CDMF-RELSUS concept: reliable products are sustainable products – influences on product design, manufacturing and use phase

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Abstract: Based on the customer’s product recognition, sustainability and environmental protection become key sales arguments within the automotive industry. The customer expects reduced resource consumptions, environmentally friendly manufacturing and a long usage phase. Especially product reliability saves resources in many ways. Manufacturer product reliability is associated with higher development and production costs, but, especially in industries with high innovation rates, customer usage is limited to the product actuality, which leads to two key questions: a) How much product reliability makes sense out of the view of manufacturers, customers and environmental protection? b) What is the impact of reliable products regarding the reduction of resources?

This paper outlines the ‘Collaborative development, manufacturing and field verification for higher product reliability towards sustainability (CDMF-RELSUS) concept’ focusing on influences and interdependences of product development, manufacturing planning and field observation regarding the successor development including the combination of reliable and sustainable product characteristics.

Keywords: life cycle engineering; product reliability; sustainable design; manufacturing processes; field data analysis.

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1 Introduction

Sustainability and environmental protection have become key sales arguments for manufacturing (Seliger, 2012), especially within the automotive industry: thereby the customer expects reduced resource consumptions, environmental friendly manufacturing, optimised usage, assortment of raw material and long customer usage phase (product reliability) and product recovery by remanufacturing (Ilgin and Gupta, 2010) throughout the whole of product lifecycle (Wang and Gupta, 2011). In the opposite, the customer expects functionalities, innovations and modern equipment regarding a new automobile. In summary the customer wants a product with a high quality for use. These requirements are all required by the customer. But in general, valid for all product branches, there are some preconditioned product characteristics, which none of the customers would directly express in a quantitative way: reliability, quality and basic functions.

Especially product reliability saves resources in many ways: prevention of manufacturing new products at an early stage, reducing logistic costs or reducing spare parts.

Manufacturer product reliability is associated with higher development and production costs, but, especially in industries with high innovation rates, customer usage is limited to the product actuality. Therefore, there are two key questions with respect to this conflict area:

a. How much product reliability and, in addition, customer usage makes sense out of the view of manufacturers, customers and environmental protection?

b. What is the quantitative impact of reliable products regarding to the reduction of resources?

The method life cycle assessment (cf. DIN EN ISO 14040) considers the entire product life cycle (for example, Yamada, 2012) in relation to environmental pollution. Therefore, during the product development phase the fundamental product design and manufacturing has to be defined in relation to economic and environmental aspects (Lu et al., 2011). Additional expenditure in environmental aspects increases the effort of the development phase and thereby causes environmental burden. Furthermore, environmental measures have to be contemplated in relation to the customer usage phase. But the method life cycle assessment includes not explicit aspects of reliability, multiple life spans and reuse of components. The development of methods that are able to combine multiple aspects with regard to sustainable manufacturing should be the goal to verify sustainability over the whole life cycle assessment. A few methods have already been established (Zhang et al., 2012). Therefore, it should be considered with regard to four life-cycle stages defined (Gupta et al., 2011) as follows:

- **Pre-manufacturing:** The foremost stage in the life-cycle of any product is the extraction of raw material from the natural reserves. Pre-manufacturing includes mining metal ores and smelting them into metal alloys, extraction of crude oil and processing it into hydrocarbons, cutting trees and transforming them into usable wood or paper, etc.
• **Manufacturing:** It is the phase where raw materials are transformed into finished products. A wide range of processing techniques is involved in this phase based on the desirable performance characteristics that are needed for the final product. Assembly (manual or automated), product packaging etc., are also considered to be a part of the manufacturing phase.

• **Use:** The use phase pertains primarily to the amount of time the consumer owns and operates the product. During its use stage, the product needs to be energy-efficient, safe, reliable, easy to operate, maintain and repair, etc.

• **Post-use:** The post-use stage involves the final processing of a product for disposal, incineration, recycling, remanufacturing, or other end-of-life processing. Different end-of-life options can be considered during this stage to prolong the product life-cycle and also to ensure perpetual material flow in continuous development of next generation products from successive life-cycles.

To increase the customer usage phase in innovative industries enhanced development strategies have to be implemented to ensure long customer usage, environmental protection and economic aspects. One strategy is the development of reliable (increase of product reliability) and upgradeable products. Through the upgrade capability additional functions or efficient components can be integrated or replaced over the customer usage phase, which leads to an extension (Bracke, 1999; cf. Figure 1). Precondition is an adjustment of the manufacturing planning regarding to the production of wear parts and remanufacturing possibilities with regard to the extended use phase. Finally, the verification of the product reliability – and therefore the sustainable product concept – can be based on field data.

**Figure 1** Level of customer’s product requirements versus successor development

![Level of customer’s product requirements versus successor development](image)

*Source: Bracke (1999)*
Therefore, the main question regarding future environmental products is: What are the influences and interactions of product development, manufacturing and use phase regarding the focus ‘Reliable products are sustainable products’ of this paper?

2 Main thesis and goals

The focus of this paper is the main thesis ‘A reliable product is also a sustainable product from the ecological point of view’ With regard to the substantiation of this thesis, the main pros and cons are as follows:

- **Pro**: a reliable product with a long useful life span area saves the following resources: spare part production, spare part distribution, reuse of components (recycling), disposal of used parts, logistic efforts, et cetera

- **Con**: a reliable product with a long useful life span area inhibits cycles of innovation with regard to their functionality and it inhibits clean technology regarding the interaction with the environment during the use phase.

The Chair of Safety Engineering and Risk Management (University of Wuppertal) in cooperation with the Meiji University (Department of Mechanical Engineering Informatics) and the University of Electro-Communications (Department of Informatics) contrasts traditional with extended, environmental friendly development approaches in relation to economic and environmental aspects and useful customer usage phase. The main thesis ‘Reliable products are sustainable products’ will be substantiate: This paper outlines the ‘Collaborative development, manufacturing and field verification for higher product reliability towards sustainability (CDMF-RELSUS) concept’. The focus is on influences and interdependences of the product development, the manufacturing planning and the field observation regarding successor development. It includes the combination of reliability and sustainability product characteristics.

3 The CDMF-RELSUS concept

The ‘Collaborative development, manufacturing and field verification for higher product reliability towards sustainability (CDMF-RELSUS) concept’ deals with three points of view to evaluate a product regarding to the thesis ‘Reliable products are sustainable products’. The three evaluation directions are as follows:

1. **impact of product design**: development of reliable products in contrast to product innovation cycles and reparable during use phase

2. **impact of manufacturing planning**: analysis of machines/facilities/materials/suppliers/material flow during manufacturing (water, electricity, operating fluids, additives, etc.)

3. **impact of use phase**: verification of product reliability in the use phase; allowance of product recycling efforts regarding to the end of product’s life span area.
These main impact factors are substantiated in the following chapters: the basic idea of the CDMF-RELSUS concept and the CFMF-RELSUS application process is the comparison of possible values which can be determined during the manufacturing planning and the use phase to support the decision making during the product life cycle (cf. Figure 2). This assists to find an optimum solution for positioning innovation cycles (e.g., upgradeability) during the product life cycle with regard to the main goals of reliability and sustainability. The general process of this concept based on the total life-cycle stages (Gupta et al., 2011) is shown in Figure 2, which combines on the one hand excerpt of the product life cycle and on the other hand the different innovation cycles (cf. Figure 3). With regard to the total life-cycle stages (Gupta et al., 2011), manufacturing and use phases are mainly focused in this paper. Each upgrade cycle $\lambda$ is referred to an assembly $i$ and its grade of upgrade $k$. Inside one upgrade cycle $\lambda_{i,k}$ the product design phase deals with a number of assemblies $i$ to $z$ with an amount of components 1 to $n$. After the assembly is designed, the manufacturer plans the needed assembly, disassembly time and thus the proposed energy consumption for each assembly process $i$ to $z$. Due to different perspectives, varied sustainability values $val_i$ can be generated for each assembly process. After the products are delivered the reliability of each assembly (e.g., component) $i$ to $z$ can be verified by state of the art methods [e.g., prognosis method based on Eckel (1977)] to determine the probability for upcoming defective assemblies $val_i$. By building a non-linear mathematical function of the values $val_i$ and $val_j$, the $Release_{factor_i}$ can be obtained for each assembly.

**Figure 2** The CDMF-RELSUS concept and the application process inside the product life cycle with total life-cycle stages (see online version for colours)
The \textit{Relsus factor}, can be a key element to specify a time-depending area for a strategic upgrade-cycle $\lambda_{i,k+1}$. If the decision leads to an upgrade-cycle, the former assembly $i$ is renewed inside this cycle. With this significant assembly change by new materials or single components a new value $\lambda_{i,z+1}$ has to be determined in the manufacturing planning process. Afterwards the reliability of the assembly $\lambda_{i,z+1}$ has to be verified again, to examine the accomplished upgrade.

3.1 Impact of product design

For long-term use of highly reliable products, repairability and upgradability of the products should be discussed. A disassembly (Lambert and Gupta, 2005) and assembly (Yamada et al., 2006) efficiency of the products are very important factors for repairability of the products. On the other hand, the customers often discard the products because of the functional obsolescence before the end of their physical life such as durability life. Therefore, the two types of the product life: the physical life and the value life should be considered for the sustainability of the product. Design for upgradability enables products to be used for longer than their conventional counterparts (Xing and Belusko, 2008). Figure 3 shows deterioration of a product value over time and the extension of the value life through upgrading to deal with obsolescent functionality (Murakami et al., 2012).

\textbf{Figure 3} Extension of the value life by upgrade

When considering the issue of the design for upgradability, product modules are classified as target modules for upgrade and platform modules as constant sub-system. It is required that the platform modules are highly reliable modules and can adapt to the various changes during product lifetime. However, one of the difficulties of design for upgradability involves the prediction of future trends such as technological development and market movements; therefore upgradable products must be robust against such future uncertainties (Fukushige et al., 2012). Watanabe et al. (2007) proposed a methodology for upgrade planning based on the future technological trends and user demands by using roadmap information and a component database. Such plans include information on the
timing of product upgrades and which components should be updated. The other difficulty is the over-specification problem of the platform modules for adaptability of the upgrade. Therefore, this research project needs to consider the multi-objective evaluation including over-specification of the platform modules, cost, durability life, value life, and the total environmental loads in an environment possessing such uncertain information. Inoue et al. (2012) proposed a decision-making support method for sustainable product creation which can obtain satisfactory multi-objective solutions considering technical performances and sustainability issues under various sources of design uncertainties (Inoue et al., 2012).

Therefore, a checklist overview regarding to the evaluation of the influence of the product design could be verbalised as follows:

- ensure maintainability during engineering design
- arrange resettability during the design phase: assortment of materials
- due to innovation cycle: upgrade capability to assure attractiveness during a long lifetime
- consideration of energy consumption due to provided parts/materials during possible assembly processes [example: design engineer determines a high energy consumption by choosing aluminium (special alloy)]
- energy consumption regarding to the provided upgrade capability
- repairability during use-phase (example: automobile accident, crash, a small amount of parts damaged lead to a change of the whole component, lead to an impact on resource consumption during use phase)
- design of components concerning life durability.

3.2 Impact of manufacturing planning

In terms of the product management by highly reliable products for sustainability, supply chains (Stadtler and Christoph, 2000; Shapiro, 2001) should be discussed and drawn by relating to product lifecycle management (PLM) (Yamada, 2012) including four total life-cycle stages (Gupta et al., 2011) as shown in Figure 4. The engineering process means flows of product information among product plan, development, design, production preparation and production (assembly). On the other hand, the supply chains, which mean value chain process, are flows of product materials among procurement, production (assembly), sales, use, maintenance and disposal. In addition, collection and disassembly for reuse and recycling are nowadays added for a reverse supply chain, so that they are known as closed-loop supply chains (Ilgin and Gupta, 2010). The four total life-cycle stages (Gupta et al., 2011) are also identified such as pre-manufacturing, manufacturing, use and pose-use.

As shown in Figure 4, it is noted that the product design and development in the engineering process basically affects all of the processes in the supply chains and PLM. Since products by the supply chains inevitably consume natural resources for materials and energy throughout their product lifecycle, it is necessary to minimise the material and energy consumptions during the whole product lifecycle. To realise the sustainability, there are two essential types of supply chains required for low-carbon and closed-loop
The low-carbon supply chains are visible and reduce CO$_2$ volumes as the whole of supply chains to prevent global warming. One of the reasons is that one product is produced in the supply chains beyond processes and companies as well as borders and continents.

When highly reliable products are developed, designed and managed, they have high potential to reduce the environmental load for the whole product lifecycle. For example, they can promote longer usage by users and spare parts reuse, which reduces new material and energy consumptions comparing to new products input.

However, to promote sustainability by highly reliable products for industries, it is essential to harmonise environment and economy at the same time in designing the supply chains (Yamada, 2012). It is a challenge to visualise environmental impacts and profit simultaneously by product, factory and logistics designs in the whole supply chains. Therefore, the supply chains should be designed and managed environmentally and economically with the highly reliable products for sustainability.

Figure 4  Supply chains in product lifecycle management with total life-cycle stages (see online version for colours)

The supply chain is known as products flow downstream from vendors to plants, plants to distribution centres, and distribution centres to markets (Shapiro, 2001). A network of organisations is involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer (Stadtler and Christoph, 2000). Hence, the supply chain design here consists of three phases: product, factory and logistics designs. Even if the factory design only is focused by assembly configurations with 3M&I (cf. example in Figure 5) in terms of efficiency for material flow and process, there are a lot of design parameters such as cycle time, inventory buffers, operators/work stations, material
handling, line balancing and scheduling (Yamada, 2012). All these factors, of course, affect not only environmental impacts but also profitability. Therefore, this research project needs to visualise the effectiveness of the environmental and economic impacts by the highly reliable products with exchange to the data and information (Yamada et al., 2009) among product development, design and management.

Figure 5  Factory design by assembly configurations with 3M&I (humans, materials/machines, money and information)

Therefore, a checklist overview regarding the evaluation of the influence of the manufacturing planning can be verbalised as follows:

- production planning of OEM: needed machines, facilities, operating fluids
  
- supply (chain) management: selection of sustainable suppliers (example: OEM added value depth 20%, BUT depth of added value supplier 80%, therefore supplier significant)

- exchange of data and information between development (construction handicap) and production (implementation during production planning)

- possibilities of an exchange of environmentally product-manufacturing technologies

- choice of sitting regarding to environment interactions.

Source: cf. Yamada et al. (2006), partially changed
3.3  Impact of use phase

The impact of the use phase can be divided into two influences:

a verification of product reliability during the use phase
b analyses of the intended end of the product’s life cycle: product recycling or material recycling.

Product field observation during the use phase is important for the verification of the product reliability. One way for a quantitative verification is the determination of failure rates and probabilities depending on life span variables, load cycles and use conditions. The field data source is guarantee data regarding to damage cases, which are collected by members (garages) of the trade organisations. Therefore, the focus of the reliability verification within the field product monitoring is the application of statistical reliability analysis and interpretation of failure data. A comprehensive process was developed by Bracke and Haller (2009b, 2010): Advanced and structured statistical methods and organisational aspects are integrated in a generalised ‘field damage analysis’ (FDA)-process. The FDA-process allows analysing field data on complex, multiple damage causes to predict potential damage cases in field, in detail:

- comprehensive mapping of the component failure behaviour in terms of damage causes and differences of affected production batches, product optimisations (component changes), climatic influences and regional influences (through customer usage)
- detailed and full statistical mapping of complex, multiple damage causes
- interpretation of the statistical analysis results regarding possible damage causes
- prediction of possible future damage causes in the use phase and minimisation of replacement parts within the product’s life cycle
- use of further qualitative data and information from value added networks to identify and verify damage causes before technical failure analysis
- reflection of knowledge out of the reliability analysis into the value added network (e.g., lessons-learned-method) for the long term goal of sustainable product improvement
- verification of the efficiency of introduced actions for troubleshooting, e.g. in the field or in the current product generation.

The result is the comprehensive mapping of the failure behaviour and allows the verification of product reliability. Figure 6 shows an example of a precise mapping of an automotive coolant pump complex damage behaviour to the life cycle (use phase) in a life-span kilometrage area from 40 to 300 * 10⁷ km. The multiple damage failure mode is fitted by a weighted combined function approach using the trust-region method (Celis et al., 1985). The idea of the weighted combined function approach is the disengagement of usual industrial art distribution models and the summation of multiple distribution functions of same or different types \( F_i(t) \), which can be weighted by different factors \( n = n_1 + n_2 + \ldots + n_r \) [cf. equation (4) (Meyer, 2003)]. The weighting factors can be chosen analogously to the separation points detected by the damaged part analysis.
supported by differentiation of complex damage (DCD) causes algorithms (Bracke, 2008). One appropriate distribution model \( F(t) \) is mapping one single damage cause.

The selection of suitable distribution models – e.g., Hjorth distribution, SB-Johnson distribution or Weibull distribution – is based on empirical knowledge on reliability analysis within the automotive industry (Bracke, 2008; Bracke and Haller, 2009a).

\[
F_{\text{WCF}}(t) = \frac{n_1}{n} F_1(t) + \frac{n_2}{n} F_2(t) + \ldots + \frac{n_r}{n} F_r(t)
\]  \hspace{1cm} (1)

In the case study, ‘damaged coolant pump’ five damage causes – by means of the DCD algorithm differentiated and verified by the value added network – can be mapped with the weighted combined function approach by choosing

- the Hjorth distribution function \( F_{\text{HD}}(t) \) for the damage causes during the early failure phase, which is differentiated by the DCD algorithm in two damage causes \( (F_{\text{HD}}(t) \) is weighted with \( n_1 / n = 0.4) \)
- three Weibull distribution functions \( F_{W}(t) \) [cf. equation (1), with \( t_0 = 0 \)] regarding the wear out damage phase, which is differentiated by the DCD algorithm in three potential damage causes \( (F_{W1}(t) \) is weighted with \( n_2 / n = 0.1; F_{W2}(t) \) with \( n_3 / n = 0.21; F_{W3}(t) \) with \( n_4 / n = 0.29) \).

Based on the chosen distribution model \( F_{\text{w}}(t) \) for simultaneously describing several damage causes, equation (5) shows the WCF approach of the present case study. This approach includes a total of 16 parameters that differentiate in 11 form parameters (form characters: \( b_i, T_i, \beta_i, \delta_i, \theta_i, t_{HJ} \)) and four weighting factors \( n_i \).

\[
F_{\text{WCF}}(t) = \frac{n_1}{n} \left( 1 - e^{-\frac{(t-t_0)}{\beta_1}} \right)^{n_1} + \frac{n_2}{n} \left( 1 - e^{-\frac{(t-t_0)}{\beta_2}} \right)^{n_2} + \frac{n_3}{n} \left( 1 - e^{-\frac{(t-t_0)}{\beta_3}} \right)^{n_3} + \frac{n_4}{n} \left( 1 - e^{-\frac{(t-t_0)}{\beta_4}} \right)^{n_4}
\]  \hspace{1cm} (2)

It is shown in Figure 6 that the weighted combined function approach \( F_{\text{WCF}}(t) \) excellently represents the cumulative probability of known coolant pump damages in the field regarding the whole life span area in contrast to the industrial state of the art Weibull distribution \( F_{\text{WD}}(t) \).

\[
F_{\text{WD}}(t) = 1 - e^{-\left(\frac{t-t_0}{\beta-\theta}\right)^{\phi}}
\]  \hspace{1cm} (3)

The use of Weibull distribution models only allows to describe simple product failures and to identify different damage phases or behaviours in a product life cycle (Birolini, 2007).
Furthermore, the second part of the impact of the use phase is the end of the product’s life cycle. There are two basic strategies for influencing the interaction between product and environment: product recycling or material recycling (cf. Figure 7; Bracke, 1999).

**Figure 6** Cumulative probability of known field coolant pump damages, weighted combined function distribution \( F_{WCF}(t) \) fit and Weibull distribution \( F_{WDL}(t) \) fit (state of the art)

**Figure 7** Different strategies and subsequently different outputs for intended product life cycle end

*Source:* Bracke and Haller (2009b)

*Source:* Bracke (1999)
Depending on the chosen strategy, product recycling or material recycling, the influence depends on the output (repaired/refreshed products, replacement products or secondary raw material) and the interaction regarding to possible environment pollution is to analyse. For example, possible environmental and economic influences for disassembly parts selection and its system design can be quantitatively measured in terms of recycling rate/cost and disassembly line by Igarashi et al. (2013).

The product recycling strategy is the interesting part of the chosen strategy regarding to the main thesis ‘Reliable products are also sustainable products’. Base of operations is a product or component refreshment. Afterwards, there are three fundamental possibilities (cf. Figure 7, right side): reliable products can be repaired (product identification number is the same) or reliable components can be used to assemble a new product with a new product identification number. The third possibility is the offering of refreshed, reliable components as spare parts to the markets. The precondition for an integration of the product recycling activities in the manufacturing structure is an optimal information flow to the product recycling with regard to refreshment work instructions, quality specifications and material requirements. Therefore the integration of the product recycling strategy should be done in the product service or maintenance centre of the manufacturer (cf. Figure 8, Bracke and Reim, 1998). Based on the direct interface between original working processes with regard to the product service (during first product life span) and product recycling (preparation for second life span), the information flow can be designed without data loss. As a result, the product service/maintenance centre of the manufacturing structure gets used components for the refreshment process and information about the important, functional component characteristics regarding to the product reliability.

Figure 8  Integration of product recycling in the product service/maintenance centre of the manufacturing structure

Source: Bracke and Reim (1998)
4 Conclusions and outlook

The ‘Collaborative development, manufacturing and field verification for higher product reliability towards sustainability (CDMF-RELSUS) concept’ shows aspects, influences and strategies to substantiate the thesis ‘A reliable product is also a sustainable product from the ecological point of view’. It shows the complexity and the interdependences of the three main impacts product design, manufacturing planning and use phase. The CDMF-RELSUS concept and the shown CDMF-RELSUS application process is the base of operations for the development of a successor model, which combines the characteristics of sustainability and reliability. Therefore it is a base of operations for saving resources in different ways: Prevention of manufacturing new products too soon at an early stage and subsequently reducing production material stream. Furthermore it reduces logistic efforts regarding to damaged field components and finally spare parts are reduced.

Future research work will contain checklists and criterions, which help the design engineer to consider the combination of sustainability and reliability with regard to the pre-manufacturing and post-use (Gupta et al., 2011), product construction and manufacturing. Furthermore, case studies and design examples can be adopted to validate the CDMF-RELSUS concept and the application process. The case study contains the verification of the product reliability based on field data in the successor development. Finally, the CDMF-RELSUS case study considers the interaction of the intended end of the product’s life cycle (product recycling or material recycling) regarding to the environment.

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