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End-of-Life Management of Electronics Products Through Functional Signature Analysis

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Abstract
This paper presents a functional signature analysis method for the end-of-life management of products, particularly for electrical-electronics and electromechanical applications.

Due to the fast (r)evolution of electronics and, related, software new functionality becomes available in at an increasingly fast rate. This means that, quite often, products are economically outdated before the technical end-of-life of a product is reached. This is a far from optimal situation; often good working products are discarded because they are economically outdated with all negative side-effects not only in financial terms but also with respect to terms of ecology. In this respect the ability to analyze and predict the (remaining) technical life of a product would enable manufacturers either to re-use good sub-assemblies in the manufacturing process of new products or to design products with such design margins that economical and technical lifetime match. This requires models with the ability to predict function performance degradation over life.

Therefore, this project aims at defining methods (and related tools) to extract the mentioned indicators by analyzing the function performance over life and to have a single measure of the reliability performance to identify source of failure and performance deterioration by signals available for external measurement.

The signature analysis method uses a complete new approach, which differs significantly from methods used in preventive maintenance, designing for reliability, or on-line monitoring of quality characteristics in production processes. This paper presents the signature analysis method. The protocol for carrying out the signature analysis is discussed and the application of functional signature analysis for end-of-life management is reviewed.

Introduction

The main advantage of signature analysis is that this method provides a solution for three major points of interest for companies by following only one protocol, instead of attacking the three points of interest separately. The three major points of interest are:

1) Designing robust reliable products,
2) Re-use of modules, components, or sub-systems
3) Preventive maintenance of products.

Currently produced innovative products are highly reliable and the technical lifetime of products significantly exceeds the economical lifetime of products. A recent trend in product design is that products are modular in design. Modularly designed products have many advantages. Modules can be used in more product groups. Producing modules that can be used for more product groups make it possible to save a lot on production facilities. Not every module of all products needs to be produced on separate production lines. Not all modules in new products are newly developed. In fact, most modules, or parts, of products are exactly similar to previous versions of those particular products. The most obvious examples can be found in the area of hardware products using software. Software is highly innovative and is rapidly changing, but the hardware usually does not change for most parts. Therefore, when products are modularly built, some modules could be re-used in new products. Or they could replace failed modules of products that are still in use. This results in major cost savings, because else new modules should be produced, and re-using modules is much more cheaper than reproducing modules.

A very important point of interest for companies is the design aspect. In current times it can be observed that the complexity of products is rapidly increasing, but the technology becomes less transparent to the customers. Customers often do not realize the complexity behind the systems they use; they just expect it to work.This implies a shift in the customer attitude towards products.

Re-using modules, or parts, save a lot of waste of material and energy consumption for manufacturers.
Therefore, the signature analysis method provides an environmentally friendly tool for manufacturing companies. Also from an economical perspective of companies this method is very useful. Re-using modules, or parts, or even components, is much cheaper than reproducing the same modules that are currently thrown away.

Another important application of the signature analysis method is in the area of preventive maintenance. Failed products cannot be used for a certain period of time, while when using preventive maintenance, this downtime could significantly be reduced. In other words, when maintenance engineers can actually predict failure of products, they can replace the failing module or part before it actually fails. This results in a minimum downtime of the product. Actually, it becomes even more important in safety related products, like plane engines, or modules in the process industry, where the consequences of failure can be catastrophic.

If reliability is defined as "the ability of a product or system to fulfill its intended purpose for a certain period of time" the best way to make products reliable, is to thoroughly test all possible product-customer combinations for an extended period of time before releasing a product to the market. Unfortunately this is too time consuming and expensive. Manufacturers of high volume consumer products are currently under strong (financial and time-) pressure, because they have to deal with four different, but often conflicting, business drivers simultaneously:

1) Time: does the product reach the market at the required moment in time?
2) Profit margin: is the difference between product cost and product sales price adequate?
3) Functionality: is the product able to fulfill its intended functions?
4) Quality: does the product fulfill its intended purpose?

The necessity for the companies to introduce new products to the market in a short time is because of the competitive market. This time-to-market aspect has a large impact on product development as is explained in the article *Revolutionizing Product Development* written by Wheelwright and Clark. Therefore, due to the time-to-market pressure it is impossible to test all products.

This can affect also product reliability if no precautions are taken. The earlier potential problems are recognized, the cheaper are the changes.[3] For this reason, it is important to start optimising during the design phase. In this phase the Robust Design tools can be used. This therefore naturally leads to the problem of trying to understand the product and trying to optimise its design.

These reasons provide the motivation for the research on the signature analysis method.

The next part of the paper is about the background of research and the ideas behind the signature analysis method. The paper then proceeds with the presentation of the method and the protocol to make the method applicable. The last part of the paper reviews the importance and consequences of the signature analysis method for end-of-life management.

Module Based Signature Analysis

This paper is the result of an on-going research project that is partly funded by the Ecology, Environment and Technology (EET) programme of the Dutch Ministry of Economic Affairs (EET Grant EETK 20037). The purpose of the EET programme is to provide a generally applicable, useful method that stimulates environmentally friendly development and production processes, but on the other hand the method has to be economically sensible and technically innovative. Since the project is on going, the paper is more general of nature. The principal idea behind signature analysis will now be discussed.

Perhaps the most important idea behind this research and the development of the functional signature analysis method was to raise the level of conceptual modelling and analysis from the individual "micro" level to a higher "macro" functional level. From the user perspective, failure is represented as an inability of the product, or system, to perform its function, or sub-functions. Therefore, one of the main ideas behind the signature analysis concept is to look at functional levels. When an intended function is not properly performed, it is identified as a failure.

The second main idea behind the concept of signature analysis is to think in terms of modules, where modules are discriminated by functions. Therefore, the signature analysis method is used on modules, or sub-modules level (Figure 1). In summary, the definition of failure is function performance related at module level rather than related simply to individual component failures.

The starting point is a concept of reliability within the full product life-cycle of conceptual design, design, prototype testing, manufacture, use, re-use and final disposal. This concept is well known and is partly driven by the environmental pressures for maximum use and safe disposal. By thinking in terms of components we have a situation in which a product of a roughly fixed life may in fact be composed of parts with varying lives, even when maintenance is taken into account. These differing technical lives translate into different economic lives. The downside of this is that economic life of the whole product may be much shorter than the technical life of the components. But then it is a simple step to say that there is economic life locked up in the components.

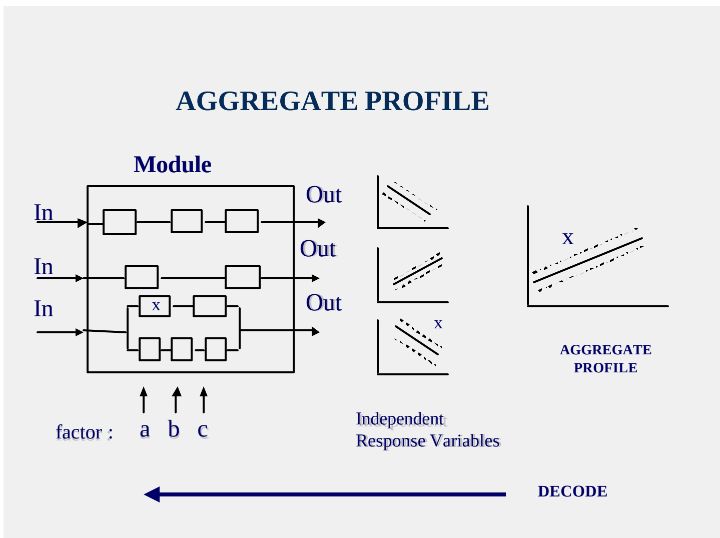

Figure 1 – Signature Analysis Method

Now imagine the two themes of (i) the modular/system approach and (ii) the extended life of components put together with (iii) signature analysis and one begins to create a radically new approach. Thus one can argue that whole sub modules have an extended economic life and that it is the job of signature analysis to help extract the economic value locked up in these modules. The same methodology which helps us to determine the performance of a function and its closeness to failure enables us also to model and predict its life and hence its availability for re-use, with or without maintenance. This combination of ideas we call "end-of-life analysis".

Strategies

The aim of the project is to develop a protocol for carrying out signature analysis. It has adopted a mix of reliability methods, like stressor-susceptibility analysis [2] [JEN95]), reliability through degradation analysis,[1] combined with test strategies, like design of experiments (DOE),[4] and accelerated lifetime (ALT) test strategies.[6] Signature analysis also combines data analysis methods, like analysis of variance,[8] with signal processing methods, in particular Wavelets analysis .[7,10]

Generally, DOE became very popular in engineering around the start of the modern quality revolution in the early 1980s. Robust engineering and statistical engineering initiated these quality related test strategies. In the latter, the massive savings of experimental effort for companies by carefully choosing input factor level combinations were enough to encourage the use of DOE. The analysis part of DOE is a combination of analyses of variance methods (ANOVA) and regression analysis, which is highly effective. DOE provides a method that makes it possible to model the functional behaviour of the output function of a module by relating its behaviour to dominant design parameters. Robust design methods[8,9] taught the importance of interactions between design parameters and the output function. DOE takes in account the interactions between modules, or sub-modules, that highly possibly exist due to the fact that all modules depend on each other.

In the project, information about the relations between design parameters and output functions was required. A special type of design (echelon design) has been computed in order to estimate all interactions with a minimum number of runs. The properties of this design have been studied for use in new modules. The results will appear elsewhere.

To check the part-to-part variations, we used DOE test strategies and analysis methods combined with graphical analysis methods. Our analyses indicated severe measurement problems for some parameters. By graphical methods we could detect that groups of modules that were thought to be similar actually were quite different. Further we also have tested the product to product variation.

This was confirmed later by an extra in-depth analysis of the individual products. Hence, our data analysis methods on the output functions or parameters have proven to be capable of discriminating unknown changes in product manufacturing.

In signature analysis the key word is signature. A “signature” means a recognizable function in the analysis that can be attributed to particular performance deterioration. This means that there is a signature under normal operation and a signature when deterioration is present. For example wear may not be enough to stop the product from functioning, but it may be a lead indicator of future failure.

Technically speaking there are two classes of failures: instantaneous failures where there is no prior indication of product failures and gradual failure mechanisms where indicators can be found that signal the expected residual life of a product for this failure mechanism. Measuring these indicators without disassembling (or even destroying) the product is not always easy. Therefore this project aims at defining methods (and related tools) to extract the mentioned indicators by analyzing the function performance over life and to have a single measure of the reliability performance to identify source of failure and performance deterioration by signals available for external measurement.

For the practical implementation of the signature analysis method, a step-by-step protocol needs to be followed. The protocol is presented below:

1. Objectives of the experiment

The objectives of the experiment should be described in detail. The following issues should be addressed:

- Description of module function
- Objectives in relation to lifetimes and performance
- Relation with other parts of project
- Robustness requirements (in particular w.r.t. user environments)
- Environmental objectives
- Management (in particular responsibilities)
- Financial objectives
- List of KPI: Key Performance Indicators + translation of objectives into terms of KPI’s
- Resources needed to conduct experiment
- Resources available to conduct experiment
- Scheduling of experiment

2. Available information

The proposal should make use of available information as much as possible. Typical items to be included are:

- Results from related previous experiments and reports
- Measurement system analysis (MSA) (in case this is not available, it must be performed prior to further actions)
- Failure mode effect analysis (FMEA) (in case this is not available, it must be performed prior to further actions)
- Design specifications of the module (where relevant)
- Other formal methods (e.g. Quality Function Deployment, conceptual design etc)
- Warranty and field data (where relevant)

3. Input factors

The input factors should have a clear connection with the FMEA of item 2. A brainstorm should yield an initial input to output table for factors and interactions between them. For each input factor, a proper description should be made that must at least address the following issues

- Noise or control factors
- Type of factor (continuous, discrete, functional, time-dependent etc)
- Nominal (center) value, typical range etc
- Type of control, manual, automatic
- Difficulty of change
- Blocking factors, sources of trend etc
- Flow of inputs to outputs in measurement hierarchy
- Link with monitoring scheme

4. Outputs and output measurement

The output measurements should have a clear connection with the KPI's and the experiment objectives.

- Classification of outputs: continuous, discrete, functional, time-dependent etc
- Measurement: sensor specification, instrumentation, on-line/off-line, laboratory, post processing, sampling and sample rate, units of measurement
- Full list of all variables, with all characteristics
- Link with monitoring scheme
- Relation of output to function: measurement hierarchy

5. Output analysis

The experiment proposal should include a description of the analysis methods that are likely to be used. Typical methods include

- Regression analysis
- ANOVA
- PCA, PLS
- Kernel methods
- Wavelet
- Other function data analysis methods

The output analysis should also address the following items:

- Automated feature measurement, detection (computer macro)
- Preliminary concepts for signature analysis

6. Type of experiment

The next three items describe three different main types of experiments. The experiment proposal should clearly describe which type of experiment is intended.

a) Initial and Screening experiment
- Choice of inputs and outputs
- Initial experiments to check measurement, control etc
- Screening experiment to detect: significant factors, interaction
- Use of screening experiment, search design, super-saturated design or similar
- Possible use of sequential screening experiment
- Analysis: modeling inputs against outputs

b) Complex experiments
- Detailed multilevel experiment for particular key inputs/outputs
- Experimental design: response surface design, optimal design, design for non-linear models etc
- Experiments over "time" to measure life
- Accelerated life tests
- Multi-stage experiments for modules: input to output to input.
- Analysis 1: regression, kernel methods, time series, wavelet etc
- Analysis 2: signature analysis for top level output (root-cause analysis)

c) Confirmatory experiments
- KPI for success of confirmation
- Test of full module for signature analysis: success rates, false negatives, false positives etc.

Beyond the single module one would like to aggregate the measures from modules to produce a measure for the whole higher-level system, in a hierarchical way. From a statistical point of view this fits well with notions of hierarchical, also called multi-level, modeling. Models are built up of layers and parameters from different layers aggregate to a high level (output) effect. Also related is the idea of causation (see for example modern Bayesian causal analysis). Low-level failures causing high-level failure is the primitive version, built for example into classical system reliability. Signature analysis goes one step further. We have causal effects by virtue of the functional modularization. It would be better to say that low- level performance effects high-level performance. The ideal is that the statistical modeling tracks the performance up through the different levels refining the measurement analysis, in its broadest sense, on the way.

Measurements and Features

The project provided an excellent opportunity to describe an electronic module with clearly defined input-transfer and output functions (Figure2).

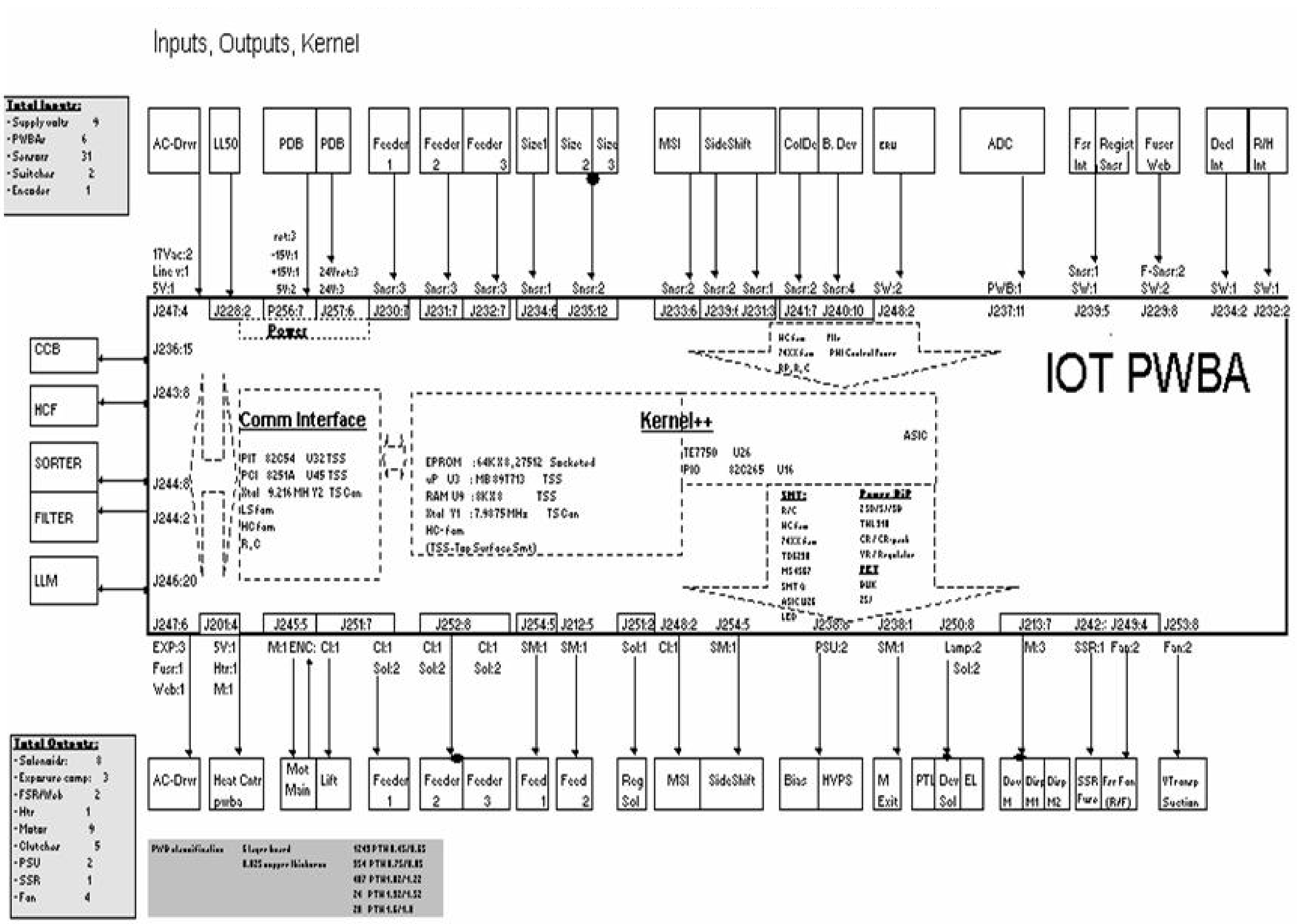

Figure 2 – IOT Block Diagram

Classification of key inputs: There is typically quite good prior knowledge about which factors are likely to effect which performance measures. It is a common task in industrial DOE to elicit some kind of ranking of importance by using for example Failure Modes and Effects Analysis (FMEA) Relation (interaction) diagrams (Figure 3).

Component	Failure Modes	Cause of failure	Possible effects	O	C	D	R
Solenoid	Does not energize	no supply voltage	no paper feed	1	5	1	5
	energizes slowly	low voltage, high temperature	late paper feed	2	4	5	**40**
	broken spring	bad quality spring	no paper feed	1	5	2	10
Sensor	no output signal	no supply voltage	solenoid does not energize	2	5	1	10
	high response time	low sensitivity, low supply voltage	solenoid energizes late	2	4	3	24

O: occurrence C: criticality D: detection R: risk factor

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Figure 3 – Failure Modes and Effects Analysis

Sequence of experiments: First, small screening experiments need to be conducted to get a general feeling of existing relations and dominances of input parameters. Next, large-scale experiments need to be conducted to build simple models relating the input parameters to the output measure.

Next, the aggregate signature (Figure 4) representing the function performance during the life of the module has a single measure of the reliability performance of the whole module/function including the performance limits (tolerance band) that can be used to identify the source of failure or performance deterioration.

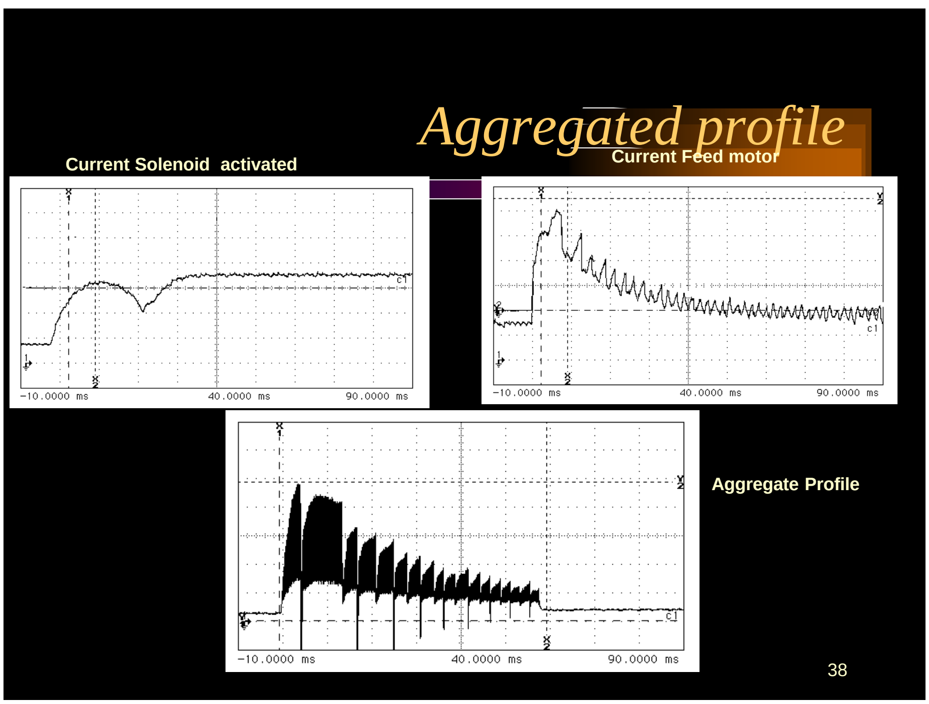

Figure 4 - Aggregate Signature Representing the Function Performance during the life of the Module

A problem common to all areas where complex measurements are made in conjunction with statistical modelling is that the form of the data presented from the post processing may not be the most suitable for modelling. Thus, care has to be taken to extract the data in the right form for analysis.

Thus, in imaging analysis edge detection is a type of feature extraction. In modern statistical modeling, particularly areas like non-parametric regression special kernels are used to model features. This discussion connects signature analysis with these other developments. A KPI is a feature related to the performance of the module. This can be modeled using a kernel method on the output measurements. The weighting given to the different kernels in the output analysis is modeled against the inputs via the DOE.

The innovation is the use of experimental design and the concentration on high- level features.

In the project the analyses of the experiments in this way has yielded several insights. First of all, as we have just said, we demonstrated that changes in internal machine parameters indeed lead to changes in output parameters. We were able to identify dominant parameters and interactions. Changes in these parameters can now be used to get insight in current performance of several modules that are sent back for refurbishment.

Product Design and the Supply Chain

The present version of this project has concentrated on existing projects. But much more is at stake. A world in which economic and environmental pressures are suggesting a new area of end-of-life analysis must also readdress two other areas (at least). The first is design. It is commonplace in modern robust design that one should bring into the laboratory prototype-testing environment as much as possible of the downstream variation that a product will attract, from manufacture and use. At its simplest, manufacturing tolerances need to be taken into account in design. But we are saying here something a little more profound. Design must take into account the full end-of-life philosophy: the real and economic life of the components and (better) whole modules. Glimmers of this have already been seen with "design for maintainability" and so on. Even "life-cycle design" is not quite sharp enough. Design should look at the life cycle of every component and module, its re-use, disposal, material value, and maintenance needs.

The product is a physically integrated *whole* but it hides an *economic whole* which is a complex sum existing over a longer time horizon than that of the product. Design needs to take this into account. Something like "total economic life cycle design" might be closer with "total" meaning that the product is really the total of its parts and modules. And, to repeat, the end-of-life analysis is the key.

Finally, the second area which needs to be addressed is the supply-chain which feeds the product design and manufacture. Within Europe the current emphasis is on "network enterprises" and "extended enterprise". Groups come together to do a job such as supply a particular customer or market. The key is flexibility: risk sharing contracts, supply chain management and logistics, distributed management, local as well as global decision making and so on. This is critical for the end-of-life considerations we have sketched. Every stakeholder in the operations needs to subscribe to the same philosophy. In this way the benefits will outweigh the risks. The stakeholders include, of course the customer, who will benefit personally in terms of cost, quality, delivery but also in terms of more intangible environmental benefits.

End-of-Life Management for Electrical and Electronics Products

The unsatisfiable appetite of consumers for new electronic gadgets means that more and more products are being retired while still functional. The volume of the end-of-life (EOL) electrical and electronic products has exceeded the capacity of landfills. The recently enacted EU WEEE (waste electrical and electronic equipment) legislation, several years in the making, mandates that effectively 2006, producers must be responsible for the take-back and disposition of their products at EOL. The legislation is designed to tackle the fast increasing waste stream of electrical and electronic equipment.

The functional signature analysis methodology provides a powerful tool for managing EOL, by assessing the remaining life of the components, and thereby enabling the conscious and managed re-use of functional components, modules and sub-assemblies and their re-introduction into the product life cycle. This "cradle-to-cradle" approach promises to fully exploit the "total economic life cycle" of products.

Often, a product is retired from the market, either because of functional failures of the product caused by one or more non-functional components, or because the product is no longer valued by the customer for whatever reasons such as the introduction of a newer model. That is to say, that the "valued lifetime" of a product is often much shorter than its viable physical lifetime (or life expectancy). Even if the product is retired from the market because of true functional failures, a large number of components in the product may still have considerable remaining lifetime.

By assessing the remaining lifetime of the components, modules and sub-assemblies (including electrical, mechanical, electronic, electromechanical, etc) of a product at the end of its first life cycle through signature analysis (Figure 5), certain components, modules and sub-assemblies of the product can be appropriately recovered for new use ("second life"), for example, to be assembled into new products, knowing the remaining lifetime of the components and the target life of the new product.

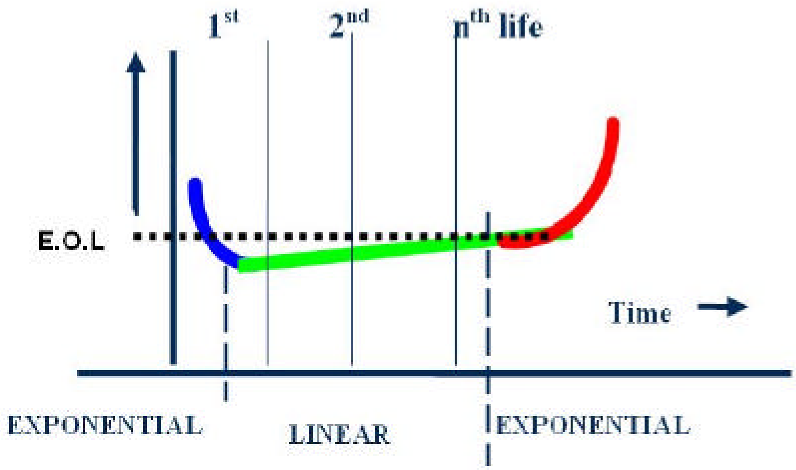

Figure 5 - Multiple Lives of Components or Modules

Functional signature analysis offers an effective tool to manage the lifetime of components separately from that of the product, such that the total economic life cycle of the product and its components can be fully exploited. Use of components throughout their "multiple lives" will greatly reduce the amount of electrical and electronics waste going to landfills.

Summary

In this paper, functional signature analysis for the end-of-life management of products is presented, particularly for electrical and electronics applications. The signature analysis method is described, and the strategies for carrying out the signature analysis are discussed. The application of functional signature analysis for end-of-life management is reviewed.

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