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Development of design for remanufacturing guidelines to support sustainable manufacturing

Winifred L. Ijomah*, Christopher A. McMahon, Geoffrey P. Hammond, Stephen T. Newman

Department of Mechanical Engineering, University of Bath, Bath, BA2 7AY, UK

Abstract

Developing sustainable approaches to manufacture is a critical global concern. Key measures towards this include practicing design for environment (ecodesign), for example by improving remanufacturing efficiency and effectiveness. Remanufacturing is a process of bringing used products to a "like-new" functional state with warranty to match. Its significance is that it can be both profitable and less harmful to the environment in comparison to conventional manufacturing. Remanufacturing has a low profile in world economies and is poorly understood because of its relative novelty in research terms. However, environmental and competitive pressures are changing the global and business environment and this is fuelling interest in the practice. This paper provides the background to remanufacturing together with the findings from workshops recently undertaken in the UK as part of research into design and manufacturing approaches to facilitate remanufacturing.

Keywords: Remanufacture; Design for environment; Sustainable manufacture

1. Introduction

Following the Brundtland Report and the 1992 Rio Earth Summit it is clear that balancing economic and social development with environmental protection is a key challenge in securing long-term sustainability [1]. As manufacturing generates in excess of 60% of annual non-hazardous waste [2], increasingly severe legislation demands a reduction in the environmental impacts of products and manufacturing processes. For example, producer responsibility legislation requires producers to recover used products to reduce landfill. Such pressures, combined with mounting competition due to global industrial activity, challenge companies to alter attitudes to product design. Companies must design products for longevity and ease of recovery of their materials at end of life, and must consider the business potential of processing used products to harness the residual value in their components.

Remanufacturing, a process of bringing used products to a "like-new" functional state with warranty to match, can be both profitable and less harmful to the environment than conventional manufacturing as it reduces landfill and the levels of virgin material, energy and specialised labour used in production [3–7]. It is preferable to recycling because it adds value to waste products by returning them to working order, whereas recycling simply reduces the used product to its raw material value. Key remanufacturing barriers include consumer acceptance [3], scarcity of remanufacturing tools and techniques [8] and poor remanufacturability of many current products [9]. These result from a paucity of remanufacturing knowledge including ambiguity in its definition [10]. The terms repair, reconditioning and remanufacturing are often used synonymously. Consequently, customers are unsure of the quality of remanufactured products and are wary of purchasing them. Also, designers may lack the knowledge to consider end of life issues such as remanufacturing in their work because design has traditionally focused on functionality and cost at the expense of environmental issues. This paper addresses these issues by describing the remanufacturing domain and differentiating it from repair

*Corresponding author. Tel.: +44 1225 384049.
E-mail address: W.L.Ijomah@Bath.ac.uk (W.L. Ijomah).

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and reconditioning, and by presenting the findings from recent workshops undertaken in the UK to explore the design features that hinder and assist remanufacturing.

2. Workshop methodology

The workshop methodology comprised group work by brainstorming, discussion, and practical product disassembly. The workshops were held at the University of Bath and at the 4th International Conference on Design and Manufacture for Sustainable Development, The University of Newcastle Upon Tyne. They involved manufacturing engineers and designers from academia and industry in order to fuse academic and industrial knowledge. The objectives were to identify the key factors that influence product remanufacturability, to list the most significant product features and characteristics in this respect and to align the product features with the activities of the remanufacturing process. *Product features* are factors under the control of the designer e.g. product material. *Product characteristics* are factors that the designer cannot control e.g. level of demand for the product. The participants were divided into groups of four or five. Each group had a leader to ensure orderly progression of tasks and a rapporteur to explain the group's results to the workshop in general. A range of products, some fully assembled, some partially disassembled and some with cutouts to reveal their internal structure were provided. There was also a recorder to record discussions and an overhead projector for the presentation by the researcher who was also the workshop facilitator. To ensure adequate understanding of remanufacturing and of the tasks to be undertaken, information explaining remanufacturing as well as workshop function and content were sent in advance to each participant. This included a description of remanufacturing and the chart shown in Fig. 1, as well as a list of the characteristics of remanufacturable products given in Section 3 below. This information was again given to participants at the workshop.

The workshop had three parts, introduction/background session, group activities and final sharing of ideas. The introduction/background session aimed to ensure that participants had a clear understanding of the workshop objectives, the requirements from them, as well as adequate remanufacturing knowledge to undertake workshop tasks. It began with a short presentation that explained remanufacturing and gave an overview of the research and its goals. The workshop objective and tasks were described. Descriptions and examples of product features and characteristics were also given along with those of repairable, reconditionable and remanufacturable products. The group activities first involved a session to test participants' understanding of remanufacturing. Here, the groups discussed repair, reconditioning and remanufacturing, and provided examples of products falling into each category. This first session was followed by identification of product features influencing remanufacturability and their categorisation into two groups—those hindering and those assisting remanufacturability. Practical work then took place in which the groups used supplied products, for example through practical disassembly, to help them come to final decisions that they then recorded on their flip charts. For the final sharing of ideas the groups transferred the information on their flip charts to a general notice board in the centre of the room where all participants could see it. The rapporteurs explained their group's results to the workshop as a whole so that individual groups' opinions could be debated to arrive at generally agreed views on design for remanufacture issues. Following the workshops the results were summarised and returned to participants for verification. The verified results were then documented to facilitate their comparison with information from case studies and literature survey.

3. The remanufacturing concept

Remanufacturing typically begins with the arrival of a used product (called a core) at the remanufacturer, where it passes through a series of industrial stages including

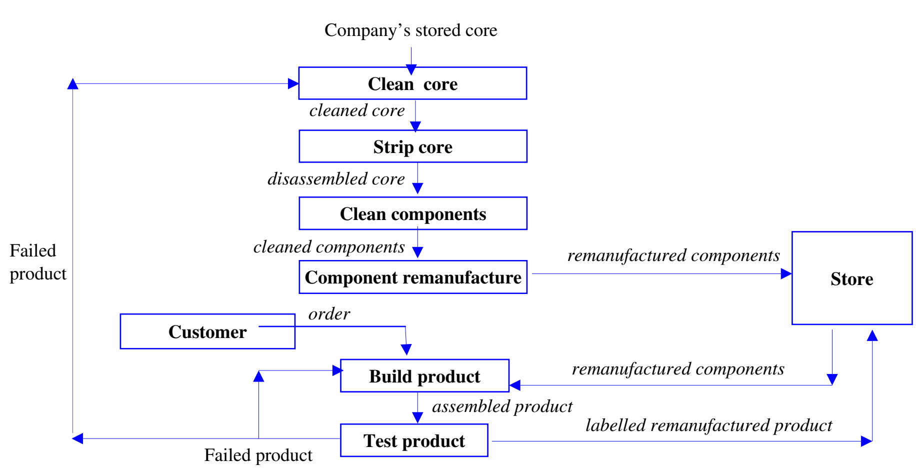

Fig. 1. A generic remanufacturing process chart.

disassembly, cleaning, part remanufacture and replacing of unremanufacturable parts, reassembly and testing to produce the remanufactured product. The order in which these activities, described in Ijomah et al. [11] and shown in Fig. 1, are undertaken may differ between different product types [12]. The key remanufacturing drivers are environmental concerns (the need to reduce waste during the material extraction and manufacturing processes and throughout the remainder of the product life cycle), legislation (international agreement to reduce the environmental impact of products and manufacturing processes) and economics, because remanufacture is often a quality and cost-effective option [6,13,14]. Andrue [15] lists the characteristics of remanufacturable products as:

- The product has a core that can be the basis of the restored product and a continuous supply of such cores is available.
- The product is one that fails functionally rather than by dissolution or dissipation and is factory built rather than field assembled.
- The core is capable of being disassembled and of being restored to original specification and the recoverable value added in the core is high relative to both its market value and its original cost.
- The product and the process technology are stable.

A key problem for practitioners and researchers has been the ambiguity in the definition of remanufacturing. Work by Ijomah [16], determined a robust definition, described below, to define remanufacturing to be for the first time differentiated from repair and reconditioning. Its advantage is that it assists researchers to explicitly understand remanufacturing so that they can undertake effective research in it and correctly disseminate their findings.

3.1. A robust definition of remanufacturing

The definition explained in [17] was obtained through industrial case studies in the mechanical and electromechanical sector of the UK remanufacturing industry and by examining two of the most popular remanufacturing definitions, one by Amezquita et al. [18] and the other by Haynesworth and Lyons [13]. It was proposed by Ijomah et al. [19] that although the Haynesworth and Lyons [13] definition is one of the most precise, it also is insufficient because it does not permit the purchaser to easily recognise that remanufactured products have higher quality than repaired and reconditioned alternatives, or that remanufactured products have similar quality to new alternatives. Ijomah [16] explained that the processes could be differentiated using two factors, the level of quality of products when compared to that of an equivalent new product and, the standard of the warranty given in comparison to that given to the equivalent new product. The Ijomah [16] definition, provided in Table 1, augments previous ones by introducing "warranty" as a quality indicator to allow remanufacturing to be differentiated from repair and reconditioning on the basis of the quality of its products relative to that of the equivalent OEM product. The giving of a warranty that is equivalent to that of the OEM product is important because remanufacturers believe that it is evidence that the remanufactured product and the OEM product are of equivalent quality. Remanufacturing typically involves a greater degree of work content than repair and reconditioning, so its products generally have superior quality. This is because remanufacturing requires the total dismantling of the product and the restoration and replacement of its components. Table 1 presents the definition along with the proposed definitions of repair and reconditioning. Fig. 2 shows the three operations in 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
Proposed definitions of remanufacturing, reconditioning and repair [19]

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. 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 replaced

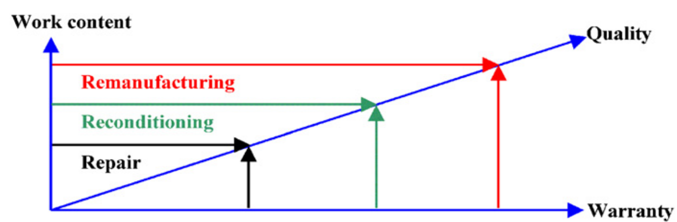

Fig. 2. A hierarchy of secondary market production processes.

4. Workshop findings

The key workshop findings include categorisation of products as repairable, reconditionable and remanufacturable and some understanding of how product features and characteristics influence remanufacturability.

Fig. 3 shows a connecting rod in which the large end bore can be returned to its original size during remanufacture. The mating faces between bearing cap and

Fig. 3. Old version connecting rod (remanufacturable product).

Fig. 4. New version connecting rod (unremanufacturable product).

Fig. 5. Electric drill (repairable/reconditionable product) with detailed view of internal structure and motor.

connecting rod are machined so that when bolted together again a smaller hole is produced. This smaller hole is then re-machined to return the big-end bore to its original size. Newer versions of connecting rods, as in Fig. 4, are not remanufacturable because they are fracture-split. Here the big-end cap is separated from the connecting rod by breaking it off, leaving a rough fracture surface. Advantages of this include ease of production and lower production cost because there is no requirement to manufacture doweled bolts. Also, there is a very strong adherence between the contacting parts because of the rough surface created when the component was fractured. This makes the mating surfaces less likely to move in comparison to the older connecting rod manufacturing method. However, fracture-split connecting rods cannot be remanufactured because shaving down the contacting surfaces would remove the self-alignment properties of this type of connecting rod. However, it should be noted that if fracture-split rods are lighter than traditional connecting rods as claimed, then they may save energy in use and the benefits of the savings in energy may exceed the benefits from connecting rod remanufacturing.

Fig. 5 shows an electric drill with cutout section to reveal internal parts with the second figure providing a more detailed view. The drill's initial price is high enough for customers to consider purchasing a reworked version to save cost. It is a mature product, giving ample supply of used products to recondition, and to be cannibalised in reconditioning. Also, it should be noted that drills are not affected by fashion so their age and model are far less important than their functionality. As a whole it is not remanufacturable because of parts that cannot be returned to as new condition, for example, its trigger and other plastic parts. However, some of its more expensive internal parts like the motor can be returned to good working order but the reworked product's guarantee will be less than that of the new drill. The drill is thus repairable/reconditionable, but not remanufacturable.

Some of the opinions from a typical workshop on the product features influencing remanufacturing are shown in Table 2. The results from group A were excluded for this aspect of the workshop only, as they failed to indicate which activities of the remanufacturing process that the product features that they had identified influenced. Table 2 illustrates that particular product features may impact on several remanufacturing activities. For example, results from group B show that type of material has an influence on the remanufacturing activities of clean core, clean components, remanufacture components, and test product.

Table 2
Product features affecting remanufacturing in general identified from the workshops

Process activities	Workshop groups			
	A	B	C	D
Clean core		Material	Surface type Non-entrant shapes e.g. tight corners	Surface type Material
Strip core (disassembly)		Modularity and durability	Fixture/union method	Types of union e.g. glue rivets and crimps
		Design for disassembly features	Modularity	Standardisation
		Joining methods	Design for disassembly features	Ease of identification. Hybrid fixings
Clean components		Part complexity	Surface type e.g. smooth	Surface type, complexity and durability
		Material	Durability and complexity	
Remanufacture components		Method of effective union between parts	Standardisation	Extra material for rework
		Material type	Design for maintenance features e.g. components with "extra" material to enable rework	Modularity
			Parts complexity	High spec extra thickness and low fatigue materials
			Component condition identification	Easy identification
				Use of cheap exterior to assist reuse of expensive core
Store component		Durability Easy identification	Identification	Ease of identification
Build product (assembly)		Modularity, complexity	Design for assembly	Features enabling easy of assembly e.g. design for assembly features
		Durability, type of fixing		
Test product		Material	Easy identification features e.g. unambiguous labeling	Wear indicating features
			Features that record important details e.g. sensors to identify component history and condition, e.g. load and wear	Easy identification e.g. date

Group C identified different Design-for-X (DFX) approaches for different remanufacturing activities. DFX is an umbrella term for the many design philosophies and methodologies that help to raise designers' awareness of the characteristics that are most important in the finished product. The "X" in "DFX" may stand for one of the aims of the methodology for example, assemble-ability or manufacturability. The philosophies were developed to address lack of knowledge in important product life cycle areas, for example, manufacturing among designers. Both groups C and D noted that ease of identification of parts impacts on most of the activities of remanufacturing. Table 3 shows examples of the nature of the influence of some product features on some remanufacturing activities. Table 4 gives some key product characteristics influencing remanufacturing identified by the workshop participants whilst Table 5 shows the nature of the impacts of some of those features on remanufacturing.

Table 5 also shows that some product characteristics can have both a negative and a positive impact. For example, legislation has a positive impact because it requires organisations to undertake added value recovery of their products and is making waste disposal increasingly expensive and thus may encourage manufacturers to design remanufacturable products. However, when legislation bans the use of a substance, products containing it cannot be reintroduced into the market and hence would not be remanufactured.

Two major paradigm shifts affecting remanufacturing were identified. The first is the move from product sale to sale of capability (the move to "product-service" systems [20,21]). The second is the move by some companies away from manufacturing to assembly or bought-out parts. Regarding the first, traditionally, manufacturers sold products to their customers so there is transfer of ownership from the manufacturer to the customer. Today some

Table 3
Examples of product features assisting and hindering remanufacturing identified from the workshops

Process activities	Features facilitating remanufacturing	Features hindering remanufacturing
Clean core	• Smooth surfaces • Corrosion resistance. However, this will depend on the materials as some coating materials may peel leaving debris that may damage components • Non-adhesive surfaces. However, it may be difficult to maintain the integrity of such surfaces	• Rough surface texture • Shapes such as grooves, because these may make cleaning difficult, for example, because tight corners may be difficult to reach
Strip core	• Threaded fasteners and "breakable snap fits" • Modularity • Novel disassembly techniques e.g. soluble or shape memory fasteners	• Some types of welding and adhesives • Some riveting. Although rivets are not as bad as welding but they are still time consuming to remove
Remanufacture components	• Easy to replace degrading elements to better deal with mechanical wear and aesthetic damage • Standard parts, ease of component condition identification and parts with "extra material" for rework and cascading parts	Part complexity as this may increase remanufacturing resource, for example by necessitating a greater number of tests, operations and specialist knowledge

Table 4
Examples of product characteristics affecting remanufacturing identified from the workshops

Workshop groups			
A	B	C	D
Fashion	Fashion	Rate of technology change	Demand
Legislation	Legislation	Fashion and styling	Core availability
Obsolescence	Ownership (i.e. customer–user relationship)	Legislation	Legislation
IPR, patents, anti-competitive manufacturing	Technology stability	Cyclic nature	Locality
Old product to remanufacture	Maintenance	Wide variety of the product on the market	Business model type
Remanufacturing definition	Consumer acceptance and demand	Product life span V design life span	New product cost V remanufactured product cost
Tools for remanufacturing as used product component may differ from when new because of wear, corrosion, etc	Choice of business model (service or manufacture)	Business model	Availability of remanufacturing skill
Time and expense needed to remanufacture	Used product available	Demand	

manufacturers are opting to keep ownership of their product and to instead sell the product's capability to the customer—an example being "power-by-the-hour" in the aerospace industry. The manufacturer acts as a service provider and takes any risks associated with the product's failure. As the customer purchases only the guarantee of provision of capability the focus changes to the customer's satisfaction with the capability provided and the issue of the product's newness (number of life cycles) becomes less important. Regarding the move away from manufacture, to save costs some producers now purchase components from countries with lower labour costs and simply assemble these parts. This is leading to loss of the practical engineering skills required to remanufacture.

5. Summary

The workshop results indicate that a key issue in designing products for remanufacture is avoiding features that prevent the product or component from being brought back to at least like-new functionality. These include:

- Non-durable material that may lead to breakage during remanufacturing or to deterioration during use to the extent that product is beyond "refurbishment".
- Joining technologies that prevent separation of components or that are likely to lead to damage of components during separation.

Table 5
Examples of product characteristics impacts on remanufacturing identified from the workshops

Product characteristics facilitating remanufacturing	Product characteristics hindering remanufacturing
• Long product life V short product life. If product life were longer than the design life, by the time the product is ready for remanufacturing, technology would have moved on making it obsolete or undesirable to customers. Also, with long design life products there may be subassemblies that are remanufacturable even if the whole product is not • Service business model because the product is not consumer owned. • Relatively static design and low rates of technology change • Cascade of products between markets. For example initial life with more affluent, more developed countries then subsequent life following remanufacturing with less developed, less affluent countries • Legislation e.g. requiring end-of-life recovery or making disposal expensive • Cyclic nature because a manufacturer could use remanufacturing to prop up business when demand for major product is low	• High rate of technological change unless there is a cascading/"hand me down" type of policy • Styling and fashion • Manufacturers' prohibitive practices e.g. IPR and patents • Legislation e.g. emissions

- Features that prevent or discourage upgrading or that require banned substances or processing methods.
- Features that may make returning to as-new functionality cost prohibitive.

It was also noted that individual product features could influence several remanufacturing activities but that the nature of that influence may vary between the different activities. Thus, a particular product feature may have a positive impact on one remanufacturing activity and at the same time have a negative impact on another activity (s). For example, use of adhesive bonding may facilitate assembly but may also hinder disassembly.

The workshop results also suggest, however, that many of the key determinants of remanufacturability fall outside the designer's control. The major ones of these include legislation, demand, fashion and manufacturers' prohibitive practices. Remanufacturing is only appropriate where there is a market for the remanufactured product. Thus fashion-affected products are inappropriate because users may prefer the newer product no matter the quality and cost of the remanufactured alternative. Some customers demand newness as a lifestyle choice thus products, especially those requiring relatively low initial financial outlay or that are in prominent locations in homes, are generally less amenable to remanufacturing. Manufacturers' prohibitive practices such as patents, intellectual property rights and anti-competitive manufacturing also hinder remanufacturing. For example, some printer manufacturers have designed their inkjet cartridges so that they self-destruct when empty thus preventing their remanufacture. The workshop participants also suggested that design for remanufacturing enables learning and that technological obsolescence both hinders and assists remanufacturability. This is because if the technology for producing new components for a product is no longer available the only way of returning the product to working order may be to cannibalise parts from similar used products. However, if there are no old products to cannibalise, or good parts cannot be obtained from existing used products, and the technology for producing new parts becomes obsolete, then remanufacturing of the product would be impossible. It was also noted that remanufacturing was being affected by paradigm shifts in industry. The key ones identified were, manufacturers moving from product to service sale and from manufacturing and assembly, to assembly only. The former was said to favour remanufacturing by reducing customer demand for newness in the products they use. The later was said to hinder remanufacturing due to loss of the practical engineering skills required for manufacturing. These results are in line with the findings from literature survey (e.g. [12,22,23]) and from industrial case studies being conducted in associated research.

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