AN APPROACH TO INTEGRATE MANUFACTURING PROCESS INFORMATION IN PART DESIGN PHASES

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ABSTRACT

Design for Manufacturing (DFM) is the integrated practice of designing components while considering their manufacture (O'Driscol, 2002). The benefits of this practice have been widely acknowledged in the industry. Several techniques fall under the umbrella of Design for Manufacturing (DFM), and their implementation depends heavily on the context in which they will be applied. How to enhance their use by designers is still an issue. The use of a formalized design process, in which a software application is used to bring manufacturing knowledge to the forefront, would improve DFM implementation. In such a context, a fundamental issue is to define the manufacturing information that should be presented to the designer.

This work addresses the capture and documentation of essential DFM information to make design decisions. Essential manufacturing information is that which can affect the fulfilment of functional requirements and product constraints. The proposed approach combines DFM techniques and principles of Axiomatic Design (AD) theory. The manufacturing information is represented by the concepts of Process Property and process Execution Variable. The ultimate aim of the approach is to define manufacturing knowledge structures and develop a knowledge based application for DFM.

The approach was applied to a case study in which a connecting rod was the part to de designed and manufactured. The manufacturing processes selected were forging and powder metallurgy. The DFM information about these manufacturing processes, related to the connecting rod, was identified and formalized in a table based data structure.

KEYWORDS: Design for Manufacturing, Manufacturing Information, Axiomatic Design.

1 INTRODUCTION

The integration of manufacturing issues into the design process helps to develop better products in terms of requirements fulfilment, cost, quality and development time (Swift, 2003). In general, manufacturing process constraints, capabilities and costs are considered during the embodiment and detailed design phases. Technologies to be used could also be specified during the conceptual phase. The availability of manufacturing information and knowledge is key to achieve Design for Manufacturing (DFM) and to avoid redesigns. It is widely acknowledged that suitable methods and tools should be used to integrate manufacturing information into the design process as early as possible (Swift, 2003). The application of DFM demands the integration of several design activities from user requirements to production (O'Driscol, 2002). The application of DFM is particularly complex and it should be done in a concurrent engineering environment (Herrmann et al., 2004). Depending on the design stage: conceptual, embodiment, and detailed; different tools and techniques can be used as part of DFM, e.g.: Quality Function Deployment (QFD), material and process selection, Failure Mode and Effect Analysis (FMEA) and Computer Aided Manufacturing (CAM) (Herrmann et al., 2004).

Manufacturing issues are also brought into the scene by the designer when making use of DFM techniques such as: design guidelines (Bralla, 1999), manufacture and assembly guidelines (Boothroyd et al., 2002) and manufacturing process selection guidelines (Ashby, 2000). Process modelling based on guidelines, empirical data, statistical data and physical models can be used to perform the manufacturing process selection (Shercliff and Lovatt, 2001). Additionally, computer aided engineering applications can be used to simulate manufacturing processes and predict their performance, and to evaluate manufacturability aspects of the part to be processed (Altintas et al, 2005). The use of these resources depends heavily on the industrial context and on designer experience. Knowledge based applications are developed to create software solutions that improve the design process and help the designer make decisions. When applied to the integration of the manufacturing knowledge throughout the design cycle, the complexity of such development increases greatly because capturing and formalizing manufacturing knowledge can be a complex task. There are several reasons for this (Swift, 2003):

- The shortage of systematic procedures to capture, organize and represent such information and its associated rationale.
- It depends on the collection of empirical data derived from years of experience.
- There is a wide range of manufacturing processes. Some of them become obsolete, new ones are developed, and others are improved.
- There is a variety of data and information associated with each one of them, but little explicitly represented knowledge about how to use them in DFM.
- In addition, the variety of sources and formats make it difficult to have access to such information and knowledge when needed. Therefore the trend among the companies is to develop DFM guidelines in house, according to their needs.

Making manufacturing information and knowledge electronically available when needed would help implement DFM. The main issue is to define which information and knowledge should be given. For that purpose, the proposed approach makes use of the Axiomatic Design theory (AD) (Suh, 2001). This paper presents an approach to the capture, formalization and representation of DFM information and its connection with the design process. This approach demonstrates how AD can be used to support DFM.

The results obtained are the first step towards developing a Knowledge-Based DFM application.

2 MANUFACTURING KNOWLEDGE AND DESIGN

2.1 Design for Manufacturing (DFM)

DFM comprises empirical guidelines based on good design practices. It involves the simultaneous consideration of design characteristics and constraints, some of them imposed by manufacturing. It demands an understanding of the technical limitations and capabilities of the manufacturing processes, and how they affect design solution characteristics. Rather than following a formal method, the application of DFM is based on observation of a set of rules, objectives, and practices (e.g. Table 1) (Swift, 2003). Design guidelines suggest how to better design parts for a particular manufacturing process, and how such a process may affect the shape, dimensions and internal structure of the part (Swift, 2003). In general, the information provided is primarily focused on the definition of the dimensions and the geometry of the part. In the case of the forging process, for instance, these include the parting line location, draft angles, corners, fillets and radii, shapes, part section thicknesses, tolerances and machining allowances. In addition to the data and information provided in handbooks, standards, and in-house guidelines, it is very important to understand the rationale for and the evidence in support of such guidelines, mainly because most of the knowledge is derived from empirical data obtained during many years of experience. The lack of systematic procedures to develop these guidelines may lead to incomplete knowledge, making it difficult to use it without prior experience (Swift, 2003).

[Caption table 1: DFM rules and objectives (Swift, 2003)]

In the literature, several authors make different proposals for when to apply DFM during the design process. Ulrich and Eppinger (Ulrich and Eppinger, 2004) believe that DFM should start in the conceptual phase when the functions and specifications of the product are determined. Pahl and Beitz (1996) consider it more appropriate to start in the embodiment phase, when the production process should be defined and a set of 'Design for' guidelines applied. When considering the approach to selection of materials and processes from Ashby (2000), DFM could be considered as part of the process selection task. This task is conducted iteratively and implies the use of a selection strategy (Ashby et al., 2004). It comprises process selection, followed by adaptation of the design to the process to enhance part manufacturability. DFM should be applied during the adaptation phase. Manufacturing Process Selection Based on Quantitative Analysis (MPS-BQA) and DFM are complementary (Ashby, 2000). The selection is made by comparing design specifications with manufacturing process attributes and finding the best match (Ashby, 2000). Process attributes describe the capabilities of the process in terms of material, shape, size, tolerances, production rate, cost and environmental impact (Ashby, 2000). Ultimately, this approach was implemented in a software application (Esawi and Ashby, 2000a).

MPS-BQA was analyzed to identify candidate process attributes that should be part of the essential manufacturing information to be provided to the designer. As a consequence of such analysis, it was concluded that many of the so called 'process attributes' have a direct mapping with 'design parameters'. Design parameters are part of the product specification and they should be defined to satisfy its functionalities. This reasoning leads to the approach presented by Ulrich and Eppinger (2004), in which DFM starts in the conceptual phase. Ultimately, the relation between 'part functions', ‘part specification’ and ‘manufacturing process attributes’ leads to the Axiomatic Design (AD) theory (Suh, 2001).

2.2 Axiomatic Design Theory

The Axiomatic Design (AD) theory considers four domains: Customer, Functional, Physical and Process. Each domain is characterized by set of information: Customer Needs (CNs) in the Customer Domain; Functional Requirements (FRs) and constraints in the Functional Domain; Design Parameters (DPs) in the Physical Domain; and Process Variables (PVs) in the Process Domain. AD proposes an iterative process that goes forward and backward to define three mappings: CNs/FRs, FRs/DPs, and DPs/PVs. AD focus on the mappings between FRs and DPs, and between DPs and PVs. As a result of each mapping, two design matrices are defined. DPs represent physical properties that define the design solution in the Physical Domain. PVs are variables of the process that can generate the specified DPs. So, the second matrix defines the link between the design specification and the manufacturing process. When an existing process is used, PVs act as constraints in choosing DPs. AD also states that the design should be defined with the minimum amount of information in each domain (Suh, 2001). Considering these AD concepts, we conclude that AD could be used to identify and make explicit essential manufacturing process information. Such information should be made available so the designer can apply DFM.

3 AXIOMATIC DESIGN TO SUPPORT DFM - PROPOSED APPROACH

The basis of the approach defined in this research is the AD theory. It is matrix based and that helps to make explicit the link between design and manufacturing. The main research question aims to address the following two issues: what and how manufacturing process information could be integrated with the AD concepts following the domain mappings to apply DFM. This section aims to address both issues.

Needed Design Parameters (DPs) are those that fulfil the Functional Requirements and Constraints defined in the Functional Domain (Figure 1). As a result of limiting design information to the one that satisfies FRs, the manufacturing information is also narrowed. Any manufacturing information related to how to produce the needed DPs, how the process could affect the needed DPs, and what kind of processing defects could appear constitutes manufacturing process information that is essential to DFM application. The concept of Process Attribute from MPS-BQA has been considered and evaluated against the concepts of DP and PV from AD. Such an analysis led to a first draft of essential manufacturing information (Figure 1). Capturing and documenting essential manufacturing information and the connection with the design process were the main focuses of this research. As a consequence, a systematic procedure to formalize manufacturing information is proposed.

[Caption Figure 1: Axiomatic Design supporting DFM- proposed approach]

3.1 Approach description

The proposed approach starts in the Functional Domain. The mapping between the Customer Domain and the Functional Domain is beyond the scope of this research. Functional Requirements (FRs) and Constraints (Cs) are the starting information. The approach is divided into two phases, Design Information and Manufacturing Process Information, and stages are defined in each phase. They lead to essential manufacturing process information for DFM (Figure 2).

[Caption Figure 2: Structure of the proposed approach]

Phase 1: *Design Information*. The aim is to define and formalize the DPs needed to satisfy the Functional Requirements (FRs) and Constraints (Cs) of the component. It comprises Functional and Physical Domains. The Functional Domain is characterized by FRs and Cs. A FR represents what the component has to do. A constraint limits the range of possible design solutions (Suh, 2001). FRs and Cs have to be structured and formalized to facilitate their use throughout the process (Hunter et al., 2006). The structure of a FRs comprises three main elements: action, object, and qualifiers (Rios et al., 2006). The Physical Domain is characterized by DPs, meaning any physical property whose value satisfies the previously defined FRs. DPs allow the design solution to be materialized (Suh, 2001). They also have to be structured and formalized to facilitate their use and understanding (Ferrer, 2007). The mapping between both domains is an iterative task that it is resolved during the analysis and synthesis loop typical of the design process. The result of this phase is the first design matrix (Suh, 2001).

Phase 2: *Manufacturing Process Information.* The aim is to identify, define and formalize essential manufacturing process information for DFM. It is achieved by making explicit the connection between DPs and manufacturing processes. This phase is developed entirely in the Process Domain (Figure 2).

The Process Domain starts with the selection of manufacturing processes that able to manufacture the component. Since this task is carried out during the early design phase, it is recommended to use Manufacturing Process Selection Based on Quantitative Analysis (MPS-BQA). Several software tools have been developed by different research groups to address material and process screening and selection. (Howard and Lewis, 2003) proposes a development for process selection at early design stages. (Gupta and Chen, 2003) proposes a method to be used during the embodiment phase. The approach developed by (Giachetti, 1997) allows the designer to incorporate precision level and importance weight to the specified requirements. In this particular case, the MPS-BQA approach from Ashby (2000) was considered. CES Selector is the software tool that implements such an approach (Esawi and Ashby, 2000b). DPs can be mapped to the input design information required by CES. A set of viable manufacturing processes is provided as a result.

Once the manufacturing processes are selected and the list of viable ones is available, the stages in defining the essential DFM information start. Extending the PV concept from AD and the process attribute concept from MPS-BQA, two concepts have been defined in this research: Process Property (PP) and Execution Variable (EV) (Ferrer, 2007). A PP is a process characteristic that reflects a process constraint or requirement to achieve the design parameters (DPs) (e.g. the material anisotropy generated during the forging process can affect whether some mechanical properties are obtained (Afzal and Fatemi, 2004)). A PP is a type of process attribute, but it is only related to DPs and not to other design specifications or constraints like product cost (Ferrer, 2007). An EV is a process variable that should be controlled during execution of the manufacturing process to obtain a specific PP value range. The correct value and control of EVs should lead to correct parts. This means without unfulfilled DPs or defects as a consequence of the manufacturing process selected (e.g. forging temperature and strain rate to obtain the specified dimensional tolerances (Repgen, 1998)). There are two reasons that support the importance of EVs for DFM. The first one is their relation with the manufacturing PPs to achieve the DPs. The second one is their relation with possible manufacturing defects that could lead to failure to obtain the DPs. The consideration of EVs would be the link between DPs and the Failure Modes and Effect Analysis (FMEA) (Ferrer, 2007).

The mapping between the Physical Domain and Process Domain is resolved in three steps (figure 2) (Ferrer, 2007). First, the DPs affected by the process are identified. Then how the process affects the DPs has to be explicitly defined by the PPs. Finally, the EVs that affect the achievement of each PP are identified and defined. To specify the PPs, each affected DP is taken and then iterative searches are made in three basic knowledge sources: design and manufacture experts, internal practices and specialized literature. Then for each PP it is necessary to identify which EVs affect it and how they do it. The result of this process is formalized and documented in different tables (Ferrer, 2007). All the information documented during this process constitutes information and knowledge for DFM. The formalization of such information in the form of tables allows a data structure to be defined for its future implementation in a software application. This will allow the DFM information to be reused in future designs, and also to automate how the manufacturing information is presented to the designer.

Throughout the application of the process, it is important to limit the information that has to be managed. So far, this aspect has been addressed by considering only the DPs that are directly linked to the FRs. The AD theory has an information axiom, which relates information content with the probability of satisfying FRs (Suh, 2001), but applying this axiom to minimize DFM information demands further investigation.

3.2 Approach validation

The first validation of the methodology was conducted in a case study related to an internal combustion engine part, a connecting rod. The selected manufacturing processes were closed die forging and powder forging. Two reasons led to their selection. First, by using the CES application (Esawi and Ashby, 2000b) to select a manufacturing process, viable manufacturing processes were obtained. Second, they are currently the most common process technologies for the bulk production of connecting rods (Afzal and Fatemi, 2004).

In the Phase 1, the Functional Requirements (FRs) and Design Parameters (DPs) were identified, defined and formalized. Figure 3 shows two examples of DPs that were defined to satisfy the FR to support alternative load. These DPs are tensile strength and section type; and they are linked to the beam part of the connecting rod. In Phase 2, a set of Process Properties (PPs) related to each DP were identified, defined and formalized. The analysis of the PPs relation with each DP was carried out for each manufacturing process. The selected PPs were material type, anisotropy, microstructure changes and material requirements. All these PPs affect the tensile strength DP. The information related to each PP (set of values or rules) was then defined. Finally, the Execution Variables (EVs) of the processes that affect each PP were formalized. Figure 3 shows the PPs related to the tensile strength DP and the EVs related to the microstructure changes PP.

[Caption Figure 3: Example of the approach application - forging process]

The results obtained from the application of the proposed approach for the connecting rod were presented to manufacturing experts. Two main issues arose:

- The use of matrices and tables help to visualize the information and some of the decisions taken during the design process, but they demand discipline and plenty of time to be created. Eventually, the correct application of the method depends on the designer's criteria.
- It was not clear how the DFM knowledge captured from the methodology application could be reused to apply DFM in new designs.

The first issue reflects and confirms some of the problems already identified in the literature (Rios et at., 2007). Both issues lead to the proposal to develop a support software tool. As a first step to such an application, and based on the matrices and tables already defined, a data structure was created (Ferrer, 2007). The objective was to store FRs, DPs, PPs, EVs and their corresponding relations. The designer could query the system to look for relevant DFM information to take decisions on DPs. This idea is shown by means of two examples in Figure 4. Figure 4(a) shows the example of the section type DP, with PPs that should be provided to the designer to apply DFM if the closed die forging process is used. Figure 4(b) shows the example of the tensile strength DP, with PPs that should be provided to the designer to apply DFM if the forging powder process is used.

[Caption Figure 4: Example of design for manufacturing information. (a) Closed die forging. (b) Forging powder]

4 CONCLUSIONS

The proposed approach helps to make explicit the connection between design and manufacturing information. A designer carrying out the different steps could capture and document essential manufacturing information for DFM. The approach is complementary to the application of the Axiomatic Design theory. The originality of the work is the integration of Axiomatic Design (AD), manufacturing process selection based on quantitative analysis (MPS-BQA), and Design for Manufacturing (DFM) by documenting the manufacturing information directly related to the specified Design Parameters (DPs). It extends the concept of Process Variable from AD by incorporating the concept of Process Attribute from MPS-BQA, and by proposing the concepts of Process Parameter (PP) and process Execution Variable (EV). Along with the DPs/PPs/EVs matrices, a set of tables has been defined. Such tables include fields to formalize the writing of DPs/PPs/EVs, and to add guidelines, rules, rationale and evidence based on industrial practices.

The findings are in line with conclusions from other authors, although the methodology was tested in just one case study. This is particularly true in relation to documenting FRs, DPs and their relationships, the discipline needed to document the decisions made during the design process, and the benefit that software support tools could bring to the designer. In this case, the complexity of identifying and documenting manufacturing knowledge for DFM is also shown. Certainly the proposed approach makes this task easier but designer expertise and discipline are still needed to carry it out. It also demonstrates the relevant increase in the amount of information to be managed when manufacturing issues are introduced.

The next steps in this research are directed towards the development of a DFM knowledge base application. The development of such a tool will address the issues related to guiding and assisting the user in the method, storing the information collected, providing lists of possible FRs, DPs, PPs and EVs, and permitting queries and manufacturability analyses to the designer. In this sense, MOKA (Methodology and tools Oriented to Knowledge based engineering Applications) is the methodology selected to achieve such development.

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