Environmental and economic implications of a shift to halogen-free printed wiring boards

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Abstract

The 'Restriction of Hazardous Substances Directive' (RoHS) and the 'Waste from Electrical and Electronic E-quipment Directive' (WEEE) enforced by the European Commission require new materials and processes to be implemented in the production of electrical and electronic equipment (EEE). In response to this, the project grEEEn (Cost Management System for greening Electrical and Electronic Equipment) was defined and carried out within the 5th framework programme of the EU. This paper presents the grEEEn method and the outcome of applying the method on a case study. The study addressed the material shift in printed wiring boards (PWBs), from the traditional FR4 material containing halogenated flame retardants to halogen-free FR4 materials. The paper presents the product, process and scenario modelling and the results from analysing costs, environmental profile and legal compliance.

1 Introduction

The 'Restriction of Hazardous Substances Directive' (RoHS) and the 'Waste from Electrical and Electronic Equipment Directive' (WEEE) [1, 2] enforced by the European Commission require new materials and processes to be implemented in the production of electrical and electronic equipment (EEE). In order to meet the requirements posed by the directives, to minimise costs and to ensure the competitiveness of EEE manufacturers, strategic decisions are needed in product development. In response to this the project grEEEn (Cost Management System for greening Electrical and Electronic Equipment) was defined and carried out within the 5th framework programme of the EU from 2001 till 2003.

As part of the grEEEn project, five case studies were carried out by applying and evaluating the grEEEn method. This paper presents the outcome from one of these case studies that addressed the material shift in printed wiring boards (PWBs), from the traditional FR4 material containing halogenated flame retardants to halogen-free FR4 materials.

The question of going halogen-free is highlighted by the RoHS-directive requiring two brominated flame retardants to be phased out, by environmental labelling schemes such as the TCO labelling for computers and by findings of flame retardants in the environment [3] and in human beings.

The prospects of halogen-free technology were addressed in a study by IVF in 1997-1999 [4]. The study showed that a wide range of halogen-free materials are available, but that there is a lack of knowledge in terms of economic and environmental effects of a shift to halogen-free technologies.

The purpose of the case study presented in this paper was to analyse the economic, environmental and legislative implications associated with the shift from traditional PWBs containing halogenated flame retardants to halogen-free PWBs.

The paper originates from a report produced within the grEEEn project [5].

2 The grEEEn Method

The grEEEn method [6] supports environmental experts and design teams in developing greener EEE at minimal costs complying with WEEE and RoHS. The method provides economic and environmental assessments of EEE, presented as worst/best case scenarios which help to find alternatives for EEE design choices. Figure 1 illustrates the modules of the grEEEn method.

2.1 Product and Process Model

The model approach of the grEEEn method combines both process and product oriented aspects, which are needed for the calculation of results.

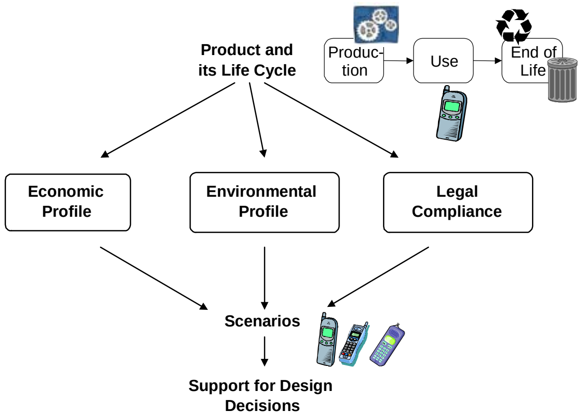


Figure 1: The modules of the grEEEn method.

A product model in the definition of the grEEEn method combines all data describing the product without any process related information.

The process model serves as the other basic approach for the grEEEn method. It describes the processes in the whole life cycle of the product including design, material production, manufacturing, use, and end-of-life.

2.2 grEEEn Assessments

2.2.1 Economic Profile

The Life Cycle Costs - the aggregation of all costs – are the main result within the economic profile. Other, more detailed results can be used to identify cost drivers within the life cycle, like costs for certain life cycle phases or processes and costs for certain years or cost elements. The cost calculations are process-based using the life cycle inventory for their calculation algorithms.

The grEEEn method represents a flexible approach in regards to the inclusion of cost elements. Depending on the availability of data, the economic profile takes not just the most relevant cost elements into account, but also more detailed elements: material cost, energy cost, personnel cost, machinery cost, transport cost, disposal cost, end-of-life value, etc.

All cost elements are split up into direct and indirect costs. To generate the indirect costs, a variable overhead rate needs to be defined by the user.

2.2.2 Environmental Profile

A number of indicators have been selected in the grEEEn method development to reflect the environmental performance of the considered products during their life cycle.

These can be simplified indicators, product-related indicators presenting Design for Recycling and process-related indicators presenting Inventory and Impact Assessment indicators from Life Cycle Assessment, see Table 1.

Simplified Indicators Number of materials Mass Toxicity index	**Inventory Indicators** Energy consumption Total waste generated
Design for Recycling Rate of recovery Rate of re-use and recycling Rate of energy recovery Recycling efficiency rate	**Impact Assessment Indicators** Raw material consumption Greenhouse index Ozone depletion index Aggregated single score

Table 1: The grEEEn environmental indicators.

The product-related indicators represent different kinds of recycling rates as they are defined in the European WEEE legislation, see Chapter 2.2.3.

The process-related indicators are based directly or indirectly on the inventory of the product's life cycle. The inventory based indicators comprise energy consumption using primary energy equivalents and hazardous and non-hazardous waste generated.

The calculation of the impact assessment indicators corresponding to the specifications of ISO 14042 [7] are based on the Life Cycle Inventory.

The aggregated single score Eco-indicator 99 integrates all environmental impacts into one indicator. In the Eco-indicator 99 method, weighting is performed at damage category level (Human Health, Ecosystem Quality, Resources) [8]. Hence, the assessment is performed at an endpoint level in the environmental cause-effect chain (polluter pays principle).

2.2.3 Legal Compliance

Legal compliance within the grEEEn method primarily concerns WEEE and RoHS compliance.

In order to make the requirements for EEE defined in e.g. the RoHS directive operable and measurable, indicators describing the legal compliance have been established (restricted substances, RoHS compliance, overfulfilment).

2.3 Scenarios

The grEEEn assessments (Economic and Environmental Profile, Legal Compliance) are recommended to be presented as worst/best case scenarios of various EEE types. The scenarios should assist in identifying optimal EEE design solutions by providing results for changes in substances, materials, components, connections or processes.

3 Analysis of PWB Technology Shift

3.1 Research Design

In the case study two 4-layer FR4 PWBs without components were compared. The PWBs differed in terms of material of the laminate and the prepreg. One of the PWBs was based on a traditional material containing a halogenated flame retardant, whereas the other PWB contained a halogen-free flame retardant.

The functional unit was defined as a PWB production panel, see Figure 2. Each panel contained 54 repeated 4-layer laser drilled PWBs for mobile phones.

Figure 2: Printed wiring boards (PWBs) are produced by means of panels containing multiple PWBs.

The study focused on two life cycle phases: the design phase and the manufacturing phase (including pre-production), with particular focus on the latter one. The data was collected from a number of system and contract manufacturers. As the PWBs differed only in terms of material, the analysis concentrated on the process steps that differed between the two types of PWBs. The process steps in which no differences could be identified were largely left out from the analyses (see further description below).

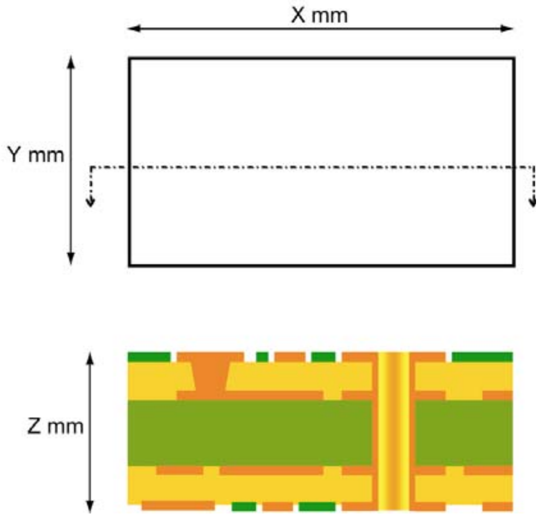
The economic and environmental profiles of the PWBs were calculated according to the procedure outlined in the grEEEn method. The Eco-indicator 99 included in the method was calculated with the Life Cycle Assessment (LCA) tool SimaPro.

3.2 Modelling

Product and process models were developed and the results of different scenarios were analysed.

3.2.1 Product Modelling

The product model was defined together with the Finnish PWB manufacturer Aspocomp Oy. A PWB panel that had been used for test production of halogen-free PWBs was used for the model. The product essentially consists of three components: 1) copper-foiled laminate, 2) prepreg, 3) copper-foil. Figure 3 shows the product model.



X = 555 mm, Y = 610 mm, Z = 0,9 mm

Figure 3: Product model of the PWB panel.

3.2.2 Process Modelling

The design process consists of many steps, but for reasons of simplicity the design process was modelled as one single process step. The PWB production process was modelled in accordance with the real manufacturing process at Aspocomp Oy. Figure 4 illustrates the process model used in the study, including the design phase and a representative model for the production phase. The process model is deliberately simplified in order to reflect the process steps upon which the analysis was focused. The material production phase is neglected due to use of aggregated upstream materials data. The economic profile considers the design and manufacturing phase whereas the environmental profile considers the material production and manufacturing phase.

Both types of PWBs (panels) followed the same process flow in the production process. Experiences from manufacturing tests with halogen-free PWBs constituted the basis for identifying the process steps where differences between the traditional and halogen-free PWB occurred. Four such manufacturing steps were identified (see the shadowed process steps in the Figure 4):

- Pressing
- Drilling
- Desmearing
- Solder mask

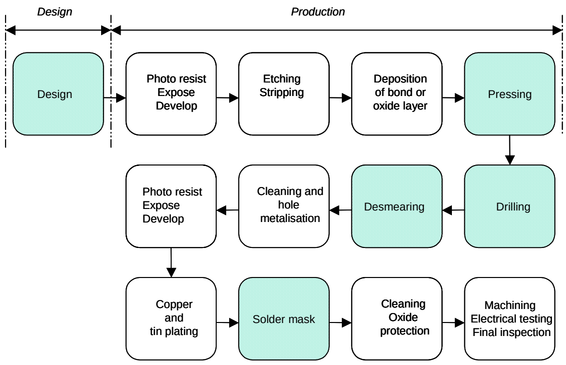


Figure 4: The process model used in the study including the design phase and a representative process model for PWB manufacturing. Shadowed steps are those which were analysed in detail.

3.2.3 Scenario Modelling

The comparison between the traditional PWB and the halogen-free PWB included modelling of two scenarios, denoted 'worst case' and 'best case'. These two scenarios were identified by discussions with the data suppliers regarding the potential effects resulting from the shift in material. The worst-case scenario describes a situation in which the worst cost effects of the technology shift occur. The best-case scenario outlines a situation where few or minor cost effects occur. For each of the scenarios the environmental effects were calculated.

Table 2 describes the implications on design and PWB production of the shift to halogen-free PWB materials compared to the traditional PWB.

Process step	Traditional PWB	Halogen-free PWB	
		Worst case	Best case
Design	Original process	Increased design cycle time	No increase in design cycle time
Pressing	Original process	Increased cycle time	Increased cycle time
Drilling	Original process	Reduction in number of panels that can be drilled at the same time	No reduction in number of panels that can be drilled at the same time
Desmearing	Original process	Increased cycle time	No increase in cycle time
Solder mask	Original process	Increased cycle time	Increased cycle time

Table 2: The scenarios (worst case and a best case) for five steps in design and PWB production.

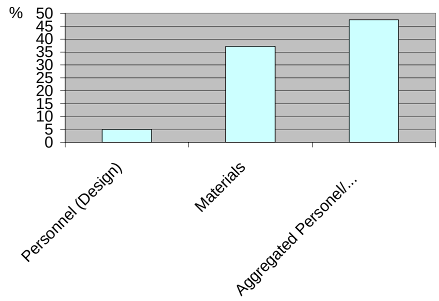
3.3 Results

3.3.1 Analysis of Costs

The analysis of costs included the following cost elements:

- Personnel costs for design
- Costs for materials
- Cost for each production process step as aggregated data, including personnel, machinery, energy and overhead costs

The analysis includes, as was mentioned above, only the process steps for which differences might occur. Figure 5 shows the increase in percentage per cost element due to the shift in material for the worst case and the best case respectively.



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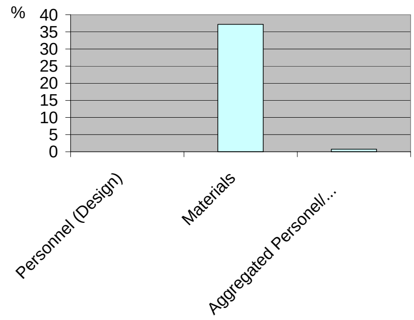


b)

Figure 5: Cost increase in percentage per cost element due to the material shift for (a) worst case and (b) best case.

Figure 6 shows a more detailed view of the cost effects in percentages. In the figure a comparison of the effects between the worst and best cases is shown for the design and production step and for the materials. In addition the figure shows the total cost effect for the analysed cost elements resulting from the shift in material, i.e. it is calculated as the sum of the cost for the analysed cost elements for the worst and best case respectively (for halogen-free material) minus the sum of the original cost for these elements (for the traditional material).

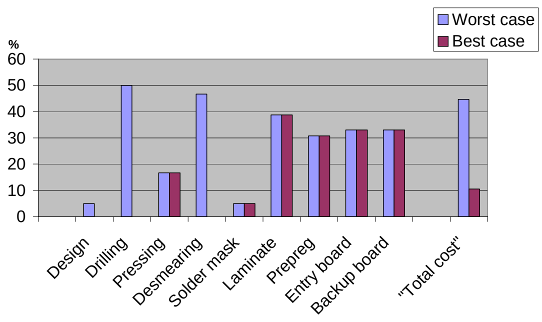
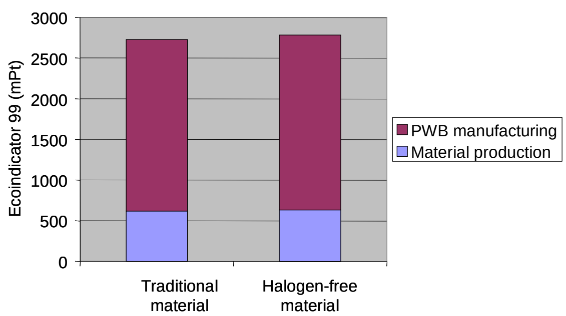


Figure 6: Comparison of cost effects in % between worst and best case. “Total cost” shows the total cost effect for the analysed cost elements resulting from shift to halogen-free.

From the figure it can be seen that if the worst case occurs, the drilling and desmearing process steps are dominant in adding to the cost increase. If the best case occurs it is the cost of material that adds to the increase cost, whereas the other process steps add costs to a very low degree.

3.3.2 Analysis of Environmental Profile

The results from the environmental analysis are presented in Figure 7 for the worst case and the best case respectively. The term “Material production” refers to upstream processes, i.e. pre-production processes.



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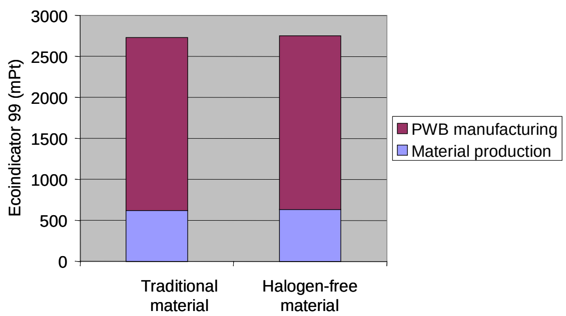

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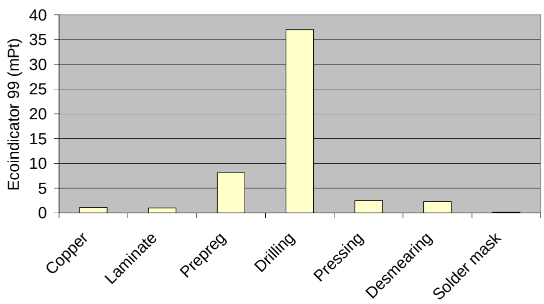
Figure 7: The environmental impact of the traditional and the halogen-free material for (a) worst case and (b) best case.

Figure 8 shows a detailed overview of the differences between the FR4 and the halogen-free material for the worst case and the best case respectively. Copper, laminate and prepreg represent what in Figure 3.6 is denoted material production. Drilling, pressing, desmearing and solder mask are those PWB manufacturing steps where there is a difference in environmental impact.

The difference between the material categories shown in Figure 6 and 8 is due to the data being accessible.



a)

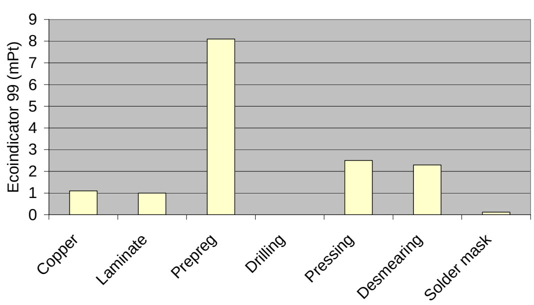


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Figure 8: Difference in environmental impact of the traditional and the halogen-free material for (a) worst case and (b) best case, in detail. The figure shows the increase in environmental impact associated with the shift from traditional to halogen-free material.

In the worst case the shift to the halogen-free material leads to a slight increase in environmental burden in the production phase primarily due to the increased energy use during drilling. In the best case, the increase in environmental burden is mainly related to the pre-production phase (material production). However, both cases lead to very limited increases of the environmental impact in comparison to the aggregated environmental impact for the pre-production and production phases. The increase in environmental impact is just a few Eco-points (about 10-40 points compared to the total impact of nearly 3 000). Thus this increase in environmental impact is almost neglectable.

3.3.3 Analysis of Legal Compliance

The RoHS directive prohibits two halogenated flame retardants. These are, however, included neither in the traditional laminate, nor in the halogen-free material. Therefore the legal compliance check results in fulfilment of the directive for both materials.

4 Conclusions

These are the main conclusions from the study

- From a life cycle point of view, the shift to the halogen-free material leads to a slight increase in environmental burden. However, the potential improvements with shifting to a halogen-free material from the traditional material with respect to toxicity is not modelled due to lack of data. Thus, the shift to a halogen-free material could mean that toxic substances are eliminated or reduced resulting in an overall improvement of the environmental performance
- The increase in environmental burden relates in the worst case to the production phase, primarily due to the increased energy use during drilling. In the best case, the increase in environmental burden is mainly related to the pre-production phase (material production)
- A shift to halogen-free PWBs causes an increase in cost ranging between nearly zero and 10 € per panel. The cost increase is caused mainly by the drilling and desmearing process (in the worst case) and by the material cost (in the best case)

5 Discussion

PWBs have been manufactured with halogen-free laminates for more than five years. However, manufacturing volumes and production experience are still limited. Thus there is an uncertainty in analysing manufacturing costs. Due to a lack of experience of volume production with halogen-free laminates and a lack of data it was not possible to assess the environmental and economic effect of the shift for the full product life cycle and the toxicological effects.

With increasing use the materials cost for halogen-free laminates is expected to decrease and cost should not restrict the use.

The findings presented in this paper are based on one single case study. Therefore, the findings should only be considered as indications of the economical and environmental implications associated with the shift in PWB material. The conclusions drawn are only valid for this specific case study and further studies are needed to attain more comprehensive insight into the implications associated with the material shift.

6 Acknowledgements

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7 Literature

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