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Addressing decision making for remanufacturing operations and design-for-remanufacture

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ABSTRACT

In recent years concern about the effect of modern production on the planet has lead to international legislation to limit the levels of virgin materials in production, landfill and harmful emission into the atmosphere. Competition has also become globalised and continues to accelerate especially with developing countries using their advantages of low labour costs to undercut producers from the more industrialised nations. The increasingly stringent environmental regulations in more developed countries have also cut the profits of manufacturers in those countries. Furthermore, the general public in such countries are more environmentally aware and have begun to expect the same from their governments and industries. These changes have increased the incentive to remanufacture in order to obtain benefits including:

- *Increased profits. For example, by extending the usefulness of products beyond their expected lifespan and reducing the use of expensive virgin materials.*
- *Enhanced "green" credentials and compliance with incoming environmental legislation such as take-back.*
- *Enhanced ability to obtain design information by using remanufacturing as a means of collecting failure mode data to inform product design improvements.*

Remanufacturing, is a process of returning a used product to at least original equipment manufacturer original performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent. This paper explains the need to combine ecological concerns and economic growth and the significance of remanufacturing in this. Using the experience of an international aero-engine manufacturer it discusses the impact of the need for sustainable manufacturing on organisational business models. It explains some key decision making issues that hinder remanufacturing and suggests effective solutions. It presents a peer validated top level design guideline to assist decision making in design in order to support remanufacturing. The design guide was developed in the UK via case studies and workshops involving selections of products, academics as well as remanufacturing and conventional manufacturing practitioners. It is one of the initial stages in the development of a robust design for remanufacture guideline.

Key word: remanufacture, decision-making, sustainable manufacture, service

1. INTRODUCTION: THE IMPORTANCE OF REMANUFACTURING IN SUSTAINABLE DEVELOPMENT

Remanufacturing, is a process of returning a used product to at least original equipment manufacturer (OEM) performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent [1]. Because remanufacturing recovers a substantial fraction of the materials and value added to a product in its first manufacture, and because it can do this at low additional cost, the resulting products can be offered to the user at substantial savings. Remanufacturing is particularly applicable to complex electro-mechanical and mechanical products with cores that, when recovered, will have value added to them that is high relative both to their market value and to their original cost [2]. Cores are used products and components. Remanufacturing falls within "Reduction" and "Re-use" the top two preferred waste management options identified in the EU's Fifth Environmental Action Programme. Research by Lund [2] indicates that 85% of the weight of a remanufactured product may come from used components, that such products have comparable quality to equivalent

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new products, but require 50% to 80% less energy to produce and that remanufacturing can provide 20% to 80% production cost savings in comparison to conventional manufacturing. Remanufacturing can limit environmental impacts. For example, it can reduce the production of greenhouse gases such as CO_2 and methane that the Kyoto agreement [3] has highlighted for reduction. This is because for most goods, raw materials production and the subsequent shaping and machining processes produce the highest CO_2 emissions, but remanufacturing by passes these processes. Also, European producers must manage their waste inside the EU because the Basel agreement [4] prohibits exporting of waste outside the EU. Thus the major remanufacturing drivers are environmental concerns, legislation - particularly landfill tax [5], and end-of-life directives and economics. Moreover, remanufacturing can help address social ills such as exclusion by reducing the major causes of poverty and lack of skills. The reason here is that remanufacturing benefits include employment creation especially for low skilled labour and provision of high quality goods at prices that the low income can afford. The former is due to the fact that many of the tasks of remanufacturing such as sorting and cleaning are easy to learn. Research by Lund, [2] indicates that in the automotive sector up to 60% of a typical remanufacturing company may be skilled or unskilled. The latter results from the ability of remanufacturing to drive down production costs, thus, enabling producers to reduce the selling price of their products. Because remanufacturing can have positive impacts on all three pillars of sustainability-economic, environmental and societal, it is being regarded as a key strategy for sustainable manufacturing and in turn of addressing the needs of sustainable development. Furthermore remanufacturing is playing a crucial role in to the paradigm shift from product sale to service industries that is occurring. The key remanufacturing problems relate to the paucity of knowledge in the area and its relative novelty in research terms and include:

(i) The ambiguity in its definition leading to its confusion with repair and reconditioning [6].

(ii) The paucity of readily available remanufacturing tools and techniques. Remanufacturers perceive the scarcity of effective remanufacturing tools and techniques as a key threat to their industry [7].

(iii) The poor remanufacturability of many current products because design has typically focussed on functionality and cost at the expense of environmental issues [8].

This paper explains the need to combine ecological concerns and economic growth and the significance of secondary market processes, in particular remanufacturing in sustainable manufacturing. It uses the experience of an organization in the aerospace industry to illustrate the impact of the need for sustainable manufacturing on choice of organizational business model and the importance of remanufacturing in this. It describes some major decision making issues in the operation of remanufacturing and in the design of products for remanufacture. It describes some key research already undertaken in design for remanufacture (DFRem), and it presents a top level design guideline to assist decision making in design in order to forward remanufacturing. The design guide was developed via case study and work shop analysis of selections of products as one of the initial stages in the design of a robust DFRem methodology. The workshop involved academics as well as design and manufacturing personnel from both conventional manufacturing and remanufacturing industry sectors to ensure that all perspectives were considered. It was tested and validated by peer review and has been found useful in instructing Masters level (MSc) students on the DFRem approach.

2. SECONDARY MARKET PROCESSES AND THE NEED TO COMBINE ECOLOGICAL CONCERNS AND ECONOMIC GROWTH

As early as 1935 geologists observed that since the beginning of the 20th century the "world has exploited more of its mineral resources than in all preceding history" [9]. It is estimated that 4 billion tons of primary metals were used for production between 1900 and 1950, but that 5.8 billion tons of metals were used between 1980 and 1990 alone. Because the world's waste has grown exponentially each year from the 1950s onwards, disposal methods such as landfills are becoming increasingly expensive as they are being exhausted. Research by Biffa [10] indicates that the UK has only 6.5 years of space remaining in existing landfills, and that by DEFRA [11] determined that house prices decrease near landfill sites making such sites undesirable in the urban areas where they are most needed. This is a great problem for highly populated countries such as the UK because of the demand for new houses and government initiatives to increase housing stocks. Moreover, the rate of waste generation is accelerating much faster in industrializing countries than in fully industrialized nations, fuelling concern because a significant proportion of the world is presently "under-developed" and aiming for total industrialization.

The relationship between pace of industrialization and increase in creation of waste was demonstrated by comparing the rate of increase in waste generation with the pace of industrialization in some European countries between 1980 and 1985. The survey showed that Denmark, one of the most industrialized European countries, increased its waste generation rate by 6%; Portugal, slightly less industrialized by 13% while Spain and Ireland had figures of 32% and 72% respectively [9]. Ireland was the least industrialized of the four countries and had the fastest pace of industrialization because of its efforts to reach the technical advances of the more developed nations. The adverse environmental impacts of conventional manufacturing have prompted the rise of organisations such as the Club of Rome and the Business Council for Sustainable Development, which aim to link economic and ecological concerns. In the 1970s the Club of Rome warned that the exponential increase in population, exploitation of resources and destruction of the environment would curtail economic growth [12]. A decade later, the Business Council for Sustainable Development declared that "economic growth and environmental protection are inextricably linked" [13]. The sustainable development ethic argues that the earth's resources are finite and that waste should be discouraged so that the present generation can satisfy its needs without jeopardising the ability of future generations to meet their own requirements. The two general aspects to sustainability are living within the critical limits of the ecosystem and balancing social, economic and ecological goals [12]. Industries addressing sustainable development include agriculture, architecture and manufacturing [13]. Because of the significant adverse impact of conventional manufacturing on the planet, for example manufacturing generates more than 60% of annual non-hazardous waste arising [14], sustainable development would be impossible without sustainable manufacturing. Within manufacturing, the needs of sustainable development are being addressed by promoting the use of secondary market processes.

In this instance secondary market processes are defined as the various production processes that use components from used products and include repair and reconditioning as well as remanufacturing**.** The importance of such processes is that they help limit landfill by prolonging the life of products and components so they take longer before needing disposal. Also, by integrating used components into the manufacturing cycle they reduce the amount of virgin components and therefore of virgin materials and energy used in production. Such processes should be relatively localized to avoid the great impact on carbon footprint due to transportation if parts of the process were undertaken in different locations or worse used products were exported for processing to countries with less expensive labour rates and then exported back to the country of origin for sale. Additionally, in some instances such as domestic appliances remanufacturing would not be profitable. This is because the cost of processing items such as fridges and cookers for recycling continues to decrease and according to the Association of Manufacturers of Domestic Appliance (AMDEA) would be less than £5.00 by 2009, whilst the value obtained at the treatment plant continues to increase. This according to AMDEA was because the value of steel doubled between 2002 and 2006. Interviews of major domestic appliance manufactures such as Lec Refrigeration and Merloni indicate that remanufacturing of domestic appliances is cost prohibitive-at least within the EU. The main reason here is the cost of manual labour involved in remanufacturing as well as additional costs such as that for testing to safety standards. Such tests are expensive to run and their costs in new manufacture can be limited by running in batches, however, with remanufacturing the test must be undertaken individually. However, although secondary market processing, particularly remanufacturing of domestic appliances, may not be justifiable on environmental or profitability grounds, it may be justifiable in terms of its societal benefits, for example, addressing poverty, unemployment and lack of skills. The great decision to be made in considering secondary market processing of certain product types such as domestic appliances is whether their environmental and profitability disadvantages can be offset by their immense societal benefits plus the environmental benefits of reworking products from other sectors. Additionally, it could be that the positive societal impacts outweigh the environmental disadvantages. The societal benefits of secondary market processes include, employment creation, creation of a living for local community and for people selling second hand goods, provision of goods for poor people who would otherwise not be able to afford them and provision of training for low skilled and unskilled labour. The societal benefits of secondary market processes can be illustrated through the work of EMMAUS, a catholic charity for the homeless. The organisation takes donated products requiring rework. It also obtains homeless people to rework the products under supervision. The key benefits of this arrangement include:

- The homeless benefit by having a roof over their heads, paid employment, confidence and new skills to help them start again.
- EMMAUS benefits by using the excess profits to continue their various charitable causes.
- Employment is created for the technician supervising the ex-homeless.
- Poor people benefit because they can afford to purchase the goods.
- Employment is created.

Table 1, defines and differentiates repair, reconditioning and remanufacturing. Figure 1 shows the three processes on a hierarchy based on the work content that they typically require, the performance that should be obtained from them, and the value of the warranty that they normally carry.

Table 1: Definitions of secondary market processes [1]

Remanufacturing The process of returning a used product to at least OEM original performance specification from the customers' perspective and giving the resultant product a warranty that is at least equal to that of a newly manufactured equivalent.
Reconditioning The process of returning a used product to a satisfactory working condition that may be inferior to the original specification. Generally, the resultant product has a warranty that is less than that of a newly manufactured equivalent. The warranty applies to all major wearing parts.
Repair Repairing is simply the correction of specified faults in a product. Generally, the quality of a repaired product is inferior to that of the remanufactured and reconditioned alternative. When repaired products have warranties, they are less than those of newly manufactured equivalents. Also, the warranty may not cover the whole product but only the component that has been repaired.

Remanufacturing is the highest of these processes because it is the only one capable of bringing a used product to a standard equal to that of the new alternative in terms of quality, performance and warranty. The key advantage of remanufacturing over reconditioning and repair is that it permits an organisation to combine the key order winners of low price and product quality, especially as remanufacturing also includes increasing the performance and quality of the used product beyond that of its original standards when new. This ability of remanufacturing to deliver high quality is especially important to "A" class manufacturers and "customers" who price the reputation of their service and brand name above low product cost. The following section describes how a major international OEM is addressing the key pressures of modern industry by using remanufacturing to support and assist its move from the product sale to the service business model.

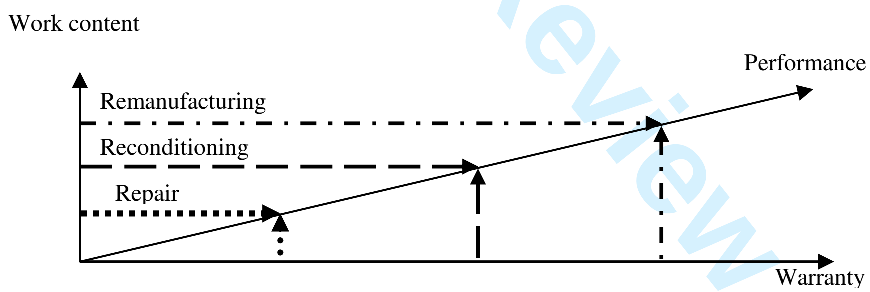

Figure 1: A hierarchy of product recovery processes [1]

3. Impact of the need for sustainable manufacturing on organisational business models

Traditionally, safety, performance and cost were the key consideration in manufacturing decisions. However, changing global and business circumstances are forcing organisations to reanalyse their strategic decisions so additional factors such as raw material costs and environmental legislation are also considered in design and manufacture decisions. This is leading to a paradigm shift from product sale to service business model. This can be exemplified from the experience of an organisation specialising in the design and manufacture of aero engines. The company's business model has changed over recent years because of advances in technology, changes in customer expectation and increased competition. These changes are shown in Table 2.

Table 2: Past and present aerospace industry business model.

Characteristics	Past business model	New business model
Initial product price	High capital expenditure for the	Low capital expenditure for the

	customer	customer
Quantities of spares	Spares sold to customers	The company does not sell spares to Total Care customers but stores spares for maintaining engines under the total care scheme.
Reliability	Same	Same
Customer expectation	Lower	Increased
Competition	Low	High
Source of profit	Spares sale High product price	Service of engine at a pre-agreed rate (£x/hour) over a predetermined period.
Period when profit is obtained	Point of sale of engine and spares	Income fixed over engine life at predetermined cost per hour flying
Focus on customer needs	Lower	Higher
The company needs & customer needs	The company needs not as closely tied to customer needs	The company needs much more closely tied to customer needs
Incentive to overhaul	Low for customer High for RR	Low for The company because it bears the costs of it. Low for customer because it disrupts work.

Table 2 indicates that in the past, the bulk of the company's profit was obtained through sales of new jet engines and large quantities of spares. This was largely because the machines had lower performance as a result of the inadequacies of the available technology, so a large stock of spares was needed to support them because they were more prone to breakdowns. At the same time competition was also much lower allowing the company to obtain larger profit margins through the sale of new engines and spares. Under such circumstances overhaul was primarily a requirement for maintenance to ensure correct functioning of the engine during its expected life span. The technological advances of the 1970s and 1980s improved engine performance and led to increased customer expectations. Engine failure rates decreased leading to a decrease in overhaul frequency as well as the quantity of spares sold. At the same time competition, increased. As some of the new competitors were from manufacturers based in countries with lower labour costs, the company profit margins from sale of new products were reduced in order to attract customers. Environmental concerns about the effect of modern manufacturing also began to mount. At this point the idea of simultaneously promoting a green image and augmenting profits by using the overhaul process to extend engine life and reclaim the materials and components from retired engines began to become attractive.

These changes in the business environment led to the company's strategic decision to begin to adopt the service business model. Although the company both sells and leases its products, it now makes the bulk of its profit by selling the customer the service of its engine at a fixed rate per hour over an agreed number of years. Thus the income is fixed throughout the lifetime of the engine, but the company profit varies depending on the resource required to maintain the engine. Here, the customer benefits from security and certainty, and the company bears any risk due to engine breakdown. This is in contrast to the earlier model where income is upfront at point of product or spares sale and risk is borne by the customer. The success of this new business model depends on the company's ability to merge its concerns with those of its customers'. For example, in the case of reliability, customers require high reliability engines in order to avoid disruptions to their work whilst The company requires the same to remain competitive by reducing maintenance costs, retaining customers' goodwill and improving the standing of the brand name so that new customers can be obtained. In the case of product price, customers want low priced products to reduce their capital expenditure whilst the company needs the same to increase the attractiveness of its products and services and thereby its profitability. The company's success in using the business model and the relative ease with which it is navigating this paradigm shift is due to the company's characteristics and that of its product. The company is forward looking and is internationally recognized as a leader in its market. This provided the organization with the capability to compete for customers on the basis of the quality of its brand name rather than on cost. With the service model the organization does not lose ownership of its product and can afford to spend much more on design and manufacture to ensure its product quality, rather than competing on price. Additionally, the characteristics of engines such as material, design life, pace of technology, impact of fashion and initial purchase price all provide incentives to remanufacture. For example the engines are long life products as they are built for a 25 – 30 year life span, although there are instances where this expected engine life span has been greatly exceeded. Aero engines are mature products, giving ample supply of used products to remanufacture, and to cannibalise for remanufacturing. They are not fashion-affected products, and are not placed in a prominent position thus age and model are far less important than functionality. Also, the remanufactured engines would be sold to those with technical understanding. Research shows that remanufacturing thrives under such circumstances. Remanufacturing reduces the costs to the organisation of adopting the service business model, for example maintenance costs are reduced through the use of remanufactured components and remanufactured whole engines can be used in place of more expensive all new engines. In fact the company's engines are being designed with increasing potential for remanufacture. As remanufacture can be labour intensive and the company is also trying to reduce cost by increasing effectiveness and efficiency. For example, automation has been introduced although this has been possible for a relatively small part of the process. Customers' constraints are a key cause of complexity in decision making in their service operation. For example, some customers specify that only their own components may be put into their engines whilst other customers insist that components from engines that work in harsh and hot desert environment may not be used to rebuild their engines. This second constraint is because components from such engines accumulate more sand wear as a result of the harsher conditions. These customer constraints increase work scheduling complexity.

The above strategic decision to remanufacture in order to maintain business sustainability in the aero engine market is in contrast to the situation in the automotive sector. Currently, OEMs in the automotive sector are operating under huge debts because of increased competition that is mainly product price based. At the same time there has been an increase in the number of producers from newly industrialised countries. As a result there are a large number of producers seeking a share in a finite market. The response of Western producers has largely been to produce more and cheaper vehicles, and this is leading to a glut of new cheaper cars in the market. This strategy is very much like turning the taps on higher when the house is being flooded by tap water. A much better strategy would be to produce less new cars and use remanufacturing to satisfy customer needs. This would however require a change in manufacturing decisions in this sector. For example, the sector designs for recycling rather than remanufacture, in an effort to reduce product cost and therefore their costs via the use of less durable material. Designing for remanufacture would require changes in the manufacturing and design methods. This would initially raise product price and thus would initially be costly but would lead to long term profitability especially given the increase in waste disposal costs and the end of life vehicle legislation. To optimise the application of remanufacturing in sustainable manufacturing its efficiency and effectiveness must be maximised and this will require enhancements in expertise in the process of remanufacturing as well as in the design of products for remanufacture. The following sections explain some key remanufacturing decision-making issues.

4. THE KEY REMANUFACTURING DECISION MAKING ISSUES

Remanufacturing is complicated by a range of decision making issues that affect the effectiveness of operational practices as well as the potential of products for remanufacture. In the case of operational decision making issues the major ones relate to uncertainty, predicting the quantity and quality of incoming cores, cores assessment criteria, pricing and quality control. The causes of these problems and their adverse effects on the effectiveness of remanufacturing practice are discussed in [15]. These factors make the scheduling activity particularly complex in remanufacturing. However, the tools of conventional manufacturing are not ideally suited to easing these difficulties because remanufacturing planning, controlling, and managing operations are significantly different from traditional manufacturing production control [7]. Table 3, describes some principal operations control issues highlighted by the author's case-study work in industry along with some effective coping strategies. The case study involved focus group discussions in workshops involving product disassembly and assessment and was conducted in a wide range of remanufacturing and manufacturing organisations including aerospace, automotive and brown goods industries. Because of time constraints the study was restricted to mechanical and electromechanical products. The findings were later validated by new companies using telephone interview and practical assessment.

Table 3: Some principal operations control issues highlighted by the case-study work

Issue	Causes	Reason	Some solutions
Uncertainty	*Demand volume variability*	• Unforeseen demand fluctuations: this is especially relevant for remanufacturers without contracts as they must take jobs as they become available. • Demand seasonality e.g. compressors are more likely to fail in very warm weather as they are forced to work harder then.	• Contracts with customers. • Build/partial build for stock. • Subcontracting agreements for times of unexpectedly high demand. • Frequently forecast and update resource needs.
	Core quality	• Internal components' quality typically cannot be assessed visually as it is not reliant on product's age, make or model.	• Keep a bank of casual and temporary labour. • Monitor suppliers regards quality of their cores. • Help suppliers improve core handling thus reducing damage in transportation.
	Core quantity	• Obtaining adequate used products to fuel remanufacture is a key issue.	• Contracts with suppliers. • Offer cash back for cores. • Other strategies to boost reverse logistics e.g. core must be returned to obtain a remanufactured product.
	Product type variability	• The remanufacturer typically accepts all orders and all cores offered. Given the high variety of product types, until cores arrive it is impossible to decide whether appropriate parts, and sometimes skills, are available to fulfil particular orders.	• Contracts with customers as this reduces variety of product types or at least makes known the types that would normally be received. This is because a contract generally states the product types it covers. However this is not fool proof as even with contracts it is impossible to precisely forecast the quantity and type of cores that will be received. For example it is impossible to predict when customer's products will fail.
	Technical knowledge availability	• OEM's are often unwilling to provide them with the product information they need for remanufacturing because they regard remanufacturers as rivals.	• Contracts with OEM's thus improving access to their product design information. • Effectively store product information obtained from experience.
	Replacement parts availability	• There may be few suppliers of some old parts and the parts cannot always be sourced from used components, thus is often uncertain whether required parts can	• Keep an inventory of spare parts "just in case". • Start to manufacture some small but rare components

		be obtained.	of strategic importance. • Contracts with customers thus specifying the type and level of work that must be carried out on particular components. For example there may be a list of components that must always be discarded whatever their condition. This determines in advance the prognosis for a significant proportion of components. This assists forecasting for component requirement.
	No possibility of adjustment	• Tolerances that are too tight. • Failures damaging parts to the point that their remanufacture would be too costly.	• Keeping inventory of spare parts "just in case".
Difficulty of knowledge acquisition and processing		• Extreme product variability thus the need to obtain and assimilate vast amounts of information to assist decision making. • Product service history unavailability. The condition of a used product depends on its history and working environment rather than by its age or make. However, customers do not often record their product's service history. • Product technical information unavailability. Intellectual property rights (IPR) restrictions as OEM's may be unwilling to provide product design information.	• Implement a sound data/ information management system to optimise information storage and retrieval. • Effective storage of product's failure history from experience to facilitate remanufacture of similar products in the future. • Contracts with OEM's. • Reverse engineering. In this instance this where a remanufacturer assesses a correctly functioning product to obtain information with which to remanufacture it on its failure.
Flexibility Issues		• Environments such as remanufacturing with high variability coupled with high uncertainty are prone to unplanned occurrences and flexibility provides an efficient channel for coping with unplanned event. However, labour costs are high for highly skilled workers. Also, there is a paucity of effective, certified remanufacturing training schemes.	Subcontracting, multi-skilled employees.

In the case of product design, there is an urgent need to develop strategies and tools, particularly design tools, databases or knowledge-based systems, to assist designers to take effective decisions that would facilitate the integration of environmental considerations in product design [16]. The significance of Design for Remanufacturing (DFRem) is that design is the stage that has the strongest influence on environmental impacts [17] and also sets the product's capabilities. DFRem requires products to be designed for ease of disassembly, with no damage to the product affecting functional performance for parts hidden from the customer, and no damage affecting performance (or provides good mechanisms to rectify damage). Various DFRem guidelines have been proposed, for example [18-27]. Examples of other relevant work include [28-30]. The most useful of such work are those that are not general guidelines and that also simultaneously consider product features and remanufacturing process activities. This is probably because the most effective way to boost remanufacturing is an integrated product and process design approach [31]. The research indicates that there is opportunity to build on previous work by introducing new parameters to enable the development of enhanced DFRem guidelines, for example based on life cycle thinking. In fact, the World Summit for sustainable development identified product life-cycle based tools, policies and assessment tools as key sustainable production requirements [32]. There appears to be a lack of DFRem guidelines based on life-cycle thinking, that simultaneously consider products' dissimilar life-cycle profiles and the impact of proposed remanufacturability enhancement product features on initial manufacture. Table 4 shows part of a high level remanufacturing design guide developed by the author as a precursor to the robust DFRem guide proposed in [33]. The design guide was developed in a similar manner to the solutions presented in Table 3. It was also validated by peer review and has been found useful in teaching MSc students about the requirements of Design-for-remanufacturing (DFRem).

Table 4: High level Design for Remanufacturing guidelines

Process Activities	**Product / Design Characteristics**			**Environmental Considerations / Safety**
	Material	**Assembly technique**	**Product structure**	
Inspect product	Use materials that will survive the inspection process. Clearly identify product material.	Use assembly techniques that allow easy access to inspection points. Ensure that assembly methods and joint locations do not conceal product details.	Structure to facilitate efficient and effective inspection. Mark inspection points clearly. Clearly identify product technical details e.g. make, model and year of manufacture etc.	Use non-hazardous material. Use environmentally friendly materials. Use environmentally friendly assembly techniques.
Clean product	Use product materials that will survive the cleaning process. Use durable materials for identification methods e.g. avoid use of stickers as these may detach during cleaning. Avoid materials that are difficult to clean e.g. material with pitted surfaces. Minimise number of different materials used in the product thus limiting use of variety of cleaning agents. Use easy-to-clean material that will not	Use assembly technique that will withstand the cleaning process but that will not allow disassembly without damage to components that have potential to be reused.	Ensure easy access to all areas to be cleaned. Ensure good resistance to dirt accumulation e.g. avoid sharp edges and thresholds that may attract dirt. Ensure ease of handling e.g. reduce product unit weight where ever possible without limiting functionality or required durability. Provide handles if product is heavy or bulky. Ensure marking on product can withstand cleaning.	Avoid hazardous or banned cleaning agents. Use environmentally friendly cleaning agents.

	collect residue from cleaning.			
Disassemble product	For components destined for reuse ensure that their materials are sufficiently durable to survive disassembly. disassembly. Ensure that fasteners' material are similar or compatible to that of base material thus limiting opportunity of damage to parts during disassembly.	Use assembly methods that would allow disassembly without damage to components.	Arrange components for ease of disassembly. Reduce the total number of parts. Reduce complexity of disassembly, for example by standardizing fasteners. Use modular components thus reducing complexity of disassembly because types of assembly techniques are reduced. Arrange components so that separation joints are easily accessible and easily identifiable. Minimise the number of joints. Reduce / Eliminate redundant parts. Simplify and standardize component fits.	Disassembly process should not require the use of hazardous substances. Use an environmentally friendly disassembly method and substances. Consider design for disassembly techniques that would not prevent reassembly.
Sort components	Identify components of similar materials. Minimise the number of different materials used for parts thus facilitating component sorting. Limit the number of material type per part to reduce sorting complexity. Identify parts requiring similar cleaning or processing modes.		Reduce/ Eliminate redundant parts thus limiting sorting time and expense. Use standardised component to limit sorting complexity. Identify parts by end of life (EOL) destination. Minimise the number of parts. Reduce unit weight as far as possible. Provide handles for parts that are heavy, bulky or difficult to handle. Limit redundant parts.	Use reusable components. Ensure that parts that can not be remanufactured can be reconditioned or repaired or in the worst case scenario can be recycled.
Clean components	Use material that would survive	Use assembly methods that allow disassembly	Ensure that all parts to be cleaned are easily	Do not use banned Cleaning chemicals.

	cleaning process. Use components that all require or at least can be divided into groups that require similar cleaning agents and procedures. E.g. limit the number of material type per part. Identify components requiring similar cleaning procedures and agents.	at least to the point that internal components can be accessed for cleaning.	accessed. Reduce/ Eliminate redundant parts. Arrange components so that all can be accessed for effective cleaning. Ensure product surfaces are smooth and wear resistant.	Use environmentally sound cleaning agents and procedures.
Remanufacture / Replace components	Use materials that are at least durable enough to survive the refurbishment process. Use materials that do not prevent upgrade and rebuilding of the product.	Use assembly methods that would allow disassembly at least to the point that internal components and sub-systems requiring work can be accessed. Use assembly methods that do not prevent upgrade of product.	Reduce/ Eliminate redundant parts. Structure to facilitate ease of upgrade of product. Arrange components so that parts that are prone to damage are easily accessible. Standardize parts.	Ensure replacements for unremanufacturable components are at least recyclable.
Test components	Identify component material.	Use joining methods that allow disassembly at least to the point that internal components and sub-systems requiring it can be accessed for testing before and after refurbishment. Input fault tracking device.	Structure to ensure ease in determining component condition. Component structure should be such that testing is sequential in that it mirrors the order in which the product is reassembled. Minimise the disassembly level required to effectively test components. Reduce test complexity. Clearly identify component load limits, tolerances and adjustments. Standardise tests.	Use environmentally test procedures and methods. Limit resource used in test e.g. energy, electricity, water, etc.

5. SUMMARY

This paper has described the reasons why economic progress must be tied with environmental concerns. It has argued that sustainable development would be impossible without a shift in manufacturing ethics, because of the significant adverse environmental impacts of conventional manufacturing. It has presented the case for remanufacturing as a key strategy for sustainable production and waste management in order to forward the aims of sustainable development. It used the experiences of an international aero-engine manufacturer to illustrate the impact of the need for sustainable manufacturing on organisational business models and the support that remanufacturing can offer in that regard. It discussed some the key decision making issue that hinder remanufacturing operations. It discussed the cause of ineffectiveness in decision making during design to ensure product remanufacturability. Research work in the area of DFRem was briefly described and a high-level DFRem guideline was presented. The guideline was developed via the analysis of selections of products during case studies and workshops involving remanufacturing and conventional manufacturing practitioners as well as academics. It was validated by peer review and has been found useful in teaching the needs of the DFRem approach. Future work will involves using the guideline as a foundation for the development of a robust DFRem methodology.

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REFERENCES

[1] Ijomah, WL "A model-based definition of the generic remanufacturing business process", PhD Dissertation, The University of Plymouth, UK; 2002.

[2]Lund, RT "Remanufacturing: The experience of the U.S.A. and implications for the Developing Countries" World Bank Technical Paper No. 3; 1984

[3]The Kyoto Protocol, United Nations Framework Convention on Climate Change (UNFCCC);2005 (http://unfcc.int/kyoto-protocol/items/2830.php).

[4]The Basel Convention, Available online at: http://www.basel.int/index.html (accessed 20 June 2006).

[5]HM Treasury, "Financial Statement and Budget Report 2004" p205 http://www.hm-treasury.gov.uk./media/7A8/DF/bud04_cha_190.pdf#page=22 [Accessed on 2/12/05.

[6] Melissen, F.W. and Ron, A.J. de, Defining recovery practices: definitions and terminology. Int. J. Environ. Conscious Des. Mfg., 1–18; 1999.

[7] Guide VD "Remanufacturing production planning and control: U.S industry best practice and research issues", Second International Working Paper on Re-use, pp 115-128.; Eindhoven, The Netherlands; 1999

[8] Ferrer, G., Theory and methodology on the widget remanufacturing operation. Eur. J. Oper.Res.,135, 373–393, 2001.

[9] Vandermerwe S. and Oliff M., "Corporate challenge for an age of reconsumption", The Columbia Journal of World Business, vol.27, No.3, pp 7-25; 1991.

[10] Biffa, Future perfect: an analysis of Britain's waste production and disposalaccount, with implications for industry and government of the next twenty years, p. 44; 2002, Available online at: www.biffa.co.uk (accessed March 2006).

[11] DEFRA Press Release: Living close to a landfill site cuts property values; 2003; http://www.defra.gov.uk/news/2003/030221a.htm [10th October 2003]

[12] Yamamoto R"Manifesto on Ecodesign", Ecodesign'99: The first international symposium on environmentally conscience design and inverse manufacturing, Tokyo, Japan; 1999

[13] Hormozi, A."Remanufacturing and its consumer, economic and environmental benefits" APEX Remanufacturing Symposium, pp. 5-7 May 20-22, USA; 1996

[14]Nasr and Varel "Lifecycle analysis and costing in an environmentally conscious manufacturing environment, APICS Remanufacturing Symposium Proceedings, pp.44-47, USA; 1996

[15] Ijomah W., Childe S; McMahon C, Hammond G.P. "A robust description and tool for remanufacturing: a resource and energy recovery strategy" Proceedings of EcoDesign 2005: 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, December 12-14, Tokyo, Japan; 2005

[16] Nissen, U, A Methodology for the development of cleaner products. J. Clean. Prod., vol 3,pp 83–87; 1995.

[17] Graedel T and Allenby B; Industrial ecology: Eds., Prentice Hall; 1995

[18] Gehin, A., Zwolinski, P. and Brissaud, D., Imaging a tool to implement sustainable end-of-life strategies in the product development phase, in Proceedings of the 10th ESCP Conference, 5–7 October, Antwerp, Belgium; 2005.

[19] Sundin, E., Enhanced product design facilitating remanufacturing of two household appliances–A case study, in

International Conference on Engineering Design ICED 01, pp. 645–652, 21–23 August,, Glasgow, Scotland; 2001.

[20] Sundin, E. and Bras, B., Making functional sales environmentally and economically beneficial through product remanufacturing. J. Clean. Prod, vol.13, pp913–925; 2005

[21] Amezquita, T., Hammond, R. and Bras, B., Design for remanufacturing, in ICED95: International Conference on Engineering Design, pp. 1060–1065, Prague, Czech Republic; 1995

[22] Bras, B. and Hammond, R., Towards Design for remanufacturing–metrics for assessing remanufacturability, in Proceedings of the 1st International Workshop on Reuse, pp. 5–22, 11–13 November, Eindhoven, The Netherlands, 1996.

[23] Shu, L. and Flowers, W., "Considering Remanufacture and Other End-of-Life Options in Selection of Fastening and Joining Methods," Proceedings of the IEEE International Symposium on Electronics and the Environment, pp. 75-80, May 1-3, Orlando, FL, USA; 1995

[24] Shu, L. and Flowers, W., Application of a design-for-remanufacture framework to the selection of product life-cycle fastening and joining methods; 15, 177–190;. Robot. Comput.-Integr.Manuf.; 1999

[25] Williams, J., Shu, L. and Murayama, T., Current status of extended producer responsibilitylegislation and effects on product design, in Proceedings of the ASME Japan-USA, Symposium on Flexible Automation, Paper No.2000JUSFA-13000, 23–26 July; Ann Arbor, MI, USA; 2000

[26] Sherwood, M., and Shu, L., Submitted by R.G. Fenton, Supporting design for remanufacture through waste-stream analysis of automotive remanufacturers. CIRP Annals, 49, 87–90; 2000

[27] Mangun, D. and Thurston, D., Incorporating component reuse, remanufacturing and recycle into product portfolio design. IEEE Trans. Engin. Manage., , 49, 479–490; 2002

[28] Rose, C.M. and Ishii, K., Product end-of-life strategy categorization design tool; Special Issue on electronic product reuse, remanufacturing, disassembly and recycling strategies; J. Electr. Manuf., 9, 41–51 1999

[29] Ishii, K. and Lee, B., Reverse fishbone diagram: a tool in aid of design for product retirement, ASME Design Technical Conference – Design for Manufacturability Irvine, CA, September; 1996

[30] Ishii, K. "Modularity: A Key Concept in Product Life-cycle Engineering" in A. Molina and A. Kusiak eds, "Handbook of Life-cycle Enterprise," Kluwer; 1998

[31] Amezquita T., Hammond R., Salazar M. and Bras B. " Characterizing the remanufacturability of engineering systems", Proceedings of ASME advances in design automation Conference, DE-vol.82, pp.271-278; September 17-20, Boston, Massachusettes, USA; 1996

[32] United Nations General Assembly, World summit on Sustainable Development: Plan for Implementation, UN Division for Sustainable Development: Johannesburg; 2002

[33] W L Ijomah, C A McMahon, G P Hammond, S T Newman "Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development" International Journal of Production Research, Volume 45 Issue 18, 4513 -4536; 2007