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Design for remanufacture: a literature review and future research needs

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ABSTRACT

'Design for Remanufacture' or DfRem, is an area of remanufacturing research that has received relatively high levels of interest in recent years, due to the recognition that a product's design may have a high impact on remanufacturing efficiency. However, the overall volume of literature dedicated to DfRem is low and there is still much to learn about the subject. The purpose of this literature review is to collate the current body of literature and establish a contemporary understanding of DfRem through analysing the trends, agreements and conflicts of opinion in the field. Much of the DfRem literature to date is focused upon the investigation of remanufacturing problems associated with product design, and the subsequent development of design methods and tools, either specifically developed to aid DfRem or as adaptations of existing design methods. These methods and tools vary in purpose and intended use but all largely remain within the academic realm to date. Within the literature there is widespread agreement that any approach to DfRem must consider both product and process, yet the 'design for X' definition of the task continues to spark debate. The key problems and issues that future DfRem research should address have been identified in this paper, from both within the literature and from the current gaps in the literature. Some key recommendations for future research include the need for 'lifecycle thinking' within design method development and the need for greater exploration into the organisational factors affecting DfRem integration into the design process, from the perspectives of the OEM and designer.

1. Introduction

1.1. Remanufacturing

Remanufacturing is the process of returning a used product to like-new condition with a warranty to match (Ijomah, 2002). The process includes sorting, inspection, disassembly, cleaning, reprocessing and reassembly, and parts which cannot be brought back to original quality are replaced, meaning the final remanufactured product will be a combination of new and reused parts. Detailed description of the remanufacturing process can be found in (Ijomah, 2007; Seitz and Wells, 2006; Sundin, 2004).

The concept of product reuse is certainly not new, and remanufacturing has been an increasingly common industrial activity since the Second World War. However, it was not until the late 1970s, early 1980s that interest in remanufacturing as an academic research topic began to emerge, with Robert Lund's original studies of the remanufacturing industry (Lund, 1984). This slow uptake of academic interest means that there is still much to learn about the subject. Today, however, interest in remanufacturing is rapidly increasing due to a greater understanding of its benefits and potentially important role in our changing society.

Firstly, remanufacturing can benefit the environment because often less energy and materials are required when compared to new manufacture, and used components are diverted from landfill (Lund, 1984). For detailed information on the environmental benefits of remanufacturing see (Amaya et al., 2010; Kerr and Ryan, 2001; Lindahl et al., 2006; Gutowski et al., 2011). Simultaneously remanufacturing can be a profitable business venture as material and energy savings can be translated to costs savings when compared to newly manufactured equivalents (Giuntini and Gaudette, 2003; Heese et al., 2005). Furthermore, extending the lifecycle of a product through remanufacturing will create additional profit when that remanufactured product is subsequently sold. Finally and critically, environmental legislation is becoming increasingly stringent, particularly in Europe (Guide et al., 2003), as can be seen in recent developments such as the WEEE (Waste Electronics and Electrical Equipment) and ELV (End of Life Vehicle) directives (European Paliament Council, 2000; European Paliament

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Council, 2003), as well as the influence of standards such as Germany's VDI 2243 (VDI, 2002) and the UK's BSI 8887 (British Standards Institution, 2009; British Standards Institution, 2010; Plant et al., 2010). Remanufacturing can be a way for many companies to meet this legislation in a profitable manner (Webster and Mitra, 2007). Remanufacture can be considered superior to the similar end-of-life strategies repair and reconditioning because the end result will be a higher quality of product with a longer extended life, making it more commercially viable (King et al., 2006).

One particular research area in the field of remanufacture is the concept of 'design for remanufacture', or DfRem. Research has indicated that whether a product is suitable for remanufacture or not greatly depends upon decisions made during the design process. There are specific product properties that may have a positive or negative effect upon particular remanufacturing process steps, such as disassembly or cleaning. The importance of considering remanufacturing issues in product design has frequently been referred to in the literature (Amezquita et al., 1995; Hammond et al., 1998; Ijomah et al., 2007a,b; Nasr and Thurston, 2006).

Improving remanufacturing efficiency through design may increase the profitability of remanufacture, making it a more viable and lucrative product end-of-life strategy. Therefore, research into the design-related requirements of remanufacture and how these can be achieved is a significant contribution to the overall remanufacturing research cause. It is this 'design for remanufacture' research that shall be the topic of discussion in this literature review.

1.2. Scope of literature review

The literature review is based upon the findings from journal and conference papers that were found to have relevance to the topic of design for remanufacture. Of these papers, only 37 were specifically about designing products for increased remanufacturability, dating from 1995 to 2011. Clearly this is a relatively new and unexplored research topic. The remainder of papers studied for this review fell under one of the following categories:

- Remanufacturing in general (the process, its importance and benefits).
- 'Design for Disassembly' (a related design activity that is commonly considered part of design for remanufacture guidance).
- End-of-life decision making in product design.
- Design for environment/ecodesign methods (design for remanufacture is often considered to be under the wide umbrella of 'design for environment' concerns).

These related papers have informed and influenced the making of this literature review; however they will not be included in the main discussion, as this review is about design for remanufacture specifically. The literature review sections of many previous DfRem papers, including Bras and McIntosh's (Bras and McIntosh, 1999) overview of remanufacturing research, have included discussions around related subjects such as end-of-life decision making and design for recycling. However, it has frequently been observed that there is still much confusion over the definitions of remanufacturing and other end-of-life strategies such as recondition, repair and recycling (Charter and Gray, 2008; Ijomah et al., 2004; Parkinson and Thompson, 2003; Parker, 2010). Discussing design for recycling or similar in a DfRem literature review will only add to this confusion. Furthermore, although DfRem is often considered to be a subset of ecodesign, the overall goals and benefits that can be achieved are considerably different meaning ecodesign and DfRem research are not entirely inter-changeable. Therefore the content of this review will focus only upon those papers that have clearly stated their intent to improve design for *remanufacture.*

For a general overview of remanufacturing literature, refer to (Bras and McIntosh, 1999) and (Subramoniam et al., 2009). For an overview of design for disassembly refer to (Desai and Mital, 2003; Go et al., 2011; Lee et al., 2001) and for an overview of literature on green product development and supply-chain management, refer to (Baumann et al., 2002; Ilgin and Gupta, 2010; Srivastava, 2007).

1.3. Purpose of literature review

Over the past 15 years or so, conference and journal papers on design for remanufacture have been slowly increasing. Of the 37 papers reviewed that are specifically dedicated to the subject, only 6 were published in 1995–1999, whilst 12 were published in 2000–2005 and 19 were published in 2006–2011. This would suggest that research interest in the topic is increasing, and as more research is conducted the overall understanding of what DfRem is and what it involves has improved. Although there is still much to learn, DfRem is not *quite* as 'new' and 'unknown' as it was for those studying it in the mid 90s, as these researchers have now provided a foundation upon which to build more detailed, specialised studies.

For these further studies to be well grounded, relevant and genuinely forward-moving it is important to begin with a clear understanding of what has been done before. Previously, Bras and McIntosh (1999) provided an overview of all aspects of remanufacturing research, including 'work seeking to improve product design for remanufacturing', the focus of this review. Their literature review offers a good introduction to early remanufacturing research, yet the ten year gap between this publication and the most recent DfRem developments means that there is a need for a new, more contemporary overview of the subject. Subramoniam et al. 2009) also discuss DfRem research in their literature review of remanufacturing for the automotive aftermarket, although not extensively or analytically.

Therefore, this literature review will aim to bring together the most key findings and developments in DfRem from recent years in order to establish what the present state of the art is, and from this provide suggestions as to where the research should go next.

This aim is achieved through a series of questions which were asked throughout the literature survey:

1. What is the present understanding of design for remanufacture?
2. What have been the trends, agreements and conflicts of opinion in this field?
3. What are the key problems and issues to be addressed by research today?

2. Literature review: understanding of the concept

2.1. DfRem definition and process

Very early studies of remanufacturing pay some attention to the properties of a typically remanufacturable product, such as durable cores capable of being disassembled, technological stability and the ability to upgrade (Lund, 1984). However, the idea that a product could be specifically designed to facilitate effective remanufacture is not proposed in these early papers.

The concept of 'design for remanufacture' as a design activity has arisen from the recognition that many of the technical barriers to remanufacture can be related back to how the product was designed (Ijomah et al., 2007a,b). Remanufacturing steps such as disassembly and cleaning cannot be carried out efficiently and effectively if the product has not been designed to accommodate them. So what exactly is DfRem? What does it involve? From a top-level perspective, there have been a variety of definitions presented in the literature, for example:

> *"Product design that facilitates any of the steps involved in remanufacture…"*(Shu and Flowers, 1999)
> *"Considering the product strategy (marketing, reverse logistics) and the detail engineering of the product in terms of remanufacture."* (Nasr and Thurston, 2006)
> *"A combination of design processes whereby an item is designed to facilitate remanufacture."* (Charter and Gray, 2008)

These descriptions provide a general overview of what DfRem is. Obviously the goal of DfRem is to enhance remanufacturability. To do this, a designer must actively consider each remanufacturing step, or issue, and how the design will affect them. The literature regards DfRem as a distinct design task; as the name would suggest, it is most often viewed as part of the concurrent engineering concept of 'design for X' (DfX), in this case X being remanufacture.

However, looking deeper, it would appear that from many researchers' perspectives DfRem is not simply one 'DfX' but in fact a number of different factors to be considered simultaneously. Sundin (2004) identified the relationship between different product properties and specific remanufacturing steps, as illustrated in the 'RemPro Matrix'. These different factors, such as ease of access or ease of separation, are achieved through appropriate product design. Conversely, if these properties are overlooked at the design stage, this may have an adverse effect on the remanufacturability of the product. The RemPro Matrix would therefore suggest that DfRem is not a single, homogenous task but actually a collection of many tasks or considerations whose prioritisation will differ depending on the processing needs of the product.

Similarly, Charter and Gray (2008) have described DfRem as a series of DfX activities: design for core collection, ecodesign, design for disassembly, design for multiple lifecycles, design for upgrade, and design for evaluation. Although worded and explained differently from the RemPro matrix, the overall goal remains the same: to facilitate the entire remanufacturing operation, through a number of tasks or considerations. Clearly, taking all these factors into consideration suggests DfRem must be a thorough, dedicated and perhaps lengthy task in order to be effective. Zwolinski et al. (2006) have criticised this 'DfX' frame of mind as it assumes that *'the remanufacturing process (and the business associated with) is perfectly known'*. Being required to consider each remanufacturing aspect individually may in theory be the most effective method, but in reality may be overly daunting to a designer. Nevertheless, the design for remanufacture task is most commonly outlined in these terms.

The next stage in understanding DfRem is to ask *how* one designs for remanufacture. This is a difficult question to answer as what enhances remanufacturability for one product, or one process, may differ from another. Therefore, much of the DfRem guidance offered in literature is fairly general. However, some researchers have attempted to compile lists of guidelines that could steer a design towards remanufacturability (Amezquita et al., 1995; Ijomah et al., 2007a,b; Ijomah, 2009). Others, whilst not explicitly offering a list of guidelines have offered similar guidance throughout their discussions (Charter and Gray, 2008; Shu and Flowers, 1999; Yuksel, 2010; Sundin and Lindahl, 2008). These guidelines will usually concern either the materials of the product, its structure/geometry or fastening and joining methods. They may also be linked to a particular remanufacturing concern, such as disassembly or durability. Such guidelines provide a clearer picture of what it means to design for remanufacture and consequently what properties a remanufactured product should have. However, there are still a number of problems and issues that these guidelines do not sufficiently address, such as conflicts with other design interests, subjectivity and guidelines customisation. There has however been some relevant research in the field of design for environment that has attempted to address similar problems, for example (Luttropp and Lagerstedt, 2005; Vezzoli and Sciama, 2006).

2.2. Participants in DfRem

The present understanding of DfRem (as presented in the literature) also includes the circumstances that enable this design activity to take place. Who should design for remanufacture, and why? Firstly, some researchers have felt it important to stress that not all products are suitable for remanufacture, either because it is not cost effective or the most environmentally preferable option (Lindahl et al., 2006; Shu and Flowers, 1999; King and Gu, 2010; King and Barker, 2007). Product end-of-life decision making is a topic outwith the scope of this literature review. For most DfRem research, it can be assumed that remanufacture has already been selected as the best end-of-life treatment for the product, and/or is already taking place. A company is considered a suitable candidate for remanufacture (and therefore DfRem) when their products possess certain qualities:

- A reverse flow of used products (Lund, 1984; Charter and Gray, 2008; Ayres et al., 1997).
- Customer demand for the remanufactured product (Ayres et al., 1997).
- High value, durable parts (Charter and Gray, 2008; Ayres et al., 1997).
- Technological stability (Lund, 1984; Charter and Gray, 2008).
- Potential to be upgraded (Shu and Flowers, 1999).

As well as the types of products, there has been some consideration of the kinds of companies that would benefit from DfRem. Lund (1984) states that there are three possible remanufacturing scenarios:

- OEM (original equipment manufacturer) remanufacturing, when the original producer is also responsible for the remanufacture of their used products.
- Contract remanufacturing, when a company remanufacture under contract from either the customer or the OEM, who continue to own the product.
- Independent, 3rd party remanufacturers who buy used products to remanufacture and resell. These companies have no connection with an OEM.

In much of the literature, it is only the first scenario- OEM remanufacturing- that is discussed as a feasible environment for DfRem (Amezquita et al., 1995; Charter and Gray, 2008; Bras, 2007; McIntosh and Bras, 1998). Indeed, the most common case study examples of DfRem used in the literature are OEMs such as Xerox, Caterpillar and Kodak. Common sense would explain why an OEM would have no desire to enhance the remanufacturability of a product simply to benefit an independent remanufacturer. In fact, it is not uncommon for an OEM to deliberately hinder remanufacture through either design or their own collection schemes in order to stifle this kind of activity, which is viewed as competition for their own new products (Hammond et al., 1998; Parkinson and Thompson, 2003; Matsumoto et al., 2010). However, if the OEM is directly involved in the remanufacture of their products, the following benefits may be gained, if they were to choose to engage in DfRem:

- Improved efficiency of existing remanufacturing activity e.g. reduced material waste or reduced disassembly times, resulting in greater profitability of the operation.
- Or, preparation for future legislative changes that will render end-of-life responsibility a necessity. The products designed today will be the waste of tomorrow, and a company that plans ahead could obtain competitive advantage.

Seitz (Seitz, 2007) carried out a study of automotive OEM incentives to remanufacture, and found that their reasons provided good justification for design for remanufacture. The study questioned the most commonly cited remanufacturing incentives: ethics (environment), legislation and profit, which Seitz did not feel were substantiated by sufficient empirical evidence. The case study findings concluded that automotive OEMs did not consider these factors key to their decision to remanufacture, and instead would remanufacture to ensure there was a supply of spare parts that would meet customer's demands for low prices and meet the company's warranty obligations. OEMs will also remanufacture to prevent independents from retrieving cores and potentially damaging OEM brand reputation. Seitz argued that these reasons were stronger incentives for an OEM to design for remanufacture than those traditionally cited.

In (Sundin et al., 2000, 2009; Sundin and Bras, 2005), the opportunity for DfRem within a 'product-service system' business model is discussed. Product-service systems is an emerging marketing concept in which the OEM will retain ownership of the physical product and instead sell the service that product offers. For example, a photocopier manufacture may charge customers per copy rather than charging a one-off amount for the equipment. That OEM would then be responsible for the maintenance and disposal of the product. This way the customer benefits from reduced responsibility whilst the OEM can benefit from the reuse of components, for example through remanufacturing. The referenced authors have therefore made an assertion that product-service systems and DfRem go hand in hand: an OEM involved in service selling would have every incentive to enhance remanufacturability through design, as a means of extending a physical product's lifecycle and therefore reducing manufacturing requirements, which are no longer the focus of a product-service system's business activities. Mont et al. (2006) demonstrate design for remanufacture and product-service systems with a case study of a baby pram and found the strategy to be financially feasible, albeit with high start-up investment. An overview of product-service systems literature can be found in (Coley and Lemon, 2008).

Alongside the discussion of who is suited to DfRem, the literature also provides some indication of the barriers and complications such a company may face despite the potential benefits of carrying out DfRem. Firstly, at present, industry does not fully appreciate the benefits of remanufacture and DfRem, and so it is not a priority issue to a normal designer. Most OEMs will primarily focus upon the product's production and use phases (Seitz and Wells, 2006; Charter and Gray, 2008). Furthermore, researchers such as Shu and Flowers (1999) have found that some DfRem principles are in direct conflict with prioritised issues such as manufacture and assembly. As long as this is the case, DfRem will be viewed as less valuable in terms of time and cost. As well as DfRem being viewed as unnecessary, there is a lack of DfRem awareness amongst designers (Ijomah et al., 2007a; Charter and Gray, 2008). Bras and McIntosh (Bras and McIntosh, 1999) say that '*remanufacture presents a fundamentally new set of challenges that producers are not prepared to deal with*'. Furthermore, the common confusion around the definition of remanufacturing (Ijomah et al., 2004) could mean that a company remanufactures without even knowing it, missing the opportunity to design for enhanced remanufacturability.

To summarise, DfRem is considered to be a distinct design activity that involves the consideration of a variety of design issues relating to remanufacture. DfRem could involve making decisions such as standardising parts or selecting a more durable material to optimise the remanufacturing process. It is most likely to occur when the OEM is carrying out remanufacture themselves, either due to environmental, legislative or economic reasons, or as a means of supplying spare parts. However, this simplified view should not overlook the challenges and barriers, as mentioned in the literature, that such 'ideal candidates' may face.

3. Literature review: state of the art

3.1. Trends in DfRem research

Much of DfRem research has involved the investigation of remanufacturing problems associated with product design, and the subsequent development of design aids: tools, methods and approaches that are designed to alleviate these problems at the product development stage. A summary of significant DfRem design aids is displayed in Table 1. Many of the design aids are in the form of mathematical models and software tools, others are static references designed to assess remanufacturability, and others aid in decision making or prioritisation.

Today, these aids remain largely within the academic realm: it is difficult to find any evidence of them being utilised in industry today (Nasr and Thurston, 2006). Part of the reason may be that OEMs will develop their own in-house methods and tools for activities such as DfRem, and may be reluctant to share knowledge of these with the outside world for competitive reasons. Also, three recurring issues are the complexity of these academic design aids, their lack of lifecycle thinking and the fact that most of these aids are only suitable for application late in the design process, when most major decisions have already been made.

Another trend in DfRem literature is to propose the use of existing design approach concepts considered relevant to the enhancement of remanufacturability. A summary of these suggestions is presented in Table 2. The advantage of using industry-wide methods, such as modularisation and QFD (Quality Function Deployment), is their familiarity- the designer may already be using these tools/methods or have understanding and experience of them, making DfRem integration much simpler. Also, these methods have other widely appreciated benefits outwith the interests of remanufacture, for example platform design is most commonly employed to reduce manufacturing costs and simplify the product development process. However, as these approaches have not been developed for DfRem purposes, they may not provide holistic assistance to improving the remanufacturability of products. Also, many are simply concepts and do not actually provide the designer with guidance as to how DfRem may be carried out.

Due to the fact that the subject of DfRem only appeared in the literature as recently as 15 years ago, it is difficult to note any clear changes in trends over time. However, it is interesting to note an apparent shift in perspective over the two decades. Whilst earlier developments focused upon finding technical, more quantitative solutions to the DfRem problem, for example Bras et al.'s (Bras and Hammond, 1996) DfRem metrics; recent research is more focused upon suggesting familiar design methods and improving the qualitative guidance provided to designers, for example (King and Burgess, 2005) platform design method and Ijomah et al. (2007a,b) robust DfRem guidelines. This change in direction could be due to the widely recognised belief that DfRem (or any significant 'DfX') is most effective when implemented early in the design process, when fewer decisions have been made yet less technical data is available (Amezquita et al., 1995; Zwolinski et al., 2006).

Table 1
Summary of DfRem design aids in the literature.

Approach	Author (s)	Format	Style	Key Purpose	Design Stage	Advantages	Disadvantages	Use in Industry
DfRem metrics	Bras and Hammond (1996); Amezquita et al. (1995)	Calculations/ software	Quant	Assess remanufacturability	Detail	• Process oriented. • Familiar concept (DfMA).	• Complex. • Retrospective. • No guidance.	No
Fastening and joining selection	Shu and Flowers (1999)	Calculations/ software	Quant	Selection of most economical joining method	Detail	• Lifecycle thinking.	• Complex. • Not holistic.	No
RemPro matrix	Sundin (2004)	Reference	Qual	Guidance, prioritisation of issues	Concept develop.	• Simple. • Offers guidance.	• Subjective. • No guidance.	No
REPRO2	Zwolinski et al. (2006); Zwolinski and Brissaud (2008); Gehin et al. (2008)	Software	Qual	Decision making, providing past examples	Concept generation	• Early in design process. • Does not require extensive knowledge. • Offers guidance.	• Subjective.	No
DfRem guidelines	Ijomah (2009); Ijomah et al. (2007a); Ijomah (2009)	Reference	Qual	Guidance	Concept generation	• Simple. • Offers guidance.	• Subjective. • Lack lifecycle thinking.	Unknown
DfRem metrics	Willems et al. (2008)	Calculations/ software	Quant	Assess remanufacturability, suggest improvements	Detail/redesign	• Lifecycle thinking. • Offers guidance.	• Complex. • Retrospective.	No
Hierarchical decision model	Lee et al. (2010)	Calculations	Quant	Design of product architecture for most profitable disassembly	Embodiment	• Lifecycle thinking	• Not holistic	No
Energy comparison tool	Sutherland et al. (2008)	Calculations	Quant	Compare manufacture and remanufacture energy usage	Detail	• Lifecycle thinking	• Not holistic • No guidance	No
Component reliability assessment	Zhang et al. (2010)	Calculations	Quant	Remanufacturing strategy decision making	Embodiment	• Customer focused • Process oriented	• Not holistic • No guidance	No

3.2. Trends in DfRem research demographics and methodology

Considering the demographics of DfRem research, there has been a clear shift across the Atlantic in recent years. DfRem research in the 1990s and early 2000s was most often carried out in USA or Canada, where remanufacturing has been established for the longest. However, research from the past seven years has been more likely to have been carried out in European countries such as Sweden, France or the UK. This change in demographic coincides with an increase in the number of papers concerning the environmental impact of remanufacturing, which in turn coincides with the introduction of stricter environmental legislation across Europe.

Another theme worth considering under DfRem research trends is the methodologies used by previous researchers. The 37 papers covering DfRem research were examined for information on adopted methodologies, the industry sector analysed in the study, and any products being used as case study examples. Although many papers did not specify what methodology was utilised to arrive at their findings, it would appear that case studies are

Table 2
Summary of recommended design concepts appropriate to DfRem.

Approach	Author (s)	Format	Style	Key Purpose	Design Stage	Advantages	Disadvantages	Use in Industry
Modularisation	Ishii et al. (1994); Kimura et al. (2001)	Concept	Qual	*Traditional:* improve manufacturing efficiency. *Reman:* ease of disassembly.	Concept develop.	• Familiar concept.	• Not holistic. • No guidance.	Yes
FMEA	Lam et al. (2000); Sherwood and Shu (2000)	Paper/ software	Quant	*Traditional:* prioritise and prevent product failure. *Reman:* reduce waste.	Concept develop, redesign	• Familiar concept. • Lifecycle thinking. • Process oriented.	• Not holistic. • Reliant on reman-OEM feedback. • No guidance.	Yes
Platform design	King and Burgess (2005)	Concept	Qual	*Traditional:* reduce manufacturing costs and retain customer choice. *Reman:* simplify process organisation.	Concept develop.	• Familiar concept. • Lifecycle thinking.	• Not holistic. • No guidance.	Yes
Active disassembly	Chiodo and Ijomah (2009)	Concept	Qual	Efficient disassembly.	Concept develop, detail	• Process oriented.	• Not holistic.	No
Design for environment tools	Pigosso et al. (2009)	Various	Varies	Improve environmental performance.	Various	• Lifecycle thinking.	• Not holistic. • Complex.	No
QFD	Yuksel (2010)	Paper/ software	Quant/ qual	*Traditional:* consider 'voice of the customer' to meet their needs. *Reman:* consider 'voice of the remanufacturer'.	Concept develop.	• Familiar concept. • Process oriented.	• Reliant on reman-OEM feedback.	Yes

Table 3
Summary of DfRem research methodologies.

Approach	Author (s)	Methodology	Industry Sector	Perspective
DfRem metrics	Bras and Hammond (1996); Amezquita et al. (1995)	Survey	Unknown	Remanufacturer
Fastening and joining selection	Shu and Flowers (1999)	Case study	EEE and ink cartridge	Remanufacturer
RemPro matrix	Sundin (2004)	Case study	Unknown	Remanufacturer
REPRO2	Zwolinski et al. (2006); Zwolinski and Brissaud (2008); Gehin et al. (2008)	Analysis/theoretical	Wide range	Designer (theoretical)
DfRem guidelines	Ijomah et al. (2007a,b); Ijomah (2009)	Case study	Various	Remanufacturer
DfRem metrics	Willems et al. (2008)	Unknown	Unknown	Unclear
Hierarchical decision model	Lee et al. (2010)	Unknown	Unknown	Unclear
Energy comparison tool	Sutherland et al. (2008)	Analysis	Automotive	Unclear
Component reliability assessment	Zhang et al. (2010)	Analysis	Automotive	Remanufacturer
Modularisation	Ishii et al. (1994); Kimura et al. (2001)	Theoretical	Unknown	Designer (theoretical)
FMEA	Lam et al. (2000); Sherwood and Shu (2000)	Case study	Automotive	Remanufacturer
Platform design	King and Burgess (2005)	Unknown/theoretical	Unknown	Unclear
Active disassembly	Chiodo and Ijomah (2009)	Various	EEE	Remanufacturer
Design for environment tools	Pigosso et al. (2009)	Literature review	Unknown	Unclear
QFD	Yuksel (2010)	Interviews	Automotive	Remanufacturer

a popular choice (see Table 3 and Fig. 1). This may be due to the fact that DfRem is a new and unexplored subject and case studies are considered an appropriate choice when there is little previous knowledge in the subject area (Eisenhardt, 1989; Yin, 2009). However, some of the earliest DfRem papers, from 1995 to 1996, adopted the more quantitative, survey approach (Amezquita et al., 1995; Bras and Hammond, 1996).

Considering industry sector and case examples (see Table 3 and Fig. 2), much research has been done from a generic standpoint. However it is interesting to note the frequency of research and examples from the electrical and electronic equipment (EEE) sector. This grouping included products such as washing machines, disposable cameras and photocopiers. However, these products do not always match the traditional definition of a remanufacturable product: high value parts and durable materials. Many of the products studied in these papers are more likely to be reconditioned or recycled at the end of their life, and therefore are not the most obvious choice for a remanufacturing paper. The reason for these choices may be due to the recent attention to consumer waste that has been drawn in by legislation such as the WEEE Directive, and that such products have been viewed as 'up and coming' in the remanufacturing industry, and so likely to play a more prominent role in the future when skills, knowledge and technologies have improved (Brent and Steinhilper, 2004). However, it could be argued that in the present time, case studies of mechanical/electromechanical are most relevant. Most of the discussion around EEE products concerns the initial decision to remanufacture or not. However, as it has already been established that mechanical products, such as automotive components, are often suitable for remanufacture (Steinhilper, 2001), the discussion has now moved towards how the process may become more efficient. This is when DfRem becomes of primary concern.

Fig. 1. The methodologies adopted in previous DfRem literature.

3.3. Agreements and conflicts

There are some points that are commonly brought up in the DfRem literature, that appear to have a general consensus around them. Firstly, although the style of proposed methods differs, what is widely agreed amongst key academics in DfRem research is that any approach to improving remanufacturability through design must consider the product and the process concurrently (Sundin, 2004; Ijomah et al., 2007a; Bras and McIntosh, 1999). It is also agreed that economic considerations must be at the forefront of DfRem considerations, there is little sense in improving remanufacturability if it will render the product not cost effective (Bras and Hammond, 1996; Linton, 2008). Some researchers have gone as far as to suggest that any DfRem decisions should be made primarily on economical terms (Shu and Flowers, 1999). From a business perspective, key academics cite the combination of remanufacture with product-service systems (where the OEM retains ownership of their products) as the ideal model to ensure the efficiency of reverse flow logistics and encourage more DfRem to take place (Sundin et al., 2000, 2009; Sundin and Bras, 2005). Such a proposal originates from the consensus that OEMs are only motivated to design for remanufacture when they are responsible for the remanufacture themselves (McIntosh and Bras, 1998).

There are also some instances where conflicts of opinion or conflicts of research findings can be found, most often one researcher or group of researchers speaking out against a common assumption. 'Design for remanufacture', as the name would suggest is normally explained in terms of 'Design for X', when a particular product quality if focused upon and enhanced (Sundin, 2004; Ijomah et al., 2007a,b; Charter and Gray, 2008). However, Zwolinski et al., (2006) criticise this definition as it assumes a level of knowledge that may not be present with designers. Shu and Flowers, (1999) have also identified a problem with remanufacture as a 'DfX': some DfRem principles are in contradiction with other 'Xs' such as assembly and environment. Similarly (Ijomah

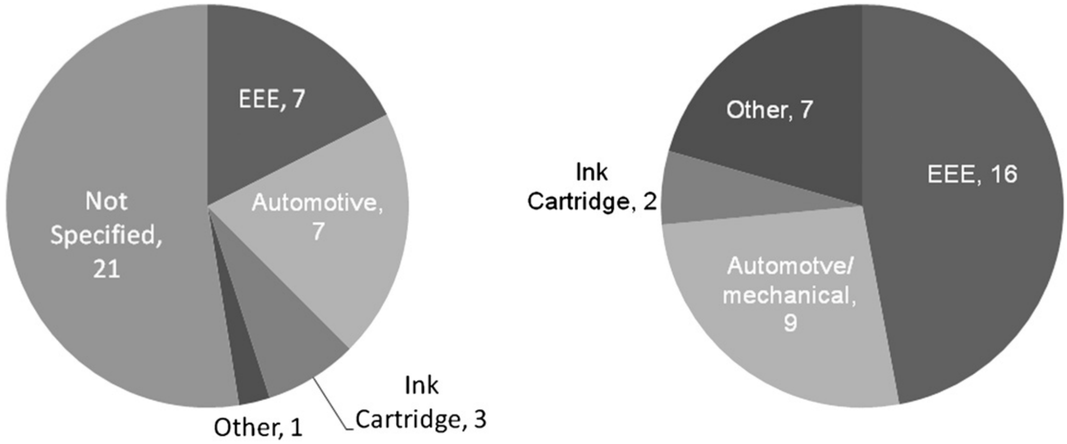

Fig. 2. Industry sectors studied in the DfRem literature (left) and case study examples present in DfRem literature (right).

et al., 2007a) criticised considering remanufacture in isolation when their findings revealed that a more 'remanufacturable' product may be inferior in terms of cost effectiveness and environmental performance when compared to a less remanufacturable design. Zwolinski et al., (2006) also argue that remanufacturing must be considered as early as possible in the design process, ideally at the 'concept generation phase' (Pahl and Beitz, 1996; Pugh, 1991; Ulrich and Eppinger, 2008). However, many of the tools being offered by academia, particularly those of a quantitative nature, are too complex and technical to be used at a very early stage (Sherwin and Evans, 2000), requiring vast amounts of data that have not yet been defined. By the time these details have been defined, it is often too late to make substantial changes to the design.

3.4. Summary

Tables 1 and 2 provide a summary of the key findings and theories in DfRem research to date. It is difficult to identify strong trends, agreements and conflicts due to the fact that design for remanufacture is a relatively young and unexplored research topic: the sample of papers under scrutiny is small. However, it would appear that the most common aim in DfRem research is design tool development, or the study of an existing tool/method's applicability to DfRem. Table 3 provides a summary of methodologies in DfRem research. Case study methodologies are popular in DfRem research, and electrical and electronic goods are commonly used to illustrate and test findings.

Whilst it is commonly accepted that any approach to design for remanufacture must consider both the product and the process, some academics believe that this is not enough, and that DfRem must not be carried out in isolation but must simultaneously consider other issues such as manufacturing, assembly and environment.

4. Future work in DfRem research

The previous two sections have discussed the key progressions in DfRem research to date: many ideas of what DfRem is, what it involves and what business conditions enable it to take place. There have also been a number of design tools and methods either developed or recommended to aid designers in improving the remanufacturability of their products. In around 15 years the research has progressed from an acknowledgement that product properties can have an effect on remanufacturing efficiency to clear lists of guidelines that can help achieve these properties. However, the volume of papers dedicated to DfRem is still relatively small, and the purpose of this literature review is to highlight those areas still lacking in knowledge. Some of those have been identified by previous researchers through an evaluation of their own findings, others have been identified though the act of reviewing the literature itself.

4.1. From the literature

The literature does not have a great amount to say about the future of DfRem research. Of those papers that do mention future work, many are concerned with the further development of their own DfRem methods and tools, or the need to study or test different products and case companies e.g. (Sundin and Bras, 2005; Bras and Hammond, 1996).

4.1.1. Tool development

It is clear to see that the majority of DfRem research so far has revolved around design methods and tools. However, there is very little evidence to suggest that any of these tools are commercially available and being used in industry today. Why is this the case? Criticisms in the literature may provide some explanation. For example, (Zwolinski et al., 2006) discuss a number of methods and tools, including Shu and Flowers' fastening and joining method tool, and are critical of the fact that they require significant knowledge of remanufacturing, can only be used in the later stages of product development, and only focus on one particular aspect of a product. Similarly in (Willems et al., 2008), Bras and Hammond's DfRem metrics are criticised for being overly complex and time consuming. Ijomah et al. (2007a) are critical of their own DfRem guidelines for not sufficiently including 'lifecycle thinking', as discussed previously.

Fundamentally, it could be said that current DfRem tools are insufficient, and not widely adopted, because they do not meet the needs of the user, whether this is because they are to complex, too time consuming, or something else. If the user's requirements are more fully understood, then methods and tools may be more effectively developed in the future. This is not to say that future DfRem research should necessarily continue to focus on more tool development, but there is certainly scope for future research to enable the development and improvement of existing ones.

There have already been similar studies in the area of 'design for environment' (DfE). In these studies, the term 'design for environment' usually refers to the basic principles of reducing pollutants, materials, toxicants and energy consumption, as well as the general concept of designing for end-of-life. These studies do not consider remanufacture specifically, and discussion around design for end-of-life tends to include recycling only. They do however provide an indication of the kind of factors that are likely to be important in DfRem tool development. For example (Lindahl, 2006; Lofthouse, 2006) studied designers' experiences, with a focus on current DfE methods and tools.

4.1.2. More case studies and examples of success

As mentioned above, many researchers identify the need for more case studies with different products or companies. Usually this need is discussed within the context of further validation of the researchers' findings or design tools, but there could be further advantages to contributing new and original product examples to the body of DfRem literature. The review of methodology has shown that there are certain products that are popular candidates for case studies and examples, such as photocopiers, ink cartridges and disposable cameras. These 'classic' examples are useful but do not represent the whole spectrum of remanufacturable products.

In the development of their REPRO2 design tool, Zwolinski and Brissaud (2008) have created remanufacturable product profiles based on 25 products that were identified as being successfully remanufactured. The profiles included car components such as engines and gear boxes, machinery such as pallet trucks and some medical equipment. In 2009 the Centre for Remanufacturing and Reuse, a UK consultancy, conducted an extensive survey of remanufacturing industry in the UK. It was found that the automotive, off-road equipment and pumps/compressors sectors all have a much higher presence in remanufacturing, when compared to electrical and electronic equipment, in terms of current and potential value (Chapman et al., 2009). Providing more varied and representative case study examples will not only enhance the robustness of any DfRem investigation, it will also provide greater inspiration to a wider variety of industry sectors. A company or designer may be more open to DfRem if they have real-life examples that are relevant to their own work.

4.1.3. 'Lifecycle thinking'

One clearly stated direction for future work is the need to incorporate 'lifecycle thinking' into design for remanufacture. Shu and Flowers,(1999) state that DfRem is often in conflict with other DfX methodologies such as assembly and manufacture. Ijomah et al. (2007a) developed a set of robust DfRem guidelines yet concluded with the words:

"There appears to be a lack of DfRem guidelines based on lifecycle thinking, that simultaneously consider products' dissimilar lifecycle profiles and the impact of remanufacturability enhancement product features on initial manufacture. However, this development would improve DfRem guidelines' effectiveness and robustness."

Some existing DfRem methods and tools have elements of lifecycle thinking, for example (Willems et al., 2008) DfRem metrics consider both product assembly and disassembly. However, it is evident that no design aid to date is fully holistic, taking all considerations and aspects of the product lifecycle into account.

4.1.4. The potential of DfRem with product service systems

As discussed previously in this paper, the idea of combining DfRem with a product-service systems business model has already been outlined by several key academics. However, these papers conclude with a call for more insight into the concept. Sundin and Bras (2005) state the need for more research into how this combination will work in practice, a need that is at least partially met in (Sundin et al., 2009), a series of case studies of Swedish companies involved in both service selling and remanufacture. However, the authors of this paper also conclude by stating a need for more study into the product requirements that facilitate both service selling and remanufacture. Mont et al.(2006) also state the need for deeper investigation of the real environmental benefits of such a strategy.

4.2. Identified knowledge gaps

4.2.1. Methodology: designer/OEM inclusion

It is apparent from this literature review that the methodologies followed by previous researchers have primarily involved the study of remanufacturers only. This means that DfRem aids to date, as well as the general understanding of the subject, have been developed solely from the remanufacturers' perspective. Researchers have identified design-related problems faced by the remanufacturer and developed a design aid aimed at solving these problems. It has not been considered how these design aids may fit in with the already-complex design process. This means that current DfRem approaches and tools may not fully address the needs of those who actually use them: the designers. A methodology that included the perspective of OEM designers could open up several new opportunities for DfRem research, including:

DfRem Integration: Despite the number of tools and approaches offered by recent research, the literature has indicated that few products are currently remanufactured and even fewer are designed for remanufacture (Seitz and Wells, 2006; Giuntini and Gaudette, 2003; Charter and Gray, 2008; Sundin and Bras, 2005). It would appear that DfRem methods and tools have been developed without questioning why DfRem continues to be an unknown or unpopular activity, despite its increasing visibility. Indeed, it has not been considered whether the provision of appropriate tools and methods is sufficient in securing DfRem's place in the design process. Factors that may affect the integration of DfRem have yet to be investigated.

Again comparisons can be made in the field of design for environment. There have been a number of investigations into the integration of DfE into the product development process. The research in this field is significantly more extensive than that of DfRem, and some of the most relevant findings may suggest that there is more to DfRem implementation than simply developing design tools. For example, Johansson (Johansson, 2002) carried out an extensive literature review with the aim of identifying the key success factors for DfE implementation. Several 'areas of concern' were identified, including management, the development process, competence and motivation. Other interesting studies of DfE integration can be found in (Akermark, 2003; Boks, 2006; McAloone, 2000; O'Hare et al., 2007; Ries et al., 1999).

DfRem Knowledge Requirements: It has been noted that the problem of little DfRem activity has occasionally been accounted for by the claim that designers are lacking in required knowledge and understanding (Ijomah et al., 2007a; Charter and Gray, 2008; Ijomah, 2010). However, these statements are not fully substantiated by empirical evidence, and may be presumptions based solely on the consensus that few products are currently designed for remanufacture. Furthermore, the cited 'cause' of this problem- that few products are designed for remanufacture because designers lack knowledge- is a problem itself that requires further investigation and greater understanding. What is the knowledge that designers lack, that is essential to effective DfRem? Current research has not yet addressed how this problem may be overcome.

4.2.2. Investigation of Contract remanufacturers and DfRem

Although it is clear that an OEM would not want to design for remanufacture if the benefits were being received by a competing 3rd party remanufacturer, the literature has very little to say about

Fig. 3. The sequence of situations that could lead to the increased relevance of DfRem research.

the second of Lund's (Lund, 1984) scenarios, the contract remanufacturer. If the OEM is paying a contractor to carry out remanufacture for them, improving efficiency through design could lower this cost. However, the practicalities of this possibility, such as the protection of intellectual property, have yet to be fully explored. It would be interesting to know more about how OEMs with remanufacturing contracts consider remanufacturing in their design process, how they communicate with the remanufacturer and what potential there is for DfRem in such an environment.

4.2.3. Empirical study of the value of DfRem

Over the years much has been written about the benefits that can be gained from designing certain products for remanufacture, and of course every paper dedicated to the subject will begin with some kind of justification for the research. DfRem improves remanufacturing efficiency and allows more products to be remanufactured, saving costs, generating new profit and benefiting the environment. However there is a lack of empirical evidence presented in the literature that demonstrates these benefits in practice. There is a need for more case studies and analysis that effectively demonstrate exactly how and to what degree DfRem has an impact on the remanufacturing process and the various stakeholders involved.

Lindahl et al. (2003) carried out a study to determine exactly how environmentally beneficial remanufacture was when compared to recycling and new manufacture, by carrying out lifecycle analysis for various products under the three scenarios. Generally, remanufacturing was found to be the most environmentally preferable option, however this was not the case in situations where there were greater transport needs to carry out the remanufacturing. If a similar study were carried out to compare remanufactured products that are designed for remanufacture and those that are not, academia would have a better understanding of when DfRem is an appropriate strategy and how much priority DfRem research should receive in comparison to other remanufacturing issues.

5. Conclusions

This literature review has presented the state of the art in design for remanufacture research, using journal and conference papers published on the subject from the past 15 years. Based on this literature the 'current understanding' of what DfRem means, what it involves and who it involves has been discussed. The trends in DfRem research have also been discussed in terms of design tool development, adopted methodologies as well as the common agreements and conflicts amongst leading remanufacturing academics to date. Following this presentation of the state of the art, the literature review has identified scope for future investigations that would enhance our understanding of DfRem, and in doing so has offered a suggestion as to the next steps DfRem research should take.

Design for remanufacture is an area of remanufacturing research that has received a relatively generous amount of attention over the years; it is widely acknowledged that it is the design stage of any product's lifespan that has the biggest impact on issues such as cost, manufacturing and end-of-life possibilities. However, remanufacturing research as a whole is limited to a small number of papers published over the past three decades, and the importance of expanding DfRem knowledge and working further towards increased DfRem activity in industry should not be overlooked.

It could be argued that the relevance of DfRem research has increased in recent years. The trend in the volume of DfRem research published would certainly seem to suggest this. Fig. 3 illustrates in simple terms how this increased relevance has occurred, from our increased environmental awareness through to an anticipated increase in OEM remanufacturing activity. Yet, in reality, it would seem that this increase in DfRem activity and increased appreciation for the importance of DfRem is yet to be realised. There are many products today that are at the end of their lives- or still on the market- that could in theory be good candidates for remanufacture, based on similar examples, yet their designs prevent this from being so. Furthermore, it would seem that many of the products that are remanufacturable today are more so through 'serendipity' rather than conscious design effort (Amezquita et al., 1995). If this problem continues un-investigated, OEMs may not achieve their full potential in terms of remanufacturing process efficiency and the number of products that can be successfully remanufactured.

This literature review has outlined several potential paths for further DfRem research, such as lifecycle thinking, design process integration and DfRem knowledge requirements. However the common goal and overall need of future DfRem research is to gain an enhanced understanding of the DfRem concept, one that is grounded in the current situation in industry. There is a need to understand DfRem in the context of current practices, current incentives and the current needs of participants.

It is the authors' belief that it is particularly crucial that future work considers the needs of the designer- in the context of an OEM. Much of the previous DfRem research has involved the development of design tools, and it could be argued that this has been a leap too far ahead, considering the users of such tools have yet to be consulted. Considering the perspectives of the OEM and the designers- as well as the remanufacturer- reveals a number of unexplored avenues that could contribute towards a greater understanding of remanufacture and product design.

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