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Product Remanufacturability Assessment Based on Design Information

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Abstract

Existing studies on CAD-based remanufacturability assessment are either based on design charts or consideration of simple embodiment design features only. This paper presents a remanufacturability assessment model based on design information in CAD models, e.g., bill of material, assembly and mating features, dimensional and tolerance features, etc. A set of design feature-based metrics is proposed for product remanufacturability assessment, namely, disassembly complexity, fastener accessibility, disassemblability, and recoverability. The metrics are integrated into a generic model to analyse the feasibility of a product for remanufacturing. A case study using an automotive part is presented to demonstrate the effectiveness of the model.

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Keywords: Product remanufacturability assessment; disassemblability; recoverability; design features

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1. Introduction

Product remanufacturing is referred to as a series of industrial processes aiming to return a used product or component to a like-new condition with a warranty to match [1]. It has increasingly been recognized as the most promising product end-of-life (EoL) recovery strategy to meet more stringent environmental directives. Compared with component reuse, repair and material recycling, it presents an excellent opportunity to prolong the useful service life, while preserving energy, material as well as lowering carbon footprint and environmental impact. Remanufacturability is a measure to evaluate the feasibility and suitability for a product or component to be remanufactured. Since design represents one of the earliest product development phases, it is important that the remanufacturability of a product design is assessed in this stage in order that the design can be modified and improved to be more in line for remanufacturing. For products and components to be remanufactured, the assessment of the product design would provide useful input to assist the decision-makers in remanufacturing processes planning as well as remanufacturing facility planning.

Technically, a component with a high remanufacturability would mean that it can be disassembled completely, cleaned and inspected/sorted easily, and has high recoverability and upgradability. Among all the necessary processes involved in remanufacturing, disassembly and part recovery are identified to have the most significant impacts on product remanufacturability [2]. Particularly, design related issues, e.g., fastening and joining methods, fastener accessibility, complexity, surface finish, etc., are of principal concerns that affect the disassemblability and recoverability of cores.

This paper presents a study on remanufacturability assessment based on design information in a CAD model, e.g., bill of material, assembly and mating features, dimensional and tolerance features, etc. Four metrics are proposed to evaluate the different facets of a product design, namely, disassembly accessibility, complexity, disassemblability, and recoverability. These metrics can be integrated into a generic model to analyse the feasibility of a product for remanufacturing. A case study using an automotive part is presented to demonstrate the effectiveness of the evaluation model.

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2. Literature Survey

Product Computer-Aided-Design (CAD) model exhibits a rich resource of information useful for product remanufacturability evaluation. Existing studies on CAD-based remanufacturability assessment are either based on design charts [3] or consideration of simple embodiment design features only [4-6]. Hammond and Bras [3] proposed a set of metrics for assessing remanufacturability by first identifying principal driving factors and existing guidelines for remanufacturing. The embodiment features, e.g., the number of parts, number of ideal parts, etc., are used to derive the metrics with respect to the processes involved in remanufacturing. The assessing metrics were further developed in [5-6] by specifically defining the scope of ideal parts. 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 to enforce design for remanufacture is based on a series of design charts with design attributes and metrics associated with all the remanufacturing phases [3]. It is a collection of guidelines to guide the design team in evaluating the remanufacturability during the product design stage, which relies on the designers' expertise to understand the design features and attributes.

Non-destructive disassembly is one of the prerequisites for successful product remanufacturing, in which the disassembly process and its efficiency are closely related to the fastening methods adopted in the assembly. Most studies have adopted disassembly time as a measure to evaluate disassemblability. Some evaluation methods are, e.g., Hitachi method, work-measurement based method, etc. [7]. The design attributes, such as disassembly force exertion, tool requirement, positioning and 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 [8-9]. However, these methods require the design team to create the evaluation chart manually, which would be tedious for products with complex structure and a large number of components.

Design complexity is factor that would affect product disassemblability. Recent studies on Design for Assembly (DFA) adopted connectivity complexity as a measure to estimate product assembly time [10-11]. The explicit connections between two components, such as the mating relationship defined originally in many commercially available CAD modelling platforms, can be used to create the connectivity graph and derive the connectivity complexity. Similarly, the connectivity graph retrieved from an assembly model can be used in assessing disassemblability and remanufacturability of the product design.

Sherwood and Shu [12] adopted a modified Failure Modes and Effects Analysis (FMEA) approach to support design for remanufacture, in which the detectability, occurrence and repairability of failures can be jointly factored in to prioritize the potential failure modes. This modified-FMEA approach can assist the design teams in identifying possible design weaknesses or drawbacks, providing feedback to improve the existing product design. However, it relies heavily on the data availability from remanufacturer waste streams, and thus may not be suitable for newly launched products.

3. Remanufacturability assessment based on product design information

3.1. Design information

Product CAD model encapsulates a substantial amount of design information, e.g., material selection, geometrical features, etc., which can be retrieved and analysed to support manufacturers in production processes. In order to assess the product remanufacturability during the design stage, design information should be interpreted to build the relationships with the evaluation criteria and metrics. Figure 1 shows some of the necessary preparation steps for remanufacturability assessment when a product CAD model is available.

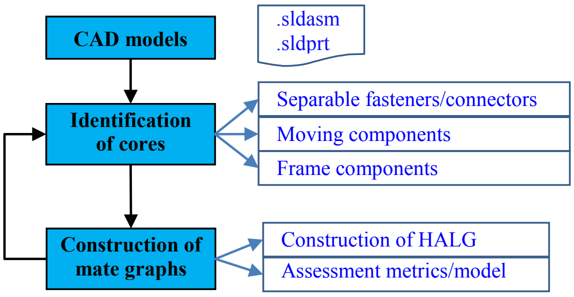

Fig.1. Components classification and design information representation.

Generally, not all the components of a product are remanufacturable. It would be useful that components (i.e., cores) having high remanufacturing value can be identified based on the design information. The components can be grouped into two categories, namely, fastener and connector type components, and common components [13]. In most cases, the fasteners and connectors (e.g., bearing, bushing, washer, etc.) are not remanufactured due to the relatively low value. The common components can be further classified into moving components and frame type components. Moving components, such as pistons in an automotive engine, are usually worn faster due to the relative motions with respect to their counterparts, and are replaced after reaching their EoL. For other moving components, e.g., shafts, gears, connecting rods, etc., the contact surfaces can be restored using additive manufacturing processes. The rest can be classified into frame type components. Based on this classification, only the common components can be suitably considered as cores to define the scope for remanufacturability assessment.

Given a complete CAD description, standard fasteners and connectors can be identified easily if the component name is used as the component identity. The moving components can be identified by analysing the mating relationships with respect to the connecting components. Li *et al.* [13] defined some common parts and classified them according to their functions in the assembly model. The shaft-type or wheel-like type moving components can be identified easily based on their signature features, such as face types, dimensions, diameter/length ratio, etc.

3.2. Design information representation

Commercially available CAD modelling packages, e.g., SolidWorks, NX Unigraphics, Inventor, etc., have the same basic principles for primitive features modelling, but each adopts different mechanisms to define the unique set of assembly features and constraints. Therefore, there is a need to have a generic data structure as a programmable wrapper to interface the design information with the remanufacturability assessment model. In this research, a graph-based data structure is used to represent the set of components or subassemblies and the interrelation mechanisms between any pair of them. Mathematically the graph can be given as $H=(N,E)$, and the definition is as follows [14]:

- $\boldsymbol{N}$ is the set of nodes, each of which is referred to a part or a subassembly. A node can have the following attributes:
  a. The node name
  b. The node type (part or subassembly)
  c. The sub-graph (for subassembly only)
  d. The contact surfaces as geometric features
  e. The physical properties: material, mass, volume

- $\boldsymbol{E}$ is a set of connections between two nodes, each of which maps to a liaison between two elements in $\boldsymbol{N}$. A liaison can be described by the following attributes:
  a. The connection type (fasteners, mates)
  b. The pair of nodes
  c. The contact surfaces
  d. The number of degree-of-freedom constrained
  e. The geometric properties: dimension, tolerance
  f. Feature parameters: position, orientation

With regard to connection types, there are generally three ways to join two parts together, namely, (1) using separate fasteners, (2) using fasteners integral to one part, or (3) using mating constraints, e.g., interference fit, friction, etc. Some commonly used fasteners are summarized from the disassembly perspective [15]. In this paper, only the separate fasteners are identified, e.g., screws, bolts, nuts, etc. The other two fastening types are recognized as mating types.

4. Methodology

4.1. A framework for remanufacturability assessment

Figure 2 outlines the framework proposed for remanufacturability assessment based on design information. Given a complete product CAD model, the separable fasteners and connectors are first identified and excluded from the list that contains the core components and subassemblies. By defining the cores as the nodes, a graph-based representation can be generated accordingly. For each component, both the design attributes as well as the connections with the adjacent component(s) are described in the graph. Four correlated metrics used to evaluate the four facets of the design, i.e., disassembly complexity ($\boldsymbol{M}_{\mathrm{COM}}$), fastener accessibility ($\boldsymbol{M}_{\mathrm{ACC}}$), disassemblability ($\boldsymbol{M}_{\mathrm{DIS}}$), and recoverability ($\boldsymbol{M}_{\mathrm{REP}}$), are derived based on the graph. The set of metrics can be used to assess the remanufacturability of each constituent component from technological perspective. The next sections present the detailed methodology in defining the four metrics.

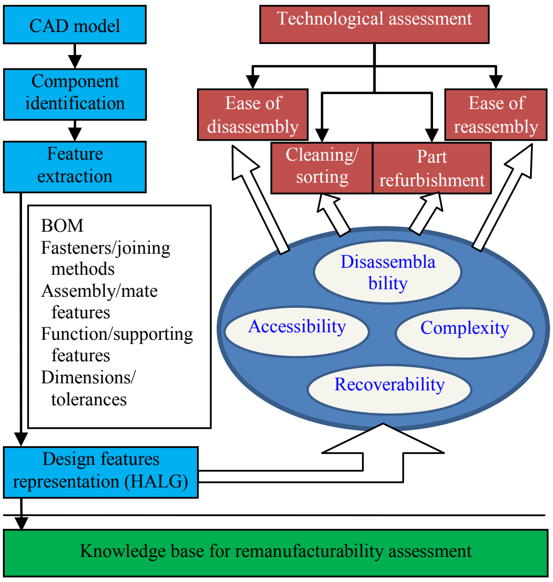

Fig.2. Framework for product remanufacturability assessment based on design information.

4.2. Disassembly complexity metric: M_{COM}

Numerical metrics have been known as the most intuitive forms of complexity measurement [10]. One primary principle in design for assembly and disassembly is the adoption of minimum number of fasteners in an assembly. In manual disassembly, especially without the assistance of properly designed disassembly fixtures, each fastener needs to be disassembled separately. Meanwhile, different fastener types may require different types of unfastening tools and different accessing directions, resulting in an increase in the disassembly time as well as disassembly cost. Therefore, the disassembly complexity of an individual part can be assessed based on (1) the variation of the fasteners types, and (2) the number of fasteners for each type.

It is reported that the effect of the number of fasteners to the complexity is nonlinear, and can be modeled using entropy in information theory [10]. When the count is low, the addition of a fastener is significant, while the opposite is true of high-count systems. The logarithmic function, which is monotonically increasing but concave, can model the impact of the number of fasteners. The number of fastener types is modeled using the summation function, considering that the effect of the variation of the fastener types could overweighs than that of the number of fasteners, since each fastener type may require a different unfastening tool during disassembly. The disassembly complexity metric can be given in Equation (1), in which $\boldsymbol{N}_{\mathrm{t}}$ is the variety of the joining types, and $\boldsymbol{N}_{\mathrm{f}}(i)$ is the number of fasteners or connectors in type i.

$$M_{COM} = \sum_{i=1}^{N_t} \log_2\left(2 \times N_f(i)\right) \tag{1}$$

4.3. Fastener accessibility metric: M_{ACC}

Accessibility measures how easy a part can be reached or a fastener/connector can be accessed by an unfastening tool during a disassembly operation. Part accessibility provides precedence in generating a set of feasible disassembly plans, which is especially useful in selective disassembly planning [16]. However, for a complete disassembly, which is often the case in remanufacturing, fastener accessibility is of greater relevance than part accessibility. Considering manual disassembly remains the main stream in remanufacturing, fastener accessibility can be measured from two ergonomics perspectives: unfastening approach direction [16] and access topology [17]. The latter case often requires a special tool to access the fasteners, and the access can be evaluated easily by the operators at the time of disassembly. For the former case, the access difficulty will increase in the following order: *Z*-axis, *X*/*Y*-axis, negative *Z*-axis. For the *i*th fastener in a part, given the approach direction as the angle to the horizontal plane $\boldsymbol{\theta}(i)$, the accessibility metric is given by Equation (2). It captures the changes in the approaching direction, i.e., the larger the angle, the better is the accessibility. Equation (3) models the accessibility when more than one fastener exists for securing 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. $\boldsymbol{N}_0$ is the total number of separate fasteners, and ω is the weighting coefficient.

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

$$M_{ACC} = \left(\sum_{i=1}^{N_0} \frac{\omega_i}{M_{ACC}(i)} \right)^{-1} \tag{3}$$

$$N_0 = \sum_{j=1}^{N_t} N_f(j), \; \omega_i \geq 0, \; \sum_{i=1}^{N_0} \omega_i = 1$$

4.4. Disassemblability metric: M_{DIS}

Disassemblability defines the extent to which a part can be dismantled easily and undestructively from the 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: the unfastening difficulties and the directional constraints during part separation [14]. Table 1 provides the relative unfastening ratings for general types of fasteners and connectors. The directional constraints of a part separation motion can be represented 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) [14]. The disassemblability metric of a part can be given in Equation (4). $\boldsymbol{N}_0$ is the total number of connections, including separate fasteners and integral fastening, used to secure the part. Equation (5) defines the disassembly effort (normalized) required for an individual connection *i*, where $\boldsymbol{X}_s(i)$ describes the unfastening difficulty, and $\boldsymbol{X}_d(i)$ gives the directional constraint in unfastening. *α* is the weighting coefficient, which satisfies 0<*α*<1. In case there could be more than one connection for securing a part, the connection that requires the most disassembly effort dominates the disassemblability (as given by $\boldsymbol{X}(i_{MAX})$). In addition, the effect of the dominated connections is reinforced by averaging the effect of these connections. The coefficient (1-$\boldsymbol{X}(i_{MAX})$) is a regulator which ensures that the exponent is normalized and falls in [0,1]. The exponential function indicates that the disassemblability is inversely proportional to the disassembly effort required for each connection.

$$M_{DIS} = e^{-\left(X(i_{MAX}) + \frac{1 - X(i_{MAX})}{N_0 - 1} \left(\sum_{i=1, i \neq i_{MAX}}^{N_0} X(i) \right) \right)} \tag{4}$$

$$X(i) = \alpha X_s(i) + (1-\alpha) X_d(i) \tag{5}$$

$$X_d(i) = 1 - \frac{DFS(i)}{6} \tag{6}$$

$$X(i_{MAX}) = Max\left(X(i)\right), i = 1, 2, \ldots N_0 \tag{7}$$

Table 1: Relative unfastening rating of fastener type (adapted from [14]).

Fastener type	Relative unfastening difficulty
Mate/insert	0.3
Bolt, bolt-nut, screw	0.5
Gear, belt-mesh	0.7
Key, interference fit, bearing	0.8
Rivet, welding	0.9

4.5. Recoverability metric: M_{REP}

The recoverability of a part describes the possibility or feasibility that it can be restored to its original specification for reuse. For the frame type parts, such as the housing of an automotive alternator, a common failure would be the fastening failure caused during disassembly [12], which makes the recovery impossible and leads to reassembly failure. Table 2 gives the relative fastening failure rate due to disassembly with respect to the two aspects, part material and fastening methods. Taking two parts made of plastics joined together with screws, the disassembly of the fasteners would destroy the thread on the parts. Subsequently, the same type of screws will form new threads and thus not be able to provide enough strength for the two parts being reassembled. In this case, the parts can only be replaced instead of being remanufactured. It is suggested that the use of inserts together with screws would enable the reuse of the parts after disassembly [18]. If two parts are joined together through a fit mechanism, there is still a high chance that the joining area may be cracked during disassembly. However, for parts made of steel or alloy that are joined using separable fasteners, the failure rate due to disassembly can be considerably lower.

Table 2: Fastening failure rate due to disassembly [18].

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

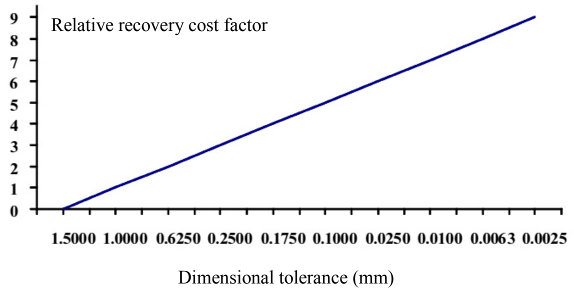

Fig. 3: Dimensional tolerance relative recovery cost factor [19].

The relative motion for moving parts with respect to the counterparts presents one major source for part failure, e.g., worn out, deformation, etc. The use of failure-isolation parts (e.g., bearings, cylinder sleeves, etc.) can be effective in reducing the impact of vibration as well as wear on the cores. In addition, the total number of contact surfaces of a moving part (which usually require machining processes to produce) and surface finish will affect the recoverability with respect to re-machining cost. Previous work [19] has 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 3. The recoverability metric can be jointly determined by the fastening failure rate (γ), the relative recovery cost factor (κ), the number of joining types (N_t), and the number of contact surfaces of each joining type ($N_s(i)$), as given in Equation (8). 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 the part reaches zero. Similar to the effect of the number of fasteners in complexity assessment, the logarithmic function is used to model the effect of the number of contact surfaces, and the addition function is used to capture the effect of the variety of joining types. The exponential function as a normalization measure ensures that the recoverability falls in [0,1].

$$M_{REP} = e^{-\sum_{i=0}^{N_t}\left(\frac{\kappa_i}{1-\gamma_i}\times\log_2\left(2\times N_s(i)\right)\right)} \qquad (8)$$

5. Case study and discussion

In this section, a CAD model of an automotive alternator is used to validate the proposed metrics. It consists of the main mechanical parts, while the electronic parts, e.g., brush assembly, voltage regulator, etc., are ignored. Figure 4(a) presents an exploded view of this model, and Figure 4(b) is a graph with the mating and connections between the parts.

The design information from a CAD model can be extracted and stored in a graph structure. With the pulley component facing up, the access direction of the fasteners for disassembly of each part can be determined (3rd column of Table 3). The unfastening difficulty and the DFS for each joining type identified in the model can be determined (4th and 5th columns of Table 3). By setting the value of α as 0.8, the disassembly effort $\boldsymbol{X}(i)$ required for each joining type can be determined according to Equation (5). The last column gives the dimensional tolerance for the connection surfaces. Table 4 shows the results of the four metrics based on part material, part type, and other design information as given in Table 3.

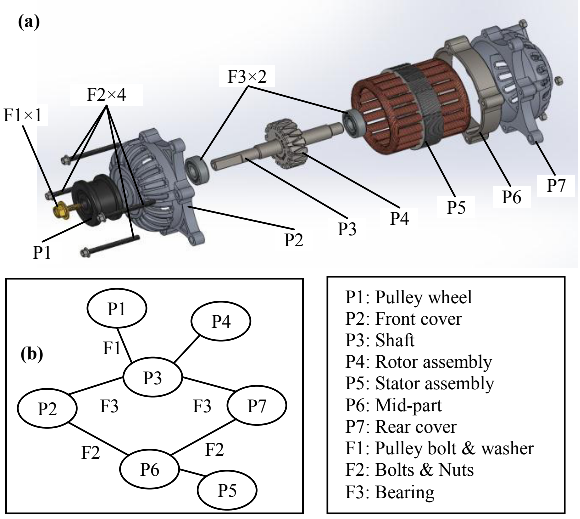

Fig. 4: An alternator model: (a) exploded view; (b) graph representation.

Table 3: Definition of edges in the graph.

Edge	Joining types	Access direction	$\boldsymbol{X}_s(i)$	DFS	$\boldsymbol{X}(i)$	Tolerance (mm)
P1-P3	Insert	-	0.3	1	0.407	IT7 (0.015)
	Screw	90°	0.5	2	0.533	-
P2-P3	Bearing	-	0.8	2	0.773	IT6 (0.011)
P2-P6	Bolt & nut	90°	0.5	2	0.533	-
P3-P4	Interference fit	-	0.8	2	0.773	IT6 (0.011)
P3-P7	Bearing	-	0.8	2	0.773	IT6 (0.011)
P6-P7	Bolt & nut	90°	0.5	2	0.533	-
P5-P6	Insert	-	0.3	1	0.407	IT7 (0.035)

It can be seen in Table 4 that the fastener accessibility of each part is favorable as they can be accessed from directly above the product. Three parts (front and rear covers, mid-part) have 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 connecting with the two bearings and the rotor; it also requires the greatest recovery effort as the need for the finest dimensional tolerance for interference fit.

Table 4: Evaluation of remanufacturability of components in an alternator.

Nodes	Material	Part type	M_{ACC}	M_{COM}	M_{DIS}	M_{REP}
Pulley	Steel	Rotational	1.0	1.0	0.485	0.504
Front cover	Alloy	Fixed	1.0	4.0	0.409	0.479
Shaft	Alloy	Rotational	-	3.0	0.401	0.110
Rotor	Steel	Rotational	-	-	0.462	0.479
Stator	Copper	Fixed	-	1.0	0.666	0.560
Mid-part	Steel	Fixed	1.0	4.0	0.464	0.560
Rear cover	Alloy	Fixed	1.0	4.0	0.409	0.479

6. Conclusion and future work

Remanufacturability assessment of a product design is to evaluate the feasibility of a product or a component to be remanufactured based on the product design information. It allows the design team and decision-makers to gain insights of the product design and different aspects of product remanufacturability in the early design stage. In this paper, four metrics are proposed to evaluate the remanufacturability of product components quantitatively, namely, fastener accessibility, disassembly complexity, disassemblability, and recoverability. A CAD model of an automotive alternator, which has been widely known as a remanufacturable product, is used to verify the set of evaluation metrics.

Improvement can be made to further develop and integrate the evaluation metrics in assessing the remanufacturability of products and components. For example, in addition to the dimensional tolerances, the positional tolerances of design features can be studied in assessing recoverability. An integration of the four evaluation metrics into a generic model would be desirable for remanufacturability assessment. The future work would be the development of a software tool to implement the proposed assessing metrics automatically with completely defined product CAD models as inputs. By studying the existing remanufacturable products and components, a knowledge base can be developed containing a variety of design feature signatures and the associated assessment metrics. The knowledge base can be used to study the newly designed part by comparing it with the existing instance in the knowledge base. This knowledge vault can also be used for benchmarking of the proposed methodologies for remanufacturability assessment against product type-specific characteristics in actual industrial practices.

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