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A DESIGN-TO-MANUFACTURE CASE STUDY: AUTOMATIC DESIGN OF POST-FABRICATION MECHANISMS FOR TUBULAR COMPONENTS

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Abstract

An automated design-to-manufacture system and the description of its implementation are outlined. The system is described in the context of rapid prototyping of a mechanism for the post-fabrication of miniature metal tubular components. Post-fabrication operations considered include dimpling, bending, slotting, lancing, punching, corsetting, and notching. The system has been demonstrated to reduce design-to-manufacturing cycle time by many orders of magnitude. The method outlined encompasses the integration of rule-based expertise with theoretical considerations underlying the manufacturing process. Using an artificial intelligence language, this module is then linked to a computer-aided design system to automatically generate detailed drawings of the mechanism. The system emphasizes the automatic design of the assembly and generation of blue prints and NC code for appropriate mechanical parts. To determine whether a component can be made using current company technology, an advise-on-manufacturability module was developed. This paper describes the methodology used in developing this system as well as the difficulties encountered during the development.

Keywords: *Rapid Prototyping, Design-to-Manufacturing, Metal Working, Machine Design, and metal fabrication.*

Introduction

The importance of software development in the manufacturing industry can be seen by a recent emphasis of CAD software developers on the production of high-level systems aimed at the complete automation of design processes. A recent trend by manufacturing companies has been their use of large-scale parametric software suitable for integration into existing design methods. Parametric-driven technology and geometric modelers have reportedly achieved a significantly higher productivity level.¹ Rule-based design has affected design-time, cost, and performance.

More recently, a new generation of systems such as seamless design-to-manufacture (SDTM)

have appeared² that integrate rule-based systems with parametric based technology. Because this type of system is a rule-based structure, it has the ability to automatically generate part geometry, process geometry, and various geometric models needed for analysis.

In some cases, these systems also include an automatic rule-driven numerically-controlled (NC) code generator, which translates CAD data into suitable NC code. A similar system that is targeted toward integrating an end-product directly from the designer's CAD system or solid modeler was presented by Mayer et al.³. This system is able to generate a process plan, a tool path, and NC code. Other systems have appeared in Chen and Voleker's work⁴ where the manufacturing engineer needs only to specify the process plan. The complete part program could be derived from the plan specified. A design-to-manufacture system for the roll-forming industry called CARDAM was reported by Nallapati and Somasundaram.⁵ The system integrates CAD and CAM facilities to design the roll form, roll profile, as well as editing and NC processing of roll profiles. In the metal working industry, most approaches to achieve a design-to-manufacture have been based upon multiple set-ups of a single part.⁶⁻⁹ Modeling methods are described by Chang and Wysk¹⁰ and Requicha and Vanderbrande¹¹. Modeling by features were presented by Shah¹² and edge-faced graphs were presented by De Floriani.¹³

Every manufacturing engineer carries a personal knowledge-base grounded upon a life-time experience. This experience, is mostly based upon rules-of-thumb that are gathered through trial and error. These rules-of-thumb, although often descriptive, are used by programmers to develop expert systems to determine the manufacturability of similar products or families of parts.¹⁴ Currently, many far-thinking manufacturers are using expert-system shells to establish setups, to determine sequence of machining operations, to set machine parameters, to select appropriate tooling, and to generate tool paths and NC code. Artificial intelligence-based systems have been tried in the manufacturing industry.¹⁵ Reducing lead times in the manufacturing environment has been the subject of many recent studies. Olsen¹⁶, for example, addresses the necessity of such systems and their impact on today's competitive market, while an economic model that addresses these issues was introduced by Ulrich et al.¹⁷

This paper discusses the *integration* of many modules including a rule-based system, a theoretical consideration module, a CAD environment, and an artificial intelligence language (Lisp) to perform the design function. The ultimate goal is to reduce lead times associated with the design of a specialized post-fabrication mechanism that include dimpling, bending, slotting, lancing, punching, corsetting, and notching.

This system will design the layout of the mechanism, generate the detailed drawings of parts, and will provide advice on manufacturability of the end-product. The choice of commercial software, programming language, or expert system shell is irrelevant to the concept introduced here and will not be given emphasis.

Given a complete description of an end-product, it is necessary to develop a system that provides a user with the following functions.

- (1) *Advise-on-manufacturability module.* This module contains two types of rules: (a) rules of thumb and (b) theoretical considerations. This module will inform the user whether the part can be made (i.e., if it is within current company capabilities). If the part is not within current capabilities, this module will check whether the part can be made according to the classical theory of metal deformation. If this module determines that the part cannot be made, a search technique is used to recommend an alternate design.

- (2) *Design-engine module.* This aspect of the system is in two parts: (a) standard components that can be stored on the shelf for immediate assembly when needed, and (b) components that require new design.
- (3) *NC code-generation module.* This module implements an algorithm for the generation of NC code for different machining processes.
- (4) *A user-interface module.* An interface that provides the user with the ability to enter the end-product description and to intervene during the design process, as well as after the detailed design is generated.

What follows is a more detailed discussion of the implementation in the context of post-fabrication. Linking of the different modules and automatic generation of blue prints is subsequently discussed.

Advise-on-Manufacturability

To program a computer with the ability to determine whether a part can be made is a very complicated task. The difficulty stems from obtaining such knowledge in terms of expert rules that can be programmed. It has been shown to be of extreme difficulty to take an experienced tool-maker or manufacturing expert and ask them to write everything they know about the process. Methods for interrogating experts and extracting expert rules are well documented¹⁸ Having achieved this stage, it is necessary to translate these rules into computer code. All conceivable situations have to be captured. Furthermore, if many experts exist and they all achieve the same end-product, their process may be significantly different and their manufacturability criteria may also differ. Thus, the task of obtaining consensus rules that everyone may agree with, may also prove difficult. These problems and many others have been addressed in the field of expert systems.^{18,19} During the development of expert systems, knowledge engineers obtain the information from experts and prototype a computer system that contains the rules. Knowledge engineers spend a great amount of time with the experts and are primarily concerned with the thought process.

For the purpose of developing a relatively small system such as the one discussed in this paper, it is our recommendation to use a scheme opposite to the one discussed above. Instead of training a knowledge engineer to extend his expertise to manufacturing, we recommend training a manufacturing expert (tool-maker or manufacturing engineer) to the role of a knowledge engineer. The motivation for this stems from the fact that other experts will feel less reluctant to volunteer their expertise, which is a common problem in expert system development. In addition, experts will feel that they still do retain job security since the development is among themselves. Assigning one or more experts to the task of learning a new technology develops a sense of ownership tied to the company's future success.

The two cases were tested at two divisions of a corporation. In one case, a knowledge engineer with significant expertise at gathering knowledge and computer programming was assigned the task of developing a rule-based system for a deep-drawing process at the company's Connecticut eyelet division. In this process, sheet metal is transformed into a cup-shaped part. In another division in Pennsylvania, a tool-and-die maker with a life-time of experience in the manufacturing of miniature metal tubular components was assigned the task of developing rules and a computer program for the post-fabrication of tubular components. This expert had no prior knowledge in expert system development.

The results were significantly different. The manufacturing expert had collected rules, learned basic programming, expert system shells, and developed a full-scale system in 16 months. The knowledge engineer took approximately the same time to interact with the experts to learn the process. It took the knowledge engineer an additional number of months to implement it into a computer. This experience has showed that for at least this case, it is much more efficient for a manufacturing expert to learn programming rather than for a knowledge engineer to learn the ins and outs of a specific process.

System Limits

Once the rules are obtained, a module that advises on manufacturability was developed. This module works interactively with the user to define the end product and to respond with a decision on whether this specific part can be made. This decision is based primarily upon expert rules and to a second order upon theoretical considerations. It has been our experience that expert rules are usually more conservative than those allowed by the classical theories of metal deformation. For example, the shearing operation that occurs in slotting, punching, notching, and lancing of tubular components can be defined as a region of capability using expert rules as depicted in *Figure (2)*. For a certain alloy, a specified punch size, an outside diameter, and a wall thickness, the capability limits are defined. Although this graph does not take into consideration many factors, it is the outcome of the rules provided by the manufacturing experts. Thus, it does represent a viable indication whether the part can be made.

Figure 2
Window of Capability Gathered by Experts

Figure (3) depicts a number of graphed results using theoretical analysis.²⁰ *Figure (3a)* depicts the relation between shearing resistance and wall thickness and *Figure (3b)* depicts the range of the shearing resistance versus tensile strength.

Figure 3

(a) Shearing Resistance as a Function of Sheet Thickness (b) Ratio of Shearing Resistance to Tensile Strength as a Function of Tensile Strength

Figure (3c) indicates that shearing resistance becomes a constant at larger sizes. A more theoretical consideration is depicted in Figure (3d) which indicates the relation between the ratio of shearing energy to shearing area versus relative clearance.

Figure 3

(c) Effect of Punch Size on shearing Resistance (d) Ratio of Shearing Energy to Shearing Area as a Function of Relative Clearance

These curves were approximated into a single window of capability which takes into effect the material type, punch size, and part geometry. The resulting window of capability is plotted on the same graph of Figure (2) and shown in Figure (4). For the case of shearing of tubular components, it is evident that expert rules are more conservative than using the classical theory of metal deformation. Thus, to determine whether a part can be made, this module will first investigate the expert rules. If the part is not within current capability, it will advise the user that the part can potentially be made if it is within the theoretical capability window.

Figure 4

Capability of Both the Rule-Based System and the Classical Theory of Metal Deformation

Further theoretical aspects were considered, such as the computed size of the slugs inside the tubular part, the force requirement of the press, and the bending strength of the mandrel (die) that will withstand the punching force. Figure (5a) depicts a schematic of the punches and the resulting slugs. The punches, mandrel, and supporting block will be designed for the four operations (slotting, punching, notching, and lancing). Figure (5b) depicts the method of slug ejection (if needed) through an air nozzle. Note that the size of the mandrel inside the tubular part limits the force required to perform the shearing and the maximum allowable size of the resulting slugs. All of the above rules are entered into the system in mathematical form.

Figure 5

(a) Tube, Slug and Punch (b) Slug Ejection Mechanism

Case Study: Tube Bending

One of the most important aspects of bending of tubular components is necking. Theoretical criteria set forth for the bending of sheet metals do not adequately represent the deformations in bending of tubular components. Localized necking occurs at an earlier stage than that predicted theoretically.²⁰ In this case, expert rules were used again to determine the manufacturability of a part. For example, for 304 stainless steel, and for a wall thickness $0.003 \leq w \leq 0.008$, and an outside diameter to wall ratio $10 \leq (D_o / w) \leq 15$, the bend radius R depicted in Figure (6c) is subjected to the following rule.

$$R \leq 2(D_o)$$

where the minimum length for holding the tubular component (A) on each side should be $A \geq 1.6D_o$ to eliminate secondary trimming.

Figure 6

(a) Cross section of a tube subjected to pure bending (b) Elastic-plastic distribution (c) nomenclature

When designing tooling for tube bending, it is necessary to know in advance the springback ratio of the bend radius. Once this ratio is determined, it is passed on to a routine that automatically generates the tooling. Although a complete solution to the problem of calculating a springback is unknown, the following is a theoretical analysis that was implemented. From the elementary theory of strength of materials, the moment induced on a cross section is

$$M = \int \sigma y dA \quad (1)$$

where σ is the stress, y is the distance from the neutral axis, and dA is an element of area. As M increases, the stress distribution in the annulus remains linear until the stress equals the yield stress σ_y (Figure 6b). The force F , applied at the centroid of region 1 (above η) is

$$F = \sigma_y r (2\beta) t \quad (2)$$

where σ_y is the yield strength, β is defined in Figure 6(a), and t is the thickness of the tube. As the radius of curvature of the tube decreases, the thickness of the plastic region increases, and the elastic boundary approaches the neutral axis. The moment acting on region 1 is

$$M_1 = 2\sigma_y r t (\beta \bar{y}_1) = 2\sigma_y r t f_1(\eta) \quad (3)$$

where the function $f_1(\eta)$ is defined as $f_1(\eta) = \beta \bar{y}_1$. The angle β can be written as $\beta = \frac{\pi}{2} - \theta$, and the angle θ is

$$\theta = \sin^{-1} \left(\frac{\eta}{r} \right) \quad (4)$$

The moment acting on region 2 (below η) is

$$M_2 = \int_{\theta}^{\pi-\theta} y df = \int_{\theta}^{\pi-\theta} 2 \frac{\sigma_y}{\eta} (r \sin \alpha)^2 t r d\alpha \quad (5)$$

Thus the total moment M

$$M = M_1 + M_2 = 2\sigma_y r t f_1(\eta) + 2 \frac{\sigma_y}{\eta} r^3 t \int_0^{\theta} \sin^2 \alpha d\alpha \quad (6)$$

Evaluating the integral yields

$$2\sigma_y r t f_1(\eta) + 2 \frac{\sigma_y}{\eta} r^3 t \left(\frac{-\sin 2\theta}{4} + \frac{\theta}{2} \right) \quad (7)$$

where

$$f_1(\eta) = \beta \bar{y}_1 = \left(\frac{\pi}{2} - \theta \right) \frac{2r \cos \theta}{(\pi - 2\theta)} = r \cos \theta = \frac{R}{R_E} \quad (8)$$

where the centroid of the section $\bar{y}_1$, used in *equation 8*, is

$$\bar{y}_1 = \frac{\int y dA}{\int dA} \quad (10)$$

and derived as follows. For an element of area dA , each part of *equation 10* can be integrated to yield

$$\int dA = \int_{\theta}^{\pi-\theta} r t d\alpha = r t (\pi - 2\theta) \quad (11)$$

$$\int y dA = \int_{\theta}^{\pi-\theta} r^2 t \sin \alpha d\alpha = 2r^2 t \cos \theta \quad (12)$$

The location of the centroid of region 1 is determined as follows

$$\bar{y}_1 = \frac{2r \cos \theta}{(\pi - \theta)} \quad (13)$$

For a radius of curvature R from the neutral axis of the tube, the elastic-plastic condition is

$$\frac{\sigma_y}{E} = \frac{\eta}{R} \quad (14)$$

The change in the radius of curvature due to springback is R_E , thus the moment M is

$$M = \frac{Er^3 t \pi}{R_E} \quad (15)$$

For a tube that has undergone a deflection δ , and when unloading occurs, the elastic springback is δ_E , thus the final deflection δ_f is computed as

$$\delta_f = \delta - \delta_E \quad (16)$$

The springback λ is thus calculated from the following equation

$$\lambda = \frac{R}{R_F} = 1 - \frac{R}{R_E} \quad (17)$$

Substituting *equation 14* into *equation 7* and equating it to *equation 15* yields

$$2\sigma_y r t f_1(\eta) + 2 \frac{\sigma_y}{\eta} r^3 t \left(\frac{-\sin 2\theta}{4} + \frac{\theta}{2} \right) = \frac{Er^3 t \pi}{R_E} \quad (18)$$

Thus the springback is computed numerically by substituting different values for R/R_E .

Knowledge of the springback allows the automatic design of a bending mechanism. For different alloys, *Figure (7)* shows plots of the springback ratio versus the radius of curvature to diameter ratio.

Figure 7

Springback ratio versus radius of curvature to diameter ratio

Capabilities

Design of part, process, and performing analysis are iterative tasks, each composed of two primary phases: (1) component design and (2) detailed design. The conceptual design of the general mechanism needed to manufacture this family of parts has been enhanced throughout the years by the experts. This section introduces the capabilities of the system in view of an automatic blue print generation, automatic NC-code generation, and user interface modules.

Attempts have been made in the past to standardize the components that go into the design of mechanism with different degrees of success. The design process, however, still relies upon human expertise. A multiple of designs may exist for a single mechanism.

An example of a design-to-manufacture system that has been reported for a family of parts is the Seamless Design-to-Manufacture (SDTM) system presented by Hazony and Zeidner.² The authors report that this system has a fully-automated geometry generator which converts parametric part and process designs to the corresponding detailed part and process geometry. Numerically Controlled (NC) code is also generated. The part and process design in this system, however, are carried out interactively with the user and not automatically generated.

In the case study presented here, the conceptual design of the mechanism has been programmed into the system and is carried out by the system. In order to teach the computer a design method, it is necessary to set up guidelines for the design process. Eleven manufacturing experts were consulted to obtain these guidelines. In the process, several components were standardized so that no redesign of these components is needed. In fact, these standardized components were fabricated and placed on the shelf for immediate assembly and will be referred to as off-shelf components.

Design of the mechanism is governed by the part geometry, part material, slug shape, slug dimensions, and required tolerances and surface finish. Force requirements for achieving the removal of slugs are computed.²¹ The design is altered accordingly. For example, a relatively large force may require the addition of a support block to the design. A support block is a mass that surrounds the part and allows the punches to pass through. This block provides a rigid support for the post-fabrication operations. The block will also constrain the punches upon contact with the part reducing edge draw-ins. In the case of one punch, a relatively large bending moment is induced which may cause dents and deformations in the part. To eliminate such problems, it is often obligatory to design a suitable mandrel that is located inside the tube. In addition, tolerances mandated by the end-product may require a special design of the mandrel.

Penetration depths of cracks, smoothness, and burr size, as depicted in *Figure (9)*, are factors that determine the size of the mandrel and its rigidity. These aspects may contradict, however, space requirements needed for the ejection of slugs. An optimization method was used to determine a suitable mandrel size.²² The constraints used are the space requirements, tolerances, material deformation, and mandrel rigidity. The cost function to be minimized is the mandrel's inside diameter.

Figure 9

Form Errors in Shearing

To illustrate the above discussion, consider the design of a double-parallel punching mechanism depicted in *Figure (10)* (only one punch assembly is shown). Standardized components that were fabricated include the slug ejector mechanism, the hold/eject mechanism, and slide housings. The remainder of the parts are either parametrically altered or designed according to the required product.

Figure 10

A Double-Parallel Punching Mechanism

Automatic Blue-Print Generation

In order to program a computer with the ability to generate detailed drawings, it is necessary to identify a tool that performs both analysis and control. It is emphasized here that the automatic generation of blue prints means the the actual drawing of a part having various dimensions every time (i.e., depends on its functionality). Therefore, analysis is necessary in order to perform the requested calculations prior to design. Control is also necessary in order to manipulate the generation of drawings. Computer languages such as C, Fortran, Pascal, and Basic are not suitable for this type of application. Artificial intelligence languages are most suited to perform logic as well as command routines in other software packages. For example, an object oriented framework for the integration of design and manufacturing in an automated system was reported by Mo et al.²³ CAD companies have used these languages to manipulate graphical entities on the screen. CAD systems use these languages to provide a user with the capability of writing specialized functions. Examples of these artificial intelligence languages are AutoLisp for manipulating AutoCAD graphical entities; CAD-L for manipulating CADKEY graphical entities; and Pro-Develop for manipulating Pro-Engineer drawings.

For this application, AutoLisp is used to automatically generate detailed drawings. For example, consider the automatic design of a support block for the sharing operation of a tubular component. Depending on the various inside and outside diameters, length, material properties, load and tolerance requirements, a support block is automatically designed. The algorithm initiates the graphical environment (AutoCAD) by setting the pertinent parameters such as limits, zooming, and layers. For each view needed to represent this part, the program defines the coordinates of a number of key points. The program then proceeds to draw graphical entities on the screen. Three-dimensional features are then inserted. Finally, dimensions and drawing notes are added accordingly. Note that parametric CAD software can only change the dimensions of a part. Parametric systems do not have the capability to perform logic, thus do not have the capability to aid in design. The resulting detailed drawing, automatically generated by the Autolisp code, is shown in *Figure (11)*.

Figure 11

The Support Block Generated Automatically

Rules that govern the physical dimensions of the automatically generated part are written in Autolisp. These rules mathematically mandate the design criteria for the part. For example, rule 13 calculates slug clearances and determines the allowable space required for the punch. It also uses a 1.2 factor of safety to allow for space clearance based on expert advice. Rule 21 computes estimated deflections by the tube, and determines whether a support block is needed. If it is deemed necessary to design a support block, another set of rules are called upon. Rule 32 computes the force needed to perform the shearing operation for a specific material of known dimensions. Thus the forces and moments sustained by the tooling need to be estimated. The bending moment for a tubular component can be written as

$$M = D_o R_n^2 \int_{\epsilon_x = \epsilon_{x,i}}^{\epsilon_{x,o}} \sigma_x(\epsilon_x) \epsilon_x d\epsilon_x \quad (19)$$

Let $\epsilon = \epsilon_x$, then equation 19 can be written as

$$m = \left(\frac{R_n}{D_o} \right)^2 \int_{\epsilon_x = \epsilon_{x,i}}^{\epsilon_{x,o}} \sigma(\epsilon) \epsilon d\epsilon \quad (20)$$

To evaluate the unit moment, the stress-strain curve $\sigma(\epsilon)$ is evaluated where the assumption is made that the curves are equal in tension and compression such that $\epsilon_{x,o} = -\epsilon_{x,i}$. Unit moment curves are determined for many materials and are available in the literature. The bending moment is then calculated as

$$M = m D_o^3 \quad (21)$$

In order to expedite the assembly and debugging process of the mechanism, the user of this system is prompted to select the detailed drawings needed. A menu indicating all possible parts

needed for the assembly of this mechanism appears on the screen and the user is prompted to select those that are needed. Since it is possible that previously made parts can be recycled in a new mechanism, regeneration of that part is not necessary. The detailed drawings generated by the system will appear on one screen. To determine whether a part is recyclable is still a manual function which will be automated. *Figure (12)* is a snapshot of the screen with a number of detailed drawings displayed. The user then has the provision to edit the details of any drawing.

Figure 12

A Snapshot of Detailed Drawings Generated Automatically

It is emphasized that the above set of detailed drawings (*Figure 12*) represent the total set of blue print drawings necessary to manufacture and assemble a mechanism for the intended operation. It is also noted that although these drawings appear in miniature in this manuscript, they are fully accessible to the user through viewing capabilities of the CAD system being used. The intention here is to emphasize the automatic ability of the module and not the details of the drawings.

Automatic NC-code Generation

This module contains a generative numerical control method, where numerically controlled part generation programs are automatically created from CAD drawings. Using an expert system that reflects the manufacturers preferred practices, this module creates a machining program by assembling all individual operations.²⁴ The specific system that is used in this module can be found in Ragenbass and Reissner²⁵ for various stamping operations. Those for generating laser cutting NC code from CAD data can be found in Jackson and Mittal.²⁶

User Interface Using an Expert System Shell

Users of this system are machinists and manufacturing experts who are involved in the day-to-day activities of this operation. These users have little or no training in computers. It was necessary to develop a computer interface that is simple to use and yet powerful enough to integrate the various modules of this system. This interface contains rules that constitute the inference engine of this design-to-manufacturing system.

Symbologic Adept was selected to provide both a rule-based system and a graphical interface. Although any expert system shell could have been selected to perform the integration function, this commercial code was found adequate for integrating this system in a PC-based windows environment combining AutoCAD, AutoLisp, and NC-code generation code using C-language. Rules in Symbologic Adept are programmed in both logic and mathematical forms. The program has also the ability of communicating with other software packages through the Dynamic Language Library scheme in the Windows environment. Specifically, this software was linked to the AutoLisp libraries written for the automatic generation of detailed drawings. Before proceeding with demonstrating how Symbologic was used in linking the different modules together, it is necessary to identify the relevant symbols used in developing the software. *Figure (13)* depicts three different types of ‘nodes’ that constitute the building blocks of this software. A node represents various types of commands, conditionals, interfaces, and data.

Figure 13

Three Types of Nodes Used by Symbologic Adept

Connecting these nodes to each other mandates the order of execution of the program. Each node has a logical value manifested by the choice of the line connecting the rectangular block at the top and bottom of each node (c.f. Symbologic Adept manuals for more details). The program proceeds from one node to the other across several procedures. If another software is called upon to perform a function, the software is executed and upon successful completion, the program returns to the calling node (goal node).

To link the knowledge base, AutoLisp functions, and CAD environment, it was necessary to develop an expert system interface using Symbologic. Rules pertaining to the execution and guideline design of the mechanism were set in Symbologic. User interface screens were built using display nodes, while communication to other software such as AutoLisp functions and AutoCAD standard components were established using calculation nodes. *Figure (14)* depicts a

sample programming screen from symbologic. Note, however, that these screens are not visible to the user.

Figure 14

A Procedure in Symbologic Adept Used to Build the Interface and Implement Rules

Integration of the System

The different modules in this system are linked. Approximately four months were used to debug the system. Each user was introduced to the environment over a period of approximately six working hours. Issues such as interface screens, communication to plotter for blue print generation, tolerancing, dimensioning, and general file management were altered upon feedback from experts. *Figure (15)* depicts the general plan used to integrate the different modules. It is emphasized that a user has only to interface with the system through a number of graphical screens that prompt for input. The interface serves both as providing advice on manufacturability and access to the other modules.

Figure 15

A Schematic of the Integration Method

Conclusions

The concept of an automated design-to-manufacturing system was validated in this paper. A significant reduction in lead times required to design and fabricate the components was demonstrated. Original lead times varied between three to five weeks for the complete fabrication, assembly, and debugging of the considered mechanism. With this system, design and mechanism fabrication time was reduced to a few days, reducing the total fabrication time to approximately seven to ten days. Furthermore, the advise-on-manufacturability module was adopted by the sales department such that incoming inquiries are expeditiously responded to. The system is linked to several cost spreadsheets using an expert system shell. An estimated cost associated with this operation is computed. Long-term goals of the manufacturability module is to provide electronic access to customers. It is envisioned that a potential customer would be able to remote log-in to the system and determine whether this company has the capability of making the required end-product.

The mechanism designed using this module handles tubular components varying in size from 0.2 inch outside diameter with 0.03 inch wall thickness to as large as 0.75 inch outside diameter with 0.2 inch wall thickness for approximately seventy-five different alloys. Length of the tubular component is in the range of 0.5 to 6 inches. The system is able to design punches and tooling required for seven operations: dimpling, bending, slotting, lancing, punching, corsetting, and notching.

A large overhead is associated, however, with developing such systems. A significant amount of resources were allocated to this research project. One full-time senior engineer, one full-time manufacturing expert, and a part-time design engineer were allocated. In addition, interruption in expert productivity took place when rules were collected. The development spanned a period of two years. Although it has proved to be feasible in this project, a company planning to implement such a system should carefully study the feasibility against the long-term goals of the company.

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References

1. S. Ashley, "Rapid Prototyping Systems," *Mechanical Engineering*, pp. 34-43, 1991.
2. Y. Hazony, and L. Zeidner, "Seamless Design-to-Manufacture of Marine Propulsers: A Case Study for Rapid Response Machining," *Journal of Manufacturing Systems*, Vol. 13, No. 5, pp. 333-345, 1994.
3. R. J. Mayer, C.J. Su, and A.K. Keen, "An Integrated Manufacturing Planning Assistant-IMPA," *Journal of Intelligent Manufacturing*, (v3, n2, 1992), pp109-122.
4. S.C. Chen and H.B. Voelcker, "An Introduction to MPL: a New Machining Process/Programming Language," *IEEE International Conference on Robotics and Automation*, San Francisco, v1, pp333-344, 1986.
5. S.R. Nallapati and S. Somasundaram, "CARDAM. An Integrated Design and Manufacturing System for Roll Forming Tools," *Computing and Control Engineering Journal*, (v4, n4, 1993), pp151-156.
6. K. Shirai and H. Murakami, "A CAD System for Press Tools," *Design and Synthesis* (H. Yoshikawa, editor), 1985, pp75-80.
7. I.B.H. Lee, B.S. Lim, and A.Y.C. Nee, "IKOOPPS: An Intelligent Knowledge-Based Object-Oriented Process Planning System for the Manufacture of Progressive Dies," *International Journal of Expert Systems*, (v1, n8, 1991), pp19-33.
8. J.P. Tang, S.I. Oh, and F.M. Lee, "A Computerized Process Design System for Manufacturing Shells and Other Cup-Shaped Components," *Journal of Applied Metal Working*, (v4, n1, 1985), pp7-17.
9. M. Karima and R. Sowerby, "A PC Based Computer Aided Analysis System for the Cup Drawing Process," *Journal of Materials Shaping Technology*, (v6, n2, 1988), pp113-124.
10. T.C. Chang and R. Wysk, *An Introduction to Automated Process Planning Systems*, Prentice Hall, Englewood Cliffs, New Jersey, 1985.
11. A.A.G. Requicha and J. Vanderbrande, "Automated Systems for Process Planning and Part Programming," *Artificial Intelligence Implications for CIM*, (A. Kusiak, ed.)Springer-Verlag, Heidelberg, pp299-326, 1988.
12. J.J. Shah and M.T. Rogers, "Expert Form Feature Modeling Shell," *Journal of Computer Aided Design*, v20, pp515-524, 1988.
13. L. De Floriani, "Feature Extraction from Boundary Models of Three Dimensional Objects," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, v11, pp785-798, 1989.
14. A. Christman, "Software Learns Lessons from Experts", *Machine Design*, pp. 59-65, May 1994.
15. F. Feru, C. Vat, A. Timimoun, E. Cocquebert, and C. Rouchon, "Design for Manufacturing Aided System Based on Functional and Knowledge Aspects," *IFIP Transactions B: Computer Applications in Technology*, 1994.
16. R.E. Olsen, "Integration Design and Manufacturing: Beating the Competetion in Market," *Proceedings of the 36th International Conference-American Production and Inventory Control Society*, San Antonio, TX, 1993.
17. K. Ulrich, D. Sartorius, S. Pearson, and M. Jakiela, "Including the Value of Time in Design-for-Manufacturing Decision Making," *Management Science*, (v39, n4, 1993), pp428-447.
18. P. Harmon, and D. King, *Expert Systems*, John Wiley, New York, 1985.
19. W. A. Taylor, *What Every Engineer Should Know About Artificial Intelligence*, The MIT Press, Cambridge, Massachusetts, London, England, 1989.
20. K. Lange, *Handbook of Metal Forming*, McGraw-Hill, New York, 1985.

21. H. Matuszewsky, "Investigations on Shearing and Withdrawal Forces as a Function of Various Parameters in the Piercing of Sheets," (in German), *Forschungsberichte des Landes Nordrhein-Westfalen*, No. 2994, Koln/Opladen, Westdeutscher Verlag, 1980.
22. J.S. Arora, *Introduction to Optimum Design*, McGraw-Hill, New York, 1989.
23. J.P. Mo, G.E. Fernandez, and G. Liang, "Object Oriented Framework for Intelligent Manufacturing from Computer Aided Design Features," *Proceedings of the 16th Annual Energy-Sources Technology Conference*, Houston, TX, 1993.
24. T. Beard, "Automatic NC programming Arrives," *Modern Machine Shop*, (v66, n8, 1994), pp86-95.
25. A. Raggab and J. Reissner, "Automatic Generation of NC Production Plans in Stamping and Laser Cutting," *Proceedings of the 41st General Assembly of CIRP*, Palo Alto, CA, 1991.
26. S.D. Jackson and R.O. Mittal, "Path Planning and Automatic Generation of NC Programs for Laser Cutting," *Proceedings of the 2nd Industrial Engineering Research Conference*, Los Angeles, CA, 1993.

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