Design for Fixturability (DFF) Methodology for Commodity Parts: A Case Study With Connecting Rod Designs

Khurshid A. Qureshi*
Technical Specialist
Ford Motor Company,
Dearborn, MI 48124
e-mail: kqureshi@ford.com

Kazuhiro Saitou†
Department of Mechanical Engineering,
The University of Michigan,
Ann Arbor, MI 48109-2125
e-mail: kazu@umich.edu

This paper presents a methodology called 'Design for Fixturability' (DFF). This methodology enables designers to perform manufacturability analysis of their product designs upfront into the design process. The DFF approach provides a mapping between parametric representation of a part design and fixturing capability of a facility and presents a methodology to evaluate the design with respect to the fixturing capabilities. The methodology is applicable to the mass-production commodity parts and part families, which typically require dedicated manufacturing facilities. A prototype DFF system for connecting rods of an automotive engine is developed. The system enables the designers to design the connecting rods by considering the fixturing (datums) capabilities of existing manufacturing facilities during the concept design stage, when design parameters are still not frozen. The DFF system analyzes the design with respect to fixturing capabilities of facilities and generates suggestions for the designer, to modify his design if required. [DOI: 10.1115/1.1481036]

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Introduction

In this era of increased global competition, more knowledgeable and informed consumers then ever, rapidly changing consumer needs, and increasing pressure on prices, the companies are more and more relying on reducing their cost of manufacturing to increase their profits, and in some industries just to stay profitable. There is an increasing emphasis on reducing the fixed-cost component of the total cost, which really becomes a problem in the times of economic downturn, when the volumes are low and it becomes extremely difficult to even break-even. This is particularly true of industries where business is cyclical in nature—for instance Auto Industry. Global competition and rapidly changing consumer needs are also making it hard to forecast product volumes. As a result companies are finding it more and more challenging to setup dedicated facilities for their products. Ideally companies want to manufacture low volume products at the same competitive cost as their high volume products, which enjoy economies of scale. One way they can do that is by leveraging the facilities, which are currently producing similar products and have an excess capacity. The probability of finding such a facility within an organization or with a manufacturing partner, which can manufacture the new product without making significant changes to a product line and fixturing, is not very high. This is particularly true for mass production commodity parts, which typically require dedicated manufacturing facilities. The probability of finding such an existing facility can be significantly increased, if designers have an access to the capabilities of manufacturing facilities upfront into the design process, at the concept design stage. This will enable product designer to adapt his design to fit the fixturing capabilities of an existing manufacturing facility. In order to accomplish this, we are proposing a new methodology called 'Design for Fixturability' (DFF). By using this methodology, the companies will be able to better utilize the fixturing capabilities of existing manufacturing facilities particularly for products with low or unpredictable volumes, where setting up a new dedicated facility may not make much of economic sense.

A schematic of a DFF system is shown in Fig. 1. As shown in the figure, a product designer will be able to submit his design, over the Internet, to DFF analysis service (DFFAS), to perform manufacturability analysis of his design. The DFFAS will analyze the design with respect to the capabilities of existing facilities and will generate redesign suggestions for the designer, in real time. The DFFAS will also generate suggestions for the manufacturing partners to introduce flexibility in their lines. The manufacturers will also be able to create and update their capability databases, over the Internet, stored at a central server, using the DFF system. The capability databases for a given commodity part, are represented in a common format.

We have used DFF approach to develop a prototype DFF system for connecting rod of an automotive engine. We have implemented DFFAS module of DFF system using Java™ programming language because of its platform independence and its suitability for Internet-based applications.

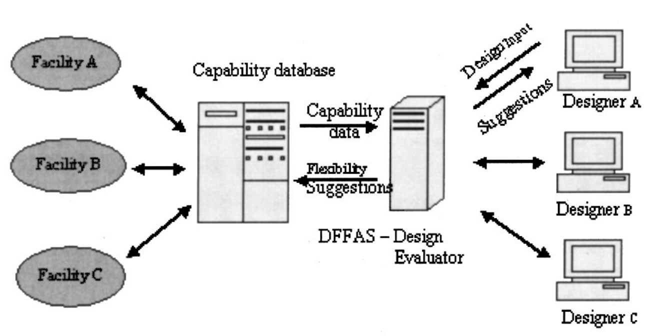

Fig. 1 DFF system schematic

*Currently a PhD student at the University of Michigan, Ann Arbor.
†Corresponding author.

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The rest of the paper is organized in the following manner. Section 2 reviews some of the work done in the area of manufacturability analysis. In Section 3, DFF methodology is presented. Section 4 presents a description of DFF system for connecting rod and DFF analysis results for an example part. Finally, the paper concludes by summary, conclusion and future work.

Previous Work

Manufacturability Analysis (DFM, DFA, DFX). In the last few decades, researchers and companies have paid a great deal of attention on integrating the design and manufacturing activities of an enterprise in an effort to reduce the number of iterations as well as iteration cycle time between design and manufacturing activities; which in turn results in faster time-to-market and high quality products. These efforts [1] have given birth to methodologies such as design for manufacturability (DFM), design for assembly (DFA), design for production (DFP) or more generally design for X (DFX) where X represents a broad variety of design considerations.

Several tools and methods have been developed to perform automated manufacturability analysis of a design and to provide redesign suggestions to a designer. Hayes et al. [2,3] developed Manufacturing Evaluation Agent to identify cost-critical design tolerances and to generate cost reducing design suggestions for prismatic parts in rapid prototyping environment. Hayes [4] described a Design Advisor, which provides specific redesign suggestions to the designer so as to reduce the overall manufacturability cost. Chu et al. [5] has presented an approach for manufacturability analysis of prismatic parts, which classifies part features according to tool approach directions. The number of setups is then minimized by combining features with the same tool approach direction in a same setup. Gupta [6] presented an approach, which is based on systematic exploration of various machining plans, to provide manufacturability feedback for the parts to be machined on 3-axis vertical machining center. The work mentioned above, mainly focused on low-volume custom CNC machining domain, whereas DFF approach we are presenting deals with the machining of mass production commodity parts typically machined in a dedicated facility.

Taylor et al. [7] described a new DFX strategy, called 'design to fit an existing environment' (DFEE), which enables one to understand impact of new product introduction on the existing capacity and anticipated product mix of the manufacturing facility at the product design stage, so that design can be modified to minimize the disruption. More recently Herrmann et al. [8] introduced a new decision support tool called 'Design for Production' (DFP) to help understand the performance of manufacturing system by analyzing the capacity requirements and estimating the manufacturing cycle time upfront at the design stage. Minis et al. [9] has described a general approach to perform plan-based partner-specific manufacturability evaluation and partner selection for detailed design. But in their work they have not mentioned how to access capabilities of manufacturing partners. Our DFF approach allows manufacturing partners to create and update their manufacturing (fixturing) capabilities, in a common format over the Internet. This capability database is then used by the DFF system to perform DFF analysis on a given design of a commodity part.

Role of Internet in Manufacturability Analysis. Wang et al. [10], described the vision and current developments in a distributed design (CAD) and manufacturing environment and the role of Internet in this new environment. They described future manufacturing environment to be a global manufacturing community with various members providing different manufacturing services and facilities. Our DFF system is addressing one of the requirements they mentioned, to form a global manufacturing community i.e., to have central analysis service to guide users to the right facility.

CyberCut [11] is the project going on at the University of California at Berkeley to develop manufacturing service for rapid design and fabrication of mechanical parts over the Internet. Kim et al. [12] developed a design interface for CyberCut, called WebCAD. WebCAD is an on-line CAD tool which designer can use to define the final geometry of the part to be readily machined with the 3-axis milling machine. Inouye et al. [13], described Mechanical Design Rule Checker (MDRC) to perform manufacturability checks for web-based 3-axis machining. The checks are performed real-time in the CAD system, on each DSG feature (such as holes, rectangular pockets, arbitrarily shaped pockets), during the design process. Veeramani et al. [14] developed an agent-based system called 'WebScout', that enables matchmaking between customers who have matching needs and the suppliers who have capability to meet those needs. The suppliers in their case are machine job shops whereas our DFF methodology is applicable to special-purpose facilities dedicated to a particular commodity. Some other work [15–19] in the area of web-based design/manufacturability analysis and concurrent engineering, we found interesting, is also listed in the reference section.

Design for Fixturability

Design for Fixturability paradigm describes a technique to evaluate a manufacturability of a part design with respect to the fixturing capabilities of existing manufacturing facilities dedicated to the same commodity part. The part fixturability is computed by looking at the dimensions or parameters of a given part and location and size of machining datums for a manufacturing facility. If the part is found to be not manufacturable in a given facility with respect to machining datums, suggestions are generated for the designer to adapt his design to fit the fixturing capabilities of the manufacturing facility. Suggestions can also be generated for manufacturers to introduce flexibility in their manufacturing (fixturing) capabilities.

In the present work, the following assumptions are made:

1. Parametric geometric representation of a concept design is available.
2. A given commodity part is forged or cast to its near net shape prior to its machining. The amount of stock to be machined is small and the parametric representation of a concept model can be used for preliminary DFF analysis. Note that for more accurate analysis different parametric representation for each setup may be required to truly represent in-process geometry for each setup.
3. A given commodity part is fixtured in a similar manner by different manufacturing facilities, i.e., same machining datums are used.

Steps for DFF. Under these assumptions, the following describes the steps of the proposed DFF methodology.

1. Identify a parametric representation of a commodity part design:

$$P=\{p_1,p_2,\ldots.p_n\} \tag{1}$$

where P is a set of the geometric/engineering parameters and n is the total number of parameters. An instance of the part design can be represented, for example, as a list of parameter names p_i and their values.

2 Identify machining datums to hold the part for each machining operation:

$$D=\{d_1,d_2,\ldots,d_m\} \tag{2}$$

where D is a set of the machining datums and m is the total number of machining datums,

3 For each datum d_j, identify *dependent parameter set* DP_j of the design parameters that affect the location of datum d_j:

$$DP_j\subset P \tag{3}$$

where $j=1,\ldots\ \ldots..,m$. Let *critical parameter set* C be the union of all dependent parameter sets:

$$C = \bigcup_{j=1}^{m} DP_j \tag{4}$$

4 Partition critical parameter set C to the following three subsets: 1) set C_f, of the parameters that affect primal product function, 2) set C_n of the parameters that affect non-function factors such as weight and assembly, and 3) set C_c of the parameters that affect both (we will refer to as "combo"—combination of function and other factors):

$$C = C_f \cup C_n \cup C_c \tag{5}$$

where C_f, C_n, and C_c are disjoint each other.

5 Use the following format to represent and store the capability information of various manufacturing facilities for a given commodity part:

Company Name

Manufacturing Facility

Available Capacity (units/per year)

Part to be machined

For (each setup)
  Operations: operation-1, operation-2, ..., operation-n
  For (each datum d_j)
    a) name
    b) type (such as circular, rectangular)
    c) size (e.g., diameter for a circular datum, height & width for a rectangular datum)
    d) location in six degrees of freedom $(x,y,z,\theta,\gamma,\omega)$

6 For each datum d_j, compute a feasible region $F_j \subset \mathbf{R}^3$ on a given design, using geometric information, and machining rules and constraints for the given commodity part.

7 For each datum d_j, check whether its location in a given manufacturing facility is within F_j. If the location of d_j is outside of F_j, compute the amount of predefined violation $\nu = \nu(\mathbf{p})$, where $\mathbf{p}$ is a vector parameters in DP_j, which are causing the violation.

8 For each parameter p_i in $\mathbf{p}$, solve $\nu(\mathbf{p}) = 0$ algebraically or iteratively, to obtain p_i^* that eliminate the violation. Generate redesign suggestions to change p_i to p_i^*, sorted in the order of: 1) suggestions to change $p_i \in C_n$, 2) suggestions to change $p_i \in C_c$, and 3) suggestions to change $p_i \in C_f$. This sorting is to prioritize the redesign with the parameters that have no or less impact on the product functions, over the ones with more impact.

9 In order to analyze and generate suggestions for the part families, following procedure can be followed:

a) Identify all the critical parameters or dimensions for which part family suggestions are required.

b) Identify the datum dependency parameter sets, which contains critical parameters for which part family range is to be computed.

c) Compute the range of the critical parameters with respect to each of the identified datums.

d) Compute the most restrictive upper and lower bounds, beyond which either the feasible region or a manufacturing rule is violated.

e) Report the restrictive bounds to the designer as an allowable range for part family design.

The designer can only adopt one suggestion each time DFF analysis is run on a given design. After modifying the design, he needs to run analysis again to generate a new set of suggestions. A high-level algorithm for a DFF system is summarized below:

read (design file)
extract critical dimensions
create feasible region for each datum
read (capability databases)
for (each facility)
  for (each setup)
    extract the datum size and location

for (each facility)
  for (each setup)
    for each datum
      compute the datum violations
      identify the critical dimensions causing violations
      identify the classification info of critical dimension
      create suggestion
      add suggestion to the suggestion list
sort the suggestions
report all the suggestions to the designer
store suggestions for manufacturer in its suggestion database

Implementation of the DFF System

The DFF system for connecting rod provides a simultaneous engineering environment for both designers and manufacturers of automotive connecting rods. It enables the designers to design the connecting rods by considering the capabilities of existing manufacturing facilities upfront at the design stage. The system also enables the manufacturers of connecting rods to create and update the database of their capabilities. The fixturing capabilities (machining datums) for a facility are represented in the common format described in the previous section.

A prototype DFF system for connecting rods is implemented using the Java™ programming language. The main GUI (designer's interface) is shown in Fig. 2, which will be eventually converted into Java™ servelet, so that designers can access it over the Internet. Using the main GUI the designer specifies the name of a design file and a manufacturing facility. She also has an option of checking her design against all the manufacturing facilities. The parametric data of a connecting rod design is stored in a plane ASCII file using name-value format, and the manufacturing capability information is stored in an ASCII file using XML (Extensible Markup Language) representation.

The connecting rod design information is stored in an object called DesignParser. Design Parser class has methods to retrieve critical design parameters from the input design file. It also contains methods to create a feasible region for each machining datum. The feasible region of a datum is represented by another object called DatumFeasibleRegion.

A list of capability databases of connecting rod manufacturer is contained in an object called CrMachiningDatabase. The capability database for each manufacturer is represented by another object called MachineDatabaseFileParser, which contains methods to retrieve datum information for a facility. Datum data such as type, size and location is represented by an object called DatumInfo.

The redesign suggestions for the designer are generated by an object called SuggestionGenerator. A suggestion is represented by an object called Suggestion, which contains data such as type of suggestion (function, non-function or combo), facility name and a

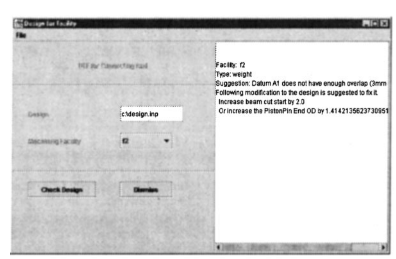

Fig. 2 Main GUI (designer Interface) of connecting rod DFF system

message text. A list of all suggestions is stored in an object called SuggestionList. The class SuggestionList contains methods to sort and report the suggestions to the designer and manufacturers.

Example Case Studies

A typical connecting rod is shown in Fig. 3. The function of a connecting rod is to transfer reciprocating motion of the piston into rotating motion of the crankshaft. The function and performance of a connecting rod is heavily dependent on dimensions such as center-to-center distance (*CToC*), crank-pin bore diameter (*CPbD*), piston-pin bore diameter (*PPbD*) and thickness of the rod (*Thk*). Besides this, dimension such as width (*Wid*) of the rod is assembly driven as it cannot be greater than cylinder block bore diameter, for assembly purposes.

The connecting rods are generally first forged or sintered and then machined to final size. The machining of a typically connecting rod involves operations such as rough, finish, grind thrust faces, drill, tap and chamfer bolt holes, rough, finish and hone crank pin and piston pin bores. For all these operations, rod is held in a similar manner using the machine datums A_1, A_2 and A_3 on the thrust face of the rod, datum Z_1 on side of the rod and datums Y_1 and Y_2 on pin end of the rod as shown in Fig. 4.

Let us use the DFF system to analyze a connecting rod design with the critical dimensions as shown in Fig. 3, for manufacturing (fixturing) feasibility with respect to machining facilities f_1, f_2, f_3, f_4 and f_5 each with slightly different fixturing capabilities (location of machining datums). The set of machining datums, dependency parameter sets for datums, critical parameter set, and critical parameter classification sets are included in the Appendix for reference purpose.

Case 1 (a): DFF analysis with respect facility f_1 currently machining CR with Datum A_1 location different (lower) from the one required for the given design

The following are the suggestions generated by the DFF system for the given connecting rod design with respect to facility f_1.

Suggestion 1:
Facility: f_1
Suggestion Type: combo
Suggestion: Datum A_1 does not clear the Piston Pin Bore. Reduce PistonPin end OD (PPEod) by 0.41 mm

Suggestion 2:
Facility: f_1
Suggestion Type: function
Suggestion: Datum A_1 does not clear the Piston Pin Bore. Reduce PistonPin bore (PPbD) by 0.29 mm.

Both of the above suggestions are illustrated in Fig. 5(*b*) and Fig. 5(*c*). Datum A_1 should clear the piston pin bore chamfer by 1 mm. But as shown in Fig. 5(*a*), datum A_1 overlaps the piston pin bore chamfer. The object Suggestion Generator compares the bounds of a feasible region for datum A_1 of given design with the location of datum A_1 of existing design, to compute the overlap. In order for datum A_1 to clear piston pin bore chamfer by 1.0 mm, the SuggestionGenerator object generates two suggestions.

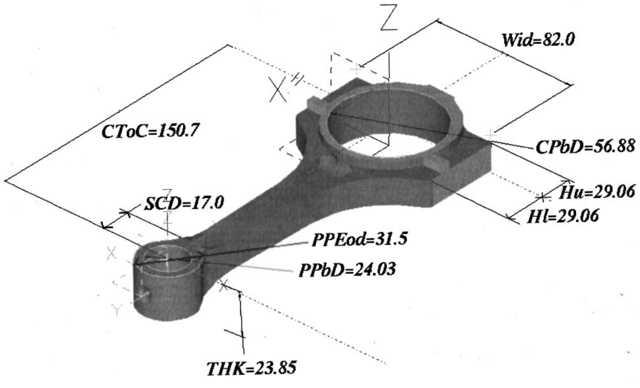

Fig. 3 A typical connecting rod

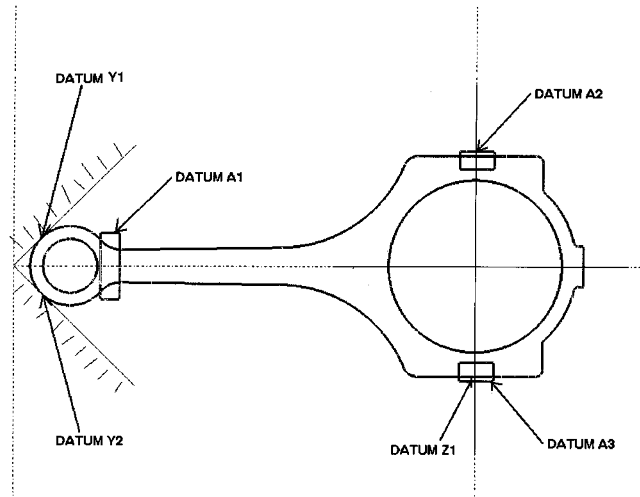

Fig. 4 A connecting rod showing machining datums

The first suggestion is to reduce the piston pin end outer diameter (*PPEod*) by 0.41 mm, i.e., from b_1 to b_2, which is computed as:

$$b_1 - b_2 = overlap/\cos(45\ \text{deg}) \tag{6}$$

where *overlap*=distance by which Datum A_1 overlaps the piston pin bore chamfer.

The second suggestion is to reduce the piston pin bore (*PPbD*) by 0.29 mm (overlap) i.e., from a_1 to a_2, which is simply computed as:

$$a_1 - a_2 = overlap \tag{7}$$

Note how DFF system has sorted the suggestions. The suggestion of reducing the piston-pin end outer diameter is made first, as changing this parameter mainly affects the weight of the rod and it has little impact on the function and performance of the rod. Note that this also depends on the amount of change, and it requires designer discretion to determine whether the change is appropriate or not.

Case 1 (b): DFF analysis with respect facility f_2 currently machining CR with Datum A_1 location different (higher) from the one required for the given design

For the same connecting rod design, following suggestions are generated by the DFF system with respect to facility f_2 with

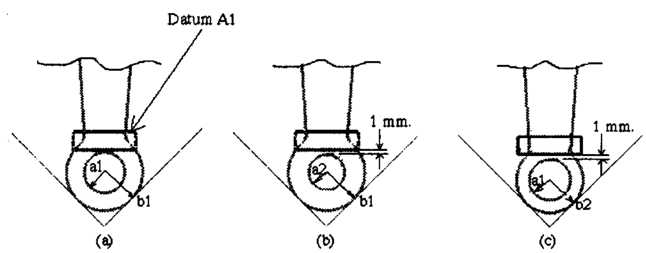

Fig. 5 Location of datum A_1 of facility f_1, with respect to 3 design variations of example connecting rod

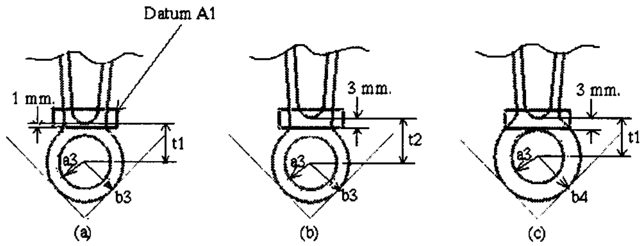

Fig. 6 Location of datum A_1 of facility f_2, with respect to 3 design variations of example connecting rod

slightly different fixturing capabilities.

Suggestion 1:
Facility: f_2
Suggestion Type: non-function
Suggestion: Datum A_1 does not have enough overlap (3 mm). Increase shank cut start by 2.73 mm.

Suggestion 2:
Facility: f_2
Suggestion Type: non-function
Suggestion: Datum A_1 does not have enough overlap (3 mm). Increase PistonPin End OD (PPEod) by 3.86 mm.

Both suggestions are illustrated in Fig. 6(*b*) and Fig. 6(*c*). datum A_1 should have a minimum material overlap of 3 mm. As shown in Fig. 6(*a*), with the given design, if it were to be machined in facility f_2, datum A_1 has an overlap of only 1 mm, which is computed by comparing the location of shank cut (t_1) with the lower bound of the datum A_1. In order to increase the overlap to 3 mm, the DFF system has made two design suggestions. The first suggestion as shown in Fig. 6(*b*) is to simply increase the start of shank cut by 2.73 mm, i.e., from t_1 to t_2 and is classified as non-function, as it mainly affects the weight of the rod. The other suggestion is to increase the piston pin end outer diameter (*PPEod*) by 3.86 mm (=2.0/cos(45 deg)), i.e., from b_3 to b_4 and is also classified as non-function as it also affects the weight of the rod.

Case 2 (a): DFF analysis with respect facility f_3 currently machining CR with Datums A_2 & A_3 locations different (lower) from the one required for the given design

Following suggestions are generated by the DFF system for the given connecting rod design with respect to facility f_3.

Suggestion 1:
Facility: f_3
Suggestion Type: combo
Suggestion: Datum A_2/A_3 does not have enough overlap. Reduce PistonPin end od (PPEod) by 2.12 mm

Suggestion 2:
Facility: f_3
Suggestion Type: function
Suggestion: Datum A_2/A_3 does not have enough overlap. Reduce center-to-center (CToC) distance by 1.5 mm.

The situation is shown in Fig. 7. Datums A_2 and A_3 should have a minimum overlap of 3 mm. As shown in Fig. 7(*a*), with the given design, Datums A_2/A_3 have an overlap of only 1.5 mm, if it were to be machined in facility f_3, which is computed by comparing the lower bound of the feasible region for datums A_2/A_3 of given design with the location of datums A_2/A_3 of CR currently being machined in the facility. In order to increase the overlap to 3 mm, two design suggestions are generated by the system. The first suggestion is to reduce the piston pin outer diameter (*PPEod*) by 2.12 mm (=1.5/cos(45 deg)). Note in Fig. 7(*c*) that center-to-center distance (*CToC*) is still c_1. The suggestion is classified as combo for the same reasons as stated earlier in cases 1 and 2. The second suggestion is to reduce the center-to-center distance by 1.5 mm, i.e., from c_1 to c_2, as shown in Fig. 7(*b*), and is classified as function driven.

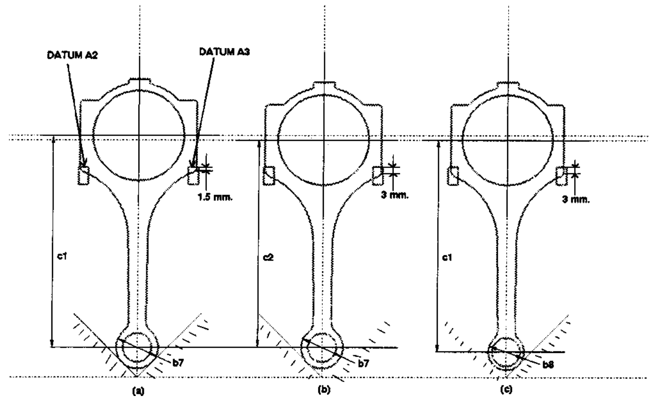

Fig. 7 Location of datums A_2 and A_3 of facility f_3, with respect to 3 design variations of example connecting rod

Case 2 (b): DFF analysis with respect facility f_3 currently machining CR with Datums A_2 & A_3 locations different (higher) from the one required for the given design

Following suggestions are generated by the DFF system for the same connecting rod design with respect to facility f_4.

Suggestion 1:
Facility: f_4
Suggestion Type: non-function
Suggestion: Datum A_2/A_3 does not have enough overlap. Increase PistonPin end OD (PPEod) by 1.4 mm

Suggestion 2:
Facility: f_4
Suggestion Type: function
Suggestion: Datum A_2/A_3 does not have enough overlap. Increase center-to-center distance (CToC) by 1.0 mm.

Datums A_2 and A_3 should have a minimum overlap of 3 mm. As shown in Fig. 8(*a*), with the given design, datums A_2 and A_3 have an overlap of only 2.0 mm, if it were to be machined in facility f_4, which is computed by SuggestionGenerator object by comparing the upper bound of the feasible region for datums A_2/A_3 of given design with the location of datums A_2/A_3 of CR currently being machined in the facility. In order to increase the overlap to 3 mm, two design suggestions are generated by the system. The first suggestion, is to keep center-to-center (*CToC*) distance same as c_3 but increase the piston pin end outer diameter (*PPEod*) by 1.41 mm (=1.0/cos(45 deg)), as shown in Fig. 8(*c*). It is classified as non-function, as it only impacts the weight of the rod. The second suggestion is to increase the center-to-center (*CToC*) distance by 1.0 mm, i.e., from c_3 to c_4 as shown in Fig. 8(*b*) and is classified as function driven.

Case 3: DFF analysis with respect facility f_5 currently machining CR with Datum Z_1 location different from the one required for the given design

Following suggestions are generated by the DFF system for the given connecting rod design with respect to facility f_5.

Suggestion 1:
Facility: f_5
Suggestion Type: function
Suggestion: Datum Z_1 is violated. Increase width of the rod by 1 mm.

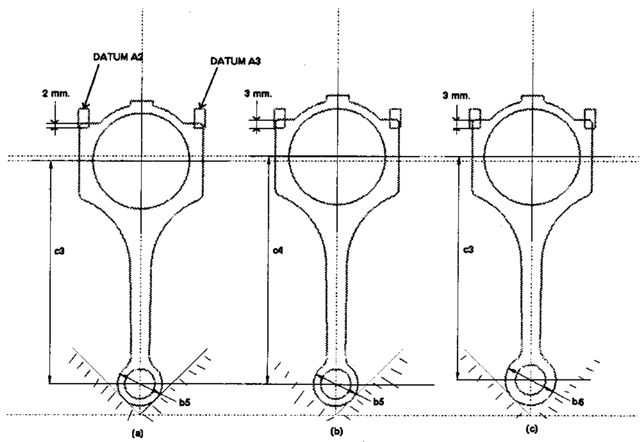

Fig. 8 Location of datums A_2 and A_3 of facility f_4, with respect to 3 design variations of example connecting rod

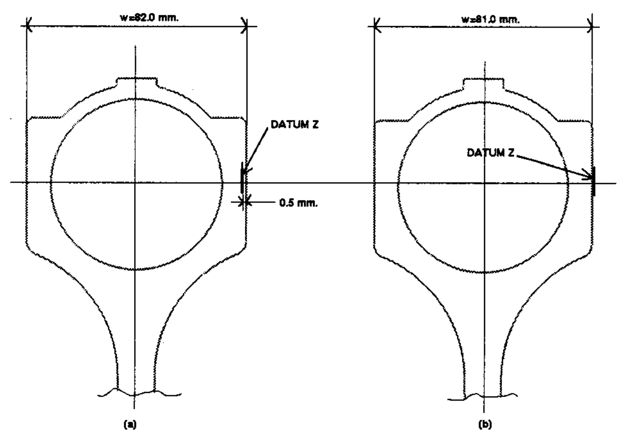

Fig. 9 8 Location of datums A_2 and A_3 of facility f_5, with respect to 2 design variations of example connecting rod

In the case of facility f_5, the location of datum Z_1 is such that the given design of the rod with width of 82 mm cannot be machined in this facility, as shown in Fig. 9(*a*). The width of the rod must be modified to 81 mm, as illustrated in Fig. 9(*b*), for the rod to be machined in this facility.

Summary and Conclusions

In this paper, a new methodology called 'Design for Fixturability' (DFF) is introduced, which enables product designers to adapt their designs according to the fixturing capabilities of existing manufacturing facilities, thus reducing the need to have all new fixturing for every new product design. The methodology is applicable to the design and manufacturing of mass production commodity parts, which are typically manufactured in special-purpose dedicated facilities. A prototype DFF system for an automotive connected rod is also developed, as part of this work, to prove out the methodology. The initial results for the example case study, as discussed above, are very encouraging. The future work will include extension of the DFF methodology to the special purpose dedicated facilities with limited flexibility. Currently DFF methodology is presented with respect to fixturing capabilities of a facility, but in future DFF methodology can also be extended to take into account other capabilities of a manufacturing facility.

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Appendix

The set of machining datums for the given connecting rod is given by

$$D=\{A_1,A_2,A_3,Z_1,Y_1,Y_2\}$$

The datum dependency parameter sets are given as follows:

$$DP_{A1}=\{PPbd,PPEod,SCD\}$$

$$DP_{A2/A3}=\{CPbd,PPEbd,CToC,Wid,Hu,Hl\}$$

$$DP_{Zl}=\{Wid,Thk,CtoC\}$$

$$DP_{Y1/Y2}=\{PPEod,Thk\}$$

The set of critical parameters C is given by:

$$C=\{CToC,CPbd,PPbd,Wid,Thk,PPEod,SCD,Hu,Hl\}$$

The critical parameter classification sets C_f, C_n and C_c are given as follows:

$$C_f=\{CToC,CPbd,PPbd\}$$

$$C_n=\{Wid,SCD,PPEod,Thk\}$$

$$C_c=\{PPEod,Thk,Hu,Hl\}$$

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