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Product Remanufacturability Assessment and Implementation Based on Design Features

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Abstract

The design of a product can have substantial and significant impact on the decision-making processes across a product’s life-cycle as well as its remanufacturability. A product CAD model provides a rich and useful source of information for remanufacturability assessment. This paper presents a product remanufacturability assessment model consisting of a set of numerical metrics, namely, disassembly accessibility, product complexity, disassemblability, and recoverability, based on the design features and information available in CAD models, e.g., bill of material, mating features, dimension and tolerance features, tools and accessories, etc. A software tool is developed for the implementation and integration of the proposed metrics based on CAD models as input. A case study using a SolidWorks model of an automotive part is presented and discussed to validate the proposed assessment approach.

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Keywords: Remanufacturability assessment; design features; disassembly; repairability.

1. Introduction

Product remanufacturing aims to return a used product to a like-new condition through a series of industrial processes, which typically include disassembly, cleaning, inspection and sorting, part refurbishment, reassembly and final test [1]. It has increasingly been recognized as one promising product end-of-life (EoL) recovery option towards a sustainable and closed-loop product life-cycle. Review studies reveal that remanufacturing activities can be found in many different industrial sectors, e.g., automotive parts, heavy-duty equipment, and machine tools, etc., and the remanufacturing business, once centered in the North American and European regions, is now growing into a globalized scale [2-3]. Compared to the practical development in remanufacturing, few studies have been made on design for remanufacturing and product remanufacturability assessment. To integrate remanufacturing successfully into a product’s life-cycle, issues that can affect remanufacturing should be considered as early as possible in the product design stage. Therefore, it is necessary to evaluate the remanufacturability of a product design in order that the design can be modified and improved to be more in line for remanufacturing.

Computer-aided Design (CAD) software enables a product to be represented with detailed well-structured design information, e.g., bill-of-material, dimension and tolerance features, mating features, etc. There are tools available in the software, e.g., exploded view of an assembly, which can help designer understand the spatial relationships of the assembly and the possible disassembly sequence. However, there is no existing CAD software that has built-in tools to interpret the design information and evaluate remanufacturability of a design automatically. To address this research issue, this paper presents a product remanufacturability assessment model based on CAD design information. The assessment consists of four numerical metrics, namely, fastener accessibility, disassembly complexity, disassemblability, and recoverability. A computer-aided system is developed for design information extraction and management as well as the implementation of the proposed metrics. A case study using a SolidWorks model of an automotive part is presented to validate the proposed assessment approach.
2. Literature survey

Few studies have been reported that address product remanufacturability assessment from the design perspective. One earlier attempt [4] investigated the simple embodiment design features, e.g., the number of parts, different types of fasteners, number of ideal parts, etc., to derive the evaluation metrics with respect to various processes in remanufacturing. These numerical metrics were further developed by specifically defining the scope of ideal parts [5-6]. For example, a part can be used to isolate wear and protect the more valuable parts from damages, e.g., washer, bearing, etc., even though it may have less intrinsic value. Another assessment model is based on a set of design charts, which is a collection of design attributes that have the potential to influence the ease of remanufacturing [7]. This approach provides a checklist for designers to identify the weakness of a design, and requires considerable designer’s expertise in understanding the design features to establish the relevance with the various items in the checklist.

Part disassembly and recovery have been identified to have the most significant impact on product remanufacturability [8]. Products to be remanufactured normally require manual disassembly due to uncertainty in return conditions, and successful remanufacturing relies on non-destructive disassembly of the cores. Currently, most studies adopt disassembly time or disassembly effort as a measure to address product disassemblability. Fastener related issues, e.g., unfastening effort, tool requirement, fastener accessibility, etc., are analyzed to form a spread sheet-like disassembly evaluation chart, and subsequently to derive the disassembly difficulty scores and the estimated disassembly time [9-10]. Since not all the components of a product are remanufacturable, selective disassembly could be a more suitable choice due to high disassembly costs. Therefore, the retrieval of remanufacturable parts may require cost effective disassembly sequence planning [11].

Part recovery is another critical step as it concerns whether a part can be restored to its original specifications. Sherwood and Shu [12] reported different failure modes and the associated recoverability for automotive parts based on the statistical failure data gathered from waste streams. Shu and Flowers [13] identified part material and fastening and joining methods can have significant effects on part recoverability.

Cleaning, inspection and sorting of parts are important in remanufacturing. However, the assessment of these processes relies less on the product design information, and thus will not be the focus of this paper. The next section presents the framework for assessing product remanufacturability based on design information extracted from CAD models, with emphasis on part disassemblability and recoverability.

3. Framework for remanufacturability assessment

The product remanufacturability assessment framework comprises two modules, namely, (1) CAD feature extraction and management, and (2) remanufacturability evaluation. Figure 1 depicts the proposed approach.

From a complete product CAD model, the separable fasteners and connectors need to be identified first and excluded from the list that contains the core components and subassemblies. For each component, the design attributes, e.g., part material, fastening and joint methods related information, relevant dimensions and tolerances, etc., need to be extracted. The design information can be represented and maintained in a generic hierarchical tree structure, in which the components and the associated design attributes are defined as roots, and the connections between adjacent components as leaves. In the assessment module, two aspects of remanufacturing, i.e., disassembly and part recovery, are evaluated using four correlated numerical metrics from the technological perspective, namely, disassembly complexity, fastener accessibility, disassemblability, and recoverability.

4. Remanufacturability assessment metrics

4.1. Disassembly complexity

Numerical metrics have been known as the most intuitive forms of complexity measurement [14]. One primary principle in design for disassembly is the adoption of minimum number of fasteners in an assembly. In the context of disassembly for remanufacturing, different fastener types may require different unfastening tools, different access directions, and/or even different disassembly setups, resulting in an increase in the disassembly effort. Therefore, two factors are considered to assess the disassembly complexity of an individual part, namely, (1) the number of fasteners types, and (2) the number of fasteners for each fastener type.

The effect of the number of fasteners on the complexity can be modeled using entropy in information theory [14].
When the number is low, the addition of a fastener is significant, while the opposite is true of high-count systems. The number of fastener types is modeled using a linear function, considering that the effect of the variation of the fastener types overweighs that of the number of fasteners. Based on the information entropy measure presented in [15], the disassembly complexity metric is given in Equation (1), in which \( N_i \) is the number of the joining types, and \( N(j) \) is the number of fasteners of type \( i \).

\[
M_{\text{com}} = \sum_{i=1}^{N_i} \log_2 (N(j) + 1)
\]

(1)

### 4.2. Fastener accessibility

Fastener accessibility measures how easy a fastener can be accessed during a disassembly operation. Since manual disassembly remains the main stream in remanufacturing, fastener accessibility can be measured from two ergonomics perspectives, namely, unfastening approach direction [16] and access topology [17]. The modeling of the access topology is difficult as it requires a complete understanding of the geometric features of the entire assembly. With respect to the unfastening approach direction, the access difficulty increases in the following order: Z-axis, \( XY \)-axis, negative Z-axis in the operator’s perspective [16]; and this require the disassembly direction of the CAD model to be aligned to the operator’s workspace. The accessibility of a particular fastener in a part can be given by Equation (2), in which \( \theta(i) \) defines the angle of the approach direction of the \( i \)-th fastener to the horizontal plane. Equation (3) models the accessibility when more than one fastener is used to secure a part. The inverse weighted addition function ensures that as long as there is a fastener which accessibility approaches zero, the accessibility of the part would approach zero. \( N_0 \) is the total number of separate fasteners, and \( \omega \) is the weighting coefficient.

\[
M_{\text{acc}}(i) = \frac{1 + 2 \times \theta(i)}{2}, \quad \theta(i) \in [-\pi/2, \pi/2]
\]

(2)

\[
M_{\text{acc}} = \sum_{i=1}^{N_0} \omega_j \cdot M_{\text{acc}}(i)
\]

(3)

\[
N_0 = \sum_{j=1}^{N_0} N(j), \quad \omega_j \geq 0, \quad \sum_{j=1}^{N_0} \omega_j = 1
\]

### 4.3. Disassemblability

Disassemblability defines the extent to which a part can be dismantled easily and non-destructively from other parts. It can be described by the effort required to disassemble the fasteners followed by separating the part. The effort can be measured in two aspects, namely, the unfastening difficulties and the directional constraints during part separation [18]. Table 1 gives the relative unfastening ratings for the general types of fasteners and connectors. In the extreme case, that unfastening difficulty equals to 1 refers to a destructive disassembly. The directional constraints of a part separation motion can be given by the Degree-of-Freedom for Separation (DFS), which is proportional to the number of possible removal directions with respect to the mating part(s) [18]. The disassemblability metric of a part is given in Equation (4), where \( N_0 \) is the total number of connections, including separate fasteners and integral fastenings. Equation (5) defines the disassembly effort required for an individual connection \( i \), where \( X(i) \) is the unfastening difficulty, and \( X_d(i) \) is the directional constraint during unfastening. \( \alpha \) is the weighting coefficient and satisfies \( 0 < \alpha < 1 \). If there is more than one connection for securing a part, the connection that requires the most disassembly effort dominates the disassemblability (as given by \( X(i_{\text{MAX}}) \)). In addition, the effect of the dominant connections is reinforced by averaging the effect of these connections. The coefficient \((1-X(i_{\text{MAX}}))\) is a regulator which ensures that the exponent is normalized. The exponential function indicates that the disassemblability is inversely proportional to the disassembly effort as required.

\[
M_{\text{dis}} = \exp \left( -\frac{X(i_{\text{MAX}}) + (1 - X(i_{\text{MAX}})) \sum_{i=1}^{N_0} X(i)}{N_0 - 1} \right)
\]

(4)

\[
X(i) = \alpha X(i) + (1 - \alpha) X_d(i)
\]

(5)

#### Table 1: Relative unfastening rating of fastener type (adapted from [18]).

| Fastener type        | Relative unfastening difficulty |
|----------------------|---------------------------------|
| Mate/insert          | 0.3                             |
| Bolt, bolt-nut, screw| 0.5                             |
| Gear, belt-mesh      | 0.7                             |
| Key, interference fit| 0.8                             |
| Rivet, welding       | 1.0                             |

### 4.4. Recoverability

The recoverability of a part describes the possibility that it can be restored to its original specification for reuse. For fixed parts of a product, such as the housings of an automotive alternator, a common failure would be the fastening failure caused during disassembly [12]. Table 2 gives the relative fastening failure rate due to disassembly with respect to part material and fastening methods. For common screw fasteners, if parts are made of plastics, the disassembly of the fasteners would destroy the thread on the parts. It is suggested that the use of inserts together with screws would enable the reuse of the parts after disassembly [13]. If two parts are joined together through integral fasteners, e.g., snap fit, there is still a high chance that the joining area can be broken during
disassembly or reassembly. Comparatively, for parts made of steel or alloy that are joined using separable fasteners, the failure rate due to disassembly would be considerably lower. For moving or rotating parts, the common failure could be wear, deformation, etc. The use of failure-isolation parts can be effective in reducing the impact of vibration as well as wear on critical components. In addition, the total number of contact surfaces of a moving part (which usually require machining processes to produce) and surface finish will affect part recoverability with respect to re-machining cost. Previous work [19] reported the influence of the dimensional tolerance and surface finish on the cost factor in manufacturability evaluation. Similarly, relative cost can be applied to the re-machining processes required for part dimension recovery, as shown in Figure 2. The recoverability can be determined by the fastening failure rate ($\gamma$), the relative recovery cost factor ($\alpha$), the number of joining types ($N_t$), and the number of contact surfaces of each joining type ($N_{si}$), as given in Equation (6). The recoverability is inversely proportional to the fastening failure rate and the relative recovery cost. In the extreme case that the fastening failure rate equals to one, the recoverability of a part reaches zero. The logarithmic function is used to model the effect of the number of contact surfaces, and the summation function captures the effect of the variety of joining types. The exponential function as a normalization measure ensures that the recoverability falls within $[0, 1]$.

$$M_{REP} = \exp\left(-\sum_{i=0}^{N_t} \frac{K_i}{1-\gamma_i} \log_2 \left(N_{si}(i) + 1\right)\right)$$  \hspace{1cm} (6)

Table 2: Fastening failure rate due to disassembly [13].

| Part material | Fastening methods                  | Fastening failure rate due to disassembly |
|---------------|------------------------------------|------------------------------------------|
| Steel/alloy   | Screw or bolt without insert       | 0.05                                     |
|               | Screw or bolt with insert          | 0.05                                     |
|               | Integral fastener/fit              | 0.5                                      |
| Plastics      | Screw or bolt without insert       | 1                                        |

5.1. Computer-aided system

The computer-aided system aims to provide a graphic user interface enabling the evaluation of a product design model with respect to four metrics. The system was implemented using the C++ programming language in Microsoft Visual Studio platform. Most available CAD packages share the same set of primitive features, e.g., vertex, edge, face, etc. However, each CAD system usually adopts different rules in defining a set of compound features, e.g., assembly features and constraints. This would require a generic data structure as a wrapper to interface the design information. In this research, a hierarchical tree structure is implemented as defined in Figure 3. The SolidWorks API was used to extract the design information from the SolidWorks CAD model. The sequence in the exploded view of the model is used to arrange the sequence of the component list, and subsequently to derive a feasible disassembly sequence.

Figure 4 is the graphical user interface with the input entries corresponding to the factors required for the assessment. The data stored in the hierarchical tree structure can be further explored and displayed as input entries. A simple classifier for the core components and separable fasteners/connectors disassembly is defined by a set of keywords, e.g., bearing, screw, and bolt, etc., through searching for keywords that can be found in the component name. By selecting a component in the core component list, the adjacent components can be generated and shown in the corresponding list. When an adjacent part has been selected, the fasteners and connectors used to join the two components are shown. The general part attributes (e.g., material type, part type) are retrieved and displayed automatically. For each fastener used, the fastening and joining attributes are generated and displayed. In particular, the access direction can be obtained based on the exploded sequence with respect to disassembling the fastener. The user may need to align the coordinate system of the CAD model to the cooperator’s frame of reference for disassembly. As shown in Figure 4, the selection of “Axis -X” means that the negative X-axis of the CAD model is aligned to the Z-axis of operator’s workspace.

5. System implementation and case study

This section presents implementation of a computer-aided system for product remanufacturability assessment, and a case study to validate the proposed numerical metrics.
The unfastening difficulty is retrieved based on the values given in Table 1. The DFS is determined by the mating relationship between a fastener and the parts held by this fastener [18]. The definition of the base dimension could be different for different types of fasteners, e.g., the thread length a bolt/screw, the diameter of a cylindrical surface (for bearing, shaft/hole configuration), etc. Such dimensions can be retrieved from the associated mating information. The tolerance is defined by the International Tolerance Grade, and the exact tolerance value is obtained by the base dimension and the tolerance grade.

In addition to displaying the necessary inputs retrieved from the CAD model, the values of all the input entries for the assessment can be keyed in manually in the event that the CAD model may lack certain design information, such as material selection, tolerance specification, etc. This enables the designers to define or modify the design information and evaluate the remanufacturability simultaneously.

5.2. Case study

With the computer-aided system, a case study using a CAD model of an automotive alternator is conducted. The CAD model consists of the main mechanical parts only; the electronic parts, e.g., brush assembly, voltage regulator, etc., are not considered. Figure 5 shows an exploded view of the alternator model.

The design information from a CAD model was extracted and stored in the hierarchical tree structure defined in Figure 3. The disassembly sequence contained in the exploded steps was used to sort the components in the tree structure. By defining the disassembly setup of the product (for the alternator used, the pulley component would need to be facing up), the access directions for accessing the fasteners for each component during disassembly were determined based on the exploded view. Only two types of separable fasteners (i.e., screw and bearing) were used in the assembly, and the unfastening ratings can be obtained from Table 1. By setting the value $\alpha=0.8$, the disassembly effort $X_i$ required for each joining type can be determined according to Equation (5). The tolerance information is not available in the original CAD model, and was thus keyed in manually. The shaft and rotor assembly is a typical shaft/hole configuration and thus joined using an interference fit. Based on the given the tolerance information of the assembly feature, the joining methods, e.g., an insert (loose fit) or a press fit, can be determined accordingly. Table 3 shows the results of the four metrics based on the part material, part type, and the associated joining and fastening attributes.

![Fig 5: An exploded view of the alternator model used in the case study.](image)
It can be seen from Table 3 that the fastener accessibility of each part is favorable as the alternator has a linear configuration. Three parts (front and rear covers, mid-part) have the highest disassembly complexity since they are assembled with separate fasteners. The shaft is the most difficult to disassemble due to the use of interference fits in the connections with the two bearings and the rotor assembly. The shaft also requires the greatest recovery effort due to the need for high dimensional tolerance for the interference fit.

Table 3: Evaluation of remanufacturability of components of an alternator.

| Nodes          | Material | Part type | ACC | COM | RES | REF |
|----------------|----------|-----------|-----|-----|-----|-----|
| Pulley         | Steel    | Rotational| 1.0 | 1.0 | 0.485 | 0.504 |
| Front cover    | Alloy    | Fixed     | 1.0 | 3.322 | 0.409 | 0.479 |
| Shaft          | Alloy    | Rotational| 1.0 | 2.585 | 0.401 | 0.075 |
| Rotor          | Steel    | Rotational| -   | -   | 0.462 | 0.479 |
| Stator         | Copper   | Fixed     | -   | 1.0 | 0.666 | 0.560 |
| Mid-part       | Steel    | Fixed     | 1.0 | 3.322 | 0.464 | 0.560 |
| Rear cover     | Alloy    | Fixed     | 1.0 | 3.322 | 0.409 | 0.479 |

6. Conclusion and future works

Remanufacturability assessment of a product design can be efficient if the design information can be fully used. This paper presents four numerical metrics for assessing product remanufacturability, namely, faster accessibility, disassembly complexity, disassemblability, and recoverability. A computer-aided system was implemented through which the assessment can be achieved by extracting the design information automatically from the CAD models. The design information can also be input manually by the designers for the assessment of under-defined CAD assembly models. A SolidWorks CAD model of an automotive alternator was used to demonstrate the system.

Improvement can be made to further develop the computer-aided system for remanufacturability evaluation. Firstly, design feature recognition and interpretation would be a more reliable way for the classification of core components and separable fasteners. It would be more generic if the computer-aided system can interpret CAD models from different modeling software. The computer-aided system can be further developed with the construction of a remanufacturing knowledge base by studying the different existing remanufacturable products and components. The knowledge base would contain prominent design features and the associated assessment metrics that dominate the different aspects in remanufacturing, and thus can be used to facilitate possible design feedback and modification to the newly designed product or component.

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References

[1] Ijomah WL, McMahon CA, Hammond GP, Newman ST. Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development. In: Int J Prod Res. 2007; 45(18):4513-36.
[2] Giutini R, Gaudette K. Remanufacturing: The next great opportunity for sustainable development. Business Horizons 2003; 46(6):41-48.
[3] Chapman A, Bartlett C, McGill I, Parker D, Walsh B. Remanufacturing in the UK: Resource Recovery Forum 2010. Available at: http://www.remanufacturing.org.uk/pdf/story/1p342.pdf; last accessed on 14 April 2014.
[4] Hammond R, Bras BA. Towards design for remanufacturing - metrics for assessing remanufacturability. In: Proc of the 1st International Workshop on Reuse. Eindhoven, The Netherlands, 11-13 Nov 1996, p. 35-51.
[5] Kalyan-Seshu US, Bras B. Integrating I-DEAS with remanufacturing and assemblability assessments. In: Proc of the 1997 ASME Design Automation Conference, ASME 1997 DETC & CIE Conference, Sacramento, CA, 14-17 Sept 1997, pp. 1-11.
[6] Harper B, Rosen DW. Computer-aided design for de- and remanufacture. In: Proc of 1998 ASME Design Engineering Technical Conference. Atlanta, GA, 13-16 Sept 1998, p.1-11.
[7] Mabee DG, Bommer M, Keat WD. Design charts for remanufacturing assessment. Journal of Manufacturing System. 1999, 18(5):358-366.
[8] Hammond R, Amezquita T, Bras B. Issues in automotive remanufacturing - an industry survey. In: International Journal of Engineering Design and Automation - Special Issue on Environmentally Conscious Design and Manufacturing. 1998, 4(1):27-46.
[9] Kroll E, Carver BS. Disassembly analysis through time estimation and other metrics. In: Robot Comput-Integr Manuf. 1999, 15(3):191-200.
[10] Desai A, Mital A. Evaluation of disassemblability to enable design for disassembly in mass production. In: Int J Ind Ergon. 2003, 32(4):265-281.
[11] Li WD, Xia K, Wang LH, Chao KM, Gao L. Selective disassembly planning for sustainable management of waste electrical and electronic equipment. In: Proc of the 20th CIRP LCE conference. Singapore, 17-19 Apr 2013, p.341-346.
[12] Sherwood M, Shu L. Modified FMEA using analysis of automotive remanufacturer waste streams to support design for remanufacture. In: Proc. of the ASME 2000 DETC & CIE Design Theory and Methodology Conference, Baltimore, MD, 10-14 Sept 2000, p.247-256.
[13] Shu LH, Flowers WC. Application of a design-for-remanufacture framework to the selection of product life-cycle fastening and joining methods. In: Robot Comput-Integr Manuf. 1999, 15(3):179-190.
[14] Mathieson JL, Summers JD. Complexity metrics for directional node-link system representations: theory and applications. In: Proc of the ASME 2012 DETC and CIE Conference. Montreal, Quebec, Canada, 15-18 Aug 2010, p.1-11.
[15] EIMaraghy WH, Urbanic RJ. Modelling of manufacturing systems complexity. In: CIRP Ann Manuf Tech. 2003, 52(1):363-366.
[16] Das SK, Yedlarajiah P, & Narendra R. An approach for estimating the end-of-life product disassembly effort and cost. In: Int J Prod Res, 38(3):657-673.
[17] Das SK, Naik S. Process planning for product disassembly, In: Int J Prod Res. 2002, 40(6):1335-1355.
[18] Dong T, Zhang L, Tong R, Dong J. A hierarchical approach to disassembly sequence planning for mechanical product. In: Int J Adv Manuf Tech. 2006, 30(5-6):507-520.
[19] Ong SK, Chew LC. Evaluating the manufacturability of machined parts and their setup plans. In: Int J Prod Res. 2000, 38(11):2397-2415.