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DESIGN FOR FACILITY OVER THE INTERNET: A CASE STUDY WITH AUTOMTOTIVE CONNECTING ROD DESIGNS

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ABSTRACT

This paper introduces a new methodology called 'Design for Facility over Internet (DFF)'. This methodology provides an Internet-based environment for designers to perform manufacturability analysis of product designs with respect to the capabilities of existing manufacturing facilities, upfront into the design process. In the current work, only fixturing (machining datums) capabilities of a manufacturing facility are considered. A prototype DFF system for an automotive connecting rod, is developed. The system enables the designers to design the connecting rods by considering the fixturing (datums) capabilities of existing manufacturing facilities upfront at the concept design stage. The complete system implementation will also enable the manufacturers of connecting rods to create and update the database of their capabilities over the Internet. The DFF system analyzes the parametric design with respect to the fixturing capabilities and generates suggestions for a designer, to modify his design if required, to fit the capabilities of specified facilities.

Keywords: Design for manufacturing (DFM), manufacturability analysis, commodity parts, special-purpose facilities, Internet-based design and manufacturing.

INTRODUCTION

A new methodology called 'Design for Facility over Internet (DFF)' is introduced in this paper. This methodology provides an Internet-based environment for designers to perform manufacturability analysis of product designs with respect to the capabilities of existing manufacturing facilities, upfront at the design process. The methodology is applicable to the mass-production commodity parts, which typically require dedicated manufacturing facilities. A prototype implementation of this methodology for connecting rods of an automotive engine is also presented.

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 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

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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. This will enable product designer to adapt his design to fit the capabilities of an existing manufacturing facility. In order to accomplish this, we are proposing a new methodology called 'Design for Facility over Internet' (DFF). By using this methodology, the companies will be able to better utilize the 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. In our DFF approach we are leveraging Internet to perform manufacturability analysis.

The DFF methodology requires parametric representation of a machined part. The fixturability information (machining datums) of a manufacturing facility is represented in a common format. Using parametric information of a design, feasible region for each of the machining datum is computed. Each of the machining datum of a facility is then checked against the corresponding feasible region. For the datums, which do not lie inside the feasible region, suggestions are generated for the designer to modify his design to fix those violations. Suggestions are also generated for manufacturers to build flexibility into their facilities. We have implemented DFF methodology to develop prototype DFF system for connecting rod of an automotive engine. Using this system, the designers can submit their designs on Internet to determine the manufacturing (fixturing) feasibility of their design with respect to existing connecting rod manufacturing facilities. The DFF system generates suggestions in real-time, for the designer, to modify his design to fit the fixturing (datums) capabilities of the existing facilities.

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 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.* (1995) 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 (1996) described a Design Advisor, which provides specific redesign suggestions to the designer so as to reduce the overall manufacturability cost. Chu, *et al.* (1996) 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 (1997) 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.* (1994) 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.* (2000) 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.* (1999) has described a general approach to perform plan-based partner-specific manufacturability evaluation and partner selection for detailed design. In their work, they did consider partner capabilities but did not address how to represent and access those capabilities.

Our DFF system 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 DFF system to perform DFF analysis on a given design of a commodity part.

Role of Internet in Manufacturability Analysis

Wang, *et al.* (1998), 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 (Wright, *et al.*, 1998) 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.* (1999) 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.* (1999), 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.* (1998) 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.

DESIGN FOR FACILITY OVER THE INTERNET

Design for facility 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 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 capability 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):

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

5. Use the following format to represent the capability information of various manufacturing facilities for a given commodity part, using XML^{TM} (Extensible Markup Language) representation. Each manufacturer will create and update their own capability databases in the following common format, at a common central website. Note that the capability database stored in XML representation can be very easily extended to include other capabilities of a facility beyond fixturing, such as accuracy, size limitations, cycle time etc.

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, θ, γ, ω)*

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 $v=v(\mathbf{p})$, 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 $v(\mathbf{p})=0$ 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.

In step 8, the designer can only adopt one suggestion each time DFF analysis is run on a given design. After modifying the design, he needs to perform the DFF analysis again to generate a new set of suggestions.

DESCRIPTION OF THE DFF SYSTEM

The DFF system for connecting rod provides an Internet-based engineering environment for both designers and manufacturers. Using the DFF system the designer can adapt his new connecting rod design according to the capabilities of existing manufacturing facilities; and can thus avoid making a huge investment (typically in millions of dollars) to set-up a new dedicated facility for the new design. The system will also enables the manufacturers of connecting rods to create and update the database of their capabilities over the Internet. The fixturing capabilities (machining datums) for a facility are represented in the common format described in the previous section. The main GUI (graphical interface) of DFF application for connecting rod is shown in Figure 1, which, will be eventually converted into Java servelet, for actual application over the Internet. Using the main GUI the designer specifies the name of a design file and a manufacturing facility. He also has an option of checking his design against all the manufacturing facilities. The design file for connecting rod is an ASCII file containing parameter names and their values.

The DFF system analyzes the design with respect to manufacturing capability information and generates suggestions for the designer, to modify his design if required, to fit the capabilities of specified manufacturing facilities. The suggestions generated by the system are classified into three categories such as function, other (such as weight, assembly), and combo (which is combination of function and other factors). For each facility suggestions are sorted in the order of other, combo and function, as design modification which do not affect function are generally easier to make as opposed to those which affect the function of the product. The designer can only adopt one suggestion each time DFF analysis is run on a given design. After modifying the design, he needs to perform the DFF analysis again to generate a new set of suggestions.

Following is a high-level algorithm for analysis module of a DFF system.

High-level Algorithm for a DFF System

read (design file)
extract critical dimensions
create feasible region for each datum

read (capability databases)
for (each facility)
    extract the datum size and location

for (each facility)
    for each datum
        compute the datum violation
        identify the critical dimension causing violation
        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

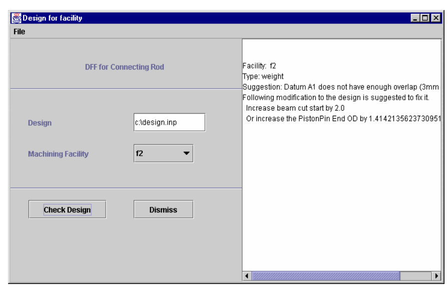

Figure 1: Main GUI (designer Interface) of connecting rod DFF system

DFF System Architecture and Implementation

DFF system for connecting rod is implemented using the Java programming language Java, because of its platform independence is highly suitable for Internet-based applications. 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. The DatumFeasibleRegion object contains information about the bounds of a datum in each coordinate-axis direction.

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, other or combo), facility name and a 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 Figure 2. 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

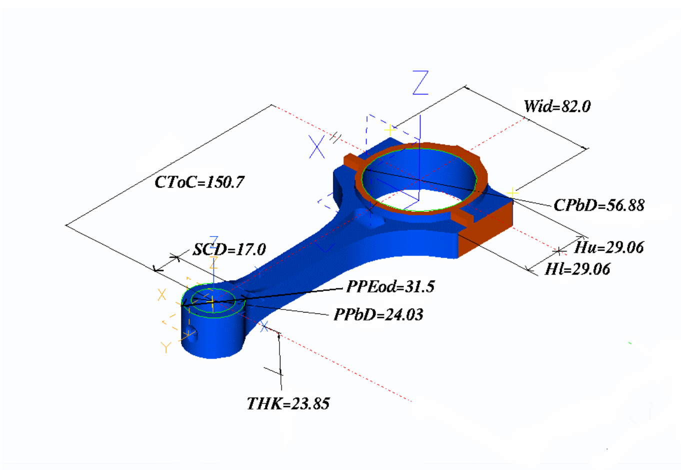

Figure 2: A typical connecting rod design

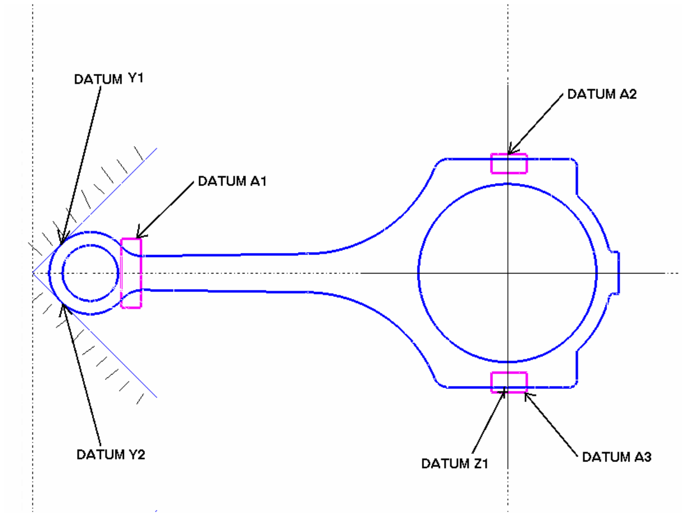

Figure 3: A connecting rod showing machining datums

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 Figure 3.

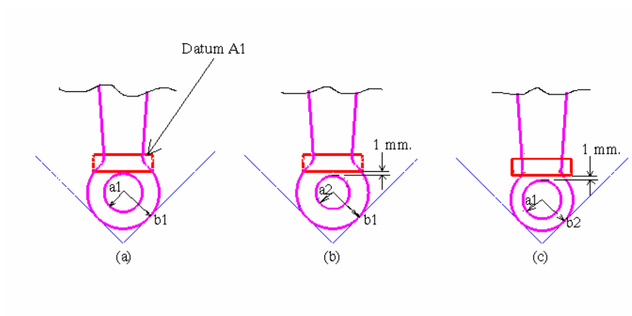

Figure 4: Location of datum A_1 of facility f_1, with respect to 3 design variations of example connecting rod.

Lets use the DFF system to analyze a connecting rod design with the critical dimensions as shown in Figure 2., for manufacturing (fixturing) feasibility with respect to machining facilities f_1, f_2, f_3 and f_4 each with slightly different fixturing capabilities in terms of location of machining datums with respect to the V-Block, which holds the pin end of the rod.

Case 1: DFF analysis of the connecting rod design with respect capabilities (datum locations) of facility f_1.

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: f1
Suggestion Type: combo
Suggestion: Datum A1 does not clear the Piston Pin Bore. Reduce the Piston Pin end OD by 0.194 mm

Suggestion 2:
Facility: f1
Suggestion: Type: function

Suggestion: Datum A1 does not clear the Piston Pin Bore. Reduce the Piston Pin bore by 0.274 mm.

Both of the above suggestions are illustrated in Figure 4 (b) and Figure 4 (c). Datum A_1 should clear the piston pin bore chamfer by 1 mm. But as shown in Figure 4 (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 with the location of datum A_1 for facility f_1, 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.

The first suggestion is to reduce the piston pin end outer diameter (PPEod) by 0.194 *mm*, *i.e.*, from b_1 to b_2, which is computed as:

$$b_1 - b_2 = overlap / \cos(45^\circ) \tag{3}$$

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

The second suggestion is to reduce the piston pin bore by 0.274 *mm* (overlap) *i.e*,. from a_1 to a_2, which is simply computed as:

$$a_1 - a_2 = overlap \tag{4}$$

Note how DFF system has sorted the suggestions. The suggestion of reducing the piston-pin end od 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 2: DFF analysis of the connecting rod design with respect capabilities (datum locations) of facility f_2

For the same connecting rod design, following suggestions are generated by the DFF system with respect to facility f_2 with slightly different fixturing capabilities.

Suggestion 1:
Facility: f2
Suggestion Type: other
Suggestion: Datum A1 does not have enough overlap (3mm). Increase beam cut start by 2.0 mm.

Suggestion 2:
Facility: f2
Suggestion Type: combo
Suggestion: Datum A1 does not have enough overlap (3 mm). Increase the Piston Pin End OD by 1.414 mm.

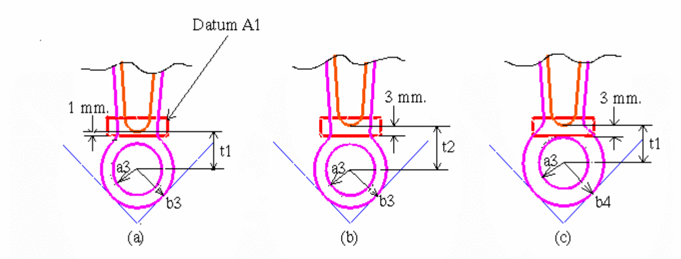

Figure 5: Location of datum A_1 of facility f_2, with respect to 3 design variations of example connecting rod.

Both suggestions are illustrated in Figure 5 (b) and Figure 5 (c). Datum A1 should have a minimum material overlap of 3mm. As shown in Figure 5 (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 beam cut (t1) 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 Figure 5 (b) is to simply increase the start of beam cut by 2 *mm*, *i.e.*, from t_1 to t_2 and is classified as other, as it mainly affects the weight of the rod. The other suggestion is to increase the piston pin outer diameter by 1.414 *mm* ($= 2.0 / \cos(45^\circ)$), *i.e.*, from b_3 to b_4 and is classified as combo as it mainly affects the weight of the rod and has a little impact on the function of the rod. But again as said earlier, designer discretion plays an important role in determining the affect of the change.

Case 3: DFF analysis of the connecting rod design with respect capabilities (datum locations) of facility f_3

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

Suggestion 1:
Facility f3:
Suggestion Type: combo

Suggestion: Datum A2/A3 does not have enough overlap. Reduce the Piston Pin end od by 1.06 mm

Suggestion 2:
Facility: f3
Suggestion Type: function

Suggestion: Datum A2/A3 does not have enough overlap. Reduce the center-to-center distance by 1.5 mm.

The situation is shown in Figure 6. Datums A_2 and A_3 should have a minimum overlap of 3 *mm*. As shown in Figure 6 (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 with the location of datums A_2/A_3. In order to increase the overlap to 3 *mm*, two design suggestions have been made by the system. The first suggestion is to reduce the piston pin outer diameter by 1.06 *mm* ($= 1.5/\cos(45^\circ)$). Note in Figure 6 (b) that center-to-center distance 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 Figure 6 (c), and is classified as function driven.

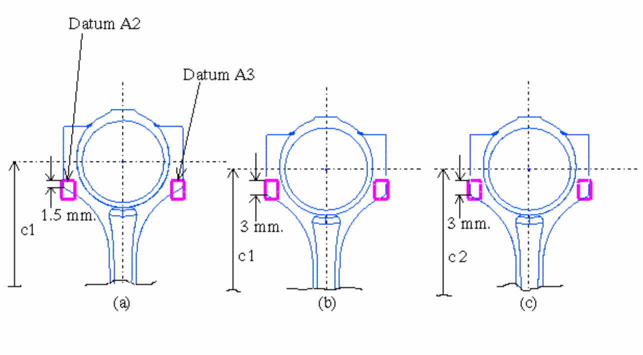

Figure 6: Location of datums A_2 and A_3 of facility f_3, with respect to 3 design variations of example connecting rod.

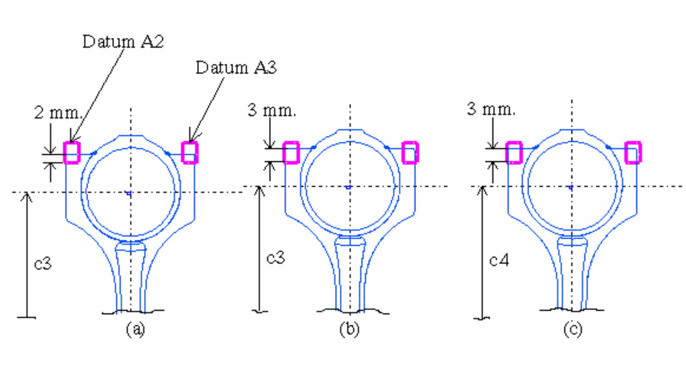

Figure 7: Location of datums A_2 and A_3 of facility f_4, with respect to 3 design variations of example connecting rod.

Case 4: DFF analysis of the connecting rod design with respect capabilities (datum locations) of facility f_4

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

Suggestion 1:
Facility f3:
Suggestion Type: combo
Suggestion: Datum A2/A3 does not have enough overlap. Increase the Piston Pin end OD by .707 mm

Suggestion 2:
Facility: f4
Suggestion Type: function
Suggestion: Datum A2/A3 does not have enough overlap. Increase the center-to-center distance by 1.0 mm.

Datums A_2 and A_3 should have a minimum overlap of 3 *mm*. As shown in Figure 7 (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 with the location of datums A_2/A_3. In order to increase the overlap to 3 *mm*, two design suggestions have been made by the system. The first suggestion, is to keep center-to-center distance same as c_1 but increase the piston pin outer diameter by 0.707 *mm* ($= 1.0/\cos(45^\circ)$). Note, as shown in Figure 7 (b), center-to-center distance is still c_3. It is classified as combo, again for the same reasons as stated earlier. The second suggestion is to increase the center-to-center distance by 1.0 *mm*, *i.e.*, from c_3 to c_4 as shown in Figure 7 (c) and is classified as function driven.

SUMMARY AND CONCLUSIONS

In this paper, a new methodology called 'Design for facility over Internet' (DFF) is introduced, to enable designers to adapt their designs according to the capabilities (fixturing) of existing manufacturing facilities, thus reducing the need to setup new dedicated facility for every new product. The methodology is applicable to the design and manufacturing of mass production commodity parts, which are typically manufactured in a special-purpose dedicated facilities. A prototype DFF system for an automotive engine component – connected rod is developed to prove out the methodology. The initial results on example case study, as discussed above, are very encouraging. The future work will include extension of the DFF methodology to a family of part designs and to the special-purpose dedicated facilities with flexibility. Currently, DFF methodology is presented with respect to fixturing (machine datums) 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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