Development and Implementation of a Design for Producibility Method for Precision Planar Stamped Products*

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In this paper, we establish the Design for Producibility Design Development Methodology for stamped products which integrates both the design and manufacture of the stamped product. The general concept of considering manufacturing techniques at the initial design stages, often termed Design for Manufacturability, is certainly not novel. However, the proper implementation of this concept is not so widely understood. Our proposed method permits the product designer to control both product functionality (which he has incorporated into an initial design) and subsequent manufacturing costs through an iterative re-design process. The key step in this method is the mapping scheme from the final product design domain to the manufacturing domain; this scheme captures the cause-effect relations between design (and thus functional) specifications and manufacturing requirements and costs. We also describe the implementation of the design methodology in a knowledge-based computer environment called the Producibility Evaluation Package (P.E.P.) that, as a result of the design methodology, also automatically generates much of the process plan.

1 Introduction

It is well known that designing a product without taking its manufacturing aspects into account will, in general, lead to uneconomical and unreliable designs of that product. The conventional Design for Manufacturability method had been proposed to overcome the shortcomings of not combining product and process design. Such a design development method generally consists of the product designer checking the part design against a set of "expert" rules, often listed in a handbook. In the case of stamping these rules are based on the assumption that there is a simple direct correspondence between the stamped part and the dies used to manufacture it (i.e., the part is stamped by a simple, single station die). For complex stampings, this is clearly not the case: the part is generally stamped by several stations in a progressive die, with possible secondary operations. The simple "handbook" rules therefore yield misleading and erroneous information about the stamped design. Moreover, because these rules are generally pass/fail in structure, with no associated consequences given for violating the rules, the product designer does not have the information necessary to decide if design modifications are worthwhile. Thus, the designer will often make unnecessary modifications to the product design, thereby losing product functionality.

To overcome these problems, we studied the purpose and origin of design rules, the stamping process itself, and the considerations that are important to product designers. Through this study, it was determined that product functionality, manufacturing reliability and costs and overall cycle time from design to final manufacturing were all important to the product designer. These requirements directly led to our definitions of product producibility, and to the structure of the Design for Producibility design development method. The key step in this design methodology is the mapping scheme from final part design specifications to the manufacturing domains, namely the die sections, punching tools, and strip layout (i.e., the basics of the process plan). To implement such a design methodology, we have developed a knowledge-based computer environment, called the Producibility Evaluation Package (PEP). Basically, the PEP predicts what manufacturing requirements and costs would be necessary to stamp the product design. From this information and from redesign suggestions output by the PEP, the designer is able to control both his product functional specifications and the subsequent manufacturing costs. Also as a result of the producibility analysis, much of a process plan is derived by the PEP for possible use by manufacturing engineers.

It should be noted that there have been attempts at automating process design for a certain class of formed parts [1]. However, this method does not explicitly relate the product design to its process plan; thus, it does not provide the designer with a strategy to improve the producibility of his product. In contrast, the Design for Producibility method inherently integrates both the product and process design in order to aid the product designer in developing the most producible product. Our method allows the product designer to control man-

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ufacturing costs by properly modifying his own design parameters. In fact, our basic premise in constructing such a design method is that product design and process design cannot be performed individually, but must be done concurrently.

The paper is structured as follows. In Section 2, we review the need for a Design for Producibility design development method. Producibility and Design for Producibility are formally defined in Section 3. In Section 4 we establish the determinants of product producibility. These determinants affect the costs of manufacturing the stamped product and are therefore called manufacturing cost factors. In Section 5 we provide the rational basis and ensuing procedures for computing manufacturing cost factors. This method of assessing product producibility leads very naturally to the Design for Producibility design development method and its implementation in the form of a computer-based Producibility Evaluation Package (PEP). The various components of the PEP are described in Section 6, along with the current status in the development of each component. Finally, in Section 7, we summarize the need for and the structuring of the Design for Producibility method, and then draw some conclusions.

While the Design for Producibility methodology is applicable to stamped products in general, we have currently restricted the scope of our implementation to the class of (complex) precision planar stamped products, such as the lead-frame shown in Fig. 1. We also feel that the general philosophy of our methodology—a closed-loop design development method which incorporates manufacturing costs (through the domain mapping scheme) with the designer's own functional specifications—is applicable to other manufacturing domains, and we aim to demonstrate this in the future.

2 Design for Producibility: The Motivation

In this section we establish the need for a new method for the development of precision planar stamping designs, such as the lead-frame shown in Fig. 1. First, we discuss the design development method used most often by design engineers. The shortcomings of this design method were discussed and proved in [2]. These shortcomings will dictate the format and structure of the new design method to be developed.

Generally, the design development method called Design for Manufacturability consists of the following steps:

(1) an initial design is created to satisfy a set of functional specifications;
(2) the design is subjected to a checklist of tests, or rules-of-thumb (often listed in a design handbook [3][4][5]);
(3) dictated by failed tests, design modifications deemed "appropriate" are made;
(4) the final design is sent to manufacturing.

However, this design strategy has many shortcomings, including providing misleading and incorrect results, and not providing most of the pertinent information important to the product designer. More specifically, the shortcomings include the following:

(1) the designer probably does not understand the origin or purpose of each rule;
(2) the set of rules used by designers is not very complete;
(3) rules are not always applicable (i.e., violating them is of no manufacturing consequence);
(4) if a design fails a certain rule, redesign suggestions to alleviate the difficulty are frequently not explicitly given;
(5) because heuristics are simply a list of "pass" or "fail" tests, the designer does not know if "fail" means the design is impossible to stamp, or if it is possible but at a higher cost; thus, he cannot determine if leaving the design unchanged (which he may require for functional reasons) is worthwile (i.e., worth the added production costs); there is no association between design (or functional) specification and subsequent manufacturing costs;
(6) for similar reasons, there is no measure of how "good" a design is with respect to manufacturing and cost;
(7) there often is unnecessary loss of product functionality.

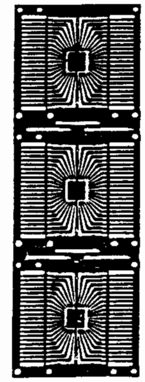

Fig. 1 A sample lead-frame cross-section

Many shortcomings listed above come from the fact that design evaluation is based on a false assumption: all the design rules listed in handbooks are based on the assumption that the designed part will be stamped with the simplest press type possible. To overcome these shortcomings, we established the Design for Producibility method for planar stampings, using the following steps: clearly defining what is important in product design development; examining the origin and purpose of design rules; and carefully studying and structuring the manufacturing process of stamping itself.

3 Defining Producibility and Design for Producibility

In this section we discuss what producibility means and how it is the crucial measure of successful product development with respect to manufacturing. We then define the overall goal of our project in terms of producibility.

A more in-depth study of stamping revealed that simply knowing a part can be manufactured is only a small portion of the information a designer would like to know in the initial design stage. Instead, we have determined that producibility is the important measure in design development, where we have defined producibility as follows:

For any design development method to be effective and successful, it must provide a structure to allow the product-designer to maximize a design's producibility as early in the design stage as possible, while still maintaining the required functionality. In short, "the objective is maximum function at optimum cost, with high quality and dependability." [6] Thus, the purpose of the current work can be stated as follows: the goal of our research is to establish a design development method, which we call Design for Producibility, to aid designers of planar stampings in developing a product with maximum producibility, while still maintaining much of the functionality of the original design. Once this design method is structured, our goal is then to construct a design tool which, given the initial part design, will help the designer, through an iterative redesign process, develop the most producible, and still highly functional, design. With the overall research goal now defined, the next two sections will discuss how we structured and defined product producibility, and how it can be assessed.

4 The Determinants of Design Producibility

In this section we discuss in more detail what comprises the producibility of a stamped product, since we stated in Section 3 that producibility must be measured. We expand on the definition of producibility given above so that all the determinants which comprise producibility can be established and measured. Since collectively the values of these determinants yield the total costs associated with manufacturing the part, we call these determinants manufacturing cost factors (MCF).

The first step in quantifying producibility requires that we expand upon the terms used in the producibility definition above:

-feasibility: is it possible to stamp the part, with no regard to difficulty or cost;

-reliability: can the part be consistently stamped to meet all specifications (e.g., can part distortion be controlled); how repeatable is the stamping of the product;

-machine costs: how expensive is the necessary die press; are additional set-ups required for secondary operations;

-labor costs: how many man-hours are needed to construct the equipment;

maintenance costs: how much tool wear and tool breakage will occur; are inspections frequently required (due to tight tolerances, wear, etc.);

-cycle time; how long will it take to develop and manufacture a final product design; how many obstacles, manufacturing problems, and subsequent time-consuming redesigns are going to occur.

A detailed study of producibility with respect to the stamping process enabled us to identify the set of MCFs which are crucial in quantifying the producibility of stamped products. More specifically, the expanded producibility definition yielded the following set of Manufacturing Cost Factors [7][8]:

(1) Type of press (e.g., compound vs. progressive)
(2) Number of punching tools
(3) Necessity of secondary operations (e.g., milling, finish grinding)
(4) Material scrap
(5) In-process inspections
(6) Necessity of die inserts
(7) Stripper requirements (e.g., necessity of a spring stripper)
(8) Punch and die replacement/maintenance costs
(9) Press tonnage
(10) Product mass and volume

Having identified the appropriate Manufacturing Cost Factors*, in accordance with the expanded producibility definition above, we state the following proposition: in order to assess a designed part's producibility (which is the first step in the Design for Producibility method), one must simply calculate values for the set of manufacturing cost factors. Furthermore, the design with the highest (i.e., best) producibility is the one for which the sum of the (normalized) manufacturing cost factors is the minimum.

The next step necessary for computing producibility is to determine a method for computing values for each of the MCFs for a given design.

5 A Methodology for Assessing A Design's Producibility

In the previous section we quantified producibility such that the overall producibility of a designed part could be calculated. In this section, we discuss the step-by-step method to actually compute values for the manufacturing cost factors, and thus the overall producibility. We then briefly discuss the key step in the producibility evaluation process, namely how to map from the final product design domain to the manufacturing domain.

5.1 The Procedure for Assessing Product Producibility. In order to calculate a design's producibility, we needed to study all the stages and operations which govern the stamping of parts. More specifically, by studying the tasks performed by stamping engineers (e.g., die design), and by studying the behavior and limitations of the stamping process itself, we were able to capture and model the essential steps that can be used to predict the final manufacturing costs associated with stamping a given part (i.e., predict the design's producibility). We determined that there exist discrete steps, or states, along the path to calculating the manufacturing cost factor values. These states, which represent crucial considerations and stages in the real stamping environment, are arrived at through actions taken on previous states, thereby exploiting the true cause-effect relations which occur in die design and the physical process of stamping a part. The states arrived at in producibility calculations are shown boxed in Fig. 3, and are listed here: product design, reasoning domains, manufacturing features and attribute values, process variables, intermediate cost factors, manufacturing cost factors. These quantities are defined next:

(1) Reasoning domains (RD) - the three fundamental manufacturing domains which are the basis of producibility calculations (i.e., the 3 main components of the process plan):

(*a*) Part strip domain (the part material strip, as it proceeds through each stamping station)

(*b*) Die section domain (the die sections, with the corresponding die openings, at each stamping station)

(*c*) Punching tool domain (the punching tools for each stamping station)

(2) Secondary specifications (SS) - the design specifications accompanying the part design:

(*a*) Material properties of the part
(*b*) Number of parts desired
(*c*) Tolerances

(3) Process Variables (PV) - the parameters which physically govern the limitations and costs of the stamping process:

(*a*) Die stresses (e.g., fatigue stresses, maximum compressive stresses)
(*b*) Part stresses
(*c*) Punch stresses
(*d*) Punch manufacturability
(*e*) Die manufacturability
(*f*) Complexity of punch/die cross-sections

(4) Intermediate cost factors (ICF) - the set of adverse physical consequences (or high costs) suffered in stamping a part in a nonideal manner (these ICFs contribute to the final manufacturing costs factors):

(*a*) Burr formation
(*b*) Punch wear
(*c*) Die wear
(*d*) Punch breakage
(*e*) Die breakage
(*f*) Part distortion
(*g*) Punch buckling

Before discussing the evaluation process, we need to discuss in more detail the process variables just listed. In real practice,

* Note that the above list of cost factors is not an exhaustive list, but it does represent many of the cost factors which can directly be controlled in the design stage. Because our goal is to establish a design development method to aid the product designer, costs such as overhead are not included in the list of cost factors (i.e., the product designer cannot really control overhead costs, associated with manufacturing the part, by modifying the design).

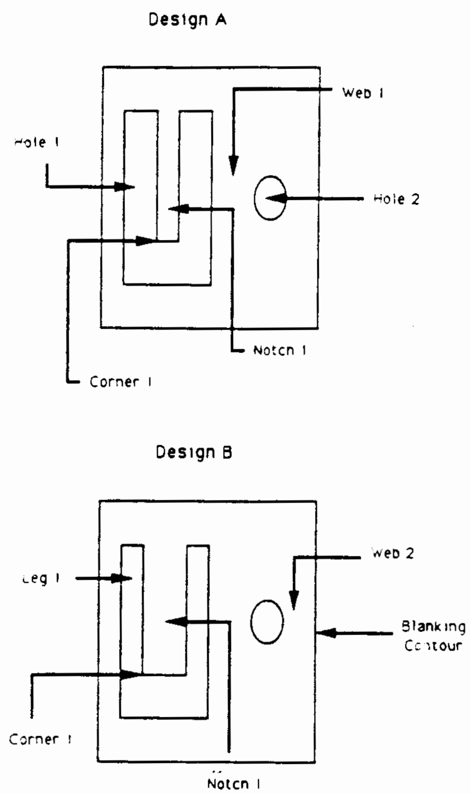

Fig. 2 Cross-sections of Design A and Design B

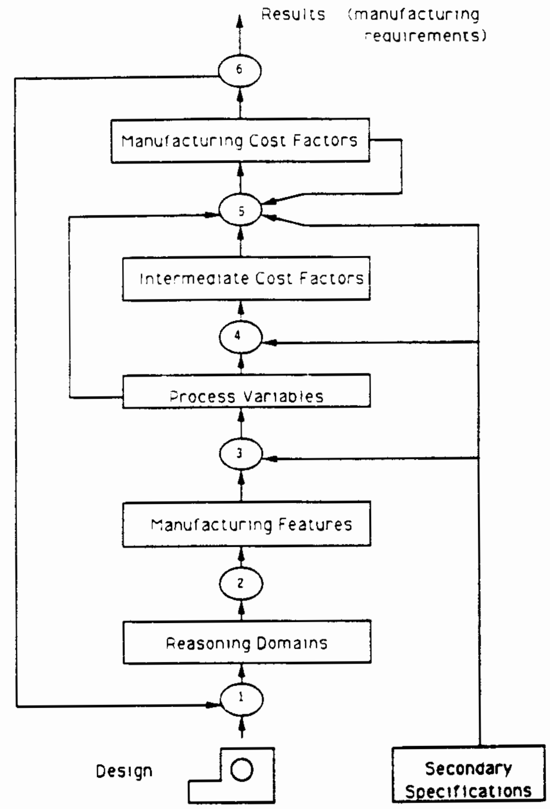

Fig. 3 The Method to assess design producibility

stamping engineers do not calculate absolute values for the stresses incurred in physically stamping a product. There are simply too many parameters which affect the stress distributions (e.g., die clearance, tool conditions, misfeeds, etc.). Instead, engineers determine the key attributes which govern stress distributions and stress concentration factors. From these attributes, they then can estimate values for stresses and stress concentration factors. Thus, based on the raw data that is needed to obtain approximations for the process variable values, we structured the part strip, the die sections, and the punching tools (i.e., the three reasoning domains) in terms of the following key parameters: manufacturing features, sub-features, feature attributes, and feature attribute values (see Fig. 2):

(1) Manufacturing features (MF) - the set of geometric primitives defined consistently in all three reasoning domains, such that producibility reasoning can be performed on the part strip, the dies, and the punches:

(*a*) Hole contours
(*b*) Blanking edge contour
(*c*) Webs

(2) Sub-features (SF) - more specific features defined within the manufacturing features:

(*a*) Corners
(*b*) Notches
(*c*) Legs

(3) Feature attributes (FA) - parameters of each manufacturing feature or sub-feature:

(*a*) Notch width
(*b*) Leg width
(*c*) Notch concavity
(*d*) Web width
(*e*) Hole complexity
(*f*) Blanking contour complexity
(*g*) Leg concavity
(*h*) Concave and convex corner radii

(4) Feature attribute values (FAV) - numerical values associated with each feature attribute.

Given these definitions, we now can describe the basic, step-by-step strategy of design evaluation, as shown in Fig. 3. This procedure, to evaluate design producibility, takes as input the design specifications and through a logical, sequential process, calculates values for the MCF's and much of the process plan. The nodes between each state of this process represent the actions necessary to calculate the next state. More specifically, each step in the producibility calculations is described below, where the numbered actions below correspond to the numbered nodes in Fig. 3:

(1) Taking the product design as input, use the domain mapping schemes (see Section 5.2) to derive an initial die press (i.e., the 3 reasoning domains). The first time through, propose the simplest and least costly press type possible: one stamping station, one punch per hole, one punch to blank the entire part, no stripper, no pressure pads (i.e., a simple compound die).

(2) From the current press specifications (i.e., die sections, punches, stockstrip) derived in Step 1), identify all the manufacturing features and sub-features and extract their attribute values (e.g., extract the punch leg width).

(3) From the attribute values of step 2, and from any relevant secondary specifications, predict values for the process variables that would correspond to the current press type (e.g., from the punch leg width, and from material properties, determine what punch stresses would occur).

(4) From the process variable values of Step 3), and from relevant secondary specifications, predict the values of the intermediate cost factors if the press type from Step 1 were used (e.g., from the punch stresses and the number of parts desired, predict the amount of punch wear that would occur).

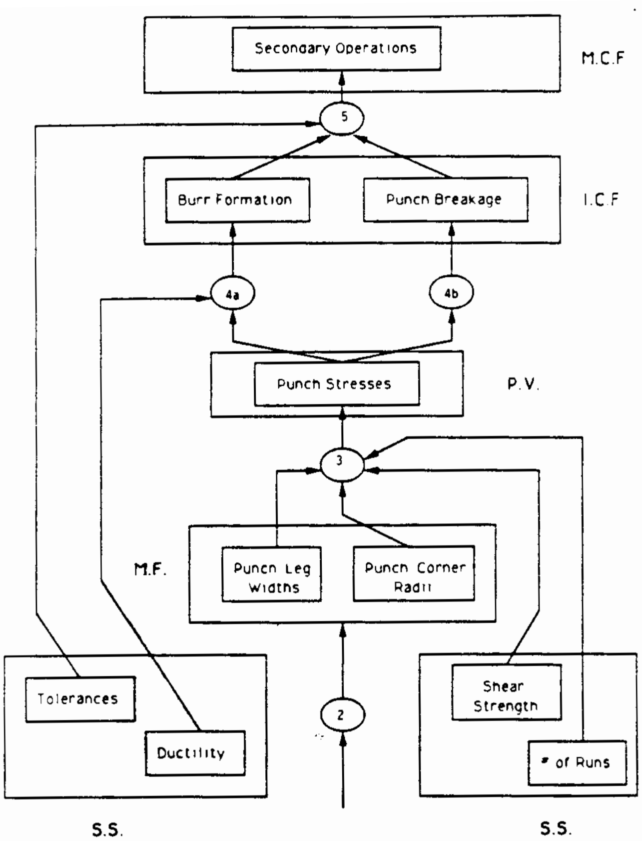

Fig. 4 Part of a cost function

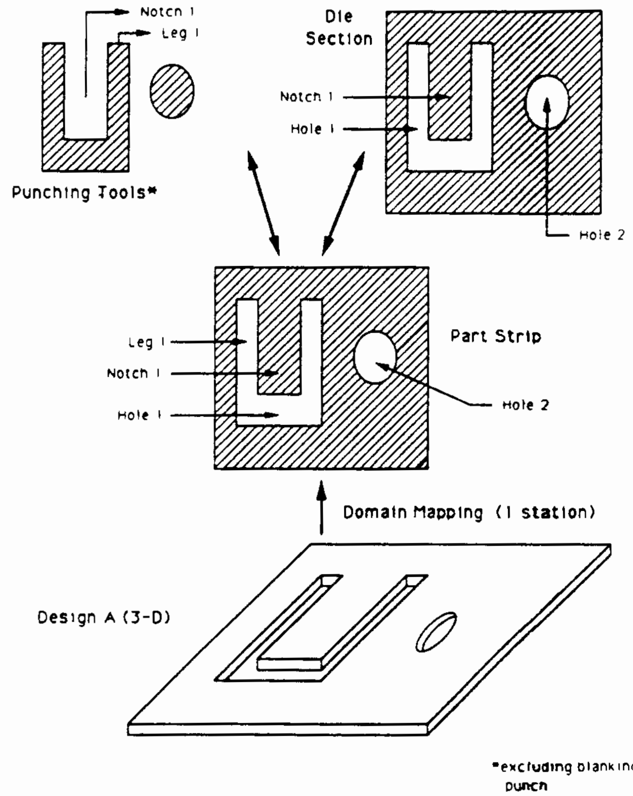

Fig. 5 Initial (and final) domain mapping for Design A

(5) From the intermediate cost factors from Step 4, from appropriate process variables, from other manufacturing cost factors, and from any relevant secondary specifications, determine the actual set of values for the manufacturing cost factors that are required to stamp the part (e.g., from knowing that the punch wear is high, set the tool inspection factor to an appropriate level).
(6) If at any step of this evaluation process the values for any of the parameters (i.e., MCF, ICF, PV) are excessively poor, go back to Step 1 and calculate a new set of punches and die sections (i.e., a new press type) to alleviate these problems. Then, go to Step 2 for re-evaluation, to determine if the new press type is the one that would actually be used to stamp the part.

At the end of the design evaluation process, the values for each of the manufacturing cost factors required to stamp the design are predicted and can be made available to the product designer.

The steps just described to calculate M.C.F.'s have been further formalized into a set of interdependent cost functions, one for each manufacturing cost factor. These cost functions are defined as follows: a cost function is a function consisting of a set of logical operators and properly used stamping domain inference rules, whose inputs are secondary specification values, manufacturing features, sub-features, feature attributes, and feature attribute values, and whose output is the corresponding manufacturing cost factor value.

Note that in order to output manufacturing cost factor values, the cost functions first estimate the process variable and intermediate cost factor values using the sequence shown in Fig. 3, where again the nodes in Fig. 3 collectively comprise the cost functions. In Fig. 4 we detail part of a possible cost function for determining if any secondary operations would be necessary. Briefly, Node 3 states that thin punch legs or sharp punch corners can cause high punch stresses (as a function of the shear strength of the stock and the number of parts desired). In turn, these stresses can cause punch breakage, as implied in node 4b, thus possibly necessitating a secondary operation (e.g., milling), as implied through node 5.

In summary, the design evaluation method first extracts the key parameters from the reasoning domains, then, by use of the cost functions, approximates the set of manufacturing cost factor values which would be required if the current design were stamped. Also, much of the process plan is designed automatically for use by manufacturing engineers.

5.2 Mapping From Final Part Design Domain To Punch/Die/Strip Domains. In this section, we will briefly discuss the critical step of the evaluation procedure, namely the domain mapping. The mapping is necessary because the only input to the DFP method is the final product design, but reasoning needs to be performed on manufacturing domains. For example, in order to compute punch stresses, the punching tool cross-section must be known. The mapping scheme will provide a way in which to step from the part design domain to the punching tool, stock strip, and die section domains.

As described in the evaluation procedure above, the first step in the evaluation process is to assume the press type to be the simplest, least costly one. This press is then tested for its feasibility of stamping the part. This simple mapping used for the initial evaluation sequence (i.e., when the least costly press type is first assumed) is shown for a simple design, Design A, in Fig. 5. Basically, the punch cross-sections match the cross-sections for the part's holes, and the blanking punch matches the outer contour cross-section of the part. Similarly, the die openings match the cross-sections of the part's holes. Thus, die webs match the webs of the part. It should be noted that this mapping is not exact: a die opening cross-section is generally 10 percent larger than the corresponding punch cross-section, to provide appropriate clearance. For now, we have decided to ignore the difference.

Once the domain mappings are complete, the only remaining

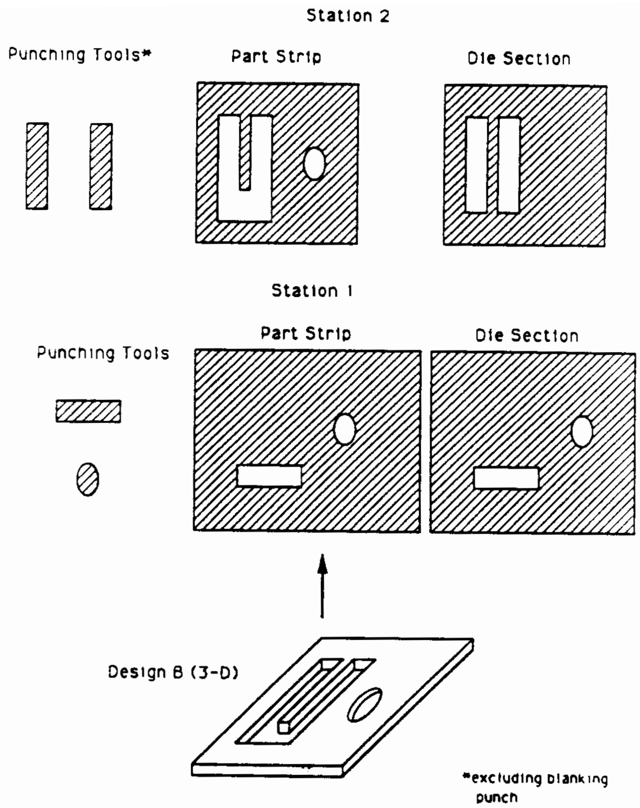

Fig. 6 Final domain mapping for Design B

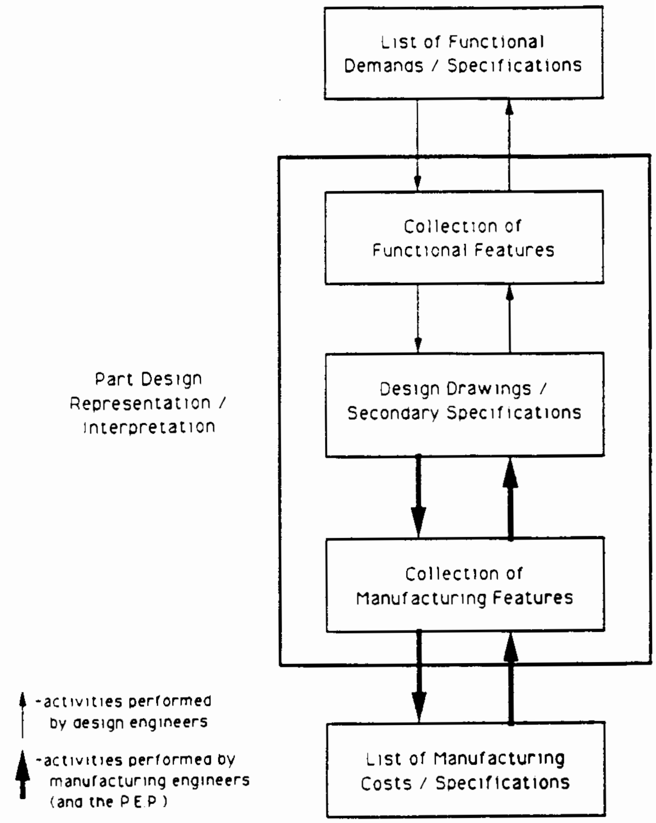

Fig. 7 Flow of product design information

task in deriving a die press is to determine where to split the die sections so the die openings can be ground. This step involves iterations and testing for feasibility, reliability, and minimum cost. Some of the guidelines used include the following: a die opening should be split perpendicular to its edge; no leg concavities in the die opening should result from die splitting (a feasibility test); try to keep all split lines at a mutual station parallel to each other.

When it is determined that the initial assumption for the least costly possible press type will not work, the mapping becomes more complex. The mapping, governed by a set of complex rules and guidelines, involves iterations, searches, and synthesis of appropriate punches and dies to be tested again for feasibility and cost effectiveness. Some of these procedures are discussed in [9]. Several of the issues involved in the new mapping scheme include splitting punches into smaller ones to alleviate punch breakage and punch manufacturability; splitting die openings into several smaller ones to alleviate die breakage; and using an optimization procedure to determine the minimum number of progressions necessary, for each set of punches and dies proposed to completely stamp the part. An example of this more complex mapping is shown in Fig. 6, again for a simple design, Design B. In this case, the domain mapping represents the final proposed press type and basic process plan that would be used if the current version of Design B were to be stamped. Note that the pilot and blanking punches are not shown, for clarity. However, these punches and corresponding die sections and strip layout are also derived using our domain mapping and die design methods.

6 Development of the Producibility Evaluation Package

In the previous section, we detailed the steps required to assess a design's producibility. In order to implement this design development method in a feasible manner, we constructed a knowledge-based computer environment. In this section we first review the purpose of constructing such a computer system and discuss how the system fits into the overall Design for Producibility methodology. We then discuss the structure and components of the computer system.

The purpose of developing the Producibility Evaluation Package (PEP) is to create a computer-based design tool which will help the product designer arrive at the most producible design possible, while maintaining the functional specifications of the initial design. Given a product's design specifications, the PEP first predicts the set of manufacturing cost factors values that would be required to stamp the current version of the design. Then, because the PEP contains all the cause-effect relations from its input (the design specifications) to its output (the set of MCF values), the PEP can present the product designer with the following information:

(1) the values for each of the manufacturing cost factors that would be required to stamp the current version of the product design;

(2) the design specification "sources" which cause the MCF's values to be high (i.e., a manufacturing feature attribute value or a secondary specification);

(3) re-design suggestions to improve the producibility of the designed part.

Using these output results of the PEP, the product designer can re-interpret the design specifications (i.e., the manufacturing features or the secondary specification) which are the source of high costs, in terms of his own design, or functional, features. Thus, the product designer can then evaluate that design specification in terms of its functionality. At that point, the designer can make the decision as to whether that functionality is worth the ensuing manufacturing costs, and then make the appropriate design modifications.

In Fig. 7 we show the "downward" flow of design information and interpretation, from initial product functional specifications, to product design by the design engineer (using design features if necessary), to the design interpretation by the manufacturing engineer, in terms of manufacturing features, to the subsequent manufacturing requirements (i.e., the

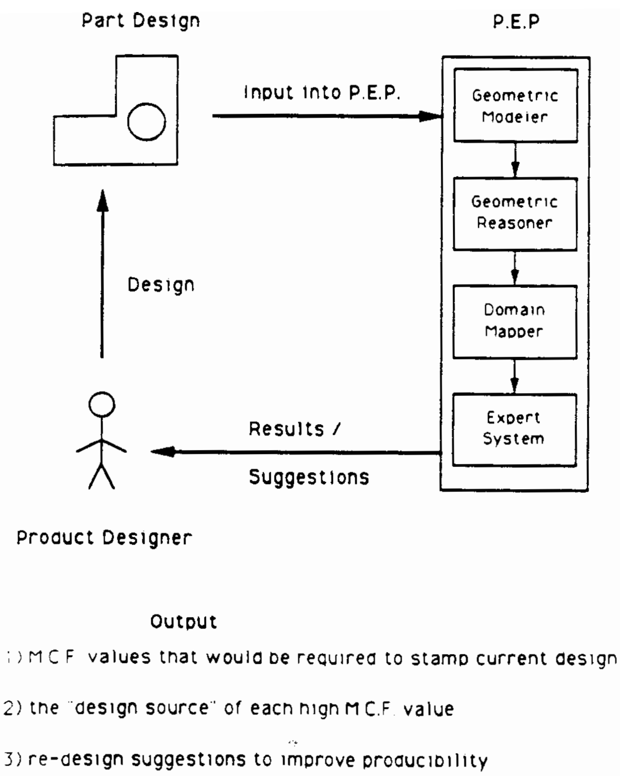

Fig. 8 Overall design for producibility methodology

set of manufacturing cost factor values). After the MCF values are determined, the functional specifications which cause the MCF values to be high can be identified by reversing back "up" the flowchart of Fig. 7. The decisions on the worth of product functionality—made by the designer—complete the DFP design development method as a closed-loop process, which includes both the part functionality (originally given by the product designer) and the manufacturing requirements.

In order to implement the Design for Producibility method, we constructed the Producibility Evaluation Package (PEP), which fits into the closed-loop design development process as shown in Fig. 8. The components of the system—the Geometric Modeler, the Geometric Reasoner, the Domain Mapper, and the Expert System-will now be described.

6.1 Geometric Modeler. All computer-based design packages require a suitable modeling system, the choice of which is dictated by matching a modeling system's capabilities with the type of information that is needed. For our purposes, the following criteria must be satisfied by the modeling system:
(1) the method of representation must be general enough to be able to represent any arbitrary stamping design;
(2) the burden of inputting a design into the modeler and flagging any key data must be minimized, as user burden is a chief factor in the package's eventual acceptance by product design engineers;
(3) all the required data for analysis must be obtainable from the design model.

Several modeling systems proposed for design and manufacturing analysis call for designing with features, or primitives [10][11]. However, these approaches violate all three criteria, given above, which we have specified for our evaluation system. First, the finite set of primitives or features used by these systems greatly restricts the class of designs which can realistically be constructed. Many of the product designs we need to evaluate are far too complex and cannot be structured completely in terms of features which can be cleanly and sufficiently parameterized (see lead-frame in Fig. 1). Secondly, it can prove to be very tiresome, tedious, and even error-prone for a designer to attempt to create his design using the proper primitives and shape operators. Finally, not all the required data can be extracted from these feature-based representational schemes.

This project makes use of the geometric modeler, NOODLES, developed in the Design for Manufacturability Lab at the Engineering Design Research Center of Carnegie Mellon University. With NOODLES as a base, we are able to develop software that satisfies all three criteria for choosing a modeling system for the class of product designs we currently study: any design can be represented in the modeling system, and for all planar stamping designs, of any complexity, parameter values can be automatically extracted, with no burden on the designer beyond entering the design into the modeler.

6.2 Geometric Reasoner. The Geometric Reasoner is a data extraction software package that we have developed which can retrieve all the raw data necessary for later reasoning from the Geometric Modeler. All the manufacturing features, subfeatures, feature attributes, and feature attributes values can be identified and calculated automatically.

6.3 Domain Mapper. The Domain Mapper is also a software package which performs the tasks described earlier (see Section 5.2). By communicating with the Geometric Modeler, and the Expert System (to be discussed below), the Domain Mapper creates and stores the cross-sections of the punches, dies, and stock strip as sets, each set being a progression, or station (of the basic process plan). These process plan specifications are then evaluated for validity and cost-effectiveness by the Expert System. If these specifications fail, the Domain Mapper uses the results from the Expert System to derive a better process plan.

This component of the PEP is the most difficult to construct, from both a geometric and a process reasoning point of view. However, substantial progress has been made in both areas, as initial algorithms have been successfully developed. In fact, in [9][12], we discuss a full-scale, complex implementation of the PEP, in which the Domain Mapper does indeed derive a complex progressive die press and process plan.

6.4 Expert System. The Expert System contains the stamping domain expert knowledge. We gathered this expert knowledge from various sources:
(1) from the existing literature on die design and on the manufacturing process of stamping itself [8][13][14];
(2) from the existing literature on product design for stamping [3][4][5][7];
(3) from the engineers of Oberg Manufacturing, a local stamping company that specializes in die design and the stamping of precision planar products.

The Expert System, which contains the properly structured expert knowledge, carries out the actual design evaluation process (discussed in Section 5.1). Given all the reasoning domain raw data (e.g., attribute values) from the Geometric Reasoner, and given the secondary specifications, the cost functions calculate the set of manufacturing cost factor values that would be needed to stamp the current design.

Currently, the Expert System component does indeed carry out the evaluation process, by means of the cost functions [9][12].

7 Summary and Conclusions

In this paper we discussed the need for and structure of a design development method, which we have called Design for Producibility. This design method combines both product design aspects as well as manufacturing design and requirements, at the initial design stages, to better ensure a successful product. In order to implement this design strategy, we have developed an initial version of the Producibility Evaluation Package, which measures a designed part's producibility, where producibility is a measure of the feasibility of stamping the design reliably, with minimal manufacturing labor and machine costs, and with minimal maintenance. The outputs of the PEP are the design sources of high manufacturing costs as well as redesign suggestions to improve the product's producibility [12]. The designer, by interpreting the suggestions in terms of their functional value, and by making "worthwhile" design modifications, completes the DFP method, thus making it a closed-loop process.

The key idea in implementing this design development method is the structuring of the Producibility Evaluation Package. In order to reason about the part design in the manufacturing domain, we modeled the entire stamping process, from the manufacturing interpretation of a design, to the subsequent die designing, to the stamping process behavior and limitations, to the costs associated with stamping, all in terms of the parameters that the product designer can control. It is this modeling and structuring of the stamping process which dictated our structuring of the PEP, thus allowing the product designer to control both the functionality and much of the manufacturing costs of stamping his designed part.

In conclusion, there are five key beneficial justifications which warrant the development of the Design for Producibility method and the associated Producibility Evaluation Package:
(1) there is very little burden placed on the designer, as all producibility calculations are automatically done by the Producibility Evaluation Pacakge;
(2) because the PEP is able to indicate to the designers the design specifications which cause the manufacturing cost factors to be high, the designer in turn can interpret these design specifications in terms of their functionality; by being able to relate the high manufacturing costs with the appropriate design specifications, he can ultimately weigh the importance of each functional specification in terms of these costs;
(3) the design-manufacturing cycle time will be reduced, since the final design developed using the PEP and the Design for Producibility method should minimize the difficulties in manufacturing the designed part, and possibly eliminate the need for future redesigns;
(4) because the process plan is generated automatically [9], higher product quality, highly reliable production equipment, and a more reliable end-product result [15];
(5) perhaps most importantly, the entire design evaluation and redesign process can be completed by the designer at a single workstation, before any manufacturing commitments are made.

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