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Assessing the Complexity of a Recovered Design and its Potential Redesign Alternatives

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Abstract
Reverse engineering techniques are applied to generate a part model where there is no existing documentation or it is no longer up to date. To facilitate the reverse engineering tasks, a modular, multi-perspective design recovery framework has been developed. An evaluation of the product and feature complexity characteristics can readily be extracted from the design recovery framework by using a modification of a rapid complexity assessment tool. The results from this tool provide insight with respect to the original design and assists with the evaluation of potential alternatives and risks, as illustrated by the case study.

Keywords:
Product Complexity, Design Recovery, Redesign

1 INTRODUCTION

When designing a product, a top-down hierarchical process is followed, where general principles are methodically applied to synthesize solutions that satisfy the need. Design parameters (DPs) are determined to fulfil the functional requirements (FRs) at the product, component and feature levels. Several engineering design methodologies such as Value Engineering (VE) [1], Axiomatic Design [2], and the Theory of Inventive Problem Solving (TRIZ) [3] assist the designer in creating a robust design that meets the necessary FRs based on logical and rational thought processes. Consequently, when reverse engineering an engineered component there must be a methodology for recognizing the design intent for the individual features, and the component structure and product architecture in both the physical (form) and logical (FR) domains. Effective design recovery consists of linking the function and form characteristics in context with the application and the operating environment in order to be able to infer the designer's intent at the system, embodiment and detail levels to produce pertinent product documentation. A comprehensive design recovery strategy must be performed to ensure that the essential attributes are captured to ensure that (i) the reconstructed design will fit within a product's architecture, and (ii) no unexpected behaviours could emerge during usage. Conditions may exist where the recovered design needs to be modified before the component can be remanufactured. These re-design requirements may be due to the introduction of a new product variant, different operating conditions or available manufacturing processes, or other design constraints. For these reasons, the design recovery framework should readily link to other formal design tools in order to assess the original design and to highlight areas of improvement. The goal of this work is to leverage the design recovery framework to quantify the original design's product complexity and subsequent design alterations using an adaptation of the product complexity analysis methodology developed by ElMaraghy and Urbanic [4].

2 DESIGN RECOVERY FRAMEWORK

The design recovery framework has been developed to provide a multi-level roadmap to allow the functional, structural and data information to be accumulated at different levels of abstraction (Figure 1). Information is gathered from the contextual to the detail levels to answer the 'what', 'how', 'where' and 'why' related questions with respect to the design in an explicit manner. The component/feature functions are enumerated for the 'Logical: What' rubric using the National Institute of Standards and Technology (NIST) design vocabulary [5]. NIST research partners developed a comprehensive, standardized terminology to reflect the intended reasons for a component's architecture. The information contained in the 'Logical: How' rubric provides a brief description as to how the functions are met in the design. The hypothesized functional requirements are presented in the 'Logical: Why' rubric. The associated design parameters and specific dimensional and tolerance data are identified in the physical and detail layers, as illustrated in Figure 1.

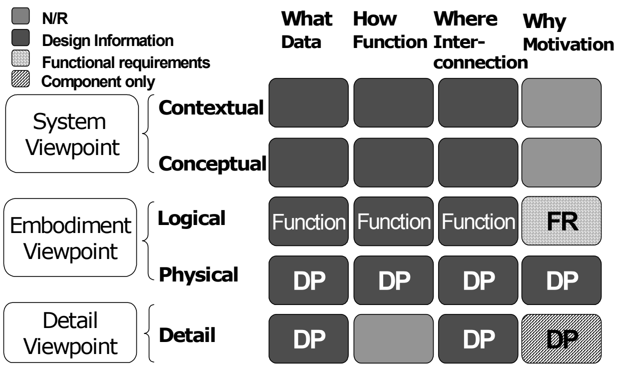

Figure 1: Design recovery framework.

Gathering this information in a modular, systematic, and comprehensive manner allows the designers the means to make informed decisions as to whether the current component design is adequate, or how may it be modified to add value and/or address the present set of design and manufacturing constraints. For a detailed description of the design recovery framework, refer to Urbanic and ElMaraghy [6].

To complement the design recovery framework, a connectivity diagram, a technique used in network design to illustrate the logical and physical connections, is used to illustrate physical feature links within a component, and the interface components. Features analysed in the design recovery framework should be illustrated in the connectivity diagram along with influential interface components. The rules developed for constructing an artefact connectivity diagram are as follows:

- Each feature must be identified, and provided with a concise, descriptive label.
- Feature patterns and pattern types must be identified and labelled. The pattern types are linear, circular, polar grid, linear grid, and peripheral.
- The mating components for each feature must be identified. If the mating component is an external component, it must be included and labelled appropriately.
- Critical external components, which influence the design of the component being analysed, must be also included in the connectivity diagram.
- Each feature type has a distinct font and connector style, as shown in Table 1. The appropriate connector style is drawn between the features.
- Transition geometry is included in the model at the discretion of the engineer.

Feature Type	Font	Connector Style	Outline Shape
External component, special	Italicized, Blue	Solid	Oval
External component, standard commercial item	Italicized, Black	Phantom	
Product	Normal, Black	Solid	Rectangle
Process	Bold	Dashed	
Assembly	Normal, Red	Solid	

Table 1: Feature summary for connectivity diagrams.

The connectivity diagram for the power steering pulley pump (Figure 2) case study is illustrated in Figure 3. The features contained in the power steering pump pulley are the:

- Crankshaft mounting bolt hole, A1 (datum -A-)
- Threaded fastener clearance holes, B1 – B3, pattern B_C1
- Threaded fastener clearance holes, C1 – C4, pattern C_C2 (which does interface with any other component on the engine)
- Locating dowel holes D1 and D2, pattern D_C2
- V groove,
- Mounting face, enclosure and blending fillet.

Each feature pattern is identified by an *xx_yy* label, where *xx* is the feature label, and *yy* is the pattern label. A common pattern label is used when multiple features are contained in a similar pattern. For this example, the dowel holes D1 and D2 lie in the same bolt circle as the threaded fastener clearance holes C1 – C4; hence the common pattern designation.

The power steering pump pulley is joined to a dual groove pulley via two locating holes (D1 and D2) and the mounting face. The dual groove pulley drives the air conditioning compressor and the water pump. This pulley system is fastened to the dampener using three 3/8-24 UNF bolts through holes B1-B3, and is connected on the crankshaft using the crankshaft mounting hole (A1). (Note: all units are in inches.) The crankshaft is the driver for this system, and the power steering pump is the driven component using a standard V groove and belt configuration. The enclosure walls are encompassed by the air-conditioning / water pump duel groove pulley.

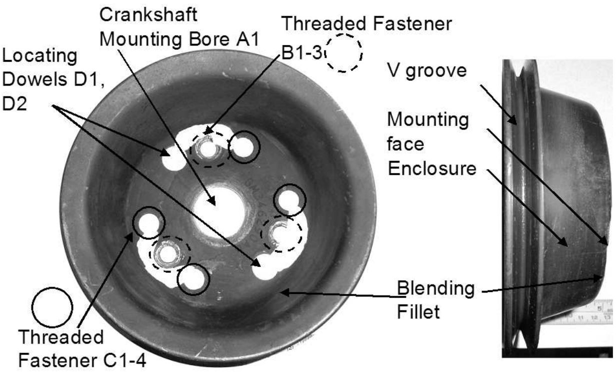

Figure 2: Power steering pump pulley.

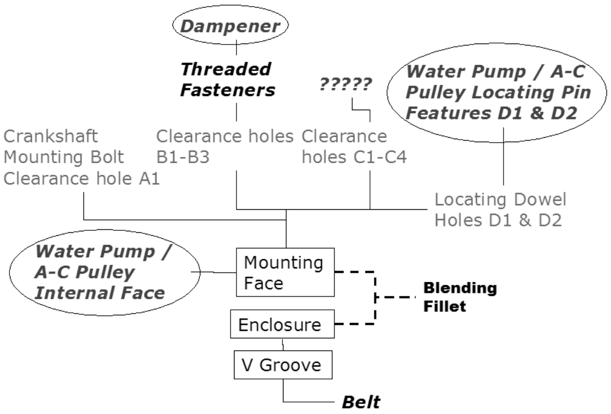

Figure 3: Power steering pump pulley connectiviety diagram.

The design structure matrix is employed to evaluate the actual design structure coupling based on the designer's understanding of the functional requirements and the features contained in the component being assessed. The design structure matrix (DSM) is a project development tool used to illustrate task coupling for individual activities in a matrix format. There are three different matrix structures to reflect activity types. Activities that occur independently are represented as a parallel structure. Activities that occur in a sequence, or have dependencies, are presented as a serial structure. Highly coupled activities, where the parameters are interdependent, as represented as a crossover structure.

This design structure matrix representation is used to illustrate the physical interconnections of the features within a component. Independent features correlate to parallel activities, dependent features (i.e. a boss containing a feature that interfaces with another component) correlate to serial activities, and coupled features correlate to interacting activities. Coupled and dependent features are sensitive to geometric, material and surface related variations. Understanding this coupling is important when assigning tolerances, and introducing any variations to the original product design.

The design structure matrix for power steering pump pulley is presented in Table 2. The mounting face is influenced by burr on clearance holes and the fillet blending, and in turn it influences the V groove position (due to its thickness, flatness and parallelism). The position and orientation of the V groove and clearance holes is influenced by the locating holes. If the mounting face thickness were deeper, this feature would also be an influencing feature on the holes. The enclosure body supports the V groove and blends into the fillet. The fillet in turn supports the enclosure body and blends into the mounting face. The fillet is included in this analysis as it is a supporting feature, and is a potential stress point.

	Crankshaft mounting bore A1	Threaded fasteners B1-B3	Threaded fasteners C1-C4	Locating holes D1, D2	V Groove V1	Mounting Face	Enclosure body	Fillet
Crankshaft mounting bore A1	■			X				
Threaded fasteners B1-B3		■		X				
Threaded fasteners C1-C4			■	X				
Locating holes D1, D2				■				
V Groove V1				X	■	X	X	
Mounting Face	X	X	X			■		X
Enclosure body						X	■	X
Fillet						X	X	■

Table 2: Design structure matrix for the power steering pump pulley.

The features catalogued in the design recovery framework, along with their functions and DPs, the connectivity diagram and the DSM inter-relationships are used as input into the complexity model.

3 THE COMPLEXITY MODEL

3.1 Introduction

Evaluation of a product's complexity is not as simple as determining the physical characteristics of an object, as each person has a unique perception of complexity. There are highly coupled relationships between the product design, the materials, the manufacturing processes, and support systems. These elements are integrated with activities within all levels of an organization and capturing a relevant perception of complexity can be problematic. A proper understanding of the nature of complexity is required in order to be able to determine its characteristics, and provide an effective relative measure, as the areas of complexity need to be identified before they can be effectively managed [7, 8]. As opposed to creating a specific model, an adaptable framework has been developed by ElMaraghy and Urbanic [4] to assess the product, process and operational complexity elements within a manufacturing process. Although all these elements are interlinked (Figure 4), when too many facets of manufacturing complexity are combined this results in a loss of meaning for the final result. Consequently, a framework was developed to decouple and relink the elements of manufacturing complexity using a systematic, uncomplicated methodology, which can be adapted for use in any design or manufacturing environment. A brief overview is presented here. For a detailed description, refer to ElMaraghy and Urbanic [4].

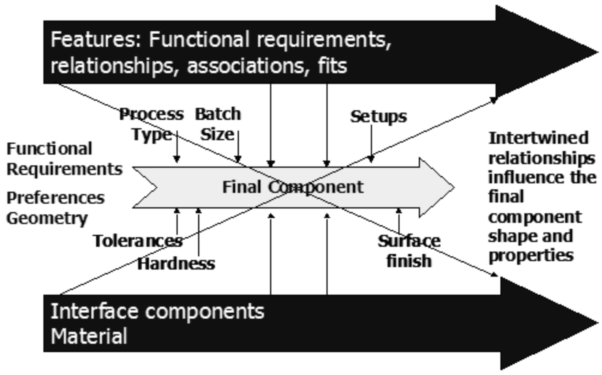

Figure 4: Coupled component attributes.

Complexity may be, in part, associated with understanding and managing a large volume or quantity of information, as well as a large variety of information. The general manufacturing complexity model introduced ElMaraghy and Urbanic [4] is a heuristic model that focuses on these elements. The model is composed of three basic components – the absolute quantity of information, the diversity of information and the information content or the "relative" measure of effort to achieve the required results (Figure 5).

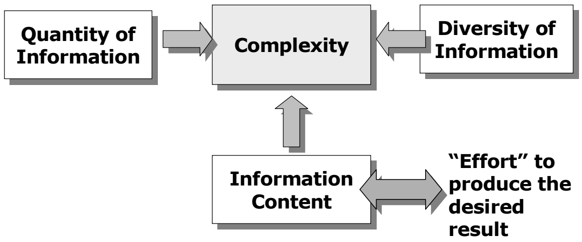

Figure 5: Elements of complexity.

Although the quantity of information is a factor of complexity, the absolute quantity of information may contain much redundancy. Therefore a compression factor, the information entropy measure H, is used to represent the quantity of information element:

$$H = \log_2(N+1) \tag{1}$$

where N is the total quantity of information.

The measure of uniqueness or the diversity ratio D_R is defined as a ratio of distinct information to total information, as given by:

$$D_R = \frac{n}{N} \tag{2}$$

where n is the quantity of unique information and

N is the total quantity of information.

Information content is defined here as a "relative" measure of effort to achieve the required result, not a measure of the probability of success as per the Axiomatic Design Theory [2]. The higher the effort (i.e. the more required stages or tools), the more complex the feature or task is. Each work environment has a different perception of complexity, but is typically consistent. The complexity index needs to effectively capture this. To this end, the relative complexity coefficient, c_j is introduced and a matrix methodology is used to determine the relative complexity coefficient. This coefficient has a value between 0 – 1, complementing the diversity ratio D_R. The method of determining the relative complexity coefficient, c_j is described in ElMaraghy and Urbanic [4], along with an example.

The product complexity analysis is performed independently from any process plan, and focuses on the product features and specifications. The product complexity indices visibly reflect the influences of the feature quantity, variety and the characteristics of the product features. The product complexity index $CI_{product}$ is a combination of the diversity ratio and the relative complexity, and is scaled by its information entropy. This is expressed as:

$$CI_{product} = (D_R + c_j) * H \qquad (3)$$

There are three types of complexity to be considered in a manufacturing environment: product complexity, process complexity and operational complexity, and each one flows into the other as shown in Figure 6. Only the product complexity can be assessed within the bounds of the design recovery framework.

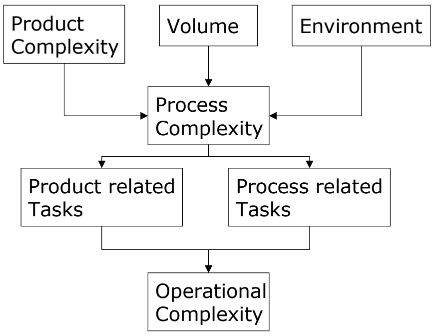

Figure 6: Manufacturing complexity cascade.

3.2 Introduction to Coding Methods

In order to streamline the complexity analysis for a recovered design, and provide a basis for other tasks such as process planning, a code is introduced to classify the component and its features. Coding methods are employed in classifying parts into part families. Product codes are used with the group technology manufacturing philosophy and computer aided process planning. The product code consists of a set of alphanumeric values each of which represents design attributes. There are three types of code styles:

1. Monocode or hierarchical code,
2. Polycode or attribute code, or
3. Hybrid or mixed code.

The monocode system was originally developed for biological classification in the 18th century. Each symbol depends on all of the information provided in the previous digits; hence, resulting in a hierarchical structure. The polycode symbols are independent of each other. Each digit in a specific location of the code describes a unique property of the component. Therefore, each code character represents a distinct piece of information, regardless of values in other code positions. The hybrid or mixed coding method combines characteristics of the monocode and polycode systems. The Opitz classification system, widely used in industry for process planning, is an example of a hybrid code. The form is represented in the first five digits, supplementary information that represents the size, material type, raw material shape, and accuracy is contained in the next four digits. An optional four digit secondary code is utilized to identify the production operation type and sequence [9].

3.3 Component and Feature Codes

In order to link the design recovery framework to the product complexity index, a complexity code that represents the essential information with representative fields needs to be developed. A feature code, used to generate the feature and component complexity indices, contains information with respect to the feature quantity and variety, its form and structure, and a selection of attributes that influence the complexity (Figure 7). The attributes being considered are: the component material, the feature shape, the pattern placement for a set of features, the tolerances related to the feature, the surface finish and the spatial relationships with respect to the feature – all information contained within the design recovery framework. A factor level is associated with each attribute highlighted with an asterisk (*) in Figure 7. The factor level corresponds to the level of "effort" to produce the feature based on the attribute being considered. A multi-tier ranking system is used where low, medium, and high effort levels correspond to factor levels 0, 0.5 and 1 respectively.

Feature Code									
Feature Related				**Complexity Analysis Attributes**					
Total Numer of Features, *N*	Number of Distinct Features, *n*	Basic Geometry	Type	Material	Shape	Pattern	Tolerance	Surface Finish	Spatial Relations
N	*n*	*1-7*	*1-12*	*	*	*	*	*	*

Figure 7: Feature codes.

The total and distinct number of the general feature types, *N* and *n* respectively, the basic construction geometry and the general feature type is contained in the feature related fields. A large variety of elements is used in design; however, standard design methods are used to create any given feature. The basic geometry can be modelled as an extrusion, a surface or solid of revolution, a swept or lofted surface or solid, a 'net' or combination of surfaces, a fillet or a blended chamfer/bevel edge. The generic set of feature types, as defined in the design recovery framework database, is presented in Table 3.

Certain materials are easier to manipulate than others are. This is based on both the material characteristics (i.e. formability, castability, and machinability) and the experience base within the manufacturing environment. The shape or geometry of the feature influences the value of the shape attribute. The more faces and edges within a feature (i.e. multiple step bore) or the more curve primitives defining an edge (i.e. an irregular shaped pocket), the higher the effort to produce the feature. The pattern type (i.e. linear or circular grid, mirror pattern, peripheral pattern), the positional relationships between features and the number of unique features within the pattern dictate the values for the pattern attribute. The effort decreases with the amount of allowable variations for the feature's dimensions and interrelationships. The tighter the tolerances, the more material removal steps are required. This is also true for the surface finish requirements. The geometry of the feature may not be challenging, but the feature's position or orientation may provide a manufacturing challenge, i.e. if the features are positioned at an oblique angle, are recessed or an under cut, or contain an internal intersection (e.g. oil holes within engine components). This effort is reflected in the spatial relationships attribute. In addition, effort levels associated with fixturing are included in this attribute.

Digit No. and Value	
1	N – total number of feature types
2	n – number of distinct feature types
3	**Feature Basic Construction Geometry:** 1 - Extrusion 2 - Revolved 3 - Swept 4 - Loft 5 - Surface net 6 - Fillet 7 -Blended chamfer/bevel edge
4	**Basic Feature Types** 1 - Clearance features 2 - Complex features 3 - Enclosing or container features (cover, o-ring groove, …) 4 - External protrusion (boss, cooling fin, tab, …) 5 - Fastening features (threads, rivets, …) 6 - Free form feature (aesthetic features, contours, 3D fillets, …) 7 - Locating features (dowels, tongue and groove ..) 8 - Planar faces (mounting faces) 9 - Precision feature (shaft / hole) 10 - Precision / complex feature (multiple step bore, gear teeth) 11 - Seating features 12 - Support features
5	**Material** 0 - Low effort 0.5 - Medium effort 1 - High effort
6	**Shape** 0 - Low effort 0.5 - Medium effort 1 - High effort
7	**Pattern** 0 - Low effort 0.5 - Medium effort 1 - High effort
8	**Tolerances** 0 - Low effort 0.5 - Medium effort 1 - High effort
9	**Surface Finish** 0 - Low effort 0.5 - Medium effort 1 - High effort
10	**Spatial Relationship** 0 - Low effort 0.5 - Medium effort 1 - High effort

Table 3: Feature complexity code.

Rules have been developed to be able to apply these codes in generating the complexity indices, and are listed below.

- The feature basic construction geometry is used to determine the shape effort value. A sample is presented in Table 4.
- Each feature is associated with a feature type. Feature types are clustered to generate a complexity index for the various feature types within the component.
- When assessing the feature complexity, only the information entropy measure H and the relative complexity coefficient, $c_{j,\ feature}$, are used. If there is only one feature for a given feature type, D_R will equal one, significantly distorting the feature complexity value.
- The maximum values for the attributes for a set of feature types are used for the complexity analysis.
- The total number of features N for a feature type is multiplied by a factor related to that type prior to calculating the information quality variable H. This is done as the explicit number of dimensions and geometric modifiers are not being assessed. Typically, there are three dimensions to locate a feature in space. Maximum and minimum values or GD and T dimensions are used to describe the allowable variation for the form and to establish feature interrelationships. There are five basic GD and T categories (form, orientation, location, profile and run out). As a rule, the profile and run out categories are not used simultaneously for a feature, nor are profile and size; therefore, four categories are considered feasible for a 'simple' feature, generating a default information quantity factor of '7'. This factor is used for feature types 1, 4, 8 and 12. Other feature types (i.e. threaded fasteners, complex features such as a gear form or a free form feature) contain more information than these '7' basic factors in order to convey the essential manufacturing information. Locating features and precision external features (feature types 7, 9) typically have simple geometry with precision tolerances; therefore, the default factor is set to '8'. Fastener features typically include chamfer and thread information; free form features may have sets of specific curvature information; multiple step bores and seating features (i.e. bearing) have additional geometry and specification; hence, the default factor for these features (3, 5, 6, 11) is '10'. For complex features (gear teeth, non-standard thread forms and so forth), the default factor is set to '12' (feature types 2 and 10). The feature type and their default factors are presented in Table 5.
- The default factors can be modified based on the feature functions and inter-relationships captured in the DSM, else the default values are utilized.
- If there are noticeable differences for features that are categorized within the same feature type (i.e. pipe thread and deep hole fastening features), a separate analysis should be performed, as there are unique factors for the features. However, features with similar characteristics (i.e. same hole size, but slightly different depths) should be clustered.
- The average 'relative effort' values for each attribute should be calculated and compared. Attributes that have higher values should be thoroughly reviewed, as the manufacturing challenges increase with higher values.

Using these rules, a feature complexity index, and subsequent component complexity index, can be quickly extracted from the description codes.

No.	Low Effort	Medium Effort	High Effort

	(0)	(0.5)	(1)
1	Basic, simple, symmetric shape, length: width ratio < 4	Complex, symmetric shape, length: width ratio > 4	Complex, asymmetric shape, draft length: width ratio > 4
2	Simple profile, no helix	Simple profile, helix	Complex profile, helix
3	**N/A**: a 1D sweep is an extrude	2D sweep, simple symmetric profile	3D, non-orthogonal sweep or complex profile
4	Ruled surface / solid	Complex profile, multiple sections but moderate amounts or no synchronizing geometry is automatic	Complex profile sets, multiple sections+ construction geometry is required to create the final shape, synchronizing geometry is challenging

Table 4: Feature basic construction geometry related to effort levels.

Feature Number	Feature Types	Factor
1, 4, 8, 12	1 - Clearance features 4 - External protrusion (boss, cooling fin, tab) 8 - Planar faces 12 - Support features	7
7, 9	7 - Locating features (dowels, tongue and groove) 9 - Precision feature (shaft / bore)	8
3, 5, 6, 11	3 - Container feature 5 - Fastening features (threads, rivets, …) 6 - Free form feature (aesthetic features, contours, …) 11 - Seating features	10
2, 10	2 - Complex features 10 - Precision / complex feature (multiple step bore, gear teeth)	12

Table 5: Default factors used to calculate *H* for the different feature types.

4 CASE STUDY: POWER STEERING PULLEY PUMP

4.1 Design Recovery Analysis

The power steering pump pulley for a mid-70's high performance vehicle, shown in Figure 2, is significantly damaged, and cannot be purchased from the original manufacturer. Flexible belt-pulley systems are used to transmit power and motion between widely spaced shafts, or when the driver and driven shafts must rotate at different speeds. This power transmission method is simple, easy to install and maintain and can be used in a variety of applications. The features to be assessed, the interface conditions and feature inter-relationships are described in section 2.

The functions performed by the power steering pump pulley are: channel – transfer, couple – join and support – position. The power steering pump pulley channels power and torque from the crankshaft to the power steering pump. The pulley is joined to the crankshaft and harmonic dampener via the dual pulley system. The power steering pump pulley is encased by the dual groove pulley that drives the air conditioning compressor and the water pump; hence, the support-position function. The features, feature functions, and design parameters are presented in Table 6.

4.2 Complexity Analysis

The complexity analysis for the power steering pump pulley is shown in Table 7. For the power steering pump pulley, there are six feature sets being considered. As the mounting holes are similar in shape, function and design parameters, these were clustered, where N = 7 total features, and n = 3 to enumerate the distinct types. Each feature is associated with a feature type. The default factors listed in Table 5 are used in this analysis. The original design utilized steel, and rolling and stamping fabrication processes. As only one replacement component is required, the pulley will be made from aluminium billet (6061-T6), and the design modified to suit. The complexity analysis presented here is performed on the adapted design.

Feature	Function	Design Parameters
Crankshaft mounting bore A1	Couple - join Support - position	Through hole: Diameter Depth Clearance tolerance
Threaded fasteners B1-B3	Couple - join	Through hole: Diameter Depth Clearance tolerance
Threaded fasteners C1-C4	Couple - join	Through hole: Diameter Depth Clearance tolerance
Locating holes D1, D2	Support - position	Through hole: Diameter Depth **Roundness** **Location tolerance**
V Groove V1	Channel - transfer	**SAE 440 V groove: Established standard design parameters** Parallelism to mounting face
Mounting Face	Support - position	Flat base: Flatness Surface finish
Enclosure body	Support Contain	Enclosing profile: Rotationally symmetric Clearance to work envelope
Fillet	Couple - join Support	Simple 2D blend, maximum radius to minimize stress concentrations

Table 6: Power steering pump pulley feature – function design parameter summary.

The feature codes and relative complexity values $c_{feature}$ are developed in Table 7 (a) and the feature and component complexity calculations are demonstrated in Table 7 (b). For the component complexity analysis: $N = 13$ and $n = 8$. The sum of $N*factor$ = 98, hence H = 6.629. The diversity ratio D_R = 0.615 and the relative complexity coefficient = 0.045. This provides a product complexity index $CI_{product}$ = 4.377.

Feature Label	Feature Type	N	n	Basic	Type	Material	Shape	Pattern	Tolerance	Surface Finish	Spatial Relations	Sum of Fields 5 - 10	Average of Fields 5 - 10
V groove	Precision features	1	1	2	10	0	0.5	0	0.5	0.5	0	1.5	0.25
Mounting faces	Planar surfaces	1	1	2	8	0	0	0	0.5	0	0	0.5	0.08
Mounting holes	Clearance feature	7	3	1	1	0	0	0	0	0	0	0	0.00
Support body	Container feature	1	1	1	12	0	0.5	0	0	0	0	0.5	0.08
Locating holes	Precision feature	2	1	1	7	0	0	0	0.5	0	0.5	1	0.17
Blending fillet	Fillet	1	1	6	12	0	0	0	0	0	0	0	0.00

Table 7 (a): Feature complexity analysis.

Feature Label	Feature Type	Factor	N* factor	H, feature	DR, part	c, feature	CI feature H* c,feature	Weighted c, feature
V groove	Precision features	12	12	3.700	(Sum of n) / N	0.25	0.925	0.019
Mounting faces	Planar surfaces	7	7	3.000		0.08	0.250	0.006
Mounting holes	Clearance feature	7	49	5.644		0.00	0.000	0.000
Support body	Container feature	7	7	3.000		0.08	0.250	0.006
Locating holes	Precision feature	8	16	4.087		0.17	0.681	0.013
Blending fillet	Fillet	7	7	3.000		0.00	0.000	0.000
	Sum		**98**	**6.629**	**0.615**			**0.045**
	Complexity product			**4.377**				

Table 7 (b): Feature and component complexity calculations.

The average attribute factors, which are associated with the effort for a specific attribute, are plotted in Figure 7. The effort associated with producing the product to the required shape, tolerances, surface finish and spatial relations is low to moderate (0.17, 0.33, 0.08 and 0.17) respectively). No other attributes are a concern.

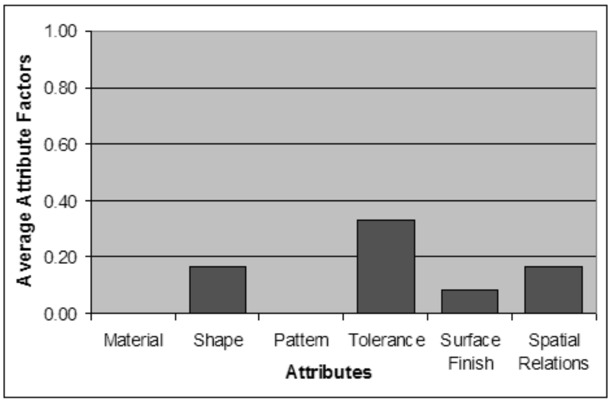

Figure 7: Relative effort comparison for each attribute.

4.3 Redesign

Further redesign was performed on this pulley. There is no air conditioning in this vehicle, and there is no apparent use for the bolt holes C1 – C4. It is speculated that these pulleys were used on multiple engine families. Based on this, it was determined to redesign and manufacture a pulley system appropriate for this vehicle, as an alternate material and manufacturing processes needed to be considered anyway. The modular nature of the design recovery framework allows the inclusion of ancillary components with minimal adjustment. The essential information is collected for all related components (water pump/air conditioning pulley and dampener). Information with respect to the water pump pulley groove V2 and the mounting hole A1 must be added. The cross section of the water pump V belt is identical to the power steering pump; hence, both grooves must conform to a standard SAE 440 type. Information with respect to the C1-C4 bolt holes and the locating features D1 and D2 on the respective pulleys is eliminated as these features serve no function. The enclosure is of no concern, but an appropriate body to support the grooves must be developed, along with an applicable material. Minor changes have been made to the mounting holes, i.e., chamfers have been added to the fastening clearance holes. A short (1/4 inch) internal cylindrical feature is added at the lip for locating purposes. The final part is illustrated in Figure 8.

Figure 8: New pulley to drive the water pump and power steering pump – CAD model and machined part.

For the modified pulley design complexity analysis, the default factors are adjusted. There are less inter-feature relationships to be considered, i.e., the top of the mounting face is not a mounting interface, and the mounting holes are not related to any intermediate location geometry; therefore, the factor values for these features is reduced (bolded in Table 8 (b). The factor for the V grooves was not adjusted, as the profile complexity and feature inter-relations are not reduced, although the assembly is being replaced by a single component.

Feature Label	Feature Type	N	n	Basic	Type	Material	Shape	Pattern	Tolerance	Surface Finish	Spatial Relations	Sum of Fields 5 - 10	Average of Fields 5 - 10
V groove	Precision features	2	1	2	10	0	0.5	0	0.5	0.5	0	1.5	0.25
Mounting faces	Planar surfaces	1	1	2	8	0	0	0	0.5	0	0	0.5	0.08
Mounting holes	Clearance feature	4	2	1	1	0	0	0	0	0	0	0	0.00
Support body	Container feature	1	1	1	12	0	0.5	0	0	0	0	0.5	0.08
Blending fillet	Fillet	1	1	6	12	0	0	0	0	0	0	0	0.00

Table 8 (a): Updated design feature complexity analysis.

Feature Label	Feature Type	Factor	N*factor	H, feature	DR, part	c, feature	CI feature H* c,feature	Weighted c, feature
V groove	Precision features	12	24	4.644	(Sum of n) / N	0.25	1.161	0.028
Mounting faces	Planar surfaces	**5 (7)**	5	2.585		0.08	0.250	0.009
Mounting holes	Clearance feature	**6 (7)**	24	4.644		0.00	0.000	0.000
Support body	Container feature	7	7	3.000		0.08	0.250	0.009
Blending fillet	Fillet	7	7	3.000		0.00	0.000	0.000
	Sum		73	6.087	0.667			0.046
	Complexity product			4.340				

Table 8 (b): Updated design feature and component complexity calculations.

For the redesigned component complexity analysis: $N = 9$ and $n = 6$. There are less features overall, but a greater variety; hence, the diversity ratio D_R = 0.667. The sum of *N*factor* = 73, hence H = 6.087. For the new design, the overall effort is approximately equivalent to fabricate this part as the relative complexity coefficient = 0.046. However, the overall product complexity index for the redesigned part is 4.340, which is slightly less than the original design due to the reduced number of features and factor multipliers. The average attribute factors are plotted in Figure 9. The shapes, tolerance and surface finish attributes require the most attention.

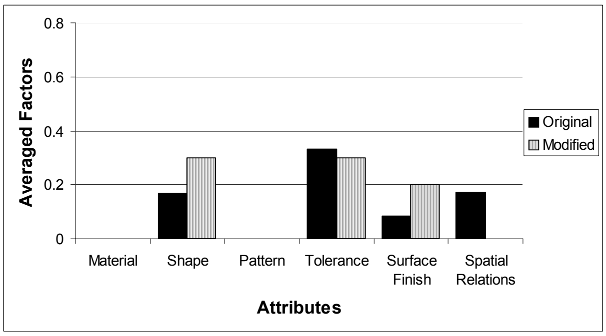

Figure 9: Relative effort comparisons for each attribute.

5 SUMMARY AND CONCLUSIONS

For effective design recovery of an engineered component, the form, functions and the features must be reconstructed effectively. A comprehensive, modular, multi-perspective framework was developed to assist with data collection and its transformation into relevant design knowledge. To assist with the analysis of a recovered design and potential redesign alternatives, an adaptation of the manufacturing complexity assessment methodology [4] is presented to assess the product complexity. Using design recovery framework information, the connectivity diagram and the DSM along with a structured set of attributes and feature-function factors, a product complexity value can be quickly determined for comparative purposes. Information with respect to the features and attributes is isolated, and can be presented in a graphical manner to highlight the critical characteristics. Conditions may exist where the recovered design needs to be modified before the component can be remanufactured due to new design constraints, as shown by the case study. These structured tools and systematic approach can be used to graphically and “mathematically” show tradeoffs for each important criterion. The attributes and rules within the framework can be adapted for a particular environment. To conclude, people with diverse backgrounds are able to rapidly evaluate alternatives and risks with respect to a reconstructed product’s attributes using these tools.

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