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Establishing EcoReliability of Electronic Devices in Manufacturing Environments

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Abstract

EcoReliability describes the inclusion of reliability aspects into the environmentally conscious design of electronic systems to address the originally separated domains from one mutual perspective. This paper motivates the importance of such an approach for the case of electronic products and in particular embedded electronics. Environmental analysis of electronics has often been narrowed down to energy use, but the total resource use is now seen as equally important. Using technical examples from promising applications in robust electronics for manufacturing equipment, measures in system design aiming at an increase of sustainability through determination of a truly balanced degree of reliability are presented. The first case is taken from the field of power electronics with demanding requirements towards robustness. Measures to increase the allowable number of thermal cycles during operation are compared towards shifts in environmental attributes. For the second case, miniaturized sensors are introduced that face issues of obsolescence when applied to machine tool environments in long-term scenarios.

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Keywords: LCA, reliability, lifetime estimation, use-time, EcoReliability

1. Introduction

Reliability and environmental aspects have conventionally been situated towards the end of the design chain: if specific challenges come up with the near-final product, then detailed tests, evaluations and improvement actions are suddenly called for. However, this has now changed drastically, both because these aspects are now considered in earlier design phases and because GreenTech has now become increasingly fashionable in industry. This paper makes the case why reliability is a very important contribution to the improvement of environmental attributes of products and processes, and in reverse why environmental approaches are an asset for reliability investigations. The two fields are in effect closely connected. EcoReliability in that sense is both a combination of existing competencies and a novel method for multi-criteria trade-off balancing, which can be used for better targeting of technologies. Against the background of climate change, carbon accounting, renewable energy and the global population growth or in other words limitation of resources many companies are now turning green in their public and marketing statements. But is the electronics industry and their multitude of products really green? And in addition how much more green must the contribution from the electronics industry be to enable a green manufacturing in total?

Although traditionally viewed separately, the case is clear that reliability and sustainability need to be examined in conjunction. For that area of overlap we would like to introduce EcoReliability as a concept.

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2. Concept of Eco-Reliability

Increasingly, the life time of electronic systems is recognized as a major influence on the environmental performance. However, in addition to the mere technical life time the following criteria determine the required use time of electronic systems or parts of it in practice:

- Technical obsolescence (i.e. standards or interfaces outdated)
- Efficiency obsolescence (i.e. lack of efficiency when compared to state-of-the-art technology)
- Obsolescence due to fashion changes (i.e. industrial design of the housing)

Blindly maximizing reliability leads to overdesign, thus wasting resources and leading to very expensive products failing in most market settings. In most cases, the trade-off between reliability and environment needs to be understood and quantified much better for future product and technology choices. The resulting solution concepts (that intuitively we seem to grasp more clearly than scientifically) range from highest reliability possible (including use of any eco-intensive materials, and redundancy) through planned service and upgrade business models to – as an extreme case – throw away products. But even for short life time products we have to assume that valuable resources will be embodied in the electronics, hence resource recovery is of even greater concern for disposable products than for high end reliability products.

Consumer goods such as LEDs and mobile phones are increasingly moving towards “throw away products” with major amounts being lost in household waste streams on a global level. This issue raises concerns regarding material use and resource recovery already today. When moved towards higher life times the implementation of environmentally critical materials, i.e. gold, silver but also traces of rare earth materials in general need to be justified by the targeted use case. This is also true for peripheral bulk materials, e.g. aluminum for cooling devices. Whilst material choices and amounts directly affect the life time of the product, a clear influence on the environmental footprint is generally the case requiring an optimization involving all criteria.

Trade-off considerations additionally involve further aspects such as miniaturization, functionality, costs and innovation cycles. The latter are of significant importance when looking at design options and possible multi-life-cycle scenarios allowing for upgrade and overhaul measures in the use phase of the product already in the design state of the system.

Figure 1 shows the evolving improvements of key component attributes in state-of-the-art microsystem technologies. Whilst battery technologies slowly evolve with capacity gains at constant volume of less than 5% per year, memory and computation speed per chip-size area as well as data rates in communication standards exhibit relatively short innovation cycles. This leads to issues of technical and efficiency obsolescence requiring system developers to come up with steadily optimized and revised technical solutions able to interact with the maturing surroundings. However, for the individual off-the-shelf component, the degree of implemented innovation strongly depends on the market sizes of the targeted applications, as these determine the mobilization of targeted research to a large degree.

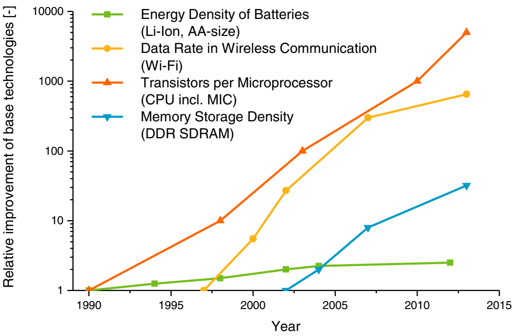

Figure 1: Relative improvement rates in key components for microsystem technologies

Trade-off scenarios for eco-reliability therefore need to include scenarios and forecast assumptions addressing obsolescence issues already in the conception phase of the product. Moreover, the definition of dedicated “Mission Profiles” describing environmental loads over time of usage apart from standardized test procedures is crucial to the development of the underlying use-cases. These in turn lead to a catalogue of system requirements that provide the basis to compare technologically feasible designs.

Depending on the depth of the resulting technical description of processes and materials involved environmental assessment procedures can be applied, starting from screening assessments to full life cycle analysis.

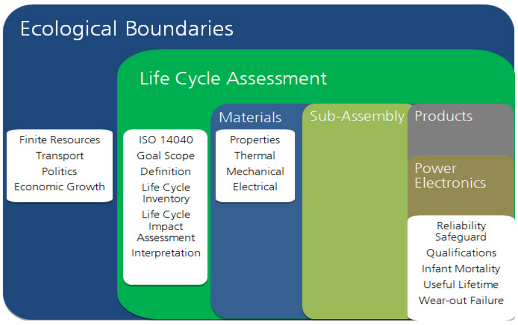

Figure 2: EcoReliability – Hierarchical levels

Principle hierarchical levels of EcoReliability are shown in Figure 2. Life cycle assessments focus on the complete product including all sub-assemblies down to material level. The final setup determines the degree of technical reliability by means of probability of failure during use phase as well as the technical life time (limited by material aging).

Electronic systems involving many partial components and can soon lead to trade-off scenarios that are too complex to quantify all non-linear relations and interactions between design choices and effects on multiple criteria within one empirically quantified model. However, the limited choice of design options derived against the background of mission profiles, system requirements and available technologies generally allows for a first decision making on environmentally benign design options whilst maintaining a reasonable degree of reliability in each design stage. This will be demonstrated exemplarily in the following chapter for an explicit design decision regarding material choice for the case of bond wires in power electronics. The importance of including general considerations on obsolescence and technical reliability issues already and the concept phase of systems involving electronics is then further discussed for the example of distributed sensors in machine tool environments.

3. EcoReliability of electronics in manufacturing environments

In this section aspects of EcoReliability are further investigated using electronic systems applied to manufacturing environments. There are three main categories of electronic equipment utilized in manufacturing:

- Sensors
- IT infrastructure
- Power electronics

3.1. Inside EcoReliability for Power Electronics

In the design of robust and reliable equipment of power electronics lays a tremendous potential to improve energy efficiency of all power consuming applications in manufacturing environments. However, the technology incorporates a large environmental footprint at the same time.

Apart from the active components (made from silicon, but also increasingly SiC and GaN) the bulk metals aluminum, copper and their alloys provide crucial mechanical, thermal and electrical characteristics required for electronics packaging (Table 1).

Properties at 20°C		Copper 99.99%	Aluminum 99.99%
Weight	g/cm^3	8.94	2.6989
Linear CTE Coefficient α	$(10^{-6}/K)$	17	23.1
CTE Coefficient γ	$(10^{-6}/K)$	51	69
Thermal conductivity	W/(m·K)	401	237
Resisitivity ρ	(Ω·m)	1.68	2.6548
Tensile-strength	MPa	242.7[4]	216GPa
Yield-strength	MPa	128±1.4[4]	30
E-Modulus	GPa	112.8±2.2[4]	
Corrosion resistant		Yes	Yes
Recyclability percentage		100%	100%

Table 1: Properties of Copper and Aluminum

Figure 3 shows a research demonstrator with active components being electrically contacted by bondwires. Here two technological options were compared in terms of reliability defined by allowable thermo-cycles using copper and aluminum wires respectively. Technical life time is determined by design, i.e. materials, material interfaces and geometry in combination with the mission profiles applied. For benchmarking, technological performance of design options need to be comparable. Since current carrying capacity mainly depends on the specific electric conductivity and the diameter of the wire, 14304 mg of copper vs. 6748 mg of aluminum were necessary in the example to provide comparable electrical properties.

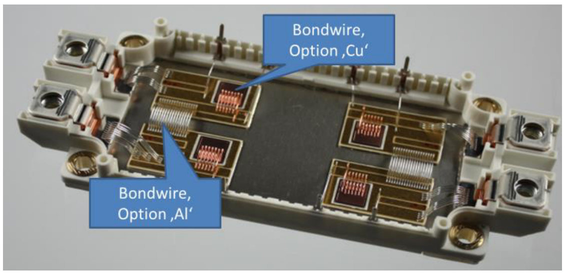

Figure 3: Al und Cu bondwires on a demonstrator for power electronics

By looking at the required function of a products task from reliability perspectives, environmental conditions at system levels must be defined more closely. Mission profiles include detailed information on:

- ambient and intrinsic temperatures levels
- storage temperatures
- humidity
- dust, corrosive atmosphere
- vibrations
- shocks, noise
- power supply voltage variations

From these boundary conditions and the knowledge of component dimensions and relevant failure modes and their effects test conditions are derived. With accelerated environmental conditions, e.g. thermal cycles from -40°C to 125°C, product life time can be predicted experimentally within short time frames. The application of accelerated testing not only reduces costs and development time but also helps to identify materials or combinations able to suffice the targeted mission profile. Therefore dedicated theoretical life time models need to be provided to found the basis for the calculation of the acceleration factor. The bathtub curve must be introduced and divided in to three phases in order to distinguish the various stages of a product lifetime. Infant mortality resembles all undesired failures due to insufficient design, failures in production processes and assembly as well as material defects or preloads outside the specification range. However, infant mortality should be reduced to a minimum to achieve high yields, saving precious resources. The useful lifetime describes the occurrence of failure due to pre-damaged products or overstress. Measures to reduce the system's sensitivity towards specific environmental loads can increase the systems robustness. However, these measures will not necessarily increase the life time since this requires influencing the underlying aging mechanisms. To prevent failures because of wear-out, preventive measures like replacement of components close to their end of life time [2] can be applied. However, this is not always possible for components in the electronic industry due to encapsulation, or due to miniaturization. This needs to be taken in account in a quantifiable measure for the use for materials, sub-assembly and end products in industrial power-electronics.

As was shown in [12] the use of copper increases the reliability by means of allowable thermo-cycles by factor 10 and upwards. However, costs for the required modification of the chip-metallization in conjunction with the more complex bonding processes are possible disadvantages of applying Cu wire. As a compromise, material mix approaches - copper wire coated with aluminum – are further investigated to bridge the technical challenges.

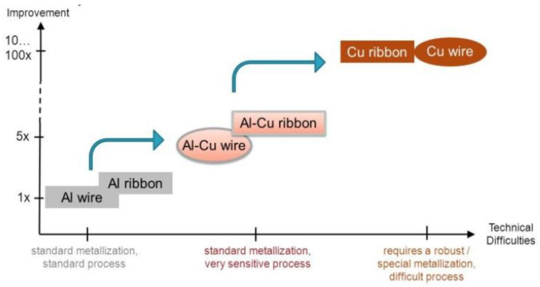

Figure 4: Reliability improvement potential vs. technical difficulties [12]

As a result of the studies carried out in [12] demonstrates the increase in reliability when shifting from Al to Cu wires. However, in order to compare the increase in reliability with respect to environmental impacts, environmental aspects are investigated in the next section to come to first conclusions on the EcoReliability of bond wires. Through analysis of impacts of design decisions on the results of life cycle assessments (or simplified methodologies) designers can contribute to more eco-friendly products. On a material level, selected environmental performance indicators were considered for the choice of Cu vs. Al. Since costs most often account for final design decisions price differences for aluminum and copper prices were studied within this context (Figure 5). During periods of high copper and aluminum prices with the price of aluminum being around on third of the price of copper, economy began to slow as a result of the global financial crisis by 2008. However, prices would soon recover mainly due to increasing demand of the rising middle-class in countries like Brazil, Russia, India and China. Fluctuations from average price level are due to availability and capacity of ores, cost of labor and energy for production [9]-[11]. However, one reason for the increasing gap between costs for Al and Cu lies in the increasing cost for mining and processing of Cu in conjunction with the increasing scarcity of the material.

Figure 5: Copper vs. aluminum price in US Dollar/kg over 5 years

Besides costs environmental aspects were compared for the case of Cu and Al:

- Toxicity, described by the Toxic potential indicator, a screening method developed by Fraunhofer IZM
- Resource scarcity, described by the Resource Availability and Risk Indicator (RARI) developed by Fraunhofer IZM
- Cumulated Energy Demand (CED)
- CO_2-Emissions during production of primary and secondary metal
- Weight

The results of the comparison of these attributes are grouped in Table 2.

	Weight	TPI	CED (prim.)	CO_2 (prim.)	CO_2 (sec.)	RARI	Costs	Lifetime
Cu/Al (ratio)	2.12	2.40	0.76	0.54	2.74	1.60	7.80	≈ 5-10

Table 2: Selected ratios of environmental properties of Cu and Al

Whilst the production of copper from primary resources consumes only three fourths of the energy required to produce aluminium, CO_2 emissions can even be cut down to 50%. This case is a direct complementary effect between reliability and sustainability. However, when using metals from recycling processes, this trend shifts towards higher energy demands for the production of copper due to the outstanding suitability of Al for recycling. Toxicity of Cu is also slightly higher, due to its potential risks to aquatic cultures. Resource scarcity is only slightly higher due to the larger amounts of weight required for copper bonds. It can be concluded from the results, that with the exception of direct costs associated only with the bulk material, gains in life time succeed increases in environmental impacts. Still, the design measure “Copper bond” is only recommended in case the mission profile of the targeted application explicitly requests this increase in reliability. The example demonstrates that a general recommendation for one material or application cannot be derived. It is rather recommended to closely examine reliability aspects in conjunction with environmental issues as proposed in this section.

3.2. Inside EcoReliability for Sensor Nodes– The case of obsolescence and technical life time

Microsystem technology based sensing is seen as one of the key drivers in sustainable manufacturing. Technological solutions arise in the following fields:

- Distributed sensing of manufacturing equipment status data, e.g. temperature, humidity or acceleration for *process optimisation*
- *Identification* of machine *parts* and their history but also the *product* itself in self-organizing production
- Sensing and/or transmission of energy consumption related data to *improve efficiency* of manufacturing equipment
- Acquisition of *system health* data to include condition monitoring functionalities

Main advantages can be achieved through implementation of miniaturized sensors that provide the listed capabilities at selected locations that are difficult to reach with conventional, cabled sensor solutions.

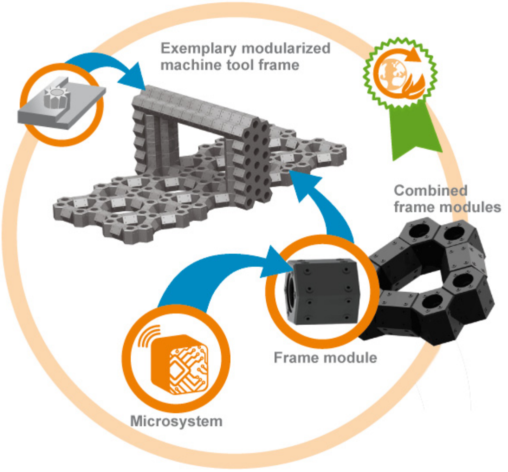

Figure 6: Principle concept of modularized machine tool structures equipped with microsystem technologies

This is especially true for concepts of microsystem technology enhanced machine tool frames as presented in Figure 6. The concept is based on a modularization of the mechanical structure hence requiring elements for compensation of static deformations due to the increase of mechanical interfaces and thermally induced mechanical stresses within the construction. Microsystem technology solutions provide main innovation hubs at the current level of machine tool (MT) and microsystem technology (MST) fusion (MT-MST). Sensors are required at distributed spots in the frame that are objected to steady adjustments due to tool reconfiguration. These miniaturized sensors provide crucial data for accuracy optimization to the control loop of the machine tool at remote locations that cannot be accessed by conventional measurement systems.

The resulting system in turn allows for adaption, extension and reconfiguration depending on the required task. Therefore significant benefits on overall sustainability of production environments are expected due an optimum usage of the machinery or single parts of it during the machine tools life span and the flexibility to react to market demands.

When designing sensors for such applications, the whole peripheral IT infrastructure needs to be taken into account. This is shown for the exemplary case of the currently developed demonstrator within the CRC1026. Figure 7 describes the required architecture including all required technical equipment for the communication flows. Data acquisition is performed by the numerous *sensor nodes* providing unidirectional data transfer to receiving nodes using 2,4GHz IEEE 802.15.4 standard and SMD-antenna. The *receiving base stations* are modified sensor nodes ready to receive data via IEEE protocol and deliver wired data communication via USB to a *personal computer*. Number and locations of the receivers can be adapted depending on the quality of radio frequency communication at the current location. The PC provides internet access and a MQTT-based data server structure thus requiring software tools able to reliably distribute the received data volumes to external systems. Besides the *control loop of the machine tool* this includes *personal devices* that are able to visualize the machine tool status as well as storage to gather information on the machine tools history.

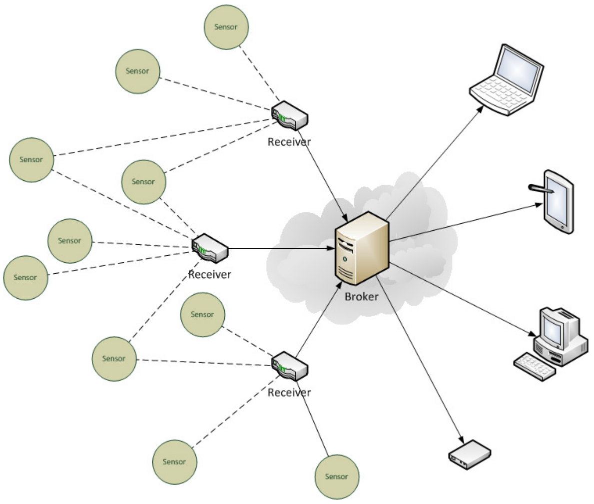

Figure 7: Setup of the IT infrastructure for miniaturized sensors

The central question on how to bring together issues of sustainability and reliability evolves when designing microsystems for machine tool environments through fusion of two complex technical domains with individual life cycles. When designing such a complex system, in addition to effects of aging and wear, aspects of obsolescence need to be considered. Within the targeted lifespan it is rather likely that production of technically superseded components is discontinued. Moreover, supporting technologies within the infrastructure of the device, e.g. wireless communication using standardized protocols, might no longer be available. There will be break-even points for replacement of efficiency improved parts from an environmental point of view that lead to exchanges even before end of life.

Machine tools exhibit use times estimated up to 20 years and more in combination with high workloads (Figure 8).

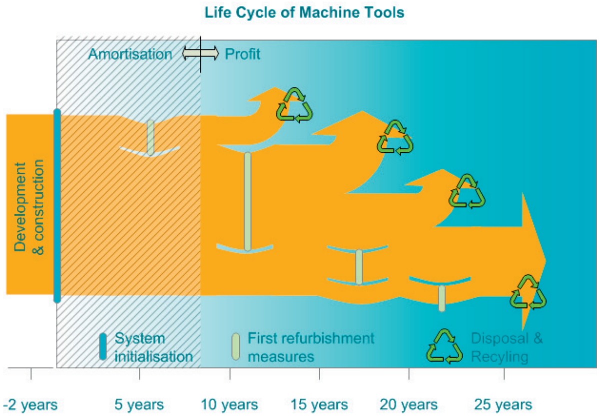

Figure 8: Typical life cycles of a machine tools including timeline until first refurbishment measures and disposal

Depending on the environmental loads occurring at the specific mounting location these life times are already challenging for micro system technology sensors from the perspective of technical reliability. However, when including aspects of obsolescence by means of availability of components for repair, efficiency and compatibility with the surrounding IT infrastructure it soon becomes clear that only a sequential usage of maturing sensor node generations will lead to a reliable solution, able to provide the targeted functionalities over a long-term period of 20 years or more.

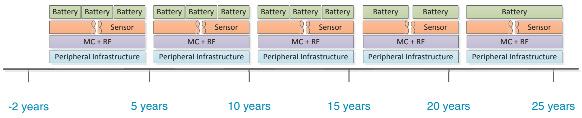

Figure 9: Multi-life-cycles of maturing sensor system generations aligned with service intervals of electronics and mechanics

This approach is described as the multi-life-cycle concept and is based on individual trade-offs that can already be considered as examples of EcoReliability. Figure 9 demonstrates the individual use times of each functional group within a microsystem technology sensor being optimized with respect to environmental performance whilst still being aligned to life times of all other sensor components. The need for regular exchange of the central PCs providing the gateway to the peripheral infrastructure lies in the expected efficiency gains by means of power consumption. Increase of lifetime by measures of system modification (over dimensioning, built-in redundancy, high reliability grade components) would not be justified as consumer good equipment would already provide the required technical life time. The switch to a new PC as central processing unit would be aligned with a general software upgrade (e.g. operating system) thus allowing for new setup of an advanced communication protocol. All modifications required in the RF interface of the sensor node would immediately involve the core microcontroller thus requiring an exchange of both, processor and RF transceiver. Efficiency gains can therefore be directly transferred to the sensor node, reducing the average annual amount of battery chemicals disposed with each innovation step being integral part of the multi-life-cycle scenario. Life time of sensors and energy supply must at least be able to suffice the time slots between regular service intervals of the machine tools. In practice, interruptions for battery exchange will be unavoidable in order to achieve adequate system dimensions. However, reliability of interconnection technology as well as components does not necessarily need to succeed the life time of microprocessor and RF transceiver as their replacement is bound to the regular upgrades planned for the latter. This allows for a broader range of possible redesigns potentially providing more environmentally sound alternatives.

By choosing this configuration, issues of technical obsolescence are avoided already in the concept phase, since any mismatch in-between interfaces due to (partial) upgrades can potentially impede the complex communication structure within the complete setup. Moreover the potential risk of discontinuance of single sensor components is excluded since this would limit the options for potential repair work on the sensor network.

All considerations discussed demand for a technical solution of the sensors that allows for a modularization of the single functional groups within the sensor, i.e. processing and radio communication, sensors and power supply. The current system design is therefore applied following the concept presented in Figure 10.

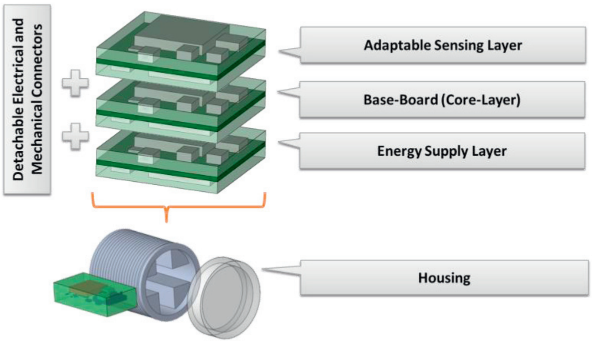

Figure 10: Resulting micro system technology sensor setup to support an EcoReliable multi-life-cycle approach

Design decisions will most often lead to contradictory results between different system criteria, e.g. degree of miniaturization vs. functionality. This limits the variety of design options allowing for an optimisation from an EcoReliable perspective. However, only the definition of both, a lean catalogue of system requirements and a realistic mission profile on the boundary condition provides the basis to establish reliability on a level that avoids unnecessary measures to improve system life time and robustness.

4. Summary

Advanced life cycle thinking including thoughts on the total cost of ownership provides the basis for the integration of environmental and reliability assessments into the early design process. Granularity and economy of assessments require improvement and are therefore main research topics. Tool development should focus on harmonization and development of life-cycle inventory models in combination with reliability simulation and testing of system boundaries.

Three main objectives for EcoReliability were identified:

1. Reduction of the consumption of resources: This includes minimizing the use of energy, materials, water and land. Useful strategies according to system reliability are product durability and the enhancement of repair and recycling.

2. Reduction of the impact on nature: This includes the minimizing of air emissions, water discharges, waste disposal and the dispersion of toxic substances. Investigations in system reliability help to prevent unexpected events in this context by synchronizing life times with already set time lines for maintenance, repair and overhaul of peripheral technologies incorporating electronics. Checklists should be adapted to the electronic specific issues accordingly.

3. Increasing product or service value: This means providing more benefits at reasonable overall costs to customers through product functionality, flexibility and modularity.

For the case of distributed sensors, the key to sustainable solutions lies in the alignment of measures for repair, exchange or upgrade of MST with regular service intervals of the machine tool structure. Therefore, the ability for multiple modifications of MST during the lifespan of the machine tool (multi life cycle of MST) has to be considered already in the design phase of the system. This includes design for recycling of electronics devices or single functional units, accessibility to mounting locations and removable connections. In terms of upgradability, interfaces between MST and MT need to be precisely defined.

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