium	- 31 ELU	- 315
SMC	- 34 ELU	- 306
GMT/Al	- 36 ELU	- 324

In Table 27 the relative total EPS values for the different design alternatives are shown and as can be observed all the three alternatives to the steel case have values of the same order, but which are significantly lower from that of the steel alternative. Important to point out is that in the preliminary analysis performed, the costs of surface treatment and thus associated contribution to the environmental load are considered the same for all the four design alternatives.

Following the suggestion, expressed by equation (4) in 2.3.4 and setting the weighting factor W_E equal to unity, the relative total EPS values have been multiplied by 9 to be comparable at least in the order of magnitude to the other cost terms which contribute to the total cost.

4.3 Conclusions from the suitability analysis of the four design alternatives for the private car back door

In Figure 20 and Figure 21 the results of the suitability analysis are summarized in relative total cost terms. As can be observed the GMT/Al alternative appears to be the most attractive alternative of all. The total relative cost for the SMC and the aluminium alternatives are slightly higher but differ from that of steel with an amount that is of the same order as the production cost for the steel alternative at the highest production volume considered.

Figure 20. Summary of the results from the suitability analysis of the four design alternatives in terms of relative total cost versus production volume. Reference for relative cost is the steel alternative at a production volume of 300 000 units/year

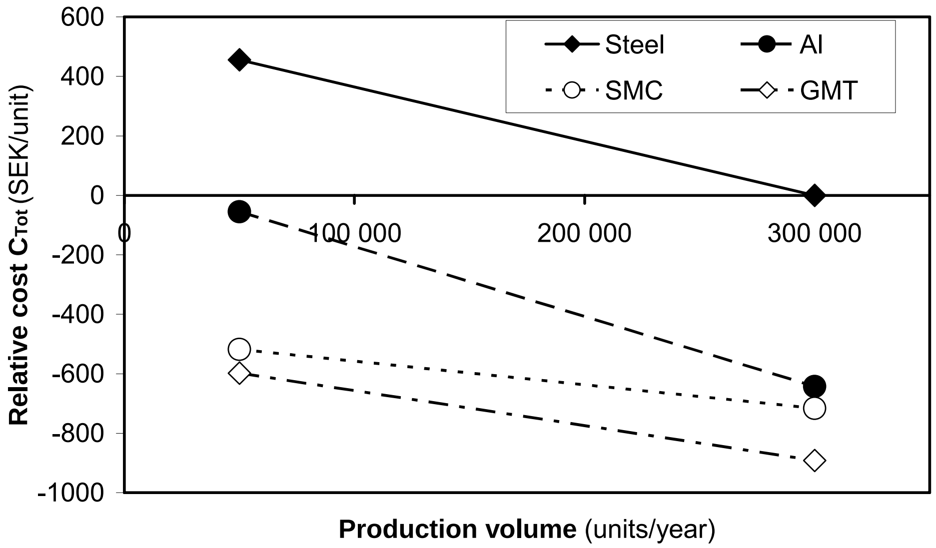
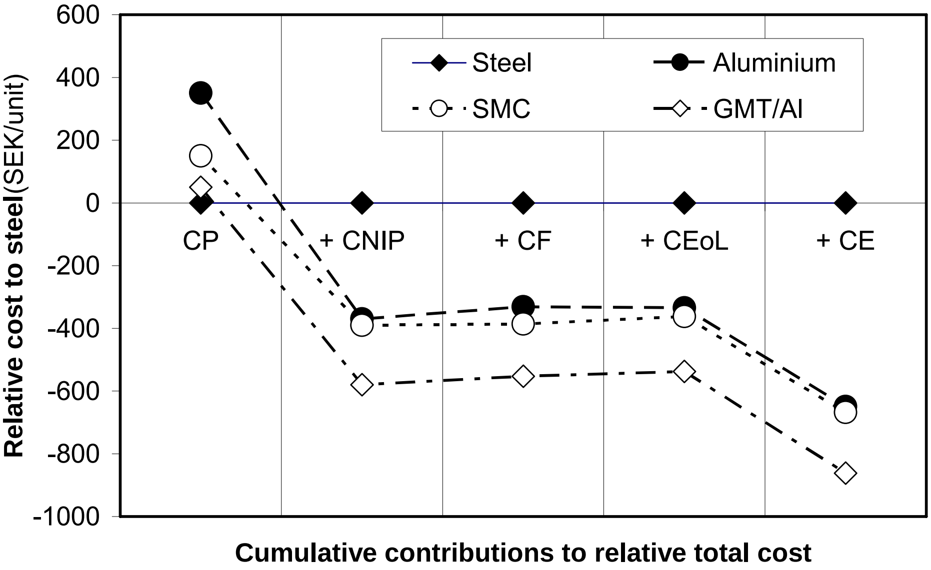


Figure 21. Summary of the result from the suitability analysis of the four design alternatives in terms of the relative cost to the steel alternative (Production volume = 300 000 units/year) versus the cumulative contributions which sums up to the total relative cost



The results from the suitability analysis can be summarized in the following general conclusions:

1 From a manufacturer point of view and considering only the production cost for the installed part of the back door, steel is the best alternative. However, this is true only if it is realistic to assume that the part studied will be produced at a volume exceeding approximately 200 000 units/year. If not the two composite materials seem more favourable. From a user point of view taking into account also cost for non-ideal performance in the form of increased fuel consumption due to excess mass and of the cost for probable failures, i.e. $C_P+C_{NIP}+C_F$, the two composite materials, particular the GMT/Al material, and aluminium are the most favourable compared to steel. From a total cost point of view or from the viewpoint of the national or global society the same conclusions can be drawn.

2 The most important contribution to the relative total cost using steel as reference comes from the reduction in fuel consumption due to the use of lower mass alternatives. This significantly lower the direct cost as expressed by the cost term for initial non-ideal performance but this also is the main factor for the reduction in the indirect costs or environmental cost, expressed by the cost term for probable environmental damage.

3 Cost for failures may arise due to crash damage and differences in repair ability make the SMC and the steel alternatives more favourable to the others in that respect. Differences in the cost for crash damage is however relative small. Costs for probable failures due to insufficient material durability are more difficult to foresee at least for the GMT/Al

alternative. It is therefore recommended to perform a more thorough evaluation of durability as described in Chapter 2. To set the qualification limit for the probability for failure at 5 % for the GMT/Al alternative in such an evaluation seems reasonable.

4. The direct End-of-Life costs are small for the different design alternatives and those contribute very little to the total relative cost. However when considering the requirement on the use of recyclable materials it can be understood that the composite materials are not ideal from an end-of-life perspective. Metallic materials have better end-of-life properties but if the overall efficiency of the recycling process is taken into account there are doubts especially about the suitability aluminium.
5. The difference in cost for possible environmental damage of the four design alternatives is dominated by the contribution from the service phase and the extra fuel consumption needed to transport the mass of the backdoor around. As a consequence the steel alternative is the most unfavourable whereas the other design alternatives have essentially the same qualities.
6. The results of the suitability analysis nicely reflect the relative importance of the various factors contributing to the total cost but the suitability analysis also points to the need of performing a more advanced suitability analysis taking into account not only reliability and long-term performance but also aspects as e.g. safety, ease of surface treatment etc.

However, by introducing the total cost concept for material selection in the automotive industry a step would be taken in the declaration of product properties in a more consumer oriented way. The important issue is maybe not the product itself but the product function and how this can be achieved and maintained in a economic sound way for the consumer as well as for the society as a whole.

This chapter could not have been prepared without the input made from many persons in particular Hans Reich, Chalmers Lindholmen School of Engineering, Bertil Qvick, Volvo 3 P and Per Johansson, Scania CV.

5 Life time design of elastomers for sealing of the turbojet engine in the Swedish marine missile RB15

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5.1 Requirements on elastomers for sealing

To guarantee a sufficiently high reliability of the RB15 turbojet engines, aged elastomers (o-rings, membranes, gaskets, packings, washers, etc.) are normally replaced with new components during overhaul at intervals recommended by the manufacturer.

Each overhaul is, however, associated with high costs and it is therefore of interest to minimize the interval for replacement of elastomeric sealants without deteriorating the long-term reliability of the turbojet engine.

This chapter will illustrate how a suitability analysis based on the total cost accounting approach may be employed in the selection of the most suitable elastomers in the turbojet engine of the RB 15 missile. The analysis is based on a report prepared for FMV by Bodycote CMK in Karlskoga[32]

If the analysis is limited to elastomers for sealing to fuel, the end-user and product requirements for the elastomeric material may be expressed as shown in Table 28**.**

[32] Life time control of elastomers inside turbo jet engine in the Swedish marine missile RB15, Dennis Taylor, Bodycote, Materials Testing, CMK, Box 431, SE 691 27 Karlskoga, Sweden.

Table 28. Specification of end-user and product requirements on elastomers for sealing to fuel in the turbojet engine of RB 15

Function and general requirements	General requirements for long-term performance during design service time	In-use conditions and severity of environmental stress in general terms
- Provide sufficient sealing to fuel	The sealing performance shall be maintained by regularly replacing the sealant with a new one during a service time of 30 years so that the failure frequency with respect to insufficient sealing can be kept lower or at $3 \cdot 10^{-3}$	Installed in a turbojet engine. During storage at a temperature of around 10 ˚C and in contact with a mixture of 10% oil (NATO C-160, AIR 1504) and 90% fuel (NATO F-34, AIR 3405) During use of the engine at temperatures between 56˚C and 71˚C and in contact with fuel JP-8/Jet A-1.

As the cost for a turbojet motor and missile failure is approximately 20 000 000 SEK, the requirement on long-term reliability means that the expected cost for probable failures is around 60 000 SEK.

To maintain the sealing capability of the elastomer for a long time period requires that the long-term performance of the elastomer must be high. The most critical property of the elastomeric sealant will be its resistance to aging under the conditions of storage. To check whether an elastomeric has been affected by aging a comprehensive test program and associated requirements on performance was set by Bodycote CMK as shown in Table 29

Table 29. Critical property, test methods and price of elastomers

Critical property	Test methods for determining that critical property is maintained	Requirement for long-term performance
Sealing performance / chemical stability	Visual inspections by optical microscopy. Measurement of setting and swelling	No visual damages (a) No visual changes (b) No dimensional. changes (c)
	Assessment by TMA of glass transition temperature (Tg), E-modulus and softness at -40 °C, 20 °C and 60°C	No change in Tg (d) No change in E-modulus (e) No change in softness at -40˚C (f) No change in softness at 20˚C (g) No change in softness at 60˚C (h)
	Assessment of tensile strength and elongation by tensile tester	No change in tensile strength (i) No change in elongation (j)
	Assessment of weight loss by TGA at 350 °C, 500 °C, 600 °C	Low weight loss (k)
	Assessment of chemical stability by FTIR	No significant spectral changes observed (l)
Suitable design alternatives of elastomers	**Sealing capability**	**Material and manpower costs (C_P)**
3 Silicone	Sufficient as new	C_P = 1-10 SEK + man power cost*
4 Silicone	Sufficient as new	C_P = 1-10 SEK + man power cost *
5 Fluoro	Sufficient as new	C_P = 1-10 SEK + man power cost *
7 Silicone	Sufficient as new	C_P = 1-10 SEK + man power cost *
8 Silicone	Sufficient as new	C_P = 1-10 SEK + man power cost *
9 Silicone	Sufficient as new	C_P = 1-10 SEK + man power cost *
10 Silicone	Sufficient as new	C_P = 1-10 SEK + man power cost *

* The replacement cost in manpower for all elastomers for sealing is roughly estimated to 15000 SEK

If the cost for replacing the elastomers at regular overhaul is considered as shown in the bottom part of Table 29**,** it can be concluded that the price of the elastomeric material has no significant influence on the total replacement cost as to be expected.

5.2 Lifetime control of elastomers replaced at overhaul

To assess the long-term performance of a series of elastomeric materials for O-rings as given in the lower part of Table 29**,** O-rings that had been taken from turbojet engines during overhaul were investigated. Those O-rings were then compared with corresponding new unaged O-rings of the same materials by making use of the test program shown in the top part of Table 29. The results of the tests are presented in Table 30.

To get an overall estimate on how much the different materials had been affected by aging, a simple way of expressing the results was made use of. Firstly, in cases where a change could be observed, the result of test was set equal to 1. In cases where no change could be observed, the result of test was set equal to 0. To rate the importance of each test, a weighting factor was used. The overall estimate on long-term performance was finely calculated as the sum of the weighted test results.

Table 30. Results from investigations of elastomeric sealants that had been taken from turbojet engines during overhaul; in one case after 9 years of storage (gently aged) and in another case after seven years of storage (rough ageing with respect to mechanical loads and temperature changes)

Failure/Damage mode	**Impor-tance (I)**	**Weighted results (C·I)***						
		(3)	**(4)**	**(5)**	**(7)**	**(8)**	**(9)**	**(10)**
Insufficient sealing performance/chemical stability								
Visual damages (a)	0.2	0	0	0.2	0.2	0	0.2	0.2
Visual visual changes (b)	0.4	0	0.4	0	0.4	0.4	0.4	0.4
Dimensional. changes (c)	1	0	0	1	1	1	1	1
Change in Tg (d)	1	1	1	0	1	1	0	1
Change in E-modulus (e)	1	0	0	0	0	0	0	0
Change in softness at -40˚C (f)	0.8	0	0.8	0	0	0	0.8	0.8
Change in softness at 20˚C (g)	0.8	0	0.8	0	0	0	0.8	0.8
Change in softness at 60˚C (h)	0.8	0	0.8	0	0	0	0.8	0.8
Change in tensile strength (i)	0.6	0	0	0	0	0.6	0	0
Change in elongation (j)	0.8	0	0	0	0	0	0.8	0.8
Weight loss (k)	0.4	0	0	0	0	0	0	0
Spectral changes (l)	1	0	1	0	(1)**	(1)**	(1)**	(1)**
Summery of weighted results		**1.0**	**3.8**	**1.2**	**2.6-3.6**	**3.8-4.8**	**5.8-6.8**	**4.8-5.8**

*C denotes result as: no change = 0 and change = 1; see Table 29
** Spectral changes observed but is not possible to conclude whether the difference is caused by ageing or by a difference in the initial chemical composition between the aged and unaged material.

As can be seen materials denoted (3) and (5) are significantly more resistant to ageing compared to the material denoted (4). Materials (7) and (8) are of about the same class as material (4), whether materials (9) and (10) seem to have significantly lower resistance to aging compared to material (4). However, for all the materials (7), (8), (9) and (10) spectral differences are observed between the aged and unaged samples, which may be caused by differences in the initial chemical composition. It should be pointed out that the observed differences in other test results between aged and unaged samples of the "same" material may also have been affected. Their aging resistance may therefore be underestimated.

The results in terms of cost are shown in Table 31 in which the cost of probable failures is given together with the cost for replacement of the elastomeric materials.

In case of material (4) significant differences in properties between the aged and unaged materials appeared at the testing. This made it reasonable to conclude that the material should be replaced after a time period of about seven years or to be conservative six years to make certain the probability for failure of the engine due insufficient sealing would be the same. This means the elastomers would be replaced 4 times during the assumed service time of 30 years for the missile.

Materials (3) and (5) were shown to exhibit little or practically no changes upon aging after the time period when the tests were performed. It seems in those cases therefore reasonable to recommend renewal of the elastomers more seldom, as every tenth year. This means that only two replacements during the 30 years of service time are needed if those materials are used.

Table 31. Cost of probable failures and cost of regular replacement of the elastomeric sealants during the expected service time of 30 years of the missile

Design alternative	Estimated cost of probable failures (C_F)	Estimated cost of maintenance/replacement of sealants (C_M)
3 Silicone	60 000	30 000 (2 replacements of sealants)
4 Silicone	60 000	60 000 (4 replacements of sealants)
5 Fluoro	60 000	30 000(2 replacements of sealants)
7 Silicone	60 000	60 000 (2 replacement of sealants)
8 Silicone	60 000	60 000 (4 replacements of sealants)
9 Silicone	>60 000 ?	> 60 000? (probably more than 4 replacements of sealants are needed)
10 Silicone	> 60 000 ?	> 60 000? (probably more than 4 replacements of sealants are needed)

In case of material (7) and (8) the resistance to ageing may be underestimated or it will be of the same order as for material (4). However, a six years interval for replacement has to be recommended any how. In case of material (9) and (10) an assessment of aging resistance may have to be performed after a shorter time period, as e.g. four years, to check whether the observed differences between the aged and unaged materials were caused by aging or by an initial difference in chemical composition.

5.3 Conclusions

Other aspects may be considered in the choice of sealant material and in Table 32 the results of the complete suitability analysis in terms of relative total costs are summarized.

Table 32. Results from suitability analysis of different design alternatives for O-rings for a turbojet motor (C_P = Production cost, C_{NIP} = Cost associated with initial non-ideal function or performance, C_M = Maintenance cost, C_F = Cost of probable failures and damage, C_{EoL} = End of life cost, C_E = Environmental cost associated with probable ecological damage).

Relative total cost estimates using elastomeric material (4) as reference (SEK)

Design alternative	ΔC_P	ΔC_{NIP}	ΔC_M	ΔC_F	ΔC_{EoL}	ΔC_E	ΔC_{Tot}
3 Silicone	0-10	0	- 30 000	0	0	0-1 mELU	- 30 000
4 Silicone	0	0	0	0	0	0	0
5 Fluoro	0-10	0	-30 000	0	0	0-1 mELU	-30 000
7 Silicone	0-10	0	0	0?	0	0-1 mELU	≈ 0
8 Silicone	0-10	0	0	0?	0	0-1 mELU	≈ 0
9 Silicone	0-10	0	> 0?	> 0	0	0-1 mELU	?
10 Silicone	0-10	0	> 0?	> 0	0	0-1 mELU	?

Cost for initial non-ideal performance, $\mathbf{C_{NIP}}$, has in this case no meaning. The end-of-life cost, $\mathbf{C_{EoL}}$, is in relative terms very small and does not need to be considered. The cost for probable environmental damage, $\mathbf{C_E}$, taking into account the manufacturing of the elastomeric sealants turns out to be very small too. The relative production cost, $\Delta\mathbf{C_P}$, is small although the absolute production cost dominated by the manpower cost for installation of the sealant into the turbojet engine is high.

There is a balance between the cost for probable failures, $\mathbf{C_F}$, and maintenance cost, $\mathbf{C_M}$ (cost for regularly replacing the sealants with new ones). In the reference case, material (4), they are estimated to be of the same order. However, if a more durable material is used, as e.g. materials (3) or (5), the interval of replacing the sealant materials with unaged materials may be increased from in the present case six to ten years reducing the maintenance cost by a factor of two.

As the cost of probable failures is high in this case, the analysis has shown that it is economically highly motivated to develop routines for lifetime control of the sealants. By this, the interval of maintenance including replacement of the sealants with new ones can be minimized. As shown this can be done without increasing the probability for failure of engine failure but decreasing the maintenance cost considerably.

Important for lifetime control to be successful is, however, access of reliable data on properties of unaged materials. This requires that such data is determined regularly on the same quality of material that is actually installed in the product of interest. Although the material order number will stay the same for many years, this is not a guarantee for that the chemical composition and the material properties are exactly the same.

The example with the elastomeric sealant materials illustrates, thus, another field of application in which suitability analysis based on the total cost accounting approach may favourably be adopted.

6 Contribution from the end of life phase to the total cost estimation

William Hogland and Marcia Marques, University of Kalmar

6.1 Introduction

The United Nations has proclaimed the ten-year period, beginning on January 2005, the *United Nations Decade of Education for Sustainable Development* and UNESCO was designated as lead agency for the promotion of the Decade. This means that education in all levels shall focus on sustainability aspects of importance to the technological, social and economic development. The new frontiers of knowledge on sustainability reached through scientific investigation shall be quickly incorporated to educational programs and more than that, shall be the main goal of post-graduation projects. The cooperation between the universities on both education and research with trade and industry must be intensified.

During the World Summit on Sustainable Development in Johannesburg, South Africa, in September 2002, the EU launched the EU Water Initiative *Water for Life* together with the Danish Government, as part of a worldwide policy of halving by 2015, the current numbers of over 1 billion people with no access to safe drinking water and over 2 billion with lack of basic sanitation in the world. This means providing these essential services to 200 000 and 400 000 new people per day respectively, until the end of 2015, which on global scale cannot be achieved with conventional means. Scientific knowledge and innovative approaches across policies and their instruments are important for tangible headway towards these goals. The President of the European Commission Romano Prodi recently emphasized that this goal…

> *"will particularly require a great mobilisation of partners ranging from researchers, governments, water agencies, water users to civil society organisations and private enterprises. Open co-ordination and co-operation at all levels from local to international will be crucial"*

The industry, shall certainly contribute to this goal, since today's industry accounts for 22% of total water used in the world, where the amount is 59% in high-income countries and 8% in low-income countries. In a near future perspective, the world industry is expected to use more then 1 000 km³/year of water. The amount of freshwater used by the industry must be reduced and alternative water sources must be found. Above all, pollution of water bodies and destruction of aquatic ecosystems must be one of the most important components of this agenda, since not only quantity but also quality is required, and new production schemes that reduce the pollutant load to water bodies must be developed. Future policies must be focused on the most relevant problems (effectiveness) and select to solve them efficiently (efficiency).

6.2 Improving estimation of the end of life cost contribution to the total costs analysis

Particularly in industrialized countries, it is clear for most industries that products and processes must be environmentally friendly already at the design stage. According to the close-loop concept, the environmental aspects must be considered in all stages of the process for product development. This approach is applied in order to minimize the negative environmental effects of a product during its whole life: manufacturing, lifetime and final disposal. Unfortunately, inventories of solid and liquid wastes are usually used as mere listing of waste types followed by their independent potential effects and impacts, ignoring the complex interactions between emissions and the environment, particularly during: (1) re-use or disassembling followed by reuse, (2) storage of functional unties that reached the end of the life, (3) material recycling or energy recovery schemes and (4) final disposal of entire or part of functional units or residues generated after (3).

Very often, the end-of-life costs for a functional unit is adjusted to zero or even considered negative depending exclusively on the value of the functional unit after the fixed service time has passed. This happens because the above-mentioned possibilities for reuse, recycling or energy recovery schemes (steps 1 t 3) and the income obtained through these schemes.

Because of the awareness regarding potential environmental impacts caused at landfill sites, many studies have been carried out about emissions and treatment costs during landfilling. This final disposal option - particularly after the EU Directive on landfilling - has been considered the last destine for waste, to be chosen only when no other use can be given to wastes. On the other hand, steps (1) to (3) are usually considered environmentally friendly strategies by definition, and they have been incorporated in the close-loop philosophy. The environmental costs related to these steps (1 to 3) have been underestimated and therefore not properly internalized when ding accounting. Therefore, deeper and more detailed assessment of the environmental burdens and respective costs generated by steps (1) to (3) at the end-of-life phase are needed.

According to the total cost estimation model presented in Chapter 1, for a fixed service time, τ_s the total cost (C_T) associated with maintaining the specific function defined for the functional unit is estimated from:

$$C_T = C_P + C_{NIP} + C_M + C_F + C_{EoL} + C_E + C_D \qquad (1)$$

Where:
C_P = Production cost
C_{NIP} = Cost associated with initial non-ideal function or performance
C_M = Maintenance cost
C_F = Cost of probable failures and damage
C_{EoL}= End of life cost
C_E = Environmental cost associated with probable ecological damage
C_D = Development cost.

Costs dictated by environmental considerations may be of two categories: direct costs and indirect costs associated with probable ecological damage. Direct costs comprise contributions from e.g. use of cleaner materials in the functional unit and use of special equipment during production to reduce environmental impact, the cost of planned maintenance in the service phase and the cost of equipment required for the end of life phase of the functional unit. Those costs are therefore parts of the production cost (C_P), maintenance cost (C_M) and end-of-life cost (C_{EoL}), respectively.

The indirect environmental cost associated with probable ecological damage (C_E) may be estimated by applying a similar approach as used to express the cost of probable failures, i.e.

$$C_E = \sum_{j=1}^{M} C_{E,j} \cdot F_j(\tau_s) \qquad (3)$$

Where
$C_{E,j}$ = Cost of possible environmental damage j
$F_j(\tau_s)$ = Probability for environmental damage j to occur during the fixed service time τ_s.

The cost term for probable environmental damage may be grouped into contributions from probable environmental damage during the manufacturing, service and end-of-life phases. Within each group many kinds of probable environmental damage exist, which for the end-of-life phase may be associated for instance with pollution and emissions to the air, surface water bodies, soil and aquifers due to hazardous pollutant transport from storage areas of recyclables (e.g.: car wrecking industry), composting piles or fly ashes storage piles. Among others, the environmental impacts (and consequently health and social impacts) due to pollution in this phase include deterioration of the aquatic ecosystems integrity due to stormwater, groundwater and river sediments pollution.

In order to provide a realistic input to the total cost estimation, recycling and energy recovery schemes (placed at the end of the life of functional units) must be better investigated in terms of emissions and interaction with the surroundings, potential impacts and costs related to treatment options or remediation actions. Such information should be available as input for each particular design option in the LCA Impact Assessment to be made for estimating the total cost for probable environmental damage, C_E

6.3 Pollution prevention and knowledge transfer from the end of the pipe to the green end

The modern industry includes in its strategic planning the industrial ecology principle as "*an approach to the design of industrial products and processes that evaluates such activities through the dual perspectives of product competitiveness and environmental interactions*". Therefore, the industrial ecology IE strategies brings from Nature Science some basic concepts and tries to understand and define industrial production and patterns of consumption through analysis of flows and cycles of materials and energy. IE seeks to optimize the total materials cycle from virgin material, to finished material, to component, to product, to waste product, and ultimately, to disposal. The human society can deliberately and rationally interfere to maintain the nature carrying capacity even in a scenario of continued economic, cultural and technological evolution. This approach must be based on better understanding of the nature and its application in environmental engineering.

Three elements form the basis of pollution prevention macro-scale engineering: (i) waste inventories, (ii) industrial metabolism (material flow) and (iii) life cycle analysis. Because these elements are in different stages of development and implementation (Allen et al. 1994), the time lag between data/information generation by (i) and (ii) and the life cycle assessment is too long. Therefore, assessments are frequently based on old data. The knowledge obtained at the end of life phase and the end of pipe technologies (e.g.: treatment plants for wastewater, incineration processes, bioreactors for composting or anaerobic digestion of organic waste, filters for cleaning up of gases) must be transferred to the green end as fast as possible so re-designing of products and processes can be benefited from the end of life updated information. Case studies in national, regional and local levels must be conducted and information gathered, analysed and translated to designers.

Waste inventory is the construction of a comprehensive list of types and quantity of wastes generated during the production, life time and end of life phases.

Material flow analysis includes: (i) system analysis of processes and goods, (ii) measurements or collection of existing data of material flow and concentration, (iii) interpretation of the data.

The system analysis involves two types of processes:

1 *Transformation processes* - the input of goods is physically and/or chemically changed. In that process the product formed (outgoing goods) has new physical and/or chemical quality and characteristics;
2 *Transport processes* - location of the goods is changed without changing the physical and chemical characteristics.

Life Cycle Assessment (LCA) is one alternative approach for tracking individual materials and chemical substances during the whole life of a product or service. LCA considers individual products and traces flows of energy and raw materials that are required for production process. The industrial process can be analyzed in detail and the physical boundaries are the gates to the factory. LCA consists of three components of importance as inventory, impact assessment and improvement analysis. Methodologies have been developed and demonstrated for performing life cycle inventories using mass balance approach to quantitatively examine the raw material, energy, and emission for a product or functional unit.

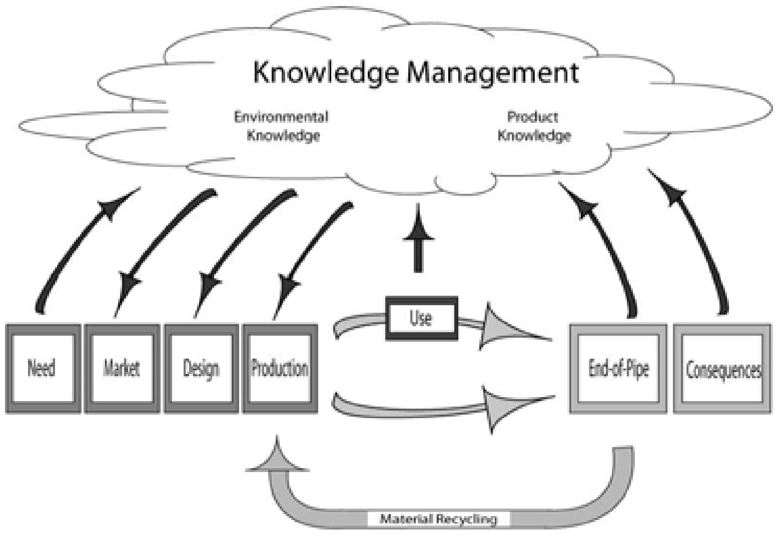
The LCA does not result in identification of environmentally superior products but can be applied in identification of pollution reduction or energy saving opportunities in a products life cycle. The following information that can be obtained at the end of the pipe stage is relevant for promoting environmental friendly technologies and products and processes re-design and estimation of the contribution of the end-of-life cost to the total costs:

- Detailed characterization and quantification of pollutants released to the soil, water and air during disassembling, storage, processing of material for recycling and energy recovery schemes, incineration and final disposal;
- Physical, chemical and biological processes associated to water and air pollutants transport;
- Estimation of environmental pollutant loads and respective environmental toxicity;
- Processes and equipment needed for pollution reduction and/or treatment of emissions and wastes generated during disassembling, storage, processing of material for recycling and energy recovery schemes, incineration and final disposal.

When an environmental problem caused by any component of a production system is detected at the "end of the pipe" stage, by trying backwards to trace the source of the problem, it might be possible to identify priority changes that are necessary, for instance, at the designing level. Today, there is a clear failure in such communication and knowledge transfer. A parallel can be made with the reverse logistics, having here, the focus on the reverse of the production flow. An important step towards a cleaner production and improvement of the total cost estimation is to transfer the accumulated knowledge and experience from the "end of the pipe" to the "green end", as a valuable input to the eco-design, operation and management. There is a need for research focused on the development of strategies and environmental impacts of this knowledge transfer, which can be an important contribution for better material selection, components and processes design and re-design, according to the market demands but also according to a more sustainable development perspective (see Figure 22).

New tools are needed to promote local, regional and global environmental progress in this field. Environmental pollution assessments through characterisation and monitoring of pollutants load over time and space in soil, water and air can be complemented by toxicity tests and in the near future, by assessment of ecosystems integrity. Such comprehensive assessment and causal chain analysis allow the construction of an indicator-based system that, in turn, supports the production sector in prioritizing investments towards sustainability.

Figure 22. Knowledge transfer and feedback from the "end-of-pipe" observations and analysis of impacts to the "green-end" including needs, market, design and production (after Reine Karlsson, personal communication).



The approach requires new team of experts that includes those with basic education in environmental engineering and management, with complementary/practical experience in natural science and those with basic education in natural science with complementary practical experiences/ education in environmental engineering and management. The hybrid background is necessary if the target is an effective integration of knowledge for development of practical applications.

The transfer of knowledge must be clear for correct interpretation in order to be understood by respective ends of the transfer system. Besides better total cost estimation, an effective implementation of knowledge transfer is likely to improve regulatory compliance, reduce pollution, eliminate waste generation, and even enhance the employee's awareness and bring cultural changes in the companies.

6.4 Example of knowledge obtained at the end of the pipe to total cost estimation

Research PhD projects currently carried out by the Environmental Engineering and Recycling Group at Kalmar University (EER) are financed by KK-Foundation and several industries. These projects assess the pollutants release and emissions at the end of the life phase and the potential impacts related to them. The projects include:

1 physical-chemical characterization of storm water pollutants in a car wrecking industry, estimation of pollutant loads from storage areas and proposal of treatment systems (Stena Metall and Läckeby Water companies);

2 physical-chemical characterization of leachate from the landfill receiving car wrecking industry waste, estimation of pollutant loads and proposal of treatment systems (Stena Metall);

3 characterization and physical-chemical and biological processes in biopiles for treatment of oily sludge generated during oil processing/refinery and with the purpose of optimizing and improving the treatment processes (Shell and Renova companies);

4 characterization of physical-chemical and biological processes in storage of waste with baling technology (baled industrial waste), assessment of pollutants released to the water and air with the purpose of improving the storage design and safety (Lidköping Värmeverk, Sydkraft Sydost, Bala Press, Trioplast, Västerviks Värmeverk);

5 modelling of different waste management schemes with focus on economic aspects (Kalmar Municipality-Graninge Research Foundation).

Figure 22 illustrates the way knowledge generated at the end-of-the-pipe can be transferred to the green-end contributing to new component design in the industry.

The above-mentioned EER projects are currently generating information that can be very useful, not only to the waste management companies but also to the total cost estimation, material selection and component design in the truck and car industries. The potential of knowledge transfer was identified by the project financed by VINNOVA in cooperation with Scania CV, Volvo Trucks, Bodycote CMK Karlskoga, Chalmers Technical University Lindholmen, Swedish Environmental Engineering Society, University of Kalmar, Swedish National Testing and Research Institute under Prof. Bo Carlson's coordination *Design of Function Unities for Products by a Total Cost Accounting Approach*.

The next step is developing models to estimate indirect costs of possible environmental damage during the end of the life period having as input data the results from the EER projects.

Figure 23. Illustration of the type of knowledge that can be transferred from the end-of-the-pipe to the green-end: research projects of the EER Group, financing companies and knowledge transfer to material selection and components design in the car/truck industry.

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VINNOVA´s mission is to promote sustainable growth
by funding problem-oriented research
and developing effective innovation systems

VERKET FÖR INNOVATIONSSYSTEM – SWEDISH GOVERNMENTAL AGENCY FOR INNOVATION SYSTEMS

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