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## Article

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## Disassembly for Remanufacturing: A Systematic Literature Review, New Model Development and Future Research Needs

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### Abstract:

**Purpose:** Disassembly is an important process that distinguishes remanufacturing from conventional manufacturing. It is a unique process that becomes focus of investigation from many scholars. Yet, most scholars investigate disassembly from technical and operational standpoint that lack of strategic perspective. This paper attempts to fill this gap by looking at disassembly from a strategic perspective by considering organisational characteristics, process choices and product attributes. To be more specific, this paper has three objectives. First, to gain understanding what has been done, and what need to be done in the field of disassembly in remanufacturing. Second, to conduct a systematic literature review for identifying the factors affecting disassembly for remanufacturing. Third, to propose a new model of disassembly for remanufacturing and also to provide avenues for future research.

**Design/methodology/approach:** This study used a systematic literature review method. A series of steps were undertaken during the review. The study was started with determining the purpose of the study, selecting appropriate keywords, and reducing the selected papers using a number of criteria. A deeper analysis was carried out on the final paper that meets the criteria for this review.

**Findings:** There are two main findings of this study. First, a list of factors affecting disassembly in remanufacturing is identified. The factors can be categorised into three groups: organisational factors, process choices and product attributes. Second, using factors that have been identified, a new model of disassembly process for remanufacturing is developed. Current studies only consider disassembly as a physical activity to break down products into components. In the new model, disassembly is viewed as a process that converts into into output, which consist of a series of steps.

**Research limitations/implications:** The opportunities for future research include: the need to develop an index of factors affecting disassembly, and how to most appropriate relationship between original equipment manufacturers and contract remanufacturers to share knowledge gained from remanufacturing operations to improve product remanufacturability.

**Practical implications:** Remanufacturers should not focus on product attributes only in order to manage their disassembly process efficiently. Rather, more strategic factors such organisational factors and process choices should also be considered as well.

**Originality/value:** This is the first study that identifies a comprehensive factors affecting disassembly in remanufacturing. In addition, it is for the first time that disassembly is not only viewed as a physical activity, but it is a process that consists of a series of step.

**Keywords:** remanufacturing, disassembly, sustainability, cores recovery, life cycle analysis, reverse logistics

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## 1. Introduction

Remanufacturing is a process where used products, which are referred to as “cores”, are returned to a good as new condition, and offers a guarantee of the same or higher level performance than new products (Ijomah, Childe & McMahon, 2004; Thierry, Salomon, Van Nunen & Wassenhove, 1995). Activities in the remanufacturing process include sorting, disassembly, cleaning, inspection and rebuilding (Ijomah, McMahon, Hammond & Newman, 2007; Ijomah, 2008; Thierry et al., 1995). A more detailed discussion on the remanufacturing process can be found in Lund (1984), Seitz and Peattie (2004) and Ijomah (2002).

Disassembly, one of the overall processes of remanufacturing, is a critical process for several reasons. It is the key link that connects product return with product recovery (Du, Cao, Liu, Li & Chen, 2012), and a prerequisite for other processes. It also is the main gateway of information, where much data related to

remanufacturing operations originates (Guide Jr., 2000; Guide Jr, Jayaraman, Srivastava & Benton, 2000; Junior & Filho, 2012). Information is valuable as it helps to minimise uncertainty in activities that are related to remanufacturing such as purchasing new parts, inventory management and production planning, and scheduling (Ferrer & Whybark, 2001; Ferrer & Ketzenberg, 2004; Ferrer, 2003). The importance of information acquired in disassembly increases when remanufacturers are dealing with complex products (Ferrer & Ketzenberg, 2004).

Knowledge and expertise regarding disassembly for remanufacturing is unique, because it is not readily available. This is due to the fact that such knowledge is only acquired by remanufacturers (Zhu, Gu, Wen & Yu, 2008). The accumulation of the knowledge are thereafter can be developed into industry standard for remanufacturing (Lind, Olsson & Sundin, 2014). Even though original equipment manufacturers (OEMs) have some advantages in that they possess new product specifications, they still find it difficult to do disassembly. A new product specification can be a good starting point for undertaking disassembly; however, disassembly is not merely the reverse of assembly (Nasr, Hughson, Varel & Bauer, 1998). Products being used in extreme conditions or unusual patterns can change the joints of products and consequently alter the original disassembly sequence that was developed using the new product specification. Moreover, modifications made by users, and defective parts can cause the original product specifications to become less relevant in disassembly (Gungor & Gupta, 1998; Tang, Zhou, Zussan & Caudil, 2002).

Companies can increase profitability through reducing uncertainties, and disassembly is a significant cause of uncertainties (Aksoy & Gupta, 2010). The advantages of reducing uncertainty in disassembly relate to production planning and control, including increased component matching (Guide Jr., 2000), shorter lead-time for new parts orders (Ferrer, 2003) and a reduction in inventory cost (Li & Rong, 2009). One of the more significant benefits is the increase in part matching during the reassembly process, which is one of the main challenges in remanufacturing (Guide Jr., 2000; Hammond, Amezcua & Bras, 1998). If these problems has been addressed successfully, profitability increases (Ferrer & Whybark, 2001; Klausner, Grimm & Hendrickson, 1998).

Using a survey of literature, Gungor and Gupta (1999), perform a literature review to identify main issues in environmentally conscious manufacturing and product recovery (ECMPRO). Eleven years later, a more updated literature undertaken by Ilgin and Gupta (2010) classify ECMPRO into four areas: environmentally conscious product design, reverse and closed-loop supply chain, remanufacturing, and disassembly. Of the four categories, disassembly play a critical role as it determines the success of the others.

Considering the importances of disassembly discussed above, it is clear that an in-depth examination of disassembly from a strategic perspective can offer significant contributions to the overall remanufacturing practices. In pursuit of this aim, the paper has three objectives. First, to map out what has already been

done in the field of disassembly in general and to identify what have been missing from current investigations. Second, to conduct a systematic literature review around the key gaps to identify the factors that affect disassembly in remanufacturing. Third, to propose a new model of disassembly in remanufacturing based on the results of the systematic literature review. Lastly, to provide directions for future research.

## 2. Current Research in Disassembly – An Overview

The central focus of this exploratory literature review is to map out what research has already been carried out in the field. As a result, it is possible to identify which research avenues are available for future research investigations, and to determine whether the recent research extends previous research, replicates existing studies, or is an entirely original work that attempts to fill a research gap (Creswell, 2014; Tranfield, Denyer & Smart, 2003).

In general, it was found that there have been an abundant number of studies conducted in the field of disassembly, and some of them have addressed remanufacturing in particular. However, it seems there is no study that has yet attempted to integrate all of the relevant factors for disassembly using a comprehensive analysis. As can be seen in Figure 1, the studies on disassembly for remanufacturing are segregated across many different topics.

The exploratory analysis found that the majority of existing studies on disassembly are purely theoretical, using mathematical modelling and simulations. This finding supports previous studies from Tang and Naim (2004) and Junior and Filho (2012), who argue that research in remanufacturing is predominantly quantitative. *Decisions in disassembly* and *product attributes* affecting disassembly are two of the most popular topics in this area. Of the three decisions made in the disassembly process – level, method and sequence of disassembly - the sequence of disassembly is the most popular one in existing research.

There are a number of previous literature review related to this topic. A comprehensive literature review pertaining to disassembly sequence was carried out by Lambert (2003). Similarly, the parameters of disassembly performance have been discussed in many studies (Ilgin & Gupta 2011; Loomba & Nakashima 2012; Tian, Liu, Ke & Chu, 2012). These topics sometimes contain environmental analysis and discuss how disassembly can contribute toward waste reduction (Tian et al. 2012). The topics of *Evaluation methods* are a less popular research area compared to other topics; nevertheless, it does have influence on other studies, as the parameters used in the evaluation methods are modified or expanded by some researchers (Go, Wahab, Rahman, Ramli & Azhari, 2011).

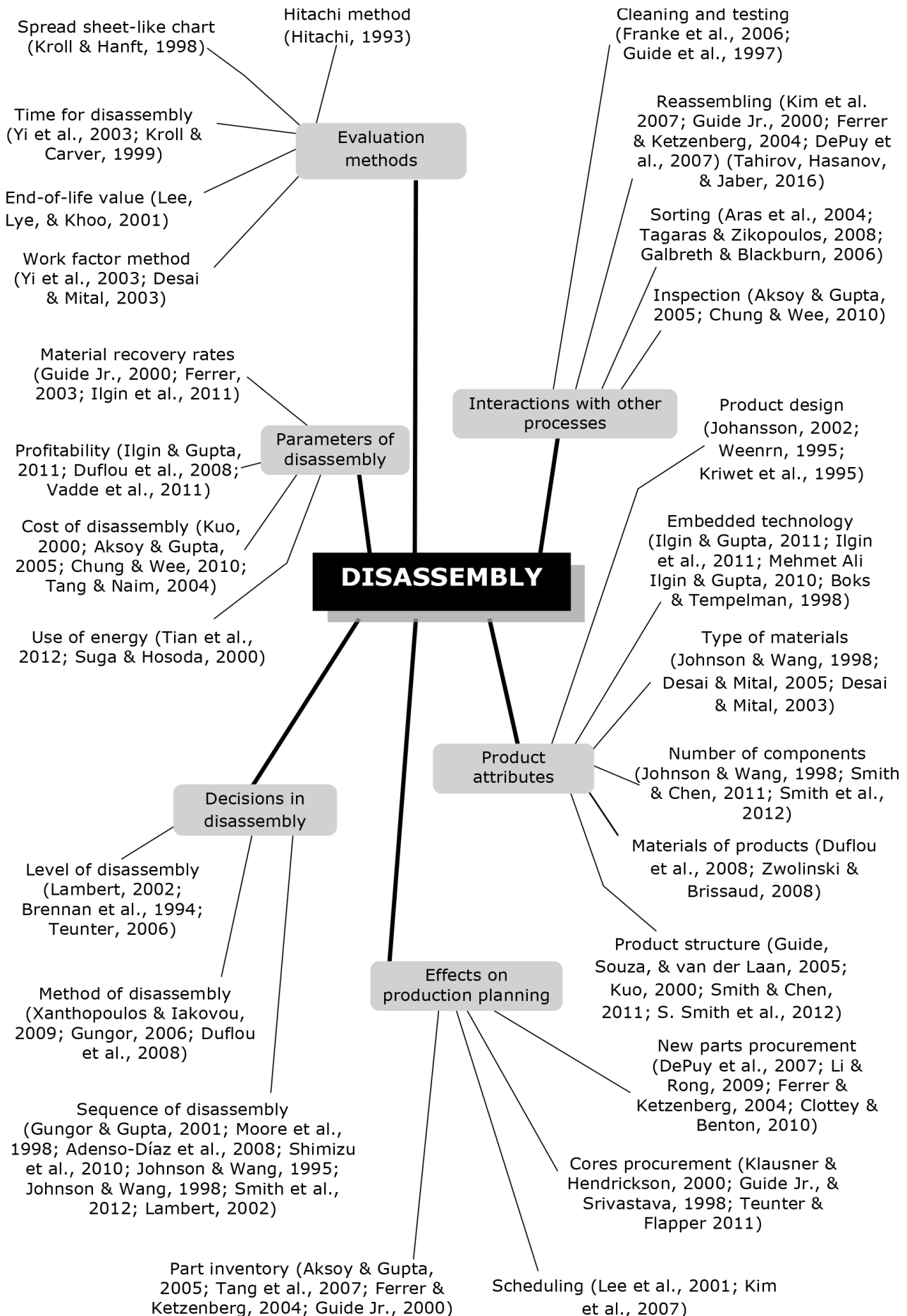


Figure 1. Map of existing works in disassembly

In general, the drawbacks of the existing research on disassembly can be summarised as follows:

- Existing studies investigate disassembly from purely operational perspectives, and lack analysis from a strategic perspective. Some relevant strategic issues in remanufacturing such as cores-supplier relationship (Lind et al., 2014; Östlin, Sundin & Björkman, 2008), inter-organisational knowledge exchange (Ijomah, 2009) and investment in facilities (Östlin et al., 2008) have been overlooked.
- The majority of the analysis of disassembly focuses on the “hard” side of the process, such as product structure, type of materials and interrelationships between components. There are four studies that have defined what disassembly is; however the definitions consider product attributes and put emphasis on hard side only (Aksoy & Gupta 2010; McGovern & Gupta 2007; Li & Rong 2009). On the other hand, the soft side of disassembly, such as factors such as product information (Ferrer & Ketzenberg, 2004; Yi, Park & Lee, 2003), the skills of the employee, human factors (Bley, Reinhart, Seliger, Bernardi & Korne, 2004), product innovativeness (Chiodo & Ijomah, 2012; Santochi, Dini & Failli, 2002) and the experience of the employees (Reveliotis, 2007; Yeh, 2012), are largely overlooked by these definitions.
- From a methodological point of view, the vast majority of studies have been conducted under a positivist paradigm, using quantitative methods. Very often, the results of mathematical modeling are valid only in situations where all the assumptions used by the given study have been met (Flynn, Kakibara, Schroeder, Bates & Flynn, 1990).

In order to overcome these drawbacks, this paper attempts to fill the research gaps by exploring disassembly from a strategic perspective combining both soft and hard factors. This aim is in line with a statement in existing literature suggesting that research in remanufacturing should consider not only product attributes, but also organisational characteristics and process choices (Bras & McIntosh, 1999; Bras, 2004; Hermansson & Sundin, 2005). Any effort to improve product remanufacturability should consider product and process concurrently (Bras & McIntosh, 1999; Ijomah et al., 2007). This is because design for remanufacturing might be in contradiction with other purposes such as design assembly and environment (Shu & Flowers, 1999).

### 3. Disassembly in Remanufacturing: A Systematic Literature Review

#### 3.1. Literature Review Method

Creation of new knowledge is enabled through use of systematic literature reviews (Tranfield et al., 2003). To ensure robustness of conclusion drawn from the literature review, there are a number of criteria to determine the suitability of publications to be included in the review. As suggested by Tranfield et al. (2003), the first decision is regarding the key words used for article selection. Initially, the keyword “disassembl\*” and “dismantl\*” were entered into four databases (Emerald, ProQuest, ScienceDirect and JSTOR) to identify relevant keywords, title and abstract.

This initial literature search identified over 35,000 articles, indicating that there is an abundance of studies addressing this topic. The large quantity of existing research is not surprising, due to the general nature of the keyword used for the search. However, it is not feasible to select and study such a large number of papers; thus, a set of formal decisions were applied, which narrowed down the number of selected papers and increased the relevance of the search results. Second, an additional keyword, “end-of-life”, was entered. The results of this second search yielded fewer results, 1,169; however, this is still too many for a systematic literature review. There are several possible end-of-life strategies, and remanufacturing is just one of them. The large number of findings yielded through a search combining the keyword “disassembly” with “end-of-life” are partly due to the fact that these search terms cover various end-of-life strategies, including re-use, remanufacturing, reconditioning and recycling. Thus, the researcher carried out a third search, replacing the key word “end-of-life” with a more specific end-of-life strategy, “remanufactur\*”. As a result, the number of results was significantly decreased, to 355; this reduction convinced the researcher that a large portion of the existing research into disassembly is not specifically intended to be relevant to remanufacturing.

In the process shown in Figure 2, book chapters, magazines, and conference papers were excluded. Using this method, this article search yields only high quality peer reviewed articles, of which there were 221 papers. Next, the results from searching four databases were combined, and duplications were eliminated from the list, leaving just 145 papers, which are sourced exclusively from scientific journals.

Then, the titles and abstracts of selected papers were read in order to assess the relevance of the papers; through this process, 17 papers were excluded, leaving 128. Next, “Bird-eye-scanning”, a speed-reading technique, was used to select the most suitable papers for the review; this was achieved by reading the abstract, introduction and conclusion of each paper to assess their suitability. Using this technique, 27 papers were excluded, meaning that 101 papers remained.



In selecting the papers included in our literature review inclusion/exclusion criteria was focused around papers that looked at disassembly in a remanufacturing context; that were strategic in nature and that addressed soft and/or hard factors identified earlier. As can be seen in Figure 2, as the keyword became narrower, and more criteria were applied, the number of findings decreased correspondingly.

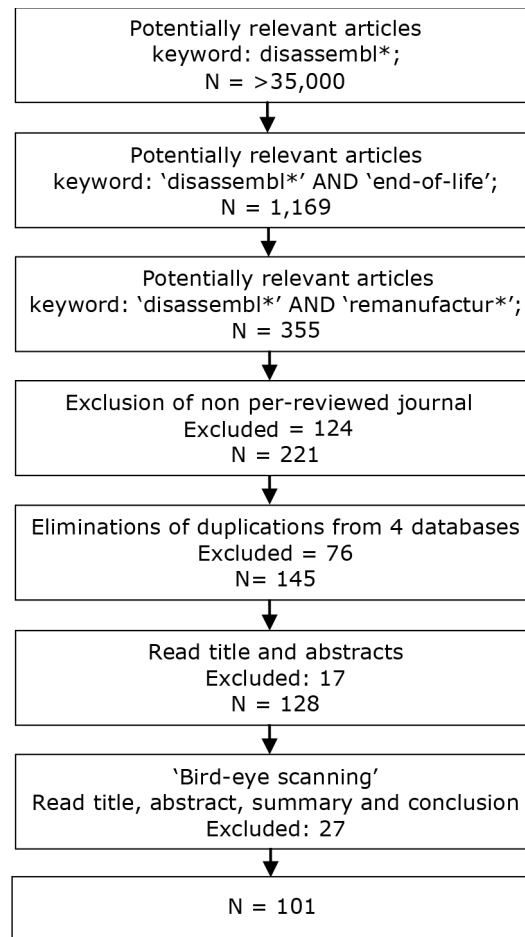


Figure 2. Procedures of literature selection process

Some of the selected papers coincidentally are also discussed in the exploratory literature review as presented in Section 2. Nevertheless, most of the papers are not. This indicates that factors affecting disassembly for remanufacturing is specific; there are factors affecting disassembly for other recovery methods that might not count in disassembly for remanufacturing.

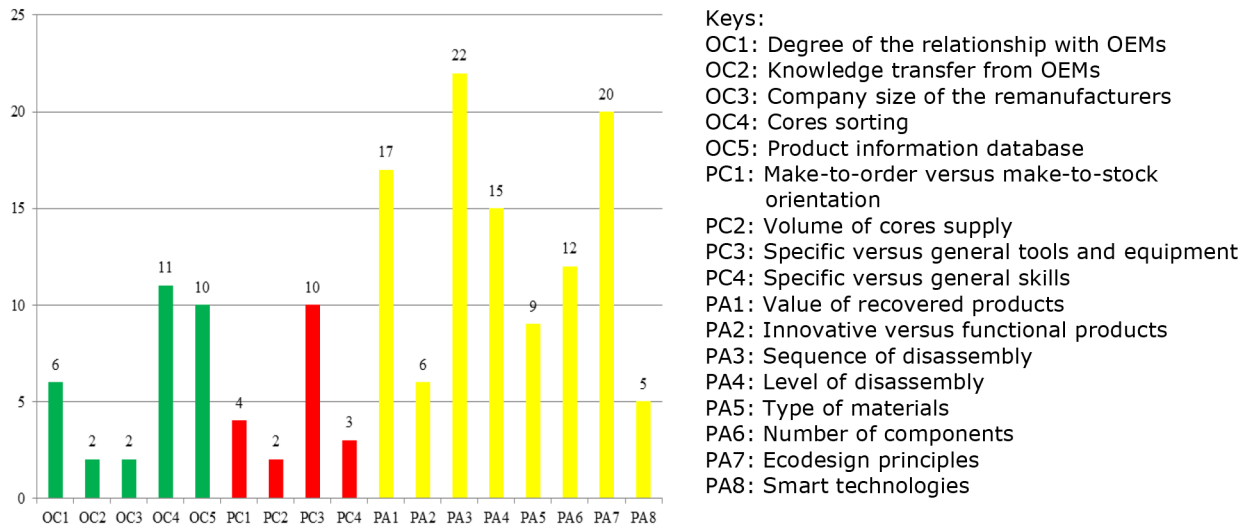


Figure 3. Factors affecting disassembly identified from the literature review

Next, the articles were analysed to identify factors that affect disassembly. Of 101 publications 21 articles do not discuss factors that affect disassembly and 17 factors were identified which are classified into three groups: organisational characteristics, process choices and product attributes as summarised in Figure 3. Since a publication might contain more than one factor, there are publications that appear more than once in Figure 3. In the following paragraphs we present our findings from literature search under the following headings:

- Disassembly in the Context of Remanufacturing – A general overview
- Organisational Characteristics
- Process Choice
- Product Attributes

### 3.2. Disassembly in the Context of Remanufacturing - A General Overview

Disassembly in the context of remanufacturing is embedded in a series of processes that are interrelated. Understanding of the context of remanufacturing as the foundation to develop a new model of disassembly is important because assuming disassembly as an independent process will make the research into the topic less relevant. The position of disassembly within the process of remanufacturing is presented in Figure 4.

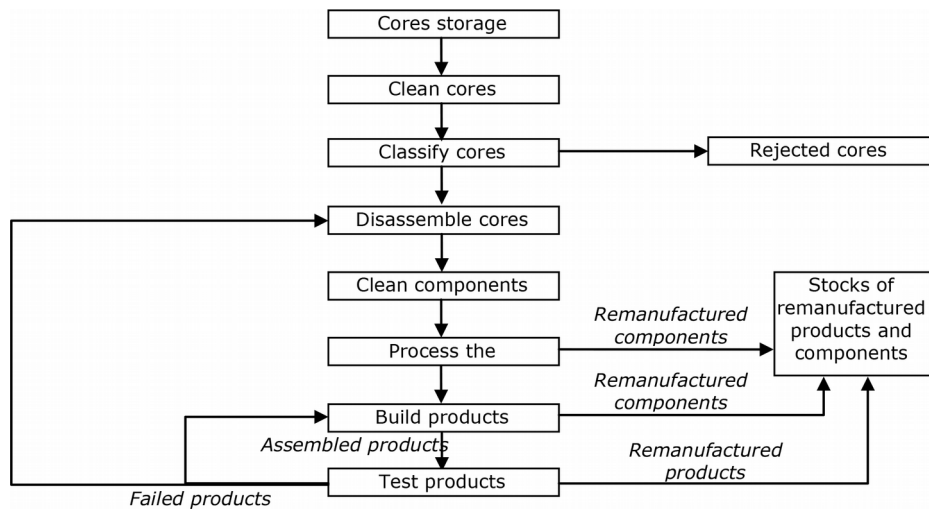


Figure 4. Process of remanufacturing (Ijomah et al., 2007)

Uncertainties are frequently mentioned as the main issue in every process of remanufacturing, including disassembly (Guide Jr et al., 2000). The uncertainties in disassembly can be divided into three different types. These are: the uncertainties that exist prior to disassembly, the uncertainties that happen during disassembly and the uncertainties that are found in other processes after disassembly, which is presented in Table 1. These uncertainties interplay with one another, and any failure to understand how these uncertainties interrelate would make research into disassembly less relevant.

Uncertainties coming from processes prior to disassembly	Uncertainties that happen during disassembly	Uncertainties in other processes subsequent to disassembly
<p><b>Customer order.</b> Uncertainty from customers involving the number and timing of orders, as well as the types of products (Kongar &amp; Gupta, 2006).</p> <p><b>Cores sorting.</b> Cores sorting reduces uncertainty about quality, but does not reduce uncertainty about quantity. Thus, cores sorting creates uncertainty in terms of the numbers of cores that are qualified for disassembly (Loomba &amp; Nakashima, 2012).</p> <p><b>Supply of cores.</b> The uncertainties predominantly come from outside remanufacturers. These include the type of cores, the quality and quantity of cores, as well as the time of arrival. These uncertainties affect almost all of the processes in remanufacturing (Jayaraman, 2006).</p>	<p><b>The level of optimum disassembly.</b> The optimum level of disassembly that should be carried out is uncertain (Lee, Cho &amp; Hong, 2010; Colledani &amp; Battaia, 2016)</p> <p><b>Number of cores to disassemble is uncertain.</b> This decision is related to product rebuild (Ferrer &amp; Whybark, 2001) and the optimisation of the holding costs of disassembled components (Li &amp; Rong, 2009).</p> <p><b>The sequence of disassembly.</b> The purpose of this decision is to obtain the sequence with the lowest cost (Smith &amp; Chen, 2011; Smith, Smith &amp; Chen, 2012; Colledani &amp; Battaia, 2016).</p> <p><b>Which parts should be taken out and which should not.</b> This decision aims to optimise the cost of disassembly (Desai &amp; Mital, 2003), particularly in the cases of selective and partial disassembly.</p> <p><b>What recovery method is suitable for disassembled components.</b> There needs to be a justification as to whether some components can still feasibly be remanufactured, otherwise they will be recycled (Vadde, Zeid &amp; Kamarthi, 2011).</p> <p><b>Disassembly yield.</b> How much recovered value from the cores would be gained. Early yield information that can be gained from disassembly reduces the dependency on new components (Ferrer, 2003; Inderfurth, Vogelgesang &amp; Langella, 2015).</p>	<p><b>Purchasing of new parts.</b> What parts to order, how many and how long the lead time is (Ferrer &amp; Ketzenberg, 2004; Ferrer, 2003). These decisions rely on the results gathered from disassembly.</p> <p><b>Product rebuild.</b> There is a need to match parts from disassembly, the inventory and new parts from suppliers (Ferrer &amp; Whybark, 2001; Ferrer &amp; Ketzenberg, 2004).</p> <p><b>Routing of each part during testing, cleaning and reprocessing.</b> Each disassembled component requires different routes for reworking and reprocessing (Guide Jr., 2000).</p> <p><b>Product costing and selling price.</b> The cost of products (Ferrer &amp; Ketzenberg, 2004) and their selling prices (Vadde et al., 2011; Wu, 2012, 2013) depends on the recovery rates of the disassembly.</p> <p><b>Number of inventory.</b> This involves an inventory of disassembled components (Ferrer &amp; Ketzenberg, 2004; Tang, Grubbstrom &amp; Zanoni, 2007) and remanufactured products (DePuy, Usher, Walker &amp; Taylor, 2007).</p>

Table 1. Uncertainties coming to and from disassembly

As we mentioned previously, existing definitions of disassembly do not specifically address the context of remanufacturing. Thus, there is a need to specifically address how the model of disassembly for remanufacturing, which covers what activities are included in disassembly, the sequence of these activities, and the stages when disassembly starts and finishes.

### **3.3. Organisational Characteristics**

#### **3.3.1. Degree of the Relationship with OEMs**

The relationship with OEMs influences the number of cores received, which is recognised as the main constraint of remanufacturing operations (Wu, 2012, 2013). Using OEMs as cores suppliers offer several benefits: higher volume of cores supply and lower selling price. In addition, cores from OEMS have lower quality variation in comparison to cores from other suppliers (Lind et al., 2014). OEMs, which have a much larger volume of cores than other type of cores suppliers, discard cores more often. This is due to the fact that OEM remanufacturers have better access to cores, have more cores stocks (Sherwood, Shu & Fenton, 2000) and operate a more automated process (Williams, Shu & Fenton, 2001).

#### **3.3.2. Information Transfer from OEMs**

Through information transfer, remanufacturers have better access to product designs, which enables them to carry out disassembly more efficiently (Gungor & Gupta, 1998; Ijomah, 2009). The original product design of the OEMs is typically used to recognise the precedence relationships (Tang et al., 2002; Zhang, Li, Shrivastava & Whitley, 2004). Utilising the information in the product design specification, remanufacturers can identify close to, or the most efficient disassembly sequence, which minimises cost (Colledani & Battaia, 2016; Smith & Chen, 2011; Smith et al., 2012). The details of geometric product information is also a necessary requirement, in order to develop computerised visual sorting (Simolowo, Mousavi & Adjapong, 2011).

#### **3.3.3. Company Size of the Remanufacturers**

Large and small companies have different disassembly approaches. Large companies have more automated processes, where the companies invest substantial financial resources to set up a disassembly facility. To support the automated process, the companies organise sorting of cores to discard those that might cause interruption to the material flows in disassembly (Simolowo et al., 2011; Williams et al., 2001). On the other hand, small companies typically are less automated. Disassembly is carried out by an employee who also undertakes other tasks in the remanufacturing process, from start to finish (Williams et al., 2001). As a result of this approach, the smaller companies are more flexible and so are able to adapt to small production volumes and charge premium prices to customers.

### **3.3.4. Cores Sorting**

Cores sorting could be used as a gate keeping to reduce uncertainties during disassembly (Zikopoulos & Tagaras, 2008) and increase homogeneity of the cores to support disassembly automation (Simolowo et al., 2011). Although a cores sorting has been carried out to reduce uncertainties, the uncertainties remain. The exact number of items that can be remanufactured is still not clear even though sorting is conducted accurately (Tagaras & Zikopoulos, 2008). Thus, cores sorting helps to reduce uncertainties but it cannot eliminate them.

### **3.3.5. Product Information Data Base**

Chung and Wee (2010) demonstrate that the adoption of information technology helps to reduce the holding cost of inventory through more accurate and up to date information. Similarly, Westkamper, Feldmann, Reinhart and Seliger (1999) point out that database, which stores accumulated information from the past, is useful to give indicators regarding the state of the cores and therefore provides early information regarding which components typically need to be replaced. By ordering the components as soon as possible, the company mitigates the risk of long lead-time of component procurements.

## **3.4. Process Choices**

### **3.4.1. MTO versus MTS orientation**

Many studies assume that remanufacturing is conducted by small size independent remanufacturers that organise MTO, for example Ketzenberg, Souza and Guide (2003), Tang et al. (2007) and Langella (2007). In fact, many small sized companies, which are typically independent remanufacturers, are less capable of remanufacturing certain product types, particularly those with complex structures that typically have a high residual value. Residual value of cores affect the optimum solution of MTO (Inderfurth et al., 2015). In many cases, OEM remanufacturers have better capability to remanufacture complex products because they have product specification (Ferrer & Whybark, 2001).

### **3.4.2. Volume of Cores Supply**

Products that have high variety (Kerr & Ryan, 2001) and short life cycles (Franke, Basdere, Ciupek & Seliger, 2006) are more difficult to achieve economic feasibility to disassemble. For example, Franke et al. (2006), who developed automated disassembly for mobile phones, requires as many as 8,000 supplies of cores per day. The high volume of cores supplies facilitate employee learning through job repetition and skills accumulation (Jaber & El Saadany, 2011) so disassembly could be carried out more efficiently by reducing disassembly time (Reveliotis, 2007).

### **3.4.3. Specific versus General Tools and Equipment**

Westkamper et al. (1999) stated that flexible and automated disassembly could be developed for remanufacturing. The flexible method allows remanufacturers to adapt with fast changing products, processes and market situations using minimum costs (Seliger, Franke, Ciupek & Bagdere, 2004). Automation in disassembly could gain much benefit since more than 50% of disassembly tasks are disconnecting joints although automation in disassembly for remanufacturing possible, general tools are still preferred. The use of such tools happens when the remanufacturers suffer a lack of prior information about the specification of the products (Zhang et al., 2004).

### **3.4.5. Specific versus General Skills**

In the disassembly stage, the higher the level of innovativeness and newness of technology featured in the products, the higher the skills required to carry out disassembly. Both innovative and new of technologies reduce the ease of disassembling the products and therefore employees require a higher level of technical skill (Ijomah & Chiodo, 2010). Westkamper et al. (1999) argued that employees should be given more responsibility and job enrichment. They further suggested that disassembly tasks be combined with assembly using shared resources. In order to be able to adapt to this technique, the employees should be flexible and possess a further set of different skills.

### **3.5. Product Attributes**

#### **3.5.1. Value of Recovered Products**

Remanufacturers will decide to disassemble whenever the added value from disassembling the components is at least equal to the cost of disassembly; the cost mostly consisted of labour costs (Westkamper et al., 1999). In addition to this, the potential value of recovered cores affects what recovery method that is suitable (Reveliotis, 2007). The value of each component determines how disassembly will be undertaken because higher value components should be given higher priority as opposed to lower ones (Adenso-Díaz, García-Carbajal & Gupta, 2008). If necessary, components with a lower value might be disassembled destructively as long as the higher value ones can be accessed.

#### **3.5.2. Innovative versus Functional Products**

From an economic perspective, there is little interest in the disassembly of product types that are susceptible to fast technological change (Chiodo & Ijomah, 2012). This is because the fast pace of relevant technological changes means that remanufacturers have to adopt new disassembly tools and equipment. A large number of tools and equipment will therefore need to be discarded more frequently, which requires remanufacturers to operate more efficiently and attain a break-even point on the facility investment in a shorter time (Du et al., 2012). Product variety as a result of innovation is also a threat to remanufacturing due to requirement for a higher number of inventories and customising parts, which results in higher operational costs than for functional products, which typically entail more standardised components (Hu, Ko, Weyand, Elmaraghy, Lien, Koren et al., 2011; Westkamper, 2003).

#### **3.5.3. Sequence of Disassembly**

The purpose of disassembly sequence planning is to identify all feasible alternatives of sequence to strip down cores into constituent components with correct precedence relations (Tang et al., 2002). Typically, remanufacturers use the original specification from the OEMs as a starting point to determine an optimum disassembly sequence. However, several factors could cause the original design to be less relevant, such as defective parts and modification by customers. Damaged parts could reduce available options for a sequence of disassembly since the parts might require destructive disassembly (Gungor & Gupta, 1998).



#### **3.5.4. Level of Disassembly**

Sundin and Bras (2005) identified product attributes that support disassembly are as follows: ease of identification, ease of access, ease of handling, ease of separation and wear resistance. Complete disassembly might be the best way to minimise damage during disassembly, although it is not always *economically* efficient (Smith & Chen 2011; Lambert 2002). Accordingly, finding the most optimum level is the aim that the remanufacturers attempt to achieve in order to remain competitive (Colledani & Battaia, 2016). Based on this explanation, there is a trade-off between resource expense and the economic benefit obtained from disassembly (Tang et al., 2002).

#### **3.5.5. Type of Materials**

The materials of products determine to what extent the components can be recovered (Go et al., 2011). Components made from steel, iron and copper are the most popular materials suitable for remanufacturing (Westkamper et al., 1999) because they are relatively stable, more durable and not easily degraded. The use of toxic materials reduces disassemblability so that can harm the operators and may need specialised handling equipment (Desai & Mital, 2005; McGovern & Gupta, 2007).

#### **3.5.6. Number of Components**

Products with higher numbers of components typically require more joints, which means they may take a longer time to disassemble. This is because, as already mentioned, more than half of disassembly tasks are the disconnecting of joints (Westkamper et al., 1999). Thus, a higher number of components leads to a more costly and complex disassembly process, which eventually reduces the economic viability of disassembly (Zwolinski & Brissaud, 2008).

#### **3.5.7. Ecodesign Principles**

Ecodesign should be considered as early as possible during product development, particularly at the idea generation stage (Zwolinski & Brissaud, 2008). Pigosso, Zanette, Filho, Ometto and Rozenfeld (2010) who focus on ecodesign method revealed the importance of disassembly when managing end-of-life strategy. Three of the methods – i.e. EDIT, D4N and EDST – use disassembly planning as a strategy to improve profitability while others only consider it as a tool to improve the level of environmental performance of products. Ecodesign principles identified in the literature that can support disassembly:

joining methods that are disassembly friendly (Ferrer, 2001; Gungor, 2006; Siddique & Rosen, 1997), modular design (Hu et al., 2011; Westkamper, 2003) and standardisation (Du et al., 2012; Westkamper, 2003). Gehin, Zwolinski and Brissaud (2008) develop a tool to identify profile of products that is remanufacturable. The tool, which is called as Repro<sup>2</sup>, reveals 11 profiles of product that support remanufacturing for various situations. However, most products are designed to be disposed, not for end-of-life processing. Products that are produced in recent times are more complex, more sleeker and use more proprietary joints (Sundin, Elo & Mien-Lee, 2012). These all make disassembly become more difficult. A comprehensive review pertaining to tools for ecodesign for remanufacturing can be found in Hatcher, Ijomah and Windmill (2011).

### **3.5.8. Smart Technologies**

Nowadays, many products are embedded with electronic control systems with the purpose of giving the products a “technical intelligence”. The devices are connected with organisation wide information technology networks, so that they can support maintenance, upgrading, reconfiguring, and managing the service (Westkamper, 2003). Most economic benefit is gained through more efficient operations, due to cost reduction in terms of labour cost, the time to identify sequence and level of disassembly, picking tools and equipment, and the need to replace damaged components during disassembly (Chiodo & Ijomah, 2012).

In the next section, we will use the factors identified from this literature review to develop a new model of disassembly.

## **4. Toward a New Model in Disassembly Process**

Having discussed disassembly in the remanufacturing context and identified factors that affect disassembly as the points of departure, a new model of disassembly for remanufacturing is developed. The new model covers the three areas that have already been mentioned: organisational characteristics, process choices and product attributes, which have been suggested by existing literature (Bras & McIntosh, 1999; Bras, 2004; Hermansson & Sundin, 2005).

In the new model of disassembly, disassembly starts with the acceptance of cores information (i.e. when the cores will arrive, number of cores, type of cores etc.). This is one of the distinguishing features of the new model from existing studies. The new model of disassembly, illustrated in Figure 5 is divided into three phases. These are: *pre-disassembly activities*, *physical disassembly activities* and *post-disassembly activities*.

- **Starting point.** *Disassembly process* starts when the shop floor receives information regarding the cores, either from the sorting facilities, cores suppliers or from other departments within the company. Based on this information, the *pre-disassembly activities* begin, although the cores have not yet arrived in the disassembly area.

This model is different from the existing ones, which require the presence of cores before disassembly can begin. Information regarding cores has a critical role, since it contains details about the number of components that are in good condition (Ferrer & Ketzenberg, 2004; Ferrer, 2003), the directions for disassembly (Desai & Mital, 2003), and an estimation of the manual force that is required during disassembling (Desai & Mital, 2003). The importance of this information is higher for products that have never been disassembled before by remanufacturers, and in cases where the company lacks of product information.

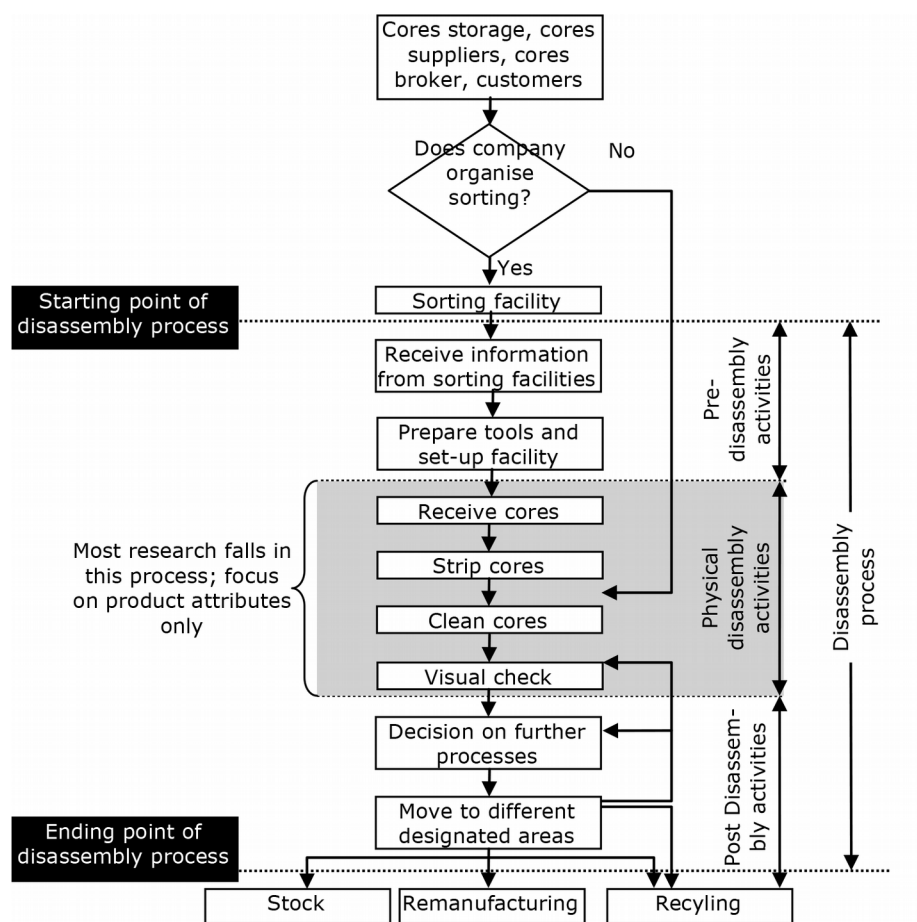


Figure 5. A new model of disassembly for remanufacturing

- ***Pre-disassembly activities.*** Once the remanufacturers receive information about the cores, the pre-disassembly process can start. Activities included in *pre-disassembly activities* are machinery set-up, gripping tools and the identification of joint elements (Yi et al., 2003). The arrival of cores information triggers these activities, which incur cost; on the other hand, the arrival of early core information helps remanufacturers to be more prepared so that disassembly can be undertaken more efficiently (Ferrer & Ketzenberg, 2004). Remanufacturers should consider the costs that are associated with moving cores from the sorting to disassembly shop floor (Yi et al., 2003) because the improper handling of cores can cause them to be rejected (Williams et al., 2001). These costs are also assigned to the *pre-disassembly process activities*.
- ***Physical disassembly activities.*** This stage covers the activities to disconnect each part of the cores. During this phase, three decisions are made about the level, sequence and method of disassembly. At this stage, remanufacturers should make decisions such as choosing the most appropriate tools, identify the simplest disassembly mechanism and minimise the use of force (Mok, Kim & Moon, 1997). Sometimes employees are supported by a product database, as well as information about the history and specification of the cores, to help them to make the decisions (Westkamper et al. 1999).
- ***Post-disassembly activities.*** Activities included in this stage are the moving and handling of disassembled components from the disassembly shop floor to the warehouse, or areas designated for other processes (Smith & Chen, 2011). During moving and handling, there might be additional costs due to component damage (Adenso-Díaz et al., 2008; Gungor & Gupta, 1998), the need to design customised equipment to handle the components, and the allocation of employees to do the various tasks. Other cost is associated with the time spent for carrying out the moving and handling which is varied according to weight, size and amount of the hazardous materials (Yi et al., 2003).
- ***Ending point.*** *Disassembly process* is categorised as being completed when all the decisions that relate to the disassembly process have been made, disassembled components have been located to a designated area, and information that has been gathered from disassembly has been sent to the other shop floors. Information that has been produced from the disassembly process includes the recovery rates of cores, the resources needed to disassemble and an estimation of the need for new parts. The information is used to determine the number of new parts that need to be ordered from suppliers, to estimate the cost of remanufacturing and the selling price of remanufactured products.

In the model presented above, there may be iterative processes between disassembly and other stages of remanufacturing, such as cleaning, testing and sorting. For example, a core is disassembled into

sub-modules, then cleaned and tested. After that, it must be disassembled further into smaller components. This occurs when remanufacturers carry out partial disassembly, whereby complex products are disassembled step-by-step without a specific target as to what the final objective is. Next, the factors affecting disassembly identified from this systematic literature review will be analysed against the new model proposed in Section 4.

## 5. Discussion – Impacts of the Factors on the Disassembly Process

### 5.1. Implications of the New Disassembly Model on Disassembly Process

This section discusses how the factors identified in the systematic literature review affect different stages in the *disassembly process*. An understanding of *which factors* affect *what stages* in *disassembly process* will help managers to highlight the factors that should be carefully managed, in order to improve certain stages of the *disassembly process*. Table 2, presented below, shows how the factors affect different stages of the *disassembly process*.

Stages of the disassembly process	Organisational characteristics				Process choices				Product attributes								
	Relationship with OEMs	Information transfer from OEMs	Company size of remanufacturers	Cores sorting	Product information database	MTO versus MTS	Volume of cores supply	Specific versus general equipment	Specific versus general skills	Value of recovered products	Innovative versus functional products	Sequence of disassembly	Level of disassembly	Type of materials	Number of components	Ecodesign principles	Smart technologies
Pre-disassembly activities	●	●	●	●	●				●	●	●		●				●
Physical disassembly activities	○	○		○	○	●	●	●	●	○	●	●	○	●	●	●	○
Post-disassembly activities							○	○	○	○			○	○	○		

Keys:

- : direct impact of the factors on stages of the disassembly process
- : direct and indirect impact of the factors on stages of the disassembly process
- : indirect impact of the factors on stages of the disassembly process

Table 2. List of factors affecting different stages of disassembly process

## 5.2. Pre-physical Disassembly Activities

In general, *pre-disassembly activities* is predominantly affected by *organisational characteristics*, while *process choices* and *product attributes* are less relevant. The factors derived from organisational characteristics include the relationship with OEMs, who offer information regarding product specification (Ijomah, 2009). Furthermore, this relationship helps remanufacturers to reduce uncertainty regarding the time of cores arrival (Östlin et al., 2008; Seitz & Peattie, 2004). A product information database storing the history of product use can indicate which tools and equipment are needed for disassembly (Ijomah, 2009; Nissen, 1995). All of this information is useful for remanufacturers setting up a disassembly facility before cores arrive with the company. Accordingly, although in the *pre-disassembly activities* stage products are not broken down into their constituent components, any investments made by companies to support *pre-physical disassembly activities* will make the *physical disassembly activities* easier.

## 5.3. Physical Disassembly Activities

In the *physical disassembly activities*, nearly all of the factors identified in the literature are judged to have either a direct or indirect impact. The factors in the category of *process choices* and *product attributes* are mostly considered to be “hard factors”, which are tangible, can be observed physically and are mostly related to day-to-day operations. This is the reason why these factors have a direct impact on the *physical disassembly activities* phase.

On the other hand, factors derived from *organisational characteristics* tend to have an indirect impact on *physical disassembly activities*. These factors are usually soft in nature, strategic, and do not have a direct relationship with the activity of breaking down products into components, which may be the reason why they receive less attention in academic research. For example, knowledge transfer from OEMs to contract remanufacturer is useful to help disassembly process (Ijomah, 2009) but to what extent its effectiveness of has not been investigated. This is different from other such as tooling, technology, type of materials and other technical issues that are directly affect disassembly. Without doubt, the change of these technical parameters will directly affect *physical disassembly process*.

Many practitioners underestimate the benefit of *organisational characteristics* in supporting the disassembly process, because of their indirect impact. In addition to this, these characteristics are soft in nature and intangible, which makes it difficult for practitioners and academics to accurately measure the benefit of managing these factors. In fact, the benefit of managing *pre-physical disassembly activities* can be very high, and the importance of *pre-physical disassembly activities*, which has an indirect impact on *physical disassembly activities*, can be higher for products that have a complex structure (Moore, Güngör & Gupta, 2001),

consist of a large number of components (Zwolinski & Brissaud, 2008), or contain high value components (Adenso-Díaz et al., 2008).

A good example of products that require intensive support in the *pre-physical disassembly process* is jet engines, the remanufacturing of which is administered through leasing agreements (Pigosso et al., 2010). In these agreements, customers are involved in the *pre-physical disassembly activities*, supporting remanufacturers by providing the information required to carry out *physical disassembly activities* (Ketzenberg, Laan & Teunter, 2009). Information has been mentioned is highly valuable when remanufacturing complex products (Ferrer & Ketzenberg, 2004). Considering the importance of this, there is no doubt regarding importance of setting up *pre-physical disassembly activities*, and ignoring this stage might cause serious difficulties for remanufacturers.

#### 5.4. Post-physical Disassembly Activities

In general, *post-physical disassembly activities* are affected by factors in the categories of *process choices* and *product attributes*. All factors derived from *product attributes* have an impact on *post-physical disassembly activities* because this stage deals with the management of disassembled components. Unfortunately, remanufacturers have little control over product attributes; the number of components, type of materials used and level of disassembly needed are all factors that are determined by manufacturers, and so are beyond the control of remanufacturers. OEM remanufacturers are able to control these variables but the remanufacturing division is typically separated from the manufacturing division and they do not communicate one another. For this reason, remanufacturers can only improve the recovery rate using curative action; therefore, remanufacturers can only improve the recoverability of products at the end of their life cycle (Mathieux, Froelich & Moszkowicz, 2008).

Unlike *product attributes*, over which remanufacturers have little or no control, *process choices* are easier to manage. For this reason, remanufacturers should adjust the design of process choices according to the product attributes (Franke et al., 2006; Seliger et al., 2004). For example, equipment for moving and handling disassembled components should be adjusted according to size, type of material, and number of components, as well as other relevant factors (Franke et al., 2006). All of these factors should be considered during the design of *process choices*. Process choice here refers to how the remanufacturers organise their resources that are used by remanufacturers to carry out disassembly, such as tool, equipment, employees, type of skills, how to design lay out etc.

*Post-physical disassembly activities* overlap with subsequent processes in remanufacturing operations, and accordingly it is critical for the success of these later processes (Ijomah et al., 2007; Thierry et al., 1995).

For instance, in complex products that require partial disassembly, an iterative process occurs between the *disassembly process* and other remanufacturing processes, such as cleaning or testing (Ijomah et al., 2007). For this reason, *post-physical disassembly activities* play a critical role, as this stage may lead to component damage, loss, or an extended period of handling and moving. In order to be well managed, the set-up of *post-physical disassembly activities* should be integrated with *process choices* planning (Franke et al., 2006), such as how to design tools and equipment for handling and moving components, in order to minimise the risk of damage (Ferrer & Whybark, 2001).

## **6. Directions for Future Research**

The two previous sections have discussed how the new model leads to differences between disassembly for remanufacturing compared with those for other recovery methods, which was followed by a systematic review to identify comprehensive factors affecting disassembly. Based on the previous discussion, this section attempts to discuss which areas could be a trajectory for future investigations.

### **6.1. Interplays between the Factors Affecting Disassembly**

Factors that have been identified from the literature presented in Section 4 as affecting disassembly represent a good departure for deeper investigations. Future studies could explore whether the factors affecting disassembly can be confirmed by empirical findings, and whether there are new factors that emerge.

In addition, researchers could extend the scope of study by analysing how factors might be interrelated. For example, employing multiple skilled workers would be more appropriate for companies that use multi-purpose tools and equipment (Seitz & Peattie, 2004), whilst the adoption of specialised tools and equipment, such as automated disassembly, requires a high volume of cores supply (Seliger et al., 2004). In this case, there would be a greater likelihood of obtaining adequate quantities of similar products to enable batch production, so that the amount of set up time required is minimised. Research that investigates the interaction between the factors could therefore be highly beneficial for remanufacturers. By understanding the interrelation of factors and their effects, the most influential factor could be controlled. With this, researchers could develop an index that would be useful for the managers who are responsible for decision-making. The ability to control the most significant factors would be extremely useful in helping remanufacturers to manage disassembly efficiently.



## 6.2. Knowledge Transfer from Contract Remanufacturers to OEMs

Many studies point out the reluctance of OEMs to share knowledge to contract remanufacturers because it might endanger their intellectual property (Martin, Guide Jr. & Craighead, 2010; Subramoniam, Huisinigh & Chinnam, 2009). OEMs attempts to hinder independent remanufacturers to enter after-market business (Lind et al., 2014). In fact, OEMs can improve remanufacturability of products by incorporating knowledge which they have gained from remanufacturers (Ferrer & Whybark, 2000). This knowledge is unique and cannot be obtained from parties other than remanufacturers, since some knowledge is created only by remanufacturers (Lind et al., 2014). This knowledge could be potentially lost unless it is used by OEMs. A short discussion presented in Saavedra, Barquet, Rozenfeld, Forcellini and Ometto (2013) point out how OEMs and independent remanufacturers can collaborate and gain mutual benefit. The research opportunity here is, how can appropriate relationships be formed that will support the transfer of knowledge from contract remanufacturers to OEMs, and vice-versa to create win-win solutions?

## 7. Conclusion

This paper contributes to existing knowledge in the area of disassembly for remanufacturing in a number of ways. First, it develops a new model of disassembly, which covers both soft and hard factors, and looks at disassembly from a strategic perspective. In the new model, the disassembly process starts when remanufacturers receive information regarding the cores and it ends when information from the disassembly process has been sent to other shop floors for further processes in remanufacturing. This is different from existing studies, which assume that disassembly requires the physical presence of the products. Second, it identifies 17 comprehensive factors identified, encompassing organisational characteristics, process choices and product attributes. Third, this paper offers trajectories for future investigations.

In addition, this paper provides some theoretical implications and further findings that were not originally intended. There are a number of indications that these factors have some interplay. Some of the factors identified in this study provide a broader context that can help us to understand why some companies can outperform others in the disassembly process. For example, the type of relationships they have with OEMs and the type of remanufacturers they are can help us to understand this phenomenon. Therefore, focusing on the techniques and methods that are used to disassemble, without considering the broader context, will make the study less complete.

This paper also offers some implications in the practical field. There are many products available in the market that are remanufactured purely because of “coincidence”; in other words they were not deliberately earmarked for remanufacturing during the product development stage. Although companies can use some optimisation methods to maximise recoverability, the figure is relatively small. If disassembly is not integrated into the product’s development stage, then remanufacturers may not achieve the full potential of disassembly and optimise the value that can be recovered from disassembly.

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