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Toward Automated Design for Manufacturing Feedback

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Abstract. Iterative loops and rework between design, manufacturing, and testing delay the development lead time for complex products like vehicles. This research focuses on creating an automated design for manufacturing (DFM) feedback system (ADFS) framework that reduces these iterations by providing early, fast, and informative feedback on manufacturability to designers. The proposed ADFS analyzes manufacturability in terms of part geometry with respect to a given set of process capabilities based on DFM guidelines for vehicle manufacturing. In order to increase the fidelity of the search, a heuristic approach to obtain manufacturing process fitness with respect to a part design is introduced. The proposed system framework will help to identify suitable manufacturing processes more quickly as well as provide visual feedback for geometric advice at the feature level with regard to the selected processes.

Keywords: manufacturing assessment system, design for manufacturing, manufacturing feedback

1 Introduction

1.1 Background

Designing a complex product like a motor vehicle is often delayed due to modifications along with subsequent verifications [1]. These iterative loops between design and testing teams make the whole new product development linger at the design stage. It has been reported that the design process can usually take up to 24 months in North America [2] and 15 to 20 years [3] for military vehicles particularly from the concept initiation to the production phase.

It would be desirable if these iterative loops can be shorten or ultimately, eliminated. If the manufacturing feedback information can be delivered to designers timely by adopting a stand-alone feedback system tool, then it can significantly reduce product lead time, in general, and vehicle development, in particular.

However, so far no manufacturing assessment system (MAS) has been developed that takes multiple manufacturing processes related to vehicle production into account simultaneously [4]. Adopting design for manufacturing (DFM) guidelines into a MAS can be an alternative to respond such difficulty [5]. If geometric features of a design

satisfy DFM guidelines of a manufacturing process, then it can be said that the design is manufacturable in terms of the corresponding manufacturing process.

Though a design may be judged as manufacturable, some potential hindrances such as visibility issues, fixturing, set-ups, etc. can still occur during the actual manufacturing execution of a design. Those details can only be investigated by the high-level assessment for a particular process. Likewise, an analysis of DFM guidelines alone cannot determine which manufacturing process is the most appropriate to consider. Therefore our goal is to provide feedback information to designers for multiple processes rather than pick a single candidate process.

1.2 Research Objective

A robust systematic framework is needed to feed-forward appropriate manufacturing processes to the next higher-level assessment as well as to provide feedback to designers based on this manufacturability assessment. It is clear that reducing iterative loops requires a stand-alone system in automated fashion to interact with designers in a timely manner. Hence, this research aims to develop an automated DFM feedback system (ADFS) framework to provide early, fast, and informative feedback for manufacturability to designers as well as feed-forward for detailed investigation. There are two main deliverables as objectives:

1. Feed-forward: the ADFS helps determine which manufacturing processes are the most appropriate for the detailed level assessment for more information.
2. Feedback: the ADFS provides geometric advice at the feature level in an intuitive and visual manner.

2 Literature Review

2.1 Manufacturability Assessment System

In the context of concurrent engineering, generating detailed manufacturing feedback in an interactive way is critical in MAS to reduce development time span [6]. With the widespread of CAD systems, studies regarding stand-alone manufacturability assessment tools were also spurred with the support of feature recognition methodology through CAD software [7]. However, those researches were mostly limited to only machining process and concentrated to calculating manufacturing cost by generating adequate process plans [8]. According to Kalpakjian et al. [9], rough statistical analysis of published works shows that approximately 92% of the researches are focusing on the applicability of MAS to machining processes only.

2.2 Utilizing DFM Guidelines

The main benefit of practical use of DFM guidelines is that each guideline of a manufacturing process can serve as one of several criteria, so that they can be also utilized as a source for generating redesign recommendations for failing features. As an ex-

ample, Jacob et al. [10] present a geometric reasoning methodology by adapting cross-comparisons of geometric features to coded design rules for grinding. When the system recognized salient features, corresponding design rules are invoked to generate manufacturing feasibility decisions automatically. Providing redesign recommendation was implemented as parametric ranges in text format verified by a knowledge base. However, the application was also bound to only single process perspective.

3 Proposed Methodology

3.1 Fast Heuristics

The capability of DFM guidelines enables a “Fast Heuristics” approach that can assess manufacturability without cost estimation analysis. Although calculating manufacturing cost is the most complete measure of manufacturability [9], investigating it is not an easy task in the early stages of design. According to Özbayrak et al. [11], estimating a manufacturing cost for a unit of product design based on activity-based costing approach requires 15+ factors to be considered. Moreover, performing cost estimation becomes worse if there are multiple candidate processes to investigate.

Process Filtering. Therefore, a heuristic filtering approach is proposed that aims to analyze manufacturability faster without losing robustness. In the system shown in Fig. 1, the part geometry extracted from submitted designs will be assessed with respect to a given set of process capabilities collected from the DFM guidelines. Here, those capabilities serve as filters that rule out infeasible manufacturing processes.

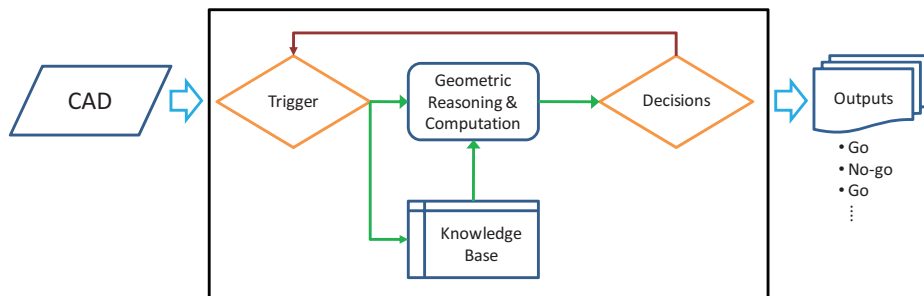


Fig. 1. Filtering system

A different manufacturing process must have its own filter set, as design rules for each manufacturing process are different. When a converted CAD file in XML format comes into the system, a trigger invokes a manufacturing process and its corresponding filter set from the knowledge base. Then each feature’s geometry is evaluated against the appropriate filter element in a set. The output database stores “Go”&“No-go” results of every process with respect to a design as well as information of failing features. The system loop iterates until all of the manufacturing processes are analyzed for the submitted design. Through this filtering system framework, it is ex-

pected that a series of analyses toward candidate manufacturing processes delivers only suitable manufacturing processes (feed-forward) so that design advice at the feature level can be provided later according to DFM guidelines.

Table 1 shows an example filtering analysis for the bracket shown in **Fig. 2**. For this preliminary analysis, minimum/maximum section thickness and minimum corner radii allowance are used for the filtering. The reason for the target thickness to be machined (4 in.) is because the machining process removes chunk of raw materials for both sides. For casting, the section thickness limits the width of center and bottom pillars. Also, it is presumed that forging and stamping require fixturing to position the datum B' to the ground. Processes that are grayed out at **Table 1** are infeasible processes to manufacture this example part.

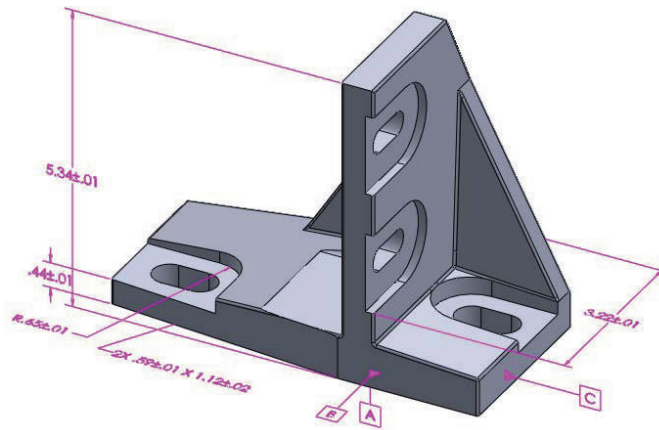


Fig. 2. Example bracket

Table 1. Example filtering 1: manufacturing capabilities of various processes

Process	Min Section Thickness (in.)	Max Section Thickness (in.)	Minimum corner radii (in.)
Metal Stamping	0.0001	0.79	N/A
Fine-blanking	0.005	0.5	N/A
Draw bending	0.035	0.109	1.5 - 8
Powder Metal	0.06	0.22	No limitation
Forging	No limitation	No limitation	No limitation
Abrasive-Jet Machining	0.005	0.032	0.004
Water-Jet Maching	No limitation	18	No limitation
Electron-Beam Machining	0.001	0.25	No limitation
Laser-Beam Machining	No limitation	0.5	No limitation
Plasma-Arc Cutting	No limitation	1	No limitation
Electroforming	0.001	0.5	No limitation
Metal Injection Molding	No data	0.25	0.015 or 0.5*WT
Machining	No limitation	No limitation	Vary (tool diameter, 1/16")
Wire EDM	No limitation	No limitation	No limitation
Sand mold casting	0.118 (3mm)	No limitation	equal to 0.5*ave. wall thickness
Permanent mold casting	0.079 (2mm)	1.96 (50mm)	equal to 1*ave. wall thickness
Plaster-mold casting	0.039 (1mm)	No limitation	equal to 0.5*ave. wall thickness
Investment casting	0.039 (1mm)	2.95 (75mm)	0.03
Ceramic-mold casting	0.039 (1mm)	No limitation	0.03
Die casting	0.019 (0.5mm)	0.47 (12mm)	equal to 1.5*ave. wall thickness

Process Fitness Function. The filtering process yields a series of “Go” and “No-go” responses for the manufacturing processes that were assessed. To increase the fidelity of the evaluation for the feed-forward, we propose to develop a process fitness (PF) function that is derived heuristically. If the number of processes in the knowledge base is 16, for example, then the system generates 16 stacks of response data of each process. The fitness will be derived from the statistics of all 16 responses and is presented as percentage value of “Go” proportioned to the total number of filtering attempts. Therefore, each PF provides a capability metric for each manufacturing process with respect to a given design; hence, it can be used to re-sequence filters in a set to derive the feed-forward faster. The modeling of the PF is shown in **Fig. 3**.

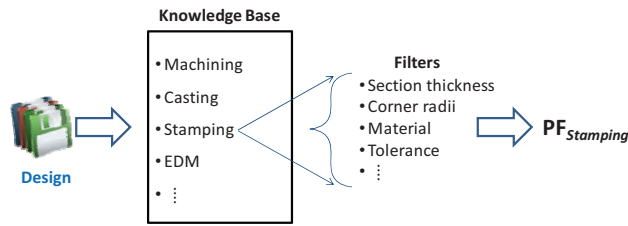


Fig. 3. PF modeling

Suppose that the knowledge base contains 16 manufacturing processes that are available. The group of manufacturing processes can be represented as:

$$P = \{P_1, P_2, P_3, \dots, P_{16}\}$$

The number of filters N in a filter set is different among manufacturing processes. A filter F_{ij} of a manufacturing process P_i can be represented as:

$$F = \{F_{i1}, F_{i2}, F_{i3}, \dots, F_{ij}\}, \text{ where } i = 1 \text{ to } 16, j = 1 \text{ to } N_i$$

Note that the number of filters is depicted as N_i since it depends on the i th manufacturing process. Toward any of submitted design D_k , where $k = 1$ to M , performing a filtering analysis with a set of filters F of a manufacturing process P_i bears a response that can be represented as:

$$F_{ij}(D_k) \rightarrow \text{“Go” or “No-go”}$$

Suppose that the system performs filtering analyses for a design D_1 with a designated set of filters for process P_1 . After a loop of analyses is performed, the filtering system generates a stack of responses as described in **Eq. 1**.

$$\begin{bmatrix} F_{11} \\ F_{12} \\ F_{13} \\ \vdots \\ F_{1j} \end{bmatrix} \times [D_1] = \begin{bmatrix} G \\ N \\ G \\ \vdots \\ G \end{bmatrix} \quad (1)$$

Process fitness PF_i of process P_i with respect to the design D_k is derived by:

$$= \frac{\text{total number of "Go" from } F_{ij} \text{ for a process } P_i \text{ toward a design } D_k}{j}$$

when $i =$ manufacturing process index, 1 to 16.

For a group of M designs, the filtering system produces following a response matrix extended from **Eq. 1** as follows:

$$\begin{bmatrix} F_{11} \\ F_{12} \\ F_{13} \\ \vdots \\ F_{1j} \end{bmatrix} \times [D_1, D_2, D_3, \dots, D_M] = \begin{bmatrix} G & N & G & \dots & G \\ N & & & & \\ G & & \ddots & & \\ \vdots & & & & \vdots \\ G & & \dots & & N \end{bmatrix} \quad (2)$$

In this matrix, each column of the response matrix stands for the results from filtering analyses for the i th process P_i toward a design D_M .

Sequencing Filters. If there is an important feature property that has a small allowance range, then a filtering analysis using that feature geometry would rule out the corresponding manufacturing process frequently. Performing that analysis before any other filters would reduce the number of remaining candidate processes quicker, so that it helps to extract a process faster and increase fidelity of the framework especially for the feed-forward.

If there is enough number of sample designs, it is possible to derive a series of PF values for a process P_i toward M number of designs from the matrix in **Eq. 2**. From the response matrix, analysis results of a filter F_{ij} toward M number of designs are the j th row of the matrix. The importance of a filter F_{ij} can be simply derived from the proportion of "No-go" responses to the number of all filtering attempts toward M designs as following:

$$\begin{aligned} & \text{Weight of a filter } F_{ij} \\ & = \frac{\text{total number of "No-go" from } F_{ij} \text{ for a process } P_i \text{ toward } M \text{ designs}}{M} \end{aligned}$$

Instead of counting the number of positive responses, negative responses are collected because the effectiveness of filtering infeasible candidates is the matter; a filter has a higher capability if it rules out the process more often.

3.2 System Framework

The proposed methodology framework for generating automated DFM feedback is presented with two separated phases. At the first phase, collected sample designs are applied to the filtering system to derive filter sequences for manufacturing process in the knowledge base. The information flow of the first phase is presented at **Fig. 4**.

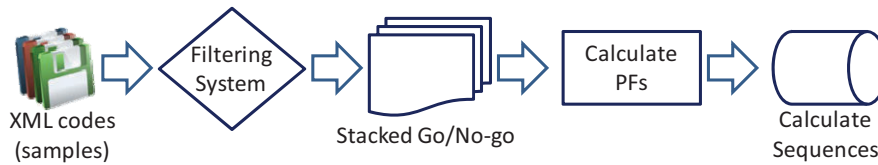


Fig. 4. Phase 1: Derive sequences of filters

When the sequencing is done, the filtering system will be refined by adopting the results from Phase 1 as described in **Fig. 5**.

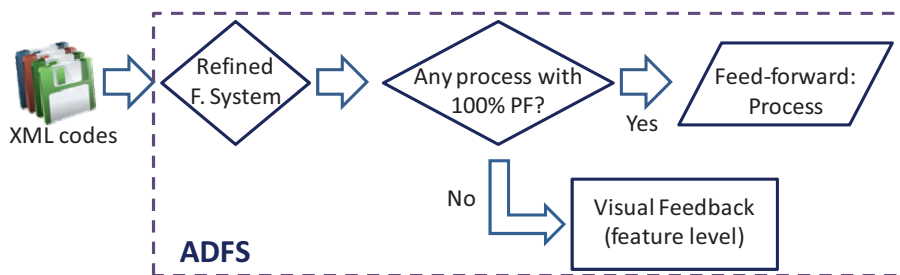


Fig. 5. Phase 2: Generate feed-forward/ feedback outputs

The PF serves as an internal metric in the ADFS. If a manufacturing process obtains 100% of the PF value, then it will be judged as manufacturable in terms of the process and can be passed forward for more detailed assessment. Else, a process with the highest PF will be selected and visual feedback on its failing features will be delivered back to the designer.

4 Closing Remarks

Through the proposed stand-alone ADFS, it is expected that designers can refine their designs for manufacturability from visualized feedback so that iterations can be reduced. Detail development of the visualization feedback is currently ongoing work.

Additionally, there are many research items that can be extended from this research. Although the proposed ADFS is built based on filtering methodology, violating a DFM design rule (i.e., a filter) does not always mean that the design is not manufacturable. In fact, a non-manufacturable design for a selected process may become manufacturable by adding additional processes. In this research, those “superset” of multiple processes and its sequencing are currently not considered. Also, providing dynamic visual geometric recommendations at the feature level would provide richer options that enable designers to “tweak” feature parameters visually on the screen. Along with such techniques, designers can search various parameter options on specific CAD software while it does not hurt the proposed part functionality.

Evaluation of the ADFS is ongoing and will be performed through benchmarking simulation for various design inputs. Any designs revealed as manufacturable (contain

100% PF) will be submitted for detailed evaluation in commercial software (e.g., [12]) so that the decision that ADFS has made can be investigated.

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