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A design feature-based approach for product remanufacturability assessment and analysis

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Abstract

Remanufacturing is a promising end-of-life (EoL) recovery strategy to achieve a close-loop product lifecycle in sustainable product development. Product design can have substantial impact on product remanufacturability and product EoL recovery strategy. Existing studies on design-based remanufacturability assessment are either based on design charts or consideration of simple embodiment design features. This paper presents a feature-based approach for remanufacturability assessment using comprehensive CAD information, e.g., bill-of-material, mating features, tolerance and dimension, etc. For each product component, a generic information model is defined to manage critical design features for remanufacturability assessment, which include both inherent attributes of the component and interrelations among connected components. The proposed approach assesses two critical aspects in remanufacturing, namely, part disassembly and recovery. Design evaluation based on the remanufacturing assessment and part EoL recovery strategy can provide feedback to enhance the product design to be more in line for sustainable manufacturing. A case study of an automotive part is presented to validate the proposed approach.

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Keywords: Remanufacturability assessment; end-of-life strategy; sustainable manufacturing.

1. Introduction

In the context of sustainable product development, remanufacturing is a promising end-of-life (EoL) recovery strategy to achieve a closed-loop product lifecycle. Remanufacturing involves a series of stringent industrial processes necessary for reprocessing or replacing the used parts in a product [1]. Prior to remanufacturing, it is necessary to examine the feasibility of a product or component for remanufacturing. Conventional remanufacturing evaluation and decision-making relies on the actual conditions of the returned products or components, e.g., usage pattern and statistical failure data [2]. Research studies on design for remanufacturing [1,3] suggest that remanufacturing consideration should be taken into account as early as possible in the product design stage. Therefore, it is necessary to assess a product design with respect to various remanufacturing considerations so that the product design can be enhanced to be more in line for remanufacturing.

Computer-aided Design (CAD) model as a well-structured representation of product design presents a rich source of useful information for examining product remanufacturability. However, there is a lack of a systematic analysis of CAD information with respect to product remanufacturability; there is no existing CAD software that has built-in tools to interpret the design information for remanufacturability evaluation automatically. To address this research issue, this paper presents a feature-based product remanufacturability assessment model based on CAD design information. The assessment consists of four quantitative metrics, namely, fastener accessibility, disassembly complexity, disassemblability and recoverability. By analyzing the evaluation outcome, possible design feedback can be made to enhance a product design for remanufacturing. A computer-aided system has been developed for design information

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extraction and management as well as the implementation of the proposed evaluation methods. A case study using a SolidWorks model of an automotive part is presented to demonstrate and validate the proposed approach.

2. Related studies

Few studies have been reported addressing product remanufacturability assessment from the design perspective. Earlier research adopts design charts as checklists to identify design attributes that have impact on the ease of remanufacturing [4], or investigates the embodiment design attributes, e.g., the number of parts, different types of fasteners, number of ideal parts, *etc*., to derive evaluation metrics [5]. Ramoni and Zhang [6] developed an entropy-based approach to evaluate remanufacturing sequences with an emphasis on the complexity of the product design. Axiomatic design theory [7] has been applied in product design and design for remanufacturing [8-10]. Zhang and Li [8] proposed that energy-saving products can be designed by integrating modular design and axiomatic design approaches. Shu and Flowers [9] adopted axiomatic design theory in product design to facilitate product remanufacturing processes and remanufacturing process planning. Du *et al*. [10] proposed remanufacturability evaluation metrics for used machine tools based on axiomatic design in three aspects of remanufacturing, i.e., technology feasibility, economic viability and environmental benefits.

Non-destructive disassembly and recovery of core components are essential for successful remanufacturing. Majority of the products that are remanufactured today require manual disassembly due to uncertainty in return conditions. Most studies adopt disassembly time as a measure to address product disassemblability. Fastener related issues, e.g., unfastening effort, tool requirement, fastener accessibility, etc., are analyzed so as to derive the disassembly difficulty scores and the estimated disassembly times [11,12]. Soh *et al*. [13] proposed a methodology for optimal disassembly route generation for remanufacturable part retrieval, so as to minimize conflicts between design for disassembly (DFD) and design for assembly (DFA). In the context of part recovery, Sherwood and Shu [2] reported different failure modes and the associated recoverability for automotive parts based on the statistical failure data gathered from waste streams. Shu and Flowers [14] reported that part material and joining methods can have significant effects on part recoverability. Such information can be obtained from the product design stage, which makes the assessment of recoverability possible given the product design model.

Appropriate EoL decision-making for a product would need to consider the actual conditions of the product returns, e.g., cumulative service time, remaining useful life of the product, number of times the product has been remanufactured or reused, etc. However, EoL strategies for products can be proposed early in the product design stage, and detailed product design information can be analyzed to assist designers in evaluating the design of these proposed EoL strategies. The evaluation would allow the design team to gain feedback to facilitate potential design modification and improvement. Zwolinski and Brissaud [15] presented remanufacturable products profiles (RPP) by analyzing the external and internal criteria gathered from successful remanufactured products. From technical perspectives, the criteria used for classifying RPPs focus on the conceptual and embodiment design attributes based on the study presented by Bras and Hammond [5]. A framework for product design has been developed by extending the RPP methodology to support product modification and redesign [16]. Sundin *et al*. [17] demonstrated the use of RemPro-matrix in addressing design improvement for product/service systems. The case studies show that disassembly-related issues, e.g., accessibility of parts during maintenance or remanufacturing operations, the joining method, etc., are important considerations for design improvements. These two approaches have provided general guidelines for product design feedback by identifying the relationships between the preferable product properties and the generic remanufacturing process steps. However, there is a need to map the design information encapsulated in a CAD model to the various remanufacturing processes.

3. CAD-based remanufacturability assessment

Remanufacturability assessment of a component can be decomposed into evaluating the technical feasibility, cost, etc., of each of the required remanufacturing steps through examining the effect of the relevant design attributes on these remanufacturing steps. Hence, this research proposes a feature-based assessment methodology for assessing remanufacturability of components given that detailed CAD models are readily available. As illustrated in Figure 1, the proposed CAD-based remanufacturability assessment comprises three modules, *viz*, CAD information extraction and representation, evaluation metrics based on technical criteria for successful remanufacturing processes, and design feedback based on remanufacturing evaluation.

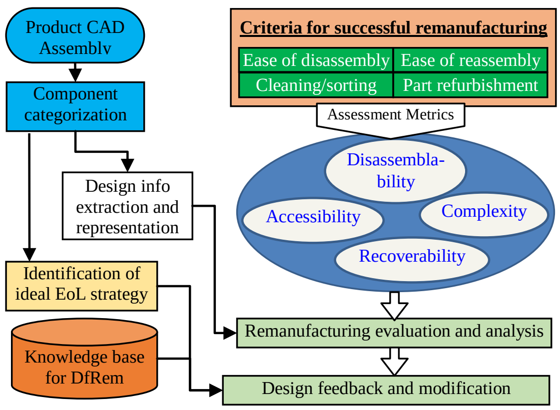

Fig.1. Framework for CAD feature-based product remanufacturability assessment.

3.1. Design information from CAD model

Design information to support remanufacturing should include the prominent features that impact the different aspects of remanufacturing, so that the data can be used to facilitate feasible design feedback and modification to the existing product or component design. The set of design information for a component with respect to remanufacturing can be organized in two categories, namely, BOM features and interfacing features. In particular, the following features need to be extracted.

- *BOM features.* These include the component type (part or sub-assembly which can be further disassembled). For each part, the BOM information includes (1) material type, which can be mapped in a material database to retrieve the manufacturing or machining property of the part, and (2) relative mass/volume, which is a simple and intuitive measure reflecting the relative intrinsic value of the part.
- *Fastening method.* This refers to the type of fasteners, the number of each fastener type, and the approach direction for the disassembly of each fastener. In general there are three connection types, namely, (1) separate fasteners, (2) integral fasteners, (3) mating connections, e.g., interference fit, etc. In this paper, only separate fasteners are identified, e.g., screws, bolts, nuts, etc. The other two fastening types are considered mating constraints.
- *Mating constraints.* These constraints are concerned with the interrelationships between any two connected parts, which include a part and the associated separable fasteners. Each mating feature is described by a specific mating type and the type of mating (geometric) entity.
- *Manufacturing features.* For each geometric entity defined as a mating feature, the corresponding manufacturing feature describes the manufacturing process to fabricate this geometric entity subject to both dimension and tolerance requirements. The types of manufacturing features are defined in STEP (STandard for Exchange of Product data) AP224 standard.
- *Dimension and tolerances.* The datum, dimensional and geometrical tolerances, limits and fits, etc., of the mating features need to be retrieved. These affect the cost and the difficulties in remanufacturing these features to their original specifications during the remanufacturing process.

3.2. Product components classification and EoL strategies

Not all the components of a product are remanufacturable. Therefore, prior to remanufacturability assessment, the components of a product are classified into four functional categories, namely, fasteners, moving components, fixed components, sacrificial part., Each category is associated with a set of ideal (designed) EoL strategies, as shown in Figure 2. For instance, the fastening components, e.g., bushing, washer, etc., are often replaced, and the obsolete components are sent for material recycling after disassembly. Moving components could be worn out quickly and they have to be replaced after reaching their EoL. For moving components which have high intrinsic value, e.g., shafts, gears, connecting rods, etc., the contact surfaces will need to be restored using appropriate additive manufacturing processes. For fixed components, e.g., engine block, alternator cover, etc., the EoL treatment is subject to change as the actual physical condition of the component needs to be assessed. Sacrificial part is usually used as an interface between a moving component and a fixed component to protect the more valuable component from possible damages. These sacrificial parts have the shortest lifespan, and thus should be replaced with new parts during remanufacturing. An example is the piston ring fitted between the piston and the cylinder block.

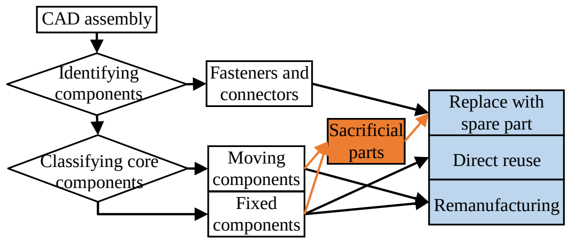

Fig. 2. Product components categorization and ideal EoL recovery strategies.

3.3. Remanufacturability assessment metrics

This study focuses on the assessment of components with respect to two remanufacturing processes, namely, part disassembly and recovery. Four numerical metrics, namely, disassembly complexity ($\boldsymbol{M}_{\mathrm{COM}}$), fastener accessibility ($\boldsymbol{M}_{\mathrm{ACC}}$), disassemblability ($\boldsymbol{M}_{\mathrm{DIS}}$), and recoverability ($\boldsymbol{M}_{\mathrm{REP}}$), have been developed to assess the ease and access of a number of fastening operations required to disassemble a part, the effort required to disassemble a part, and the possibility to restore the part to its original specification. The details of the metrics derivation were described in [18]. In addition to assessing the remanufacturability of core components, it is necessary to provide suitable design feedback based on the evaluation results and EoL recovery strategies, such as the identification of sacrificial components from the core components.

4. Design feedback based on remanufacturing assessment

4.1. Identification of relative motion between two components

In a product CAD assembly model, the spatial relationships between two components are specified by the mating conditions, which can be further analyzed to define the possible relative motion. Mating conditions are defined using basic geometric entities, *viz.*, points, lines and faces. Points and lines are used to define the location of a component, while faces are to determine the alignment and orientation of the component. The mating conditions can be classified into three groups [19], namely, against, fit and screw-fit. Table 1 summarizes the typical mating types in commercial CAD packages (SolidWorks and Autodesk) based on this definition.

The possible relative motion of a component with respect to its connected component is determined by the mating conditions required to join the two components together. The use of different mating types allows the component to have different degree-of-freedoms (DOFs). Figure 3 presents a procedure to determine the possible relative motion between two components with the corresponding mating conditions extracted from the CAD data file.

Table 1: Common mating types in commercial CAD packages

Generalized mating conditions	Mating types in SolidWorks	Mating types in Autodesk	Motion DOF permitted
Against	Coincident, distance, angle, tangent, parallel	Mate, angle, tangent, offset	2 translational DOF and 1 rotational DOF
Fit	Concentric	Insert	1 translational DOF and 1 rotational DOF
Screw-fit	Screw	--	1 rotational DOF

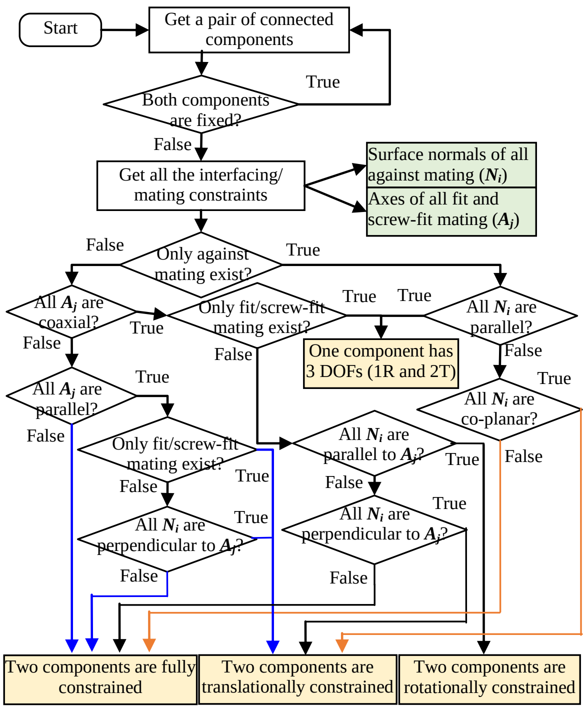

Fig. 3. Identification of relative motion between two connected components.

As illustrated in Figure 3, with different combination of the mating conditions, there exist three scenarios:

- *Against mating condition only*. Each against mating restricts three DOFs of relative motion. If there are more than one against mating with mating directions co-planar, only translational motion is permissible along the direction perpendicular to the mating directions. Otherwise, the two components are fully constrained with each other.
- *Fit or screw-fit mating condition only*. Each fit or screw-fit constrains four DOFs of motion. In case of more than one fit or screw-fit, if their axes are coaxial, there could be both translational and rotational motions with respect to the fit axis; if these axes are parallel, only translation is permissible between the two components; else the two components are fully constrained with each other.
- *Combination of against and fit/screw-fit mating conditions*. If these mating conditions coexist, each fit or screw-fit mating constrains four DOFs of motion. In the case where the axes of fit or screw-fit mating are coaxial, if the mating direction for against mating is parallel to the axes, the two components are rotationally constrained with respect to the mating axis; otherwise if the against mating direction is perpendicular to the axes, the two components are translationally constrained along the mating axis. In the case where the axes are parallel, if the mating direction of against mating is perpendicular to the axes, one component is translationally constrained to the other; otherwise, they are fully constrained with each other.

4.2. Identification of sacrificial part between two connected components

It is common to have a sacrificial part assembled between a moving part and its counterparts in order to reduce the damage to the more valuable parts due to the relative motion. In addition, the sacrificial part can be disassembled to protect the functional parts from possible disassembly failure. Therefore, it would be useful to identify the existence of such parts in an assembly model using relevant design information, so as to provide design feedback to the design teams for the possible design improvement. A sacrificial part can be a separable connector-type component (*e.g.*, a washer) or a common component. Figure 4 outlines the procedure to identify the need for a sacrificial part by analyzing the relative motion between two connected components. If a sacrificial part is required, the associated BOM features, the disassembly and the recovery properties can be utilized to determine which of the two components can be a sacrificial part, or the need for an additional part as a sacrificial part.

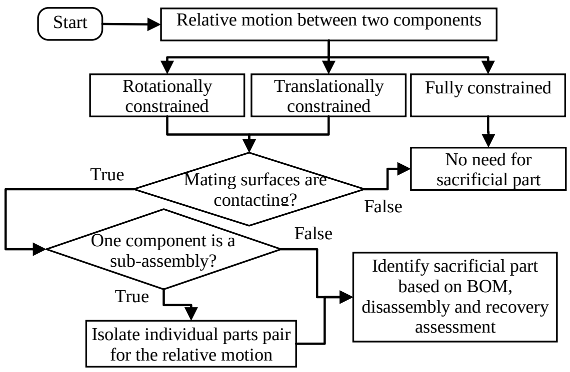

Fig.4. Decision-making on the need for a sacrificial part.

The identification of a potential sacrificial part is presented in Figure 5. Considering the possible wear due to the relative motion between the parts, the part made from a material with lower hardness and durability can be regarded as the candidate sacrificial part. In terms of other physical properties, the part with lower volume or weight is typically considered as a sacrificial part. Based on the results of the four assessment metrics, a part with lower disassembly complexity, and requiring higher disassembly effort and higher recovery cost will be the candidate sacrificial part. A sacrificial part difficult to be disassembled can be destructed to protect the part to be remanufactured from damage during disassembly. In addition, a sacrificial part should be a part with low manufacturing cost but has a relatively high recovery cost. If the candidate sacrificial part has a high intrinsic value compared to other components, an additional sacrificial part is needed to reduce the possible damage to any of the two components resulting from their relative motion.

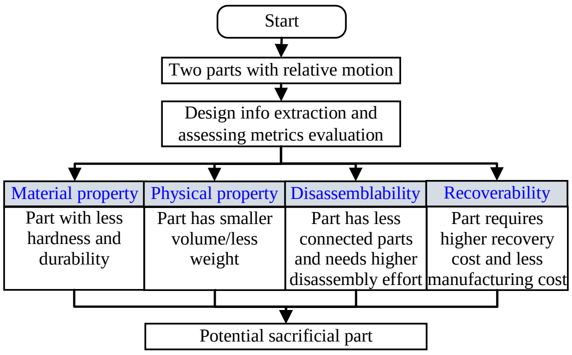

Fig. 5. Identification of possible sacrificial part.

5. Case study – A electric motor reducer

A computer-aided system has been developed to implement the proposed product remanufacturability assessment methodology. Figure 6 describes the data structure and the organization of the design information that is extracted from a SolidWorks assembly. For each component, the adjacent component(s) and the associated fasteners are identified and stored accordingly. The fastener type, the base dimension type and the dimension value of the connection are retrieved. The four metrics for each component are computed and stored in this data structure. By simultaneously considering other information, such as material, volume, etc., the EoL option for a component can be determined, *viz.*, remanufacture, reuse, or replacement with a new component.

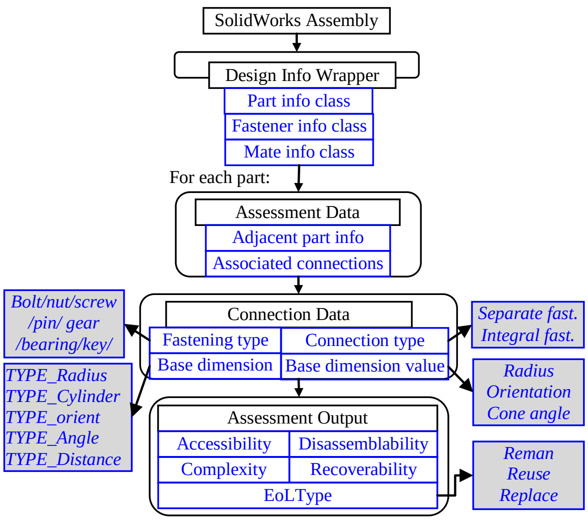

Fig. 6. CAD design information hierarchical representation.

A case study using an automotive electric motor with an integrated reducer unit is presented for the validation of the developed assessment methodology. Based on the assessment results, possible design feedback regarding the desired EOL strategy for each component and the need for sacrificial part can be provided to the designers. Rewinding of the rotor and the stator of the motors is prevailing in the remanufacturing industry. In this study, however, only major mechanical components and features are evaluated with respect to disassembly and recovery, as well as the designed EoL options. The CAD model of the automotive part is adapted from [20]. Figure 7(a) depicts an exploded view of model, and Figure 7(b) is a graph representation of the assembly, in which each node denotes a separate component, and each edge denotes a connection between two adjacent components. All the information types can be retrieved as per definition given in Ref. [18], and stored in the design information wrapper based on the definition given in Figure 6.

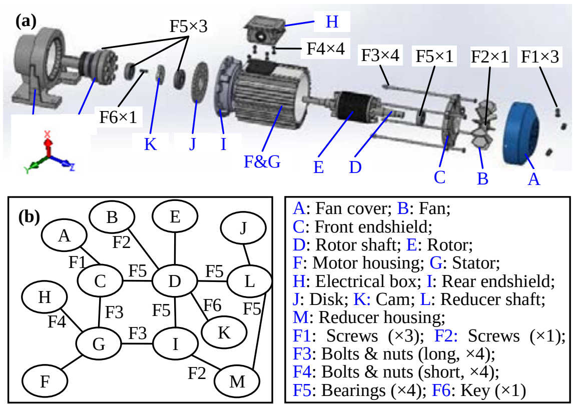

Fig. 7. An electric motor model: (a) exploded view; (b) graph representation.

Table 2 summarizes the results for each component with respect to disassemblability, recoverability, EoL option and sacrificial part determination. The EoL strategy for the fan cover and electrical box is part replacement, as they are made of plastic and assembled to adjacent parts by screws. Disk and cam are sacrificial parts, as their rotational counterpart, namely, the reducer shaft, has higher intrinsic value, and higher disassemblability and recoverability. The motor shaft is the most difficult part to be disassembled due to the large number of fastening types used, *i.e.*, interference fit, bearing, key and screw. It has the largest number of contacting surfaces with the highest tolerance, thus demanding high remanufacturing effort to restore it to original condition. Therefore, a thorough check is necessary to assess the returned condition of the motor shaft to determine whether it is worthy being remanufactured. Otherwise, part replacement would be a more favored option despite its technical feasibility for remanufacturing. For the pair of rotationally fixed parts (the shaft and endshield), the bearing, which is a separable connector, can be regarded as the sacrificial part to prevent the pair from failure caused by the relative motion. In this case, the EoL option for the shaft will be remanufacture, while the bearing will be replaced.

Table 2: EoL evaluation for components in motor electric reducer.

Comp name	Material	Part type	Vol (m^3)	Size (mm)	Thickness (mm)	M_{DIS}	M_{REP}	Sacrificial?	EoL option
Fan cover	Plastic	Fixed	0.52e-4	150	58	0.457	-	-	Replace
Fan	Steel	Rot	0.53e-4	119	38	0.485	0.532	-	Reuse
Front endshield	Cast iron	Fixed	1.03e-4	144	18	0.409	0.110	No	Reman
Rotor shaft	Cast iron	Rot	0.81e-4	260	12.5	0.387	0.028	No	Reman or Replace
Rotor	Copper	Rot	2.81e-4	115	76	0.462	0.479	No	Reuse
Motor housing	Alumi-nium	Fixed	5.03e-4	151	150	0.464	0.231	No	Reuse
Stator	Copper	Fixed	3.75e-4	115	76	0.666	0.479	No	Reuse
Electric box	Plastic	Fixed	0.27e-4	60	40	0.457	-	-	Replace
Rear endshield	Cast iron	Fixed	2.82e-4	150	45	0.409	0.110	No	Reman
Disk	Cast iron	Rot	0.41e-4	104	8	0.666	0.043	Yes	Replace
Cam	Cast iron	Rot	0.09e-4	51.2	8	0.485	0.284	Yes	Replace
Reducer shaft	Cast iron	Rot	1.89e-4	125	44	0.404	0.311	No	Reman
Reducer housing	Cast iron	Fixed	8.25e-4	180	140	0.410	0.110	No	Reman

6. Conclusion and future works

Product design can have substantial impact on remanufacturing feasibility evaluation and design feedback. This paper presents a methodology for assessing the technical feasibility of remanufacturing based on product design information. A data structure has been developed to organize the design information for remanufacturing assessment. Suitable EoL strategy for each component of a product can be determined by considering the remanufacturing assessment results. A software tool that can extract design information automatically from CAD models has been developed to assist designers to perform the remanufacturability assessment. A case study of an automotive part is presented to demonstrate and validate the remanufacturability assessment methodology.

Future works can be made to enhance the proposed approach for product remanufacturing assessment. A remanufacturing knowledge base containing typical/critical design features can be developed to facilitate assessment of core component disassembly and recovery. The knowledge base can be expanded by incorporating product usage data and frequent failure information. In addition to providing design feedback to enhance the remanufacturing of a product design, the knowledge base and the assessment outcome can be used for remanufacturing process planning, as well as other associated remanufacturing decision-making.

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