The Environmental Impact of Electronics and Its Incorporation into the Curriculum

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Abstract: *With the continuing ubiquitous use of electronic equipment and the boom in consumer electronic products, there comes a significant environmental impact, via the sources of materials and manufacturing processes and in the place of use and disposal. There is growing international market pressure on industry to act to ameliorate these impacts by good design and sensible policies. An overview of the impacts is given along with a review of several tools which can be used by industry to assess the impacts.*

In the light of the situation described above, an argument is presented that more work in this area should be done in educating undergraduate engineers and technologists and that the software tools now available are adequate, appropriate and suitable to the engineering approach to such matters. With relatively little effort on the part of academics, it is possible to teach some form of assessment of environmental impact in a way which is both realistic and meaningful to students. Some detail of the author's experiences in teaching such matters is given.

Keywords: electronics, environment, life cycle analysis, curriculum, assessment tools, sustainability

Introduction

The interaction between the electronic engineering industry and the physical environment is an area which has not been very high on the public agenda in Australia and not very significant in the curriculum of tertiary courses. This low profile in both the community and engineering curricula has been because the impacts have not been very evident. The products concerned have such evident benefit to the user and seem to do no harm immediately to either human health or to the surrounding environment, so that there has been little public pressure to think about the issue.

There have been over the past 30 years a succession of relatively minor environmental issues, mainly to do with human health, where industry has responded and beneficial changes have been made without much difficulty. Examples are barium-based heat conducting paste for heat sink applications and the elimination or reduction of cadmium and mercury from components. However while these improvements have been occurring there has been an explosion of the volume of electronics equipment being manufactured and used worldwide, with the potential for quite major environmental impact. Figure 1 shows the approximate numbers involved for Australia in a single recent year.

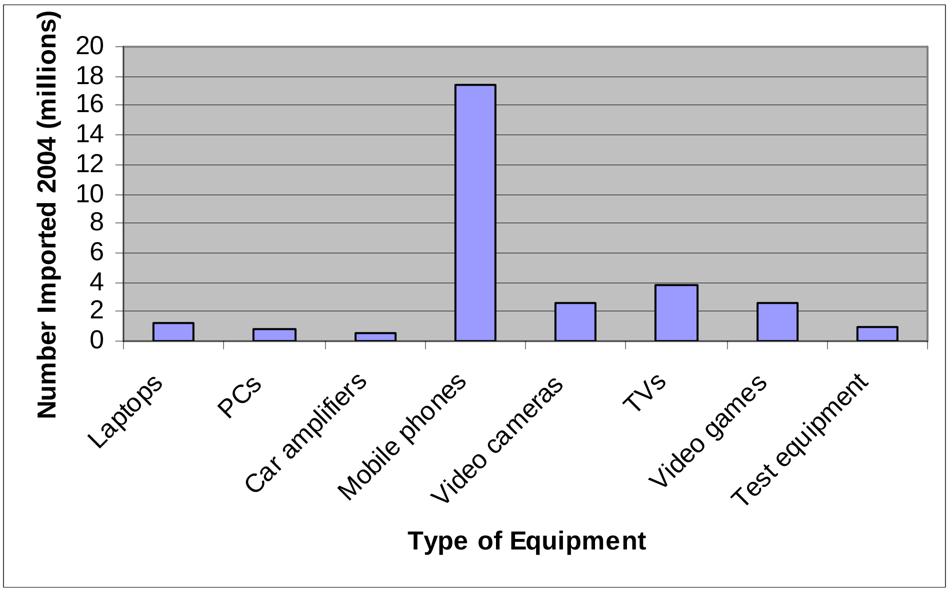

Figure 1. The volumes of electronic equipment imported into Australia in 2004. Source: Australian Bureau of Statistics (2005).

Environmental Impacts in the Curriculum

The thesis of this paper is that it is now appropriate that an awareness of the environmental significance of electronic equipment be inculcated in undergraduate electrical engineering students. Much of the actual equipment listed in figure 1 is imported consumer electronics and initially outside the direct influence of engineering graduates. However it is nevertheless those graduates who will be responsible for many aspects of the life of that equipment – its maintenance, energy supply for its use and its end-of-life disposal for examples. It is appropriate therefore that undergraduates not only learn about any potential impacts, but also develop skills in assessing and dealing with those impacts.

The Environmental Impacts of Electronic Equipment

Some of the specific ways in which electronic equipment has an adverse impact on the physical environment are:

- Lead in TV and computer monitors (CRTs). Quite large quantities of lead are used in the leaded glass used to make the sides of cathode ray tubes in TV and computer displays. Lead is a known toxin and can also leach slowly into soil and water when obsolete equipment is land-filled (Jang & Townsend 2003).
- Lead is also used in the solder used to join components together. There are now moves to replace lead solders with lead free solders using materials such as tin-silver-copper or bismuth-tin-silver (USA EPA 2005, Cui & Forsberg 2003).
- High volume of materials and energy use in integrated circuit and printed circuit board manufacturing. Both integrated circuit and printed circuit board manufacturing are highly material and energy intensive. For example the manufacture of a RAM IC uses in some form or another about 1.7 kg of material and about 56 MJ of energy (Williams

et al 2002) and manufacture of a printed circuit board involves numerous steps, many involving the use of chemicals.

- Electrical energy use. In the past equipment has been designed with little thought for its energy efficiency. Even though this has improved in the case of such things as computers with low energy LCD monitors, there is a lot of older equipment in use and little attention given to the issue by many users. Good data on this issue for computer type equipment is available in Roth et al. (2002).
- Standby energy use. Many pieces of common electronic equipment such as computers, television receivers and telephones use some electrical energy 24 hours per day to keep them ready for use or to keep memory intact. Up to 60% of energy use for such equipment in the USA is estimated to come from this standby use (Rosen & Meier 2000).
- Hazardous flame retardant materials in plastic cases and printed circuit board substrates. These plastic type materials such as the common type FR4 are very combustible and have traditionally had brominated fire retardant chemicals incorporated to reduce flammability. These fire retardants are toxic chemicals which are now being phased out in Europe. There are however counter arguments about how many deaths or serious injury due to burning TV receivers are tolerable to avoid the other deleterious impacts (Sjodin et al 2001).
- Many electronic appliances take advantage of their small size to allow portability which involves batteries. Large numbers of throw away alkaline batteries are used every year with consequent waste of resources. Fortunately there is growing interest in rechargeable batteries such as nickel metal hydride and lithium ion chemistries which seem to be relatively environmentally benign, but there remains significant use of lead-acid and nickel cadmium chemistries which, at end of life, place toxic heavy metals into landfill.
- Batteries also involve somewhat inefficient re-charging regimes with for example mobile phones being placed on charge overnight resulting in the use of more than necessary electrical energy. A possible solution here is more efficient and smarter chargers.
- Packaging of relatively fragile electronic equipment for shipping can also have a significant environmental impact via the use of foam materials, cardboard etc.
- Recycling is difficult because equipment is distributed widely in homes and industry and the cost, both monetary and environmental, to collect used equipment is often prohibitive.
- The huge volume of electronic equipment used in Australia and around the world means the use of many valuable resources. Electronics involves complex mixtures of materials which are difficult and expensive to separate after disposal. For example, the material content of a typical assembled printed circuit board is given in table 1. One of the major impacts here is the use of metals which typically use large quantities of energy to extract and refine. Hence recovery of metals is an admirable goal.

Industry Action

However, with the volumes described above, there are now emerging pressures on industry and government to attend to this issue. These pressures are becoming evident in Europe, Japan and USA in particular in which there now some laws requiring, for example, industry to be responsible for end-of-life disposal of their products, and to reduce the quantity of hazardous material used during manufacturing.

There are of course also arguments about the appropriateness of some of the requirements of the legislation, both from industry and from academia. For example, there is some evidence that recycling of printed circuit boards to recover valuable metals is of dubious environmental value given the energy needed to recover those materials (Huisman et al. 2004).

Table 1 The benefits of recovering iron and steel from used electronic equipment (after Cui & Forssberg 2003)

Benefits of using scrap iron and steel	Benefits Percentage
Savings in energy	74
Savings in virgin materials use	90
Reduction in air pollution	86
Reduction in water use	40
Reduction in water pollution	76
Reduction in mining wastes	97
Reduction in consumer wastes generated	105

Table 2. Energy saved by recovering metals from electronic equipment (after Cui & Forssberg 2003)

Recycled materials energy savings over virgin materials	Materials Energy savings (%)
Aluminum	95
Copper	85
Iron and steel	74
Lead	65
Zinc	60
Paper	64
Plastics	>80

Specifically there are two European programs which Australian and other suppliers must soon attend to if they wish to sell their products into Europe. These are:

- RoHS Restriction of Hazardous substances. Manufacturers must eliminate or substantially reduce the amount of certain substances in their products. For example polybrominated biphenyls (PBB) must have been eliminated by July 2006.
- WEEE WasteElectrical and Electronic Equipment. Industry and government have certain goals to reach by given dates regarding such things as recycling of obsolete equipment.

There is also a lot of action in industry in these same countries around design for the environment (DfE) which engineering students need to be aware of and to have begun the process of developing ideas about. An overview of some DfE aspects is given by Milojković and Litovski (2002). Specific examples are:

- Designing to reduce hazardous substances. For example electronic equipment sold in Europe must not contain cadmium or lead after July 1 2006.

- Designing to reduce material use during manufacture such as water. Some companies publish data on their progressive reduction in consumption figures, see for example Philips (2004).
- Designing to minimise energy consumption during use.
- Designing for ease of disassembly for the purpose of recycling (Sandborn & Murphy 1999, Huisman, Stevels & Stobbe 2004).
- Designing disassembly processes (for example Cui & Forsberg 2003).
- Consideration of the use of various plastics for cases of electronic equipment and their efficient recovery (Fisher et al 2005).
- Design for minimising component differences such as different screw sizes to ease disassembly for recycling.
- Use of lead free solder.
- Eco labelling, which attempts to provide information to potential consumers about the environmental impact of the product.
- Development of efficient logistics for the collection of end-of-life products for recycling or responsible disposal (Wilkinson & Duffy 2003, Jofre & Marioka 2005). This community-based activity necessarily includes the social aspects of consumer behaviour (Darby & Obara 2005).

Tools for Industry

This international pressure and activity has resulted in numerous tools to allow industry to assess where best to apply their limited budgets for maximum environmental gain. There is a need for several levels of assessment tools to suit the situation. Brief and economically acceptable assessments are useful for industries just beginning to evaluate their performance and looking initially for those areas of their operation which can be improved easily. Full detail life cycle assessments are also needed in many places to determine the real environmental priorities for larger industries of for industry bodies to give guidance to their members. Some available tools are:

- Simple check lists for staff to use during design & development. For example the following questions about the design for a power supply unit (Griese et al 2004):
  What is the operating efficiency of the unit?
  What is its no-load energy consumption?
  Are there any recycled components which could be used in the design?
  Are there any toxic materials used in the design?
- Energy and material use audits such as (Dickinson et al. 2003):
  Energy consumption, water consumption , waste discharge, use of toxic chemicals.
- Toxicity assessment tools for individual materials. For example the Toxic Potential Indicator which allows calculation of a relative score for any chemical (Fraunhofer Institute 2006).
- Structures within organisations to track action for environmental impact and provide reporting data (Boks and Pascual 2004). See for example table 3 (Philips 2004).
- Simple assessments of materials and energy impact based on known major areas of concern like energy use but avoiding areas less likely to be a problem.
- Life cycle assessment which attempts to thoroughly evaluate impact over the entire life of a product – from raw material extraction, through processing, transport, manufacturing, use and eventual recycling or disposal. Table 4 gives an example of

the kind of details obtainable from a life cycle assessment (Parsons 2006), and figure 2 gives a description of the steps involved.

Table 3. Example of industry management checklist. Source: Philips 2006.

The development department delivers products without attention to their environmental consequences
Environmental issues are taken into account only incidentally and mainly driven by individual initiatives
An EcoDesign procedure including mandatory environmental requirements is available in a development center.
EcoDesign procedure is used in some projects.
The EcoDesign procedure is used in many projects
A mandatory EcoDesign procedure is in place in a development center.The EcoDesign procedure is used in most projects
The EcoDesign procedure is used in all projects
A development center's management system (like ISO 14001/9001) is certified externally
Etc

Table 4. Example obtained from a life cycle assessment of the relative impact on various criteria of some stages of the life of a compact fluorescent lamp

Impact category	**Unit**	**Manufacturing & transport**	**Electricity use during life**	**Land-filling at end of life**
Climate change	DALY	0.000000284	0.00003	7.38E-09
Ecotoxicity	PDF*m2yr	0.0945	0.36	0.000706

Life Cycle Assessment

Steps involved in conducting a life cycle assessment are broadly:

1. Construct a model of the product or service which involves quantifying all possible inputs and outputs. This forces the student to think through the details such as transport and disposal and to develop an awareness of the possible areas of impact.

2. Enter the data into software which includes background data about each material etc, thus avoiding much effort in finding real data of things such as mineral extraction or amount of carbon dioxide released while manufacturing polypropylene. This data is of course locality dependent because for example of the varying nature of coal or the availability of hydro-electric or wind power, but in many cases can be used in other locations with minimal error or can be used as a first estimate, a useful engineering skill. Australian data is available with some commercial products. This list of materials and processes is known as the inventory of materials and processes.

3. Select a method of environmental impact. These again are incorporated in the software tools and include data on for example, the human toxicity or marine toxicity of numerous chemicals based on well-established science about which there seems to be little argument. This state of affairs means that engineering students do not need to come to grips with the scientific details of the actual environmental impact such as the impact of a certain substance on human health, although some familiarity will develop with time. This is a considerable advantage practically and allows assessments to occur based mainly on engineering-type skills.

The availability of this data also allows the electronic product to be evaluated automatically against each of several measures of environmental impact. Typical such measures are:
*Global warming potential – measured in DALY (Disability Adjusted Life Years)
*Human toxicity - measured in DALY
*Fresh water toxicity - measured in PDF*m2yr; PDF= Potentially Disappeared Fraction of plant species
*Resource use - measured in MJ surplus energy. Additional energy requirement to compensate for lower future ore grade.
*Energy use - measured in MJ surplus energy.

4. Run the analysis using the software tool to either compare alternative ways of obtaining the same function, or to identify "hot spots" or areas of the product or process which causes most environmental impact.

5. Consider the results and, using judgement about the strengths and weaknesses of the methodology and the tools, draw conclusions.

Figure 2. Steps involved in conducting a life cycle assessment

Tools for Student Use

In order to effectively teach aspects of the above to students, it is probably necessary to introduce them to some realistic tools for assessment of environmental impact, and for those assessments to be at least credible in their results. Tools suitable for student use range from full scale software packages supported by periodic updates of data through to simple paper checklists as described above. Some specific examples are given here.

Commercial tools

SimaPro. This is a software package originating in Holland and containing extensive data from many sources including significant Australian data. It can be used for simple or serious studies and is relatively easy to use at a basic level. All that is required for the user to start is to have a clear model of the life stages of the product being assessed with numerical values or reasonable estimates for all parameters. It produces useful graphical outputs which enable simple comparisons to be made easily (Pre Consultants 2006b). This product is relatively expensive for single user licences but reasonable for a network licence.

Eco-conscious design of electrical and electronic equipment. This is a web site developed by the Danish Institute for Product Development and the Danish Toxicology Centre. It contains many checklists, calculators of toxicity etc which can be used to assess a product (Danish Institute for Product Development and Danish Toxicology Centre 2006).

Eco-It. This software allows the modelling of a product's life cycle and calculation of its environmental load. This is useful to identify which parts of the life are causing the most load and would be used in industry to target those areas for closer attention. It is available with extensive databases as a 10-day free demonstration but is also relatively inexpensive for a single user licence (Pre Consultants 2006a).

EcoScan. This is a commercial software package which allows the entry of the inventory of material use, energy involved, transport etc and produces an assessment of environmental impact against several criteria. There is a free demonstration version available with a limited but useful database (TNO 2006).

Ecodesign EEG. This pilot facility by the VUT, Institute for Engineering Design is specific to electrical end electronic products and the need for products distributed in Europe to meet the Waste Electrical and Electronic Equipment and the Restriction of Hazardous Substances directives. It provides convenient sources of information about many details to allow the assessment of the extent to which products comply with those directives (Institute for Engineering Design 2006a).

EcoDesign Online. This pilot facility by the VUT, Institute for Engineering Design consists of a series of simple forms into which can be entered the description of a product and its component parts, transport etc and which returns a series of rather general guidelines about how the product could be improved. It is not specific to electrical products. The feedback at the time of writing was not very specific but the process of filling in the forms was educational for a newcomer to the idea (Institute for Engineering Design 2006b).

GaBi 4. This is a full LCA software originating in Germany and available free for 90 days as a demonstration version (Gabi 2006).

General Information. General software which can be used to investigate specific issues such as the toxicity of lead, is available from the US Environmental protection Agency (EPA 2006) and many other similar web locations.

Educating for Environmental Responsibility

An awareness of the environmental issues around electronic equipment is becoming an important part of undergraduate curriculum. The thesis here is that use of some of the tools described above is a useful and sufficiently academically-demanding way of introducing these ideas to students. Specifically, Life Cycle Assessment (LCA), which is at the top of the hierarchy above, and includes the concepts of the simpler tools, is being recommended. Conceptually this approach suits the mentality of the typical engineering person and student in particular because it is numerical, logical and sequential (and possibly because it so far avoids the human, social or economic aspects of the issue which simplifies it from a typical engineering student's perspective).Cooper and Fava (2000) report that some academics teaching life cycle assessment in North America find that engineering students are comfortable with the LCA process.

In principle, an analysis can be performed relatively simply at least for a single, discrete product, by constructing a model of the product and the steps in its life and considering the environmental impact of each of those steps. Up until relatively recently, this analysis was difficult because of the problem of obtaining appropriate data for each step, for example data about quantities of energy needed to mould the case of a TV or about the environmental impact of the use of steel in the case. The LCA community has now however accumulated quite useful data in both these two areas, mainly available in databases attached to software products designed to facilitate the analysis.

A more complete and complex consideration of life cycle assessment could include issues like boundary selection and probabilities and uncertainties in data, which, from the author's experience in Australia, are not always part of real commercial assessments.

The argument here is that small LCAs are an easy-to-set-up assignment which would not only teach students about environmental impact, but also about some of the practical issues of electronics. Simple examples which are do-able by students in the space of less that 20 hours are the disassemble and analyse any small industrial product for its hot spots - for example a pc card, compact fluorescent lamp, a keyboard or a power pack., or the comparison of steel and plastic for constructing the case of a computer.

Experiences in Introducing Environmental Impact to Undergraduates

The author has attempted the introduction of LCA ideas in small ways over the past few years and some details are given here of the experiences and student reactions.

Short Workshops

These were simple 4-hour activities attended by senior external students visiting the university for a week of intensive activity. In these sessions, students were introduced to the concepts outlined above, shown an example of an LCA on a simple product using commercial software (SimaPro) and then asked to perform their own study on a chosen product. An example of the output from such an analysis is given in figure 3.

The sessions have been found to adequately introduce the ideas and students have understood the concepts and learned how to use the software at a basic level within the four hours available.

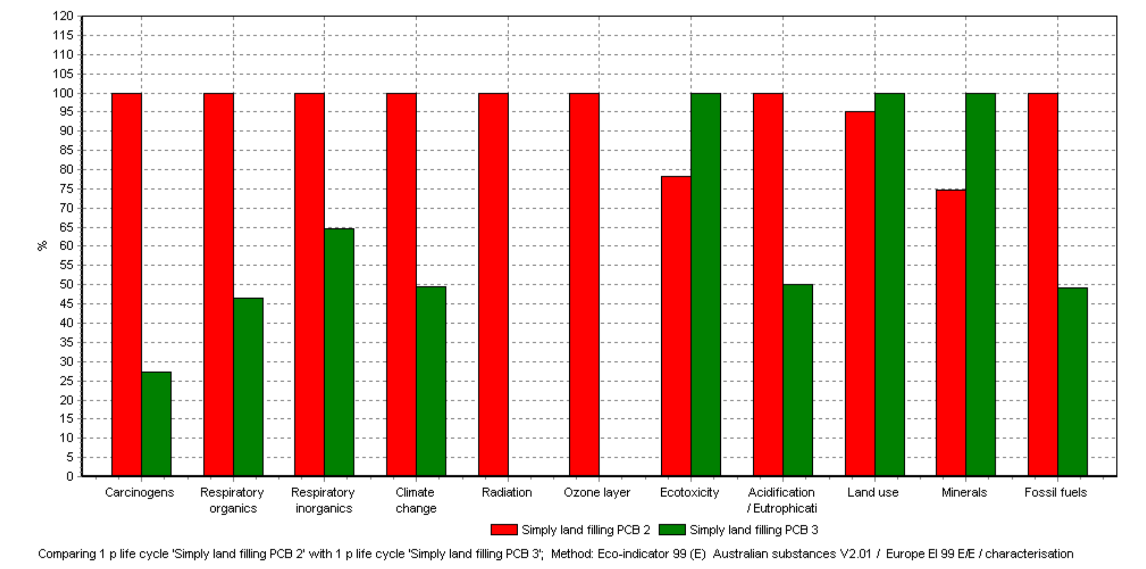

Figure 3. Example assessment output from SimaPro comparing two different printed circuit boards on eleven different criteria.

Final Year Projects

Several LCA final year research projects have been conducted on, for example, a mobile phone or a computer, requiring these items to be physically disassembled and analysed. Another has been done on semiconductor manufacturing requiring collection of data from a factory. These projects are senior activities requiring the student to master high level concepts and manage their own work. Successful students have produced results comparable to those in recently published conference papers.

For these activities, students are required to appreciate some of the subtleties of professional LCA work such as adherence to international standards (for example *AS/NZS ISO 14040:1998* : Environmental management - Life cycle assessment - Principles and framework) and sensitivity analysis, to assess the degree of reliability of their results, as well as the need to relate their work to published information.

Conclusion

This paper has highlighted the environmental impacts of electronic products and suggested that more consideration of this issue may soon need to be given in undergraduate engineering courses in Australia. The use of life cycle assessment strategies to deal with these issues is recommended because it suits the mentality of most engineering students and useful tools for its use are available at small cost.

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