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Supply Chain Implications of Sustainable Design Strategies For Electronics Products

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Abstract

Increasing legislative and consumer pressures on manufacturers to improve sustainability necessitates that manufacturers consider the overall life cycle and not be scope restricted in creating products. Product strategies to improve sustainability have design implications as many of the decisions made during the design stage will then determine the environmental performance of the final product. Coordination across the supply chain is potentially beneficial as products with improved energy efficiency can be better realised. This paper examines traditional product provision and proposes a sustainable product design process using life cycle assessment (LCA) at key points, as these decision points can provide opportunities for environmental improvements of products. Case studies of consumer and industry products in the electronics sector are examined in terms of improving sustainability by reviewing product architecture and technology solutions. This paper proposes methods and analytical models to better understand sustainable design strategies for manufacturing firms and thus aid manufacturers during the earliest stages of product planning to consider alternative product development approaches which are more sustainable.

Keywords: Sustainable Design; Closed Loop Production; Electronics Products; Life Cycle Assessment

1. Introduction

The typical life cycle stages for manufactured goods are shown in Figure 1 and although environmental improvements can be made during these stages greater improvements can be made by viewing the life cycle stages as a “closed loop” rather than an “open loop”.

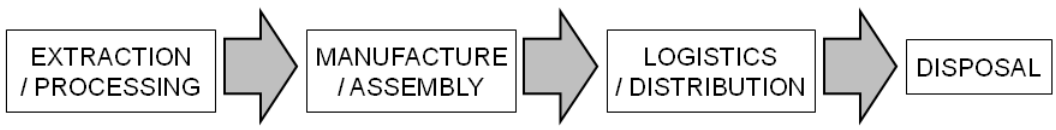

Figure 1: Conventional Life Cycle Stages

Figure 2 identifies the main life cycle stages for manufactured goods such that sustainability is optimised in a “closed loop” manner. The multi-enterprise organisation can be regarded as a virtual organisation (V-O) with the manufacturer as the recognized brand leader supported by its associated supply chain. The term Virtual Organisation has been used to describe an organisation where almost all tasks have been outsourced, leaving only a small core which has the task of managing the various outsourced parts of the process to ensure they successfully function together (as Hale and Whitham, [1]).

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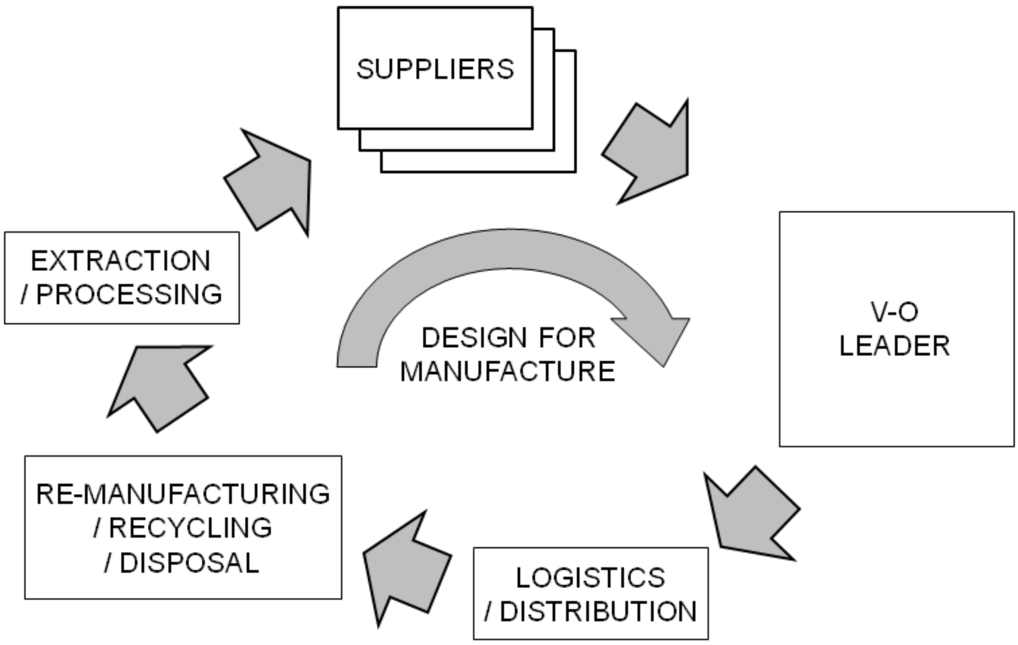

Figure 2: Closed Loop Production

It is not hard to imagine that outsourcing of specific parts of the whole manufacturing process could have both positive and negative ramifications on an organisations drive towards sustainability – positive in the sense that it can be built in to the specifications and contract and thus perhaps 'easily' achieved, but negative in the sense that control of suppliers or sub-contractors may prove problematic. Sustainable design strategies are considered here for electronic products in terms of open loop versus closed loop production. To implement the manufacturing and consumption of goods such that sustainability is optimised in a " closed loop" manner incremental changes are not sufficient. We argue that it is necessary for consumption to be improved over the entire life cycle.

Our focus in this paper is the earlier stages of the life cycle for electronics products. Both design and production are about adding value through the creation of useful products. As the process requires considerable investment, there should be economic advantages to keeping products, or at least parts of them, in use through extended service life strategies. If this is not practically possible then value should be recovered through recycling.

Consumers purchase a wide range of electronics products – from household items such as "white goods" (fridge/freezers; dish washers; washing machines etc…) through to vacuum cleaners and smaller items for use in the house (such as lighting and security systems). Computers and their various accessories (such as printers and wireless networks) are often present in a household along with televisions and other entertainment systems. Further, consumers also purchase electronics products for personal usage such as portable music devices and mobile phones. The range of electronics products is growing and consumers may have several portable devices – such as Sat Nav (satellite navigation systems). Advances in technology brings new devices to consumers such as electronic notebooks (such as the iPad from Apple) which allow easy and convenient viewing of digital content such as e-newspapers; e-mails through to e-books

The proliferation of electronic devices has been advantageous to both the firms supplying the products (the vendors and their distributors) with the resulting increase in revenues (and associated profit) as well as to the end consumers who have a myriad of devices with which to interact and make use of in their increasingly 'content rich' lifestyles. However, from a societal perspective it is very wasteful for more and more electronics devices to be manufactured and operated as 'consumption' of resources is increased at both an individual and system level. Design strategies to provide upgrades in terms of functionality without the need to purchase new electronics devices need to be embraced to improve sustainability [2].

Retailers in the UK have been interacting with consumers whose living costs are rising including their energy costs and this has raised interest with many consumers in terms of the energy usage and energy saving features available on the products they intend to purchase. White goods are frequently kept by households for many years and therefore the payback of energy efficient equipment is likely to be realised by households. Consumers are increasingly including energy considerations as part of their assessment when purchasing electronics products such as household items. To include energy considerations in their decision making consumers need to have access to product information relating to the product's energy usage and any energy saving features. This requires that the labelling of products needs to include energy consumption and needs to become part of the merchandising process.

Labelling becomes a important as it provides a means for consumers to assess the energy performance of the white goods. Terms relating to energy consumption may not be understood by consumers although the cost implications will be. This necessitates that information concerning the energy usage of products needs to be made both available and accessible (so that it is understood by consumers). Consumers are increasingly aware that their usage of products and their daily habits have an associated energy and hence cost implication and are making use of features such as dimmer switches for lowering lighting levels and other energy saving features. However preparation of such energy usage information comes at a cost and this may not always prove tenable as illustrated in the UK by the recent decision to withdraw the Home Information Pack or 'HIP'.
The provision and manufacture of products in ways that are truly sustainable are inhibited by three issues: firstly, decisions are predominantly made solely from the perspective of the "vendor" (and do not consider the wider perspective); secondly, that generally the scope of business planning is still rooted in production/manufacturing costs (and not consumption costs) and thirdly, the current performance measures (e.g. KPIs) mainly focus on profitability. The rationale for this paper is the argument that there is a need to raise the awareness during the earliest stages of product planning that there may be alternative approaches which are more sustainable. The concepts presented here will underpin further research into performance measures which encompass sustainability and resulting business planning implications.

2. Design approaches

Product strategies to improve sustainability have design implications as many of the decisions made during the design stage will then determine the environmental performance of the final product. Coordination across the supply chain is potentially beneficial as energy constraints of the end user need to be recognised and responded to which may involve substituting parts and components to realise products with improved energy performance such as dimmer switches for lowering lighting levels. Design strategies of the major brands of electronics products are often focused 'in-house' and preclude consultations with their suppliers earlier in the supply chain. This may limit the potential for improving the environmental performance of the final product. For example, washing machines have been introduced with washing cycles that operate at a lower temperature with the associated energy savings of not having to heat water to such a high temperature. These products are best realised when developed in conjunction with the firms that provide the washing powders as these need to perform at the lower temperatures or consumers will be deterred from using low temperature cycles.

To improve sustainability we need to move towards "a corporate system that integrates product and design issues with issues of production planning and control and supply chain management in such a manner as to identify, quantify, assess and manage the flow of environmental waste with the goal of reducing and ultimately minimizing its impact on the environment, while also trying to maximize resource efficiency" as cited by Ellram et al p. 1620 [3].

Environmental life cycle assessment (LCA) as a method to enable environmental product informational needs has been recognised fairly recently by Miettinen and Hämäläinen [4]. It enables quantification of product specifications so that alternate designs can be assessed in terms of the ecological impact by characterising product attributes and key elements. This approach can be compared to the use of simulation tools which are used to characterise manufacturing processes and then examine various process configurations. The end results of the simulation calculations are often displayed visually as this emphasises the differences of the configurations tested. The development of a simulation model is tailored to a given situation and this will also be the case for environmental LCA where each product type will need a tailored assessment.

The organisational implications of design approaches that utilise LCA can be considered similar to that of concurrent engineering (CE): "while traditional NPD focuses specifically on the product, concurrent engineering (CE) represents a revolution of new product development thought by simultaneously focusing on product and process using cross-functional teams" quotes Ellram et al p. 1621 [3]. However, due to its popularity, CE by itself no longer provides a source of competitive advantage. Further, "in companies that now practice two-dimensional concurrent engineering (product and process only), supply chain development tends to be haphazard" states Ellram et al p. 1621 [3].

The UK has been transitioning its broadcast television systems from analogue to digital. For several years there has been a period of overlap during which households have been able to use their existing analogue televisions to view programmes. However, the cutoff for analogue transmission is in progress around the UK which has meant that households with analogue televisions are no longer able to view programmes unless they buy a digital convertor box (which are relatively cheap) or some alternative (such as Free Sat). Many households are deterred by the high monthly subscription costs of services from satellite suppliers offering premium channels particularly those with families and the associated living expenses.

Retailers of televisions in the UK have seen consumers upgrading or replacing their televisions due to the switch over to digital broadcasting. The environmental impact has been evident as many households have taken the opportunity to upgrade their televisions from the old CRT (cathode ray tube) technology to the new flat screen televisions which usually come with a digital receiver built in. Retailers have been advising consumers on their options and have supported many consumers by taking in their old televisions when they bring them to the store following the purchase and successful installation of the new flat screen televisions. This has demonstrated on a national scale the type of organisation required to handle consumer electronics products at the EOL (end-of-life) stage.

Considerations of design approaches which address the EOL include DfE (Design-for-environment): "in general, DfE is a design process in which a product's environmentally preferable attributes – including recyclability, disassembly, maintainability, refurbishability, and reusability – are treated as design objectives rather than as constraints. DfE gives guidelines for the design engineer to examine environmental soundness of a product over its entire life cycle by introducing modifications early in the product design process" states Pujari et al. 2004 in Bereketli et al. p. 214 [3]. Further, "the argument can effectively be made that all waste begins with the design practices of an organization. In designing products, processes and supply chains that do not specifically consider environmental impact, organizations implicitly design for waste rather than for environment" as cited by Ellram et al p. 1626 [3].

Within the home there are many different applications for which consumers obtain electronics products. Each application is considered by consumers prior to purchase of products in terms of 'cost versus benefits'. However the 'cost' aspect is arguably too limited in perspective as decisions concerning the various devices tend to be made independently. This can lead to a proliferation of devices being present in the home including several previous generations of devices many of which have associated items such as auxiliary parts (such as battery rechargers etc..). It is fairly common that several generations of mobile phones; computers; cameras and other entertainment products have been purchased. Arguably we need to re-think the very nature of products and their purchase according to Birkeland p. 12 [5]: "Given the urgency of education for sustainability, the priority needs to shift to the training and professional developments of present and future decision makers. Boardrooms and branch managers generally do not design systems but they determine who does. Managers (whether trained in science, technology, business, economics, planning or engineering) make decisions and instruct staff in matters of technology and production choices that can have long term environmental consequences. Further managers are in a better position to set systems in place that reduce environmental impacts through management tools such as purchasing practices, product stewardship and leasing agreements, environmental management plans, energy audits, and so on".

The scope of environmental standards is far broader and more complex than that of quality standards. Environmental management systems span all of the interactions between a company, its physical environment, and its stakeholders including customers, stock holders, regulators, suppliers, communities, interest groups and employees according to Fiksel p. 28 [6]. One definition of green supply chain management (GSCM) is from Srivastava (cited in Bereketli et al. p. 213 [2]). His study collected and classified previous literatures relating to green supply chain management. He defined GSCM as "integrating environment thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers, and end-of-life management of the product after its useful life."

3. Sustainable product development

Innovation strategy is a part of a firm's overall strategy and develops strategies for managing technology and innovation as identified by Cooper [7] in his work on product innovation and technology strategy (PITS): the need to identify and specify the types of markets / applications / technologies and products which a firm's new products will follow. This strategic level may utilise a number of planning tools such as the product-technology roadmap which encompasses the more recent strategic management literature concerning a firm's competences as recognized by Prahalad and Hamel [8].

Recent interest in including ecological aspects into product development has highlighted a number of tools such as an "Eco-Roadmap" which according to Tischner and Nickel [9] is comparable to the product-technology roadmap but with a focus on sustainability. This "top-down" strategic approach has its merits however the reality of product development in many firms is that other tools or methods are required which do not rely on sustainability at a strategic level. The ability to renew competences in order to achieve congruence with the changing business environment is referred to as dynamic capabilities according to Fahy [10]. These dynamic capabilities are emphasized by Eisenhardt and Martin [11] as entities which enable a firm to achieve new and innovative forms of competitive advantage. Dynamic capabilities are argued to be a key part of the rationale underpinning strategic management according to Teece et al [12]. They argue that a firm's focus should be on developing the firm's capabilities – not its products.

The model proposed here is one that utilises life cycle assessment (LCA) at a number of key "decision points" for product planning as shown in Figure 3. These are shown as three "circles" which use LCA to assess the potential environmental impact at different levels of detail to support product planning decisions. The three LCA concern: firstly, life cycle costing, secondly, life cycle design and thirdly, life cycle analysis.

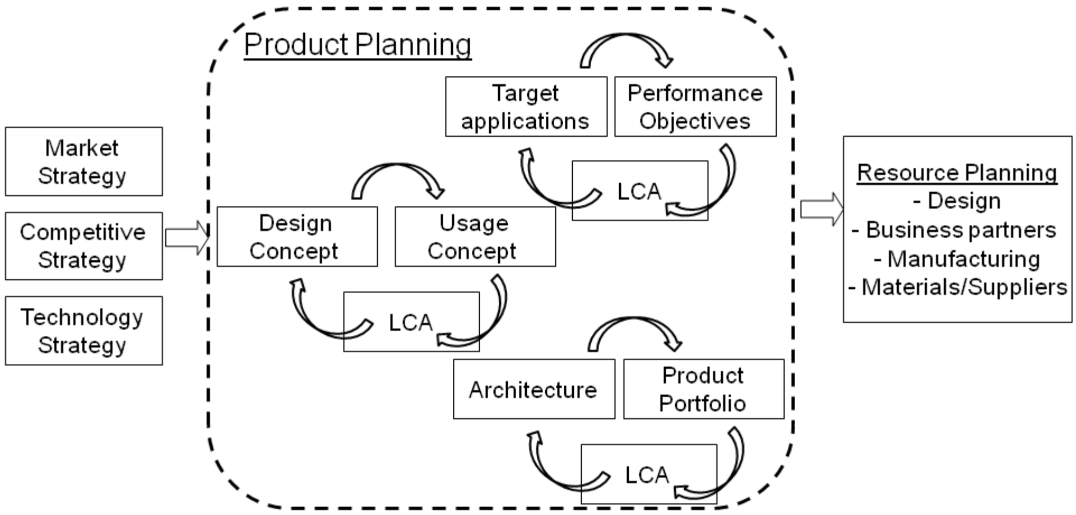

Figure 3. Sustainable product development process

The three life cycle assessment at key decision points during the product planning phase will assess environmental performance and thus provide opportunities for environmental improvements according to Maxwell et al [13]. High technology firms already have to weigh up a number of resource and technological constraints during the product planning phase as well as external considerations such customer value provision and competitive pricing. The use of life cycle assessment will provide a structured way of enhancing the decision making i.e. it will bring sustainability to the forefront of a product development process without disrupting the established practices of a firm.

The proposed product development process is one that includes LCA at the concept development stage of the design process which enables assessment of environmental performance. The model proposed here is one that utilises life cycle assessment at a number of key "decision points" for product planning as shown in Figure 4. These are shown as three "circles" which use LCA to assess the potential environmental impact at different levels of detail to support product planning decisions. The three LCA stages are also shown in Table 1 which includes examples.

The first LCA concerns life cycle costing and assesses the attributes of a product which may be represented as a decision tree where alternatives are identified. This according to Miettinen and Hämäläinen [14] is a less detailed life cycle assessment with the use of categories (of high vs medium vs low) to make a "relative" assessment rather than an "absolute" (quantitatively based) assessment. This provides a more general valuation of alternative design concepts which is commonly used in the early stages of new product development by the use of weighting systems. The intent here is to encourage the consideration of alternatives which may be more sustainable at this early design stage such as the use of technologies that require less landfill. This less detailed analysis has the advantage in that it encourages an assessment that has a wider scope.

The second LCA concerns life cycle design and concerns the more strategic aspects relating to technology management – architecture decisions and product portfolio planning. Architecture decisions can provide a competitive advantage to firms whilst product portfolio decisions should support a firm's market plans. These decisions can either support or restrict a firm's position as some architecture types lend themselves to supporting sustainable initiatives more than others. Clearly defined modules or components and their interfaces support equipment upgrades epitomised by the computing sector and the design of personal computers which anticipated the need to upgrade disk drives and other key components.

The third LCA concerns life cycle analysis and takes the proposed product and makes a more detailed assessment of the environmental impact from production onwards which may comprise three main life cycle aspects identified by Schmidt and Butt [15]: production of the product; the user phase and the end of life environmental costs. The environmental cost of the production of the product is not discussed here as it is well understood. The assessment of the user phase will vary depending on the product concerned, for example, it will examine the environmental impact of the use of the product such as emissions from vehicles. It will also need to assess user maintenance and other running costs which will require modelling typical scenarios based on anticipated usage patterns (for example, annual mileage and typical vehicle speeds).

Table 1. Life cycle assessment for sustainable product development

Life Cycle Assessment (LCA)	Focus	Examples
1) Life cycle costing	Supply chain elements: i) Suppliers ii) Vendors iii) Customers	Military Aircraft: Product-Service Systems (PSS)
2) Life cycle design	Extending usage through Technology Management: i) Architecture ii) Product portfolio planning	Computers: Modular design for user upgrades (graphics cards etc..)
3) Life cycle analysis	Environmental impact (Schmidt and Butt, 2006): i) Product creation ii) User Phase iii) EoL costs	Automotive sector: vehicle manufacture and EoL processing

These detailed assessments will need to identify the life cycle stages and the resources used (materials; energy and other resources) to conduct a detailed assessment of the environmental impact. For example, a study reported by Joshi [16] comparing the life cycle environmental performance of steel and plastic automobile fuel tank systems assessed nearly thirty items along each of the life cycle stages. Studies report that the end of life environmental costs are usually below 5% according to Schmidt and Butt [15], however, for industries with large production volumes these are still significant.

4. Sustainable product planning

In the seventies successful technology firms comprised large vertically-integrated firms. The advantages according to Jiao and Tseng [17] were that technically advanced products could be developed by carefully coordinating interface specifications and other design parameters between departments. The advancement of technology is a major external factor for firms with the organisational model of traditional businesses becoming irrelevant. In the Internet era the loose organisational structures require mechanisms to ensure successful innovation including the transfer from design to production. A generic traditional product development process is shown in Figure 4.

Figure 4: Generic traditional product development process

4.1 Product planning drivers

External factors of the marketplace along with three general factors comprising price sensitivity; performance expectations and regulatory constraints and organisational factors are the general factors that influence product design according to Noble and Kumar [18]. Product design has been well reported in the main stream literature by leading writers such as Cooper [7] with recent emphasis on faster time-to-market (TTM), open learning and improved ergonomics each of which is now discussed.

4.1.1 Faster time-to-market: Manufacturing firms are increasingly pressurised to deliver new products to the market in shorter timescales which is challenging as technology advances and becomes inherently more complicated to engineer and manage new product development. Firms have invested in solutions such CAD systems which provide 3D visualization solutions that enable the new product development process to be reduced. The benefits of fast development processes are that firms are in a position exploit new or emerging applications. These new or emerging applications may arise from the interaction among components once new technologies are in place i.e. it is hard to anticipate and plan for these emerging opportunities.

4.1.2 Open learning: The resources required to develop new technologies are prohibitive even for the larger companies and cause many firms to look outside the firm to access technology. A firm may organise their product modules or structures into “building blocks” to efficiently support platform development projects. However, they may still need to make use of other firm’s knowledge and even acquire specialist technology companies with a technological competence in an emerging area which may enhance or improve the functional performance of their product or system. Competitive advantage based on core competencies has become a recognised part of strategic thinking where the development of the necessary competences (technological or otherwise) of a firm involves accessing external knowledge as well as relying on internal knowledge building activities according to Chesborough and Teece [19].

The benefits of innovation strategies involving collaboration is one which is driven by resource limitations. As technology advances it becomes increasingly difficult for firms to have resources of sufficient breadth and depth in the required technological areas. This is problematic as the extent literature on strategic management and how firms compete puts great emphasis on a firm’s capabilities. This perspective is the resource based view (RBV) of the firm and is based around the recognition and development of core competences as epitomised by Prahalad and Hamel [8]. However, it is recognised by Gallivan [20] that trust and other issues become a factor during inter-firm projects and operations.

4.1.3 Improved Ergonomics: The brand of many major vendors of consumer products (e.g. Nokia), need protecting which requires product concepts whose design and user friendliness is going to attract consumers across global markets. Manufacturers with expertise in Global DFM (design-for-manufacture) will require a competence in product design which is highly ergonomic as consumers increasingly are time pressured and mobile thus wanting products which are highly intuitive. Gone are the days when consumers will accept purchasing video recorders which were so involved to program that the majority of consumers either were unable to record a television program or were unwilling to expend the required effort. Not only is ease-of-use a key issue for consumers but also the visual product aesthetics which must fit today’s lifestyle conscious consumers as discussed by Noble and Kumar [18].

4.2 Project selection

Many potential ideas or projects may be identified and these need to be evaluated and the appropriate projects selected for development. This narrowing of projects is known as the 'development funnel' as shown in Figure 5. Project selection is based on a number of considerations ranging from financial measures (profitability; return and payback) through to strategic considerations (fit with the firm's business goals) through to resource availability. Further, prioritization of projects may be based on existing products and customers including commitments made and the fit with the existing product portfolio. Sustainability aspects are not traditionally considered during the project selection process.

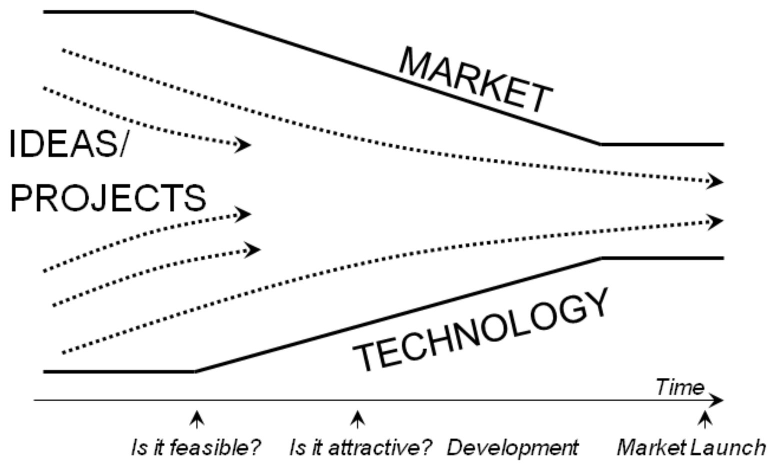

Figure 5. The innovation and new product development funnel

The product development process proposed in this paper is one that includes life cycle assessment (LCA) at the concept development stage of the design process which according to Maxwell et al [13] enables assessment of environmental performance. This is a broader assessment of a new product than the traditional approach of strategic; market and financial cost benefit analysis. Given the competitive pressures on firms and the need to bring new products to market in a timely manner; the need to consider environmental impacts during the product development process may not be realized by firms. However, the increasing legislative requirements (concerning emissions etc..) along with the growing awareness amongst consumers and other parties has necessitated that firm's consider the environmental impacts of their products and business operations.

LCA is one of the "tools" for improving sustainability, however, a broader "systems view" is necessary to align manufacturing activities with the usage of goods to be more congruent. The argument here is that sustainable production (from manufacturing through to consumption through to disposal) needs reviews of organisational structures including the overall supply chain. We argue that the following aspects must be considered to implement design for closed loop:

• The production perspective: the manufacturing of the goods is the "engine" of the enterprise operations which drives a business enterprise
• The people perspective: a shift in thinking and also behaviours - both for staff within the vendor as well as end users and other organizations
• The financial perspective: the cost implications and business case aspects – both for the vendor as well as other organizations

To improve the environmental impact of innovation and new product development measures are needed to encourage consideration of alternative technologies and solutions (such as alternative technologies for automotives) as well as a more "end-to-end" perspective of 'cradle to grave'. We now examine some case studies which provide examples of innovation and new product developments.

5. Sustainable design strategies practice

One of the major problems for any manufacturing organisation is movement towards a goal of sustainability when that goal is difficult to define. What and where is the sustainability? Increasingly manufacturers talk of producing 'sustainable' products as their route to sustainable manufacturing however both products and their manufacturing processes need to be sustainable for any approach to be called truly sustainable. For example the use of timber sourced from sustainable sources (e.g. bearing the Forest Stewardship Council (FSC) mark) may be used to promote the 'green credentials' of a company but the equipment, methods and processes used to manufacture the products may have remained unchanged for decades.

Sustainability is broader in scope than making a more environmentally friendly product as it needs to encompass the whole life cycle. A drive towards lower energy and resource usage (e.g. through lean manufacturing) is not necessarily the same as a sustainable approach - simple reduction of energy and/or resources used in manufacture with no attempt to 'close the loop' will effectively only result in resources and energy taking longer to 'run out'. Exactly what sustainability is, is not clear and the problem of defining sustainability remains as highlighted by Scholtz and Tietje [21]. In fact Jacques et al [22] concluded that "… pointing out the reasons why products are not sustainable is typically easier than defining all the attributes that would make a product so…".

The approach that we shall take here towards this is to examine and compare DFM (design for manufacturing) against closed loop design. The advantage of this approach is that DFM is a well established approach that recognizes that the majority of the cost for a manufacturer in a project or product life cycle occurs during the production phase. The scope of the design phase is enhanced such that the focus is not restricted to the product that will be produced but also the practical aspects of the manufacturing of the product.

The shift in mindset for DFM is towards one where firms optimize the product and the manufacturing process. This necessitates that the designers consider a later stage of the value chain – a shift in thinking that is also required for closed loop design. The difference being that DFM requires an understanding of manufacturing activities which are often within the same organisation (if not the same site), however, closed loop design requires an understanding of the usage and later life cycle stages which occur outside of the manufacturing organisation.

5.1 Case study analysis

Design for closed loop is not widespread amongst manufacturing firms; however, our research has highlighted examples of practices which we now consider.

5.1.1 Case Study 1 - aircraft components: The development of the 777 generation of aircraft by Boeing as the world's first aircraft developed completely 'virtually' is well publicised and documented. Virtual manufacturing utilises e-manufacturing systems and computer simulation to model real world manufacturing processes to enable optimisation prior to manufacturing.

Using computer aided design (CAD) systems as a principle driver, more than 1,700 Boeing engineers and designers developed the three million plus parts for the 777, assembled them virtually, tested the assembled plane with various virtual human passengers made appropriate modifications and improvements without any physical parts being needed. Once the manufacturing process was begun, the improved level of information and instruction available gave great benefit to the end product, saving Boeing large amounts of time and money in the development of an extremely complex machine.

5.1.2 Case Study 2 - semiconductor manufacturing: The Taiwan Semiconductor Manufacturing Company (TSMC) is one of the largest dedicated integrated circuit producers. In the late 1990's, TSMC reengineered their business along the lines of a virtual factory (VF) to differentiate themselves from their competitors and strengthen ties between them and their customers.

By use of system integration software, the company brought together engineering systems, product data management (PDM) systems, manufacturing systems and enterprise resource planning (ERP) systems to enable customers to place orders and receive confirmation feedback in real-time, share engineering data and track work-in-progress (WIP) in real time. The new system has helped customers save large amounts of money and improve development times. These closed loop design approaches enable inventory reductions whilst also resulting in improvements in cycle time with the added bonus of improved customer satisfaction.

5.1.3 Case study 3 - mobile phones: Manufacturing firms are facing the dilemma of utilising increasingly complex technology to meet their business needs whilst trying to operate cost effectively in a globally competitive environment. Opportunities for manufacturing sustainable products need to be realistic and adapt a manufacturing firm's operations rather than disrupt ongoing business operations. It is easiest to examine an example application to appreciate the various elements involved. Here we consider the example of mobile handsets which are used by people to provide communications; entertainment; corporate and other applications. There are an increasing number of mobile user devices which need to be supported – both for industrial purposes and for consumer electronics. There has been a gradually evolving range of mobile devices which is extending as different groups of users see the benefits of wireless connectivity, for example, healthcare for home patient monitoring.

The design aspects for each device, service and application need to address the service concept aspects and the mobile user interface design to ensure usability. The growth in diversity of mobile devices is yet to occur and includes Smartphones, PDAs, Portable Media Centers, retail point-of-sale systems, Global Positioning System-based devices and industrial robots. This increasing number of user devices are challenging to support as they each have different interface requirements. By using software solutions rather than hardware to handle the protocol processing the environmental impact of products are reduced and their useful life is extended as software is easily upgradeable.

5.1.4 Case study 4 - cooling units: Refrigeration systems are widely deployed in the food sector for the purposes of transporting and storing goods (such as milk) at the appropriate temperatures. Cooling units are thus required during the production process; transportation (often in specialised vehicles) and at distribution/retail sites such as food stores; supermarkets and restaurants.

In response to the Montreal Protocol and associated European legislation designed to prevent the depletion of the ozone layer, manufacturers have had to change chlorofluorocarbon (CFC) refrigerants for gases with lower environmental impact such as hydrofluorocarbons (HFCs) or hydrocarbons. The development of machines that use CO2 as the refrigerant is an example of an initiative to further minimise impact as CO2 has a relatively low global warming potential. However, CO2 can be problematic to use as a working fluid because of the higher pressures required and greater operational energy consumption. With older models of fridges, CFCs were often used as the blowing agent for the insulation foam. Today the foams for this application are more environmentally benign.

5.2 Closed loop manufacturing

A number of concepts and ideas for sustainability have been developed like green design for manufacturing, design for the environment (DFE) or environmentally conscious design and manufacturing, which attempt to consider all environmental aspects of the materials, products operations and processes with the intention that they can be considered at the very earliest stages of design and manufacture. Cradle to cradle (C2C) is a term coined in the 1970s and has been developed by a number of researchers since according to McDonough, et al [23]. It considers the impact of each stage from mining of raw materials through to recycling, paying particular emphasis on:

• sustainable and efficient manufacturing using clean technologies;
• waste free production;

• use of non-hazardous and recyclable materials;
• reducing energy consumption;
• renewable energy sources;
• minimisation of environmental impact; local sourcing of materials and energy;
• continuous review of the possibilities of reuse and recycling of materials.

In 'Cradle to Cradle' [McDonough and Braungart, 2002] used materials, from what would otherwise be waste products, are regarded as either 'technical nutrients' or 'biological nutrients'. Appropriately designed EOL products become inputs to the recycling process. Certain types of manufacturing waste could also be regarded as technical nutrients. Some producers go beyond design for materials recycling, and design and plan for product refurbishment or remanufacture. Using this type of closed loop system, increases the opportunity to retain some of the original investment and energy embodied in products during their initial manufacture. These options can often be less environmentally damaging and more economically valuable than limiting reprocessing to the recycling of materials.

Design for Recycling (DFR) uses processes from the natural world to conceptualise recycling activities. For example, the 'biological' cycle - where organic materials naturally degrade into new 'soil' to allow the growth and development of new life (product which function for their life and then can be safely discarded) and the 'industrial' cycle in which the materials in the product are recycled and reused continuously (as in the recycling of aluminium drinks cans reducing production costs by 60-70% and pollution by up to 90%).

Manufacturing firms are facing the dilemma of utilizing increasingly complex technology to meet their business needs whilst trying to operate cost effectively in a globally competitive environment. Opportunities for manufacturing sustainable products need to be realistic and adapt a manufacturing firm's operations rather than disrupt ongoing business operations. To close the loop in manufacturing terms, the ideal solution would be to be able to use scrap, waste material, broken parts, etc. as direct input raw material for the manufacturing process. In one sense this principle cannot exactly be said to be new - for example in the jewellery industry, great care is taken to save even the smallest amount of gold, silver or other precious metal filings, swarf, etc. created when the surfaces and features of cast items like rings or broaches are smoothed or finished. The scrap material is then (literally) added to the 'melting pot' ready for the new casting cycle. The main drivers here are the high cost of the raw material and the ease with which it can be directly incorporated into the manufacturing process with no requirement to reprocess, refine or separate needed. Steel, aluminium, etc. scrap and swarf from conventional machining processes is of course routinely collected for recycling but this inevitably occurs at some location far removed from the manufacturing facility like a foundry. Unfortunately, opportunities for contamination can then occur throughout the collection process

The ease of direct reuse and also ease of recycling of scrap and waste material is strongly dependant on the simplicity of the basic material. Single materials with properties which remain unchanged before and after the manufacturing process, like many metals and plastics are thus the most likely to be able to be easily reused either directly or indirectly. "One way to measure the eco-efficiency of materials is to consider the embodied energy. This energy relates to the energy required to extract the raw resources, transport them to a factory and process them into refined materials. One tonne of aluminium, for example, takes more than 100 times more energy to produce than one tonne of sawn timber. In general, materials extracted from nature and requiring little processing tend to be low embodied energy materials (typically 2-12MJ/kg), while man-made materials tend to have medium or high embodies energies (typically 10MJ/kg to over 1000MJ/kg)” according to Fuad-Luke p. 23 [24].

At the opposite end of the reuse/recyclability continuum are combined materials or product with a combination of materials in them which probably rely on specific differences in physical or chemical properties to be recovered for reuse e.g. recovery of metals from consumer products often relies on the use of chemical solvents or heat which affect plastic content but not the metal content. The disadvantage of many of these ‘solutions’ is that much of the less desirable content is damaged or converted to other materials which may be hazardous themselves and require subsequent processing even for just safe disposal.

A recently begun research project at Brunel University has the aim of developing a machine which is capable of directly reusing the items which it produces. Based on a well-proven and widely used rapid prototyping technology called fusion deposition in which the raw material in the form of a thermoplastic filament is deposited onto a platform (in much the same manner as a hot glue gun deposits glue from a nozzle) to build up, layer by layer, a complete item. Figure 6 shows a commercial variant of this type of machine.

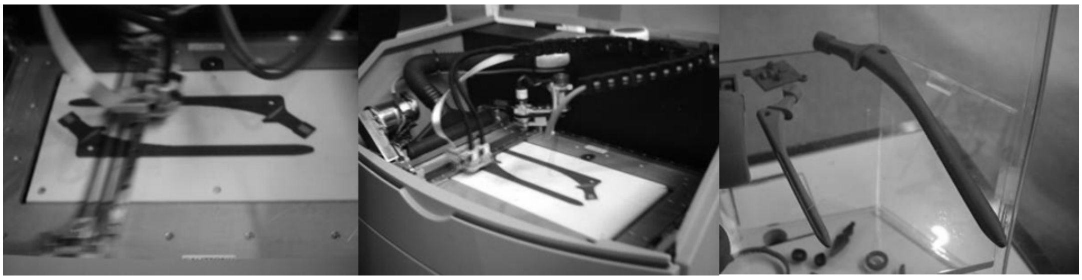

Figure 6: Unimatic FDM rapid prototyping machine

The first stage of the machine will be a shredder type device, capable of rendering the full or partial scrap plastic components previously made by the machine into small fragments or pellets. These fragments will then be fed into the second stage which will comprise a heated barrel with internal Archimedean screw (similar in design to that used in injection moulding machines) which will melt and compact the plastic and drive it towards a nozzle, where it will be extruded to form a filament suitable for input to the deposition head of the FDM machine. The aim of the project is to develop a ‘demonstrator’ system where the three existing processes are combined into the one machine as illustrated by the concept diagram for the machine shown in Figure 7.

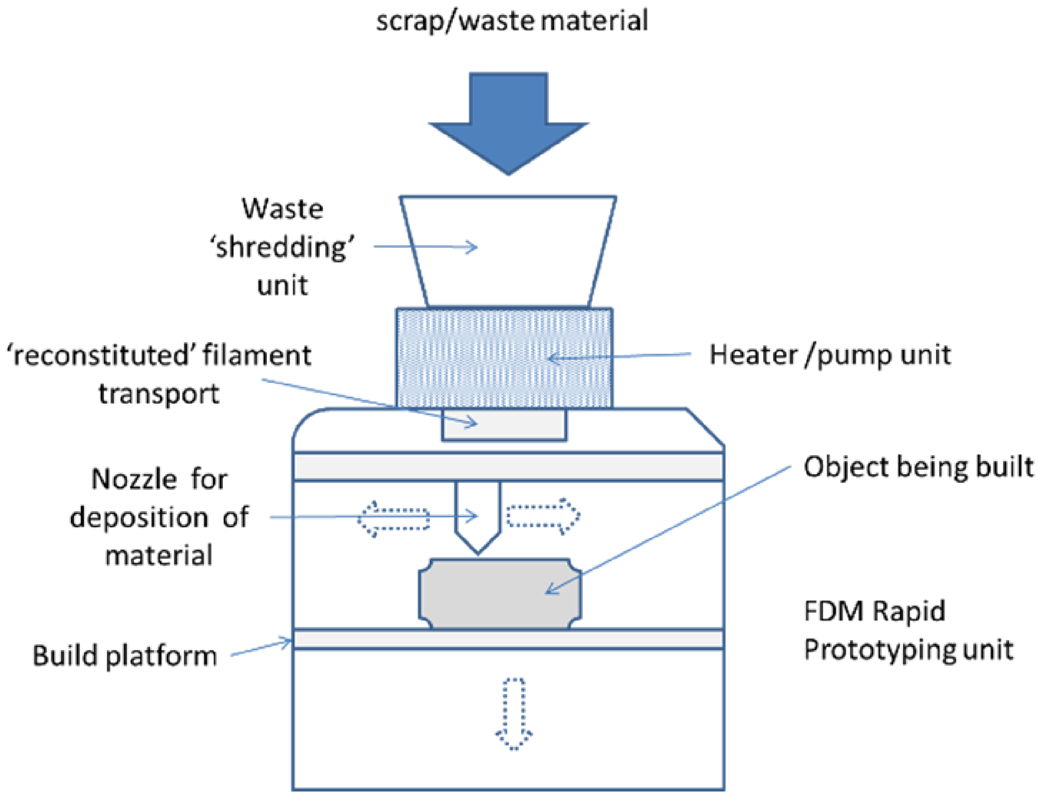

Figure 7: Concept diagram for the closed-loop manufacturing machine

In the case of this simple demonstrator machine, it is anticipated that the use of existing and well understood technologies should lead to relatively few technical problems and issues surrounding contamination and suitability of the raw material (i.e. the items previously made by the machine) will initially be limited by good housekeeping practices. Issues surrounding materials would of course be orders of magnitude more problematic in a live commercial situation than in the laboratory, but material sorting and contamination issues are things which are already widely known in the recycling industry. For example with plastic materials a number of trade bodies like the British Plastics Federation (BPF) and national/international standards like PAS103 and other directives, etc. are already in place.

It is clear that some manufacturing processes are more adaptable to direct reuse of material, those using single plastics or metals like injection moulding or casting being the most likely candidates, however there will be, as one would expect, a number of technical issues to overcome in order to develop even the simplest closed loop manufacturing. A secondary issue for direct closed loop manufacturing will be to develop the manufacturing technologies and machinery with specific capabilities to allow for this idea. A quick trawl around the different commonly used manufacturing technologies would suggest that some technologies will be more adaptable than others. Injection moulding and some versions of rapid prototyping are obvious candidates, whilst other technologies – in particular high precision machining - may be too reliant on very specific and regular material properties to function with 'inferior' quality of materials. The concept of completely closed loop systems are probably the manufacturing equivalent of 'perpetual motion' machines, so new materials will probably need to be added to improve the quality of the raw materials to acceptable standards and for some industries, e.g. medical device or aerospace, it may never be possible to use materials recycled at point of use.

However early we may be in the development cycle of direct closed loop manufacturing systems, the concept of using the scrap, waste and recyclable material as a direct raw material input to the same manufacturing process as was used to originally manufacture, despite the various issues to overcome, is surely worthy of pursuit. Further, energy and other environmental considerations also extend beyond manufacture, especially for products that consume energy during their use. When an aluminium car leaves the production line it may have more embodied energy than an equivalent steel car, but the lighter aluminium car will be more energy-efficient when it is driven hence requiring lower levels of fuel consumption.

6. Future research

When business models are based on virtual organisations (V-O) the V-O Leader (the organisation with which the consumers typically identify with) needs to develop a strategic response to sustainability drivers (legislative etc..) which is reflected in their mission statement and product strategy. Further, the V-O Leader will have reporting responsibility on the sustainability of the final product which entails placing sustainability metrics on the other firms in the lifecycle. Metrics will become the driver for management attention in the other firms who may have to look at new and alternative technologies in order to achieve energy and resource efficient approaches. Figure 8 highlights that management effort based around metrics is required to ensure integration

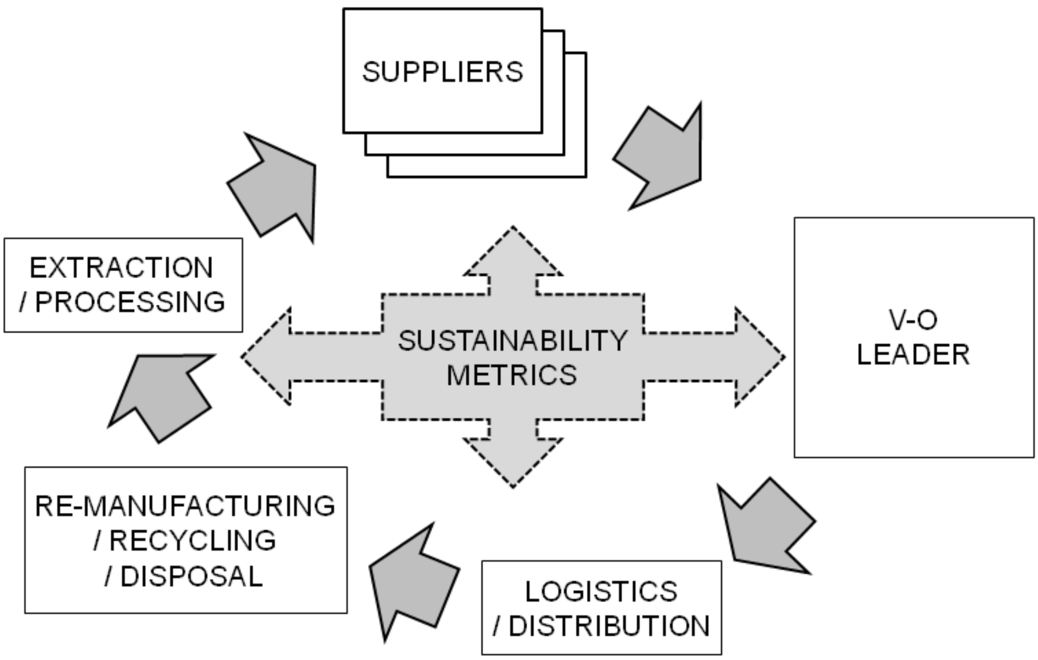

Figure 8. Closed loop production

7. Conclusions

The paper started with a review of design approaches and product development in terms of 'open loop' versus 'closed loop' systems. In the context of consumer electronics products with its diverse applications, life cycle assessment for sustainable product development has been introduced as a sustainable development approach. The proposed model for a sustainable product development process comprises three stages firstly, a high level examination of product costing, secondly, life cycle design which concerns the more strategic product and technology decisions and thirdly, life cycle analysis which involves a detailed assessment of energy and other environmental impacts. By utilising a collaborative view of product design at the early stages, it provides a methodological approach to business and product planning across the supply chain. The implications of 'closed-loop' manufacturing are then examined including a conceptual proposal for a closed-loop manufacturing machine.

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