# ERIS, Engineering Resource Information System

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## Abstract

ERIS (Engineering Resource Information System) is a knowledge base of engineering resources for the design and manufacture of window regulators. It has been created with sufficient generality to form the basis for building similar systems for other products. The form of the knowledge base is hierarchichal semantic networks of frames or schemas. This form has been shown effective for representation of knowledge ranging from simple facts to classes of parts to manufacturing processes to complex part geometries. The representation of parts in production allows a search for possible carry over parts for a new application. If a carry over part is not adequate, the parametric representation of the geometry of parts allows for redesign of an existing part to meet new specifications. Two different geometric representations were created. One represents the observed features created by a progressive-die press. The other represents the design process as it evolves through the addition of surfaces and edges.

Costs for window regulators were studied and broken down into categories that display all significant costs. Labor and raw materials are major contributors to the total cost. Better designed parts and decreased lead time are major payoffs that result when automated design methods are used.

The ERIS knowledge base has been used to demonstrate automation of facets of the design process: material selection, failure mode analysis, selection of regulator style, and either choice of a carry over part or modification of an existing part.

From a study of the design processes for parts produced by Fisher Guide an estimate was made that lead time could be reduced by a factor of three through computer automation.

# 1. Introduction

## 1.1 Domain

The domain of the project is a part known as a window regulator that raises and lowers the window of a car door. A sketch of a sector window regulator, given in Figure 1-1, shows the principal parts:

- the liftarm, the long lever which lifts the window,
- the sector, the large gear that is not a complete but only a sector of a circle,
- the backplate on which the parts of the regulator are mounted.

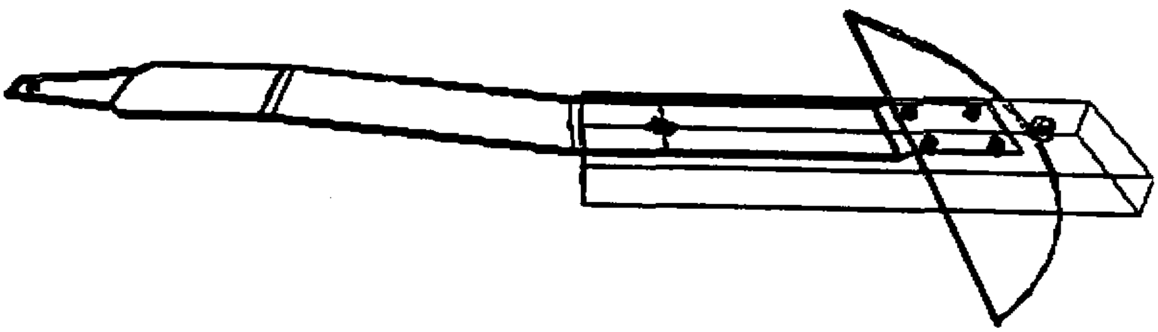


**Figure 1-1:** Sketch of a Sector Regulator

## 1.2 Goals

The goals for this work are:

- Create a knowledge base of engineering resources for the design and manufacture of window regulators.
- Maintain sufficient generality so that the categories of information form the basis for building a similar system for other parts.

The circumstances which affected the knowledge representation for window regulators are:

- Parts remain similar in form and function over an extended period of time.
- Production volume is high.
- Many decisions concerning design, costing, manufacturing, etc. are based on experience with similar parts already in production.

## 1.3 Information in the System

Information was gathered from documents and interviews with engineers and managers in areas of design, tooling, process planning, cost estimation, accounting, plant engineering, quality assurance, and materials engineering.

The categories of information incorporated in the knowledge base are:

- Parts in current production
    - Parts and subassembly breakdown by part number
    - Important features of parts: length, type of material, cost...
- Cost
    - Cost breakdown of labor, materials, purchases, etc. for a regulator.
- Lead time from design to production
- Drawings of parts
    - Retrieval and display of drawings
- Part geometry
    - Suface and feature based representation of detailed geometry
- Materials
    - Material properties
    - Cost
    - Usage
    - Cross reference to synonymous names
    - Precautions
- Customer specifications
    - Testing requirements
- Manufacturing processes
    - Formation of parts
    - Assembly of parts
- Expert systems that use the ERIS

These categories are discussed in following chapters.

# 2. Knowledge Representation

The knowledge base is hierarchically organized using frames or schemas in semantic networks linked by various relationships [6] [9]. The system used here has more flexibility than database systems which store information in tabular form, and allows complex data structures such as those needed for representation of geometry to be produced conveniently. This system has no problem of limiting the number of characters used for a.name or attribute, a difficulty which has arisen at Fisher Guide in the renaming of types of steels. As noted by Chao [1] standard relational data bases may not be adequate for representing design data; semantic networks may resolve this inadequacy.

## 2.1 Frames or Schemas

A frame or schema describes an object by a name, a series of attributes or slots, and values for each slot. For instance a particular backplate might be represented as

- Name: Backplate-21
  - Slot: Part-number 21
  - Slot: Length 84
  - Slot: Made-from SAE-1010
  - Slot: Is-a Backplate
  - Slot: Part-of Backplate-s/a-43

Some slots are relationships pointing to other schemas. The slot "Is-a" with its value "Backplate" indicates that Backplate-21 is within the general category of parts called Backplate, and Backplate is another schema which contains a description of this general category. The slot "Part-of" with its value "Backplate-s/a-43" indicates that Backplate-21 is a part of a subassembly named Backplate-s/a-43, and Backplate-s/a-43 is another schema which contains a description of this subassembly.

## 2.2 Semantic Networks

A semantic network is a series of schemas or frames which are linked to each other via relationships such as is-a or part-of to form a tree-like structure. An example from ERIS of such a semantic network is given in Figure 2-1. The tree-like structure at the top of this figure illustrates how the parts breakdown of a subassembly is hierarchically represented in the computer. The links or lines between schemas are labeled with a number. The key to the meaning of those numbers is given by the relation keys in the lower part of the figure. The part-of relation links an assembly with one of its subassemblies, where an assembly is something that can be further broken down into sub parts. The basic-part-of relation links an assembly with one of its basic parts which cannot be broken down further.

## 2.3 Relationships

The standard relationships between schemas

- Is-a
- Instance

are used to indicate membership of an object in a class.

In addition, other relationships are defined to serve the particular needs in representing window

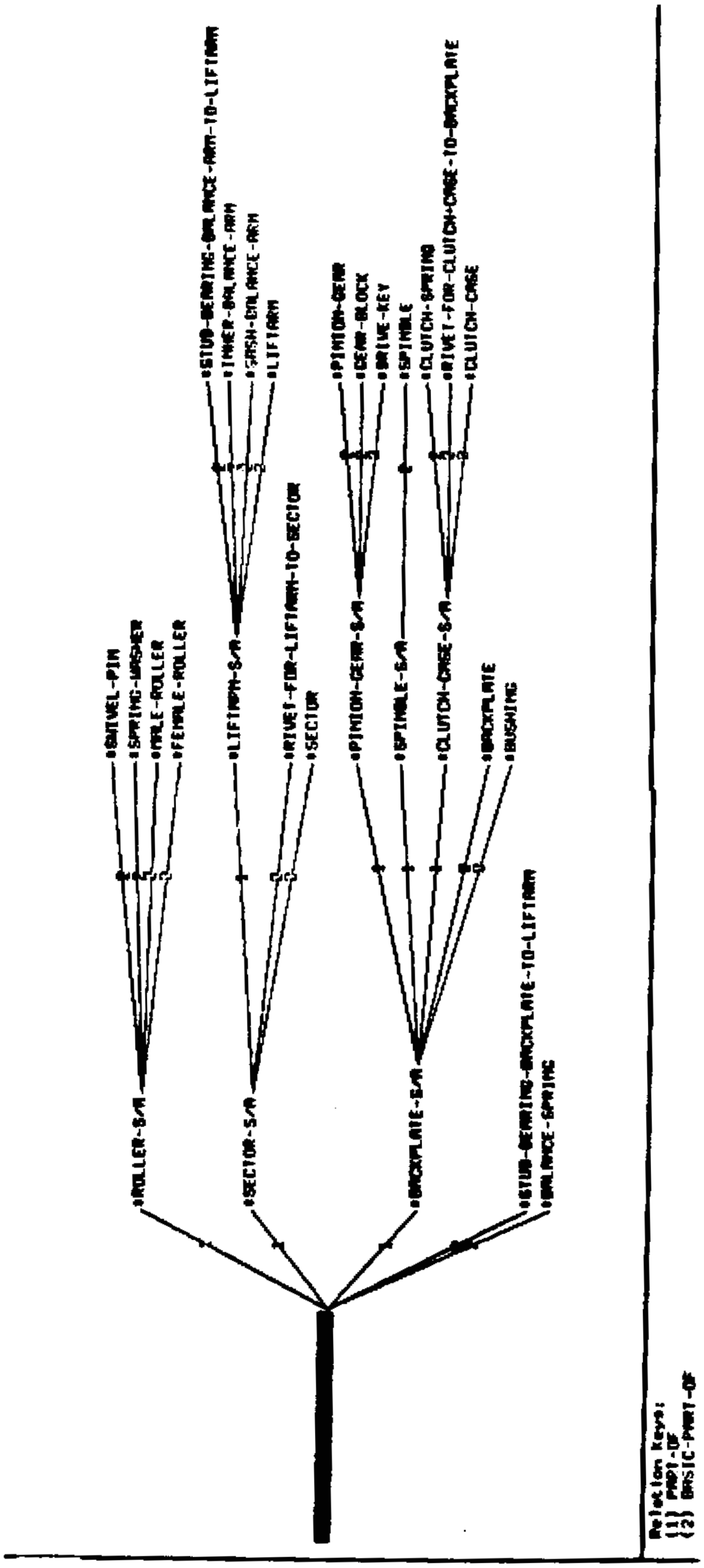



Figure 2-1: Subassembly Breakdown for a Manual Sector Regulator

regulators. Some examples are:

- Part-of: e.g. a backplate is part-of a backplate-s/a
- Material-made-from: e.g. a backplate is made from a steel called SAE-1010
- Specified-test-for: e.g. the spindle abuse test is a specified-test-for a window regulator.
- Failure-mode-for: e.g. arm buckling is a failure-mode-for the spindle abuse test.
- Cuts: e.g. circular-edge-10 cuts the cylinder-2 surface for liftarm-1.
- Is-made-into: e.g. stiffening-rib-3 is-made-into the top-surface for liftarm-1 by combining it with other surfaces.
- Process-for: e.g. progressive-die stamping followed by storage is a creation process-for a backplate.
- Sub-process-for: e.g. progresive die stamping is a sub-process-for the manufacture of a liftarm subassembly.
- Preceeds: e.g. progressive-die stamping for the drive key preceeds its tumble mill process.

Each relation also has an inverse to express the meaning when moving along a link between two schemas in the opposite direction. For example if backplate-21 is part-of Backplate-s/a-43, then the inverse relation of part-of which is has-part, expresses the relationship that Backplate-s/a-43 has a part which is Backplate-21.

The definition of the ERIS data base contains 11,000 lines of coding that creates 1500 schemas.

# 3. Parts in Production

The importance of information in this category derives from the fact that many design decisions are based on experience gained from parts in production.

## 3.1 Classification of Shipping Assemblies

Regulators may be placed into categories of manual or electrical operation and categories of mechanism type. The mechanism can be gear driven and labeled a sector regulator because of the large gear which is a sector of a circle, or it can be driven by a plastic tape which pulls the window up and labeled a tape regulator. The computer data structure or representation of this categorization is illustrated in Figure 3-1 in which the schemas for the types of regulators are linked by an is-a relationship, e.g. an electric sector regulator is-a sector regulator.

## 3.2 Subassembly Breakdown

A regulator consists of subassemblies which themselves consist of subassemblies. This parts breakdown continues until a basic part which has no sub parts is reached. This is represented in the computer by a part-of relationship and is illustrated in Figure 2-1 for a prototypic manual sector regulator.

## 3.3 Instances of Prototypes

The classification and parts breakdown of regulators in the previous two sections were in terms of prototypical parts. Schemas for a specific regulator and all of its constituent parts that are produced on the shop floor and installed in a specific door are related to the prototype schemas by the instance relationship.

## 3.4 Attributes of Parts

Attributes for each part and subassembly are stored as slot values in the schema for each part. A listing for a typical schema is given in Section 2.1. Some of the slots, e.g. made-from, are relationships, and the value of the slot is the name of another schema, e.g. the schema for the material from which the part is made. The part number is usually the same as the drawing number. The material-width, material-length, material-makes-pieces, and material-thickness refer to the raw sheet steel from which the part is made. The offset is the height of the backplate legs. The distance-pinion-to-stud is essentially the radius of the sector which can be accomodated by this backplate. Slot names are usually descriptive enough to define the meaning. Also meta information may be contained in the prototype schema which contains some words explaining the meaining of a schema or a slot. Figure 3-2 illustrates meta information of how a spindle abuse test is to be done and what the units of the value in the torque slot are. Units are generally metric, lengths in mm.

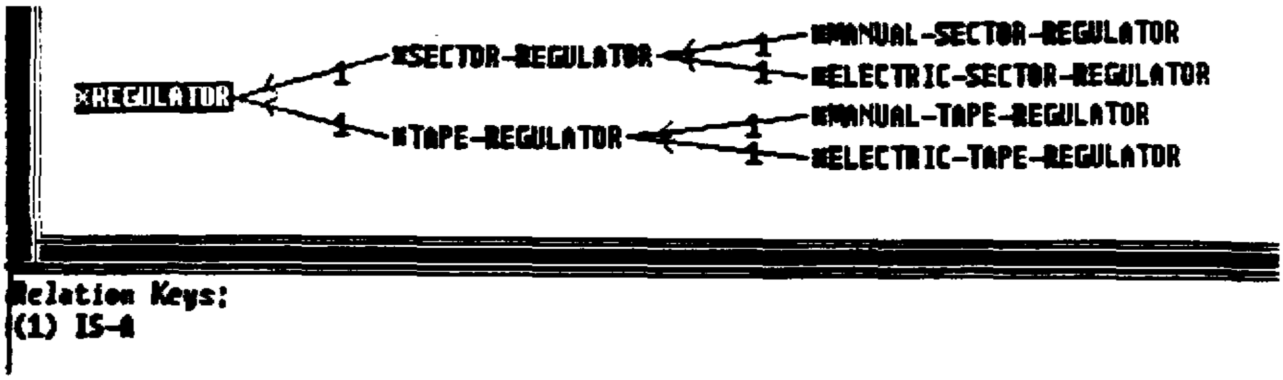



**Figure 3-1:** *Categories for Regulators*

```
(CSCHEMA 'SPINDLE-ABUSE :PARALLEL :NOTIFY :CONTEXT '$ROOT-CONTEXT
        (:META '|2736998045+1437| ('INSTANCE 'SCHEMA)
         ('COMMENT "torque applied at spindle in both directions at full u
          "and down positions"))
        ('HAS-FAILURE-MODE 'SECTOR-TO-ARM-WELD-FAIL-SPINDLE-ABUSE
         'SECTOR-TO-ARM-RIVET-FAIL-SPINDLE-ABUSE 'BACKPLATE-BEND-SPINDLE-A
         'ARM-BUCKLE-SPINDLE-ABUSE 'ARM-BEND-SPINDLE-ABUSE)
        ('IS-A 'SPECIFIED-TEST) ('INSTANCE+INV 'SPINDLE-ABUSE-TOY-1234321)
        ('SPECIFIED-TEST-FOR 'DOOR) ('TORQUE 28)
        (:META '|2736998045+4771| ('INSTANCE 'TORQUE) ('SCHEMA 'SPINDLE-ABL
         ('SLOT 'TORQUE) ('UNITS "Newton meters"))
        ('RULE 'SPINDLE-ABUSE-RULE)
        ('REGULATOR 'MANUAL-SECTOR-REGULATOR 'MANUAL-TAPE-REGULATOR) ('DOC
        ('MAX-RISK))
```

**Figure 3-2:** Meta Information Describing the Spindle Abuse Test

# 4. Costs

To assure profitability and to identify where efforts should be expended in order to increase profitability, a knowledge of costs is essential. Reasonably accurate records of the cost of current products and estimates of the cost of a new product are needed. The various categories of costs and the relation between these categories and various operations and processes indicate where the highest payoffs for improvements in operations and processes might lie.

This section reports results of a cost study for window regulators. Information was obtained from documents, i.e. routing sheets for assembly, distributions of burden, wage and fringe benefits rates, annual budgets. Additional information was obtained from interviews with accounting personnel at the manufacturing plant.

## 4.1 Cost Breakdown

The goal of the study was to account for all significant costs by breaking costs down to a level of detail so that no single item accounted for more than a few percent. Many different categories of costs exist: labor, materials, taxes, energy. Different accounting methods might lump different dollar amounts under a certain category. Labor might include wages and fringe benefits, or labor might include only wages, with fringe benefits in an overhead or burden category.

The costs for a typical window regulator were examined and a hierarchy of the breakdown into reasonable categories was chosen, Figure 4-1. At the first level of breakdown, three categories, each accounting for about a third of the total cost, were chosen:

1. Direct Labor: The wages plus fringe benefits of those people directly involved with forming and assembling parts at the manufacturing plant.
2. Purchases of materials and parts: The purchase price of raw material (mainly sheet metal) and those parts not made but used at the plant.
3. Burden: Everything else: maintenance, design, management, heat, light...

The following sections discuss these three major costs and their breakdown.

### 4.1.1 Burden

Burden includes costs of supporting activities (e.g. plant maintenance) that are not directly related to any particular product. Although detailed accounting might relate almost all but minor items to a particular product, with accounting methods used, burden is not minor. It is a third of the total cost. Its distribution to various parts of the organization or burden centers (e.g. final assembly area for regulators) is difficult and may be unrealistic. This distribution is done via burden factors. In cost estimates, direct labor cost is multiplied by these burden factors to give what may be deceptive values for indirect costs:

- Burden factors of as much as 1000% can lead to the myth that a dollar savings in direct labor leads to ten dollars total savings.
- Shifting an imaginary line on the production floor so that a machine moves to a different burden center can confuse accounting long enough to make an unprofitable product appear profitable.
- Cross subsidization of costs can occur; a complex product may make heavy use of a facility such as the QA lab. The cost of this facility may be equally distributed to all products so that the one making heavy use of the lab is subsidized.

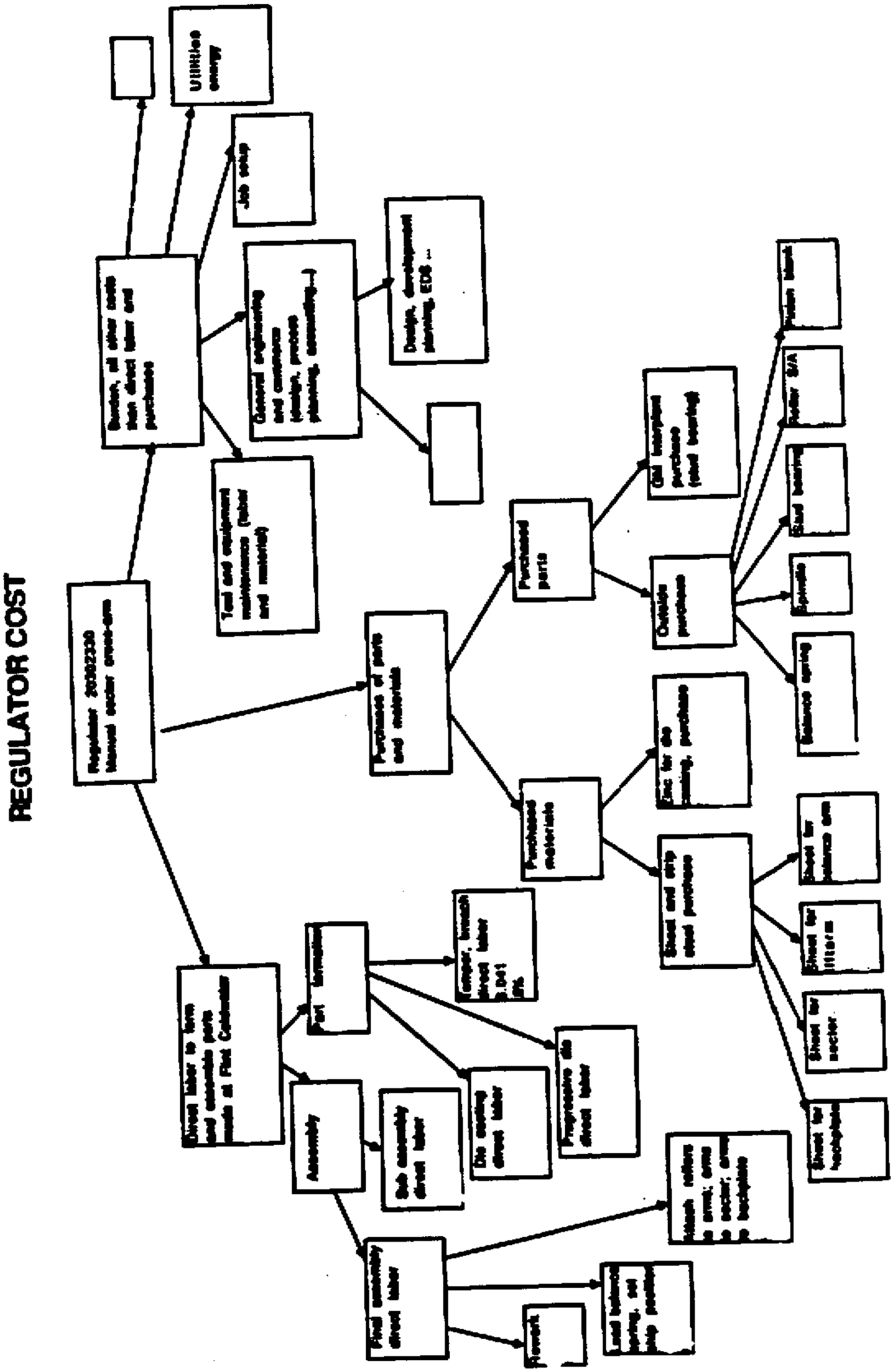



Figure 4-1: Cost Breakdown for a Typical Regulator

Several sub categories are in the general category of burden. The tool and equipment maintenance item is relatively large because the machines at some plants are old, typically having been purchased in the early 1960's. Moderate savings in categories of maintenance and job setup might be realized through modernization.

The general engineering and commerce sub category under burden in Figure 4-1 includes regulator design, the salary of the president, and management. While design cost is only a small fraction of the total cost, if the quality of the design and the lead time to produce the design can be improved, then the cost impact on manufacturing, the amount of raw material used and the ability to incorporate recent technology can be significant.

The utilities and energy cost was estimated by examining the electricity and other energy bills for the site and assigning a reasonable part of that cost to window regulators. Energy cost is minor.

Fisher Guide accounting lumps employee fringe benefits into burden; however in the breakdown created here, the entire cost of direct labor including fringe benefits is in the category of direct labor, not burden.

### 4.1.2 Materials and Purchased Parts

Purchases of materials and parts from outside vendors is a large partion of the total cost. The trend to increased use of purchased parts will require more communication between the design engineers within Fisher Guide and the engineers in outside organizations.

The sub category of purchased materials, sheet and strip steel, is significant. The amount of material in a part is controlled by the designer, and material use is recognized as an important area for optimization. Finite element modeling and results from current and prior failure mode testing promises to result in significant savings.

### 4.1.3 Direct Labor

Direct labor, including fringe benefits, to form and assemble parts is a major cost and is an important area where savings are possible. It is important in trying to estimate savings that burden accounting is not allowed to confuse the issue.

## 4.2 Cost Estimates

Accurate cost estimates can be obtained from costing software which can account for individual hand motions in the assembly of parts. Quick estimates, with sufficient accuracy for most purposes, can be derived from the knowledge base by finding a regulator already in production which is similar to the one for which a cost estimate is needed. Corrections can be made for the cost of materials, since the cost per unit mass of materials is contained in the knowledge base.

# 5. Lead Time from Design to Production

## 5.1 Motivation

US auto makers take 62 months and 5 million engineering hours to go from concept to production; Japanese auto makers take 43 months and 3 million engineering hours [3]. Reduction in lead time allows more responsiveness to recent market trends and enables state-of-the-art technology to be employed. Consequently, this is a crucial issue for GM. One method for solution to lead time reduction is introduction of computer automation. Another is changes in organization or corporate culture, e.g. Japanese management style. Below is a description of a study of the effects of computer automation on lead time, a mention of results of a comparison of organizational methods, and a discussion of computer automation solutions both stand alone and in conjunction with organizational solutions.

## 5.2 Computer Automation Study

To address the problem of lead time reduction, the design process for a sample of Fisher Guide automotive parts was studied. Parts studied were the window regulator, door handle, lock module, and seat adjuster. The various product development stages (customer request, product design, prototype build, testing, and production tooling) and times currently required for each were determined. An estimate was made of the effect on lead time of computer automation using computer tools based on existing technology, current state-of-the-art technology, and new technology presently in the research stage.

## 5.3 Computer Automation Solutions

Two areas that currently require large amounts of time are:

- Creation of tooling for both prototype and production parts
- Customer contact with other groups in GM, especially with styling.

These two areas would be affected by computer automation. Automated generation of commands for the numerically controlled (NC) machines that create the tooling could significantly reduce lead time. Currently 8 weeks is typically devoted to translating from a design on paper to NC tapes.

Customer contact, negotiation, and non-creative paperwork that can absorb a majority of engineering time could be facilitated through computer automation. Intelligent electronic mail could enhance communication. Lead times involving customer contact could be reduced through expert systems to help answer customer queries and through automatic design synthesis to produce or modify a design in response to customer requests. Any success in improving communication also leads to an organizational benefit of improving working relationships between groups. The area of design synthesis is being addressed by the joint efforts of Fisher Guide and Carnegie Mellon University (CMU).

Lead time can also be reduced by computer automation in the general areas of:

- Automatic synthesis of a new design based on a parametric variation of the geometric models of a design already in production,
- Parts deproliferation by computer search for carry over parts,
- Automated tolerance and interference checking,
- Automatic inspection systems to verify tolerances of sample parts,
- Scheduling and capacity checking of production facilities,

- Finite element modeling statistically calibrated to existing test experience,
- Kinematic and dynamic modeling of mechanisms,
- Cost and materials optimization.

## 5.4 Organizational Solutions

Clark et al [3] studied automotive lead times in the U.S., Japan, and Europe, and suggest that a 30% effect on lead time and a factor of 2 effect on man hours can be achieved through organizational changes:

- a heavy-weight project manager (i.e. a product champion for a new car line who has strong influence in the organization),
- more reliance on outside parts suppliers to provide significant engineering skills,
- fewer engineers each handling a broader range of parts (e.g. the whole door instead of just the lock),
- more intense, less formal, dialogue communication between groups (i.e. simultaneous engineering),
- more effective overlapping of tasks (e.g. starting tool design before testing of prototypes is complete).

In one of the products of the current study, the seat adjuster, the organizational solution of overlapping tasks and the identification of critical path tasks is being used. This technique also requires the use of the technique of intense, informal, dialogue communication so that when a problem arises in one task, people involved in overlapping and related tasks know about it immediately, not at the next regularly scheduled meeting of the product team. Problems with overlapping tasks have arisen at GM especially when prototype parts have not been similar enough to parts made with production tools.

## 5.5 Computer Aided Organizational Solutions

Some of the above organizational solutions can be aided by computer automation:

- Computer aided engineering reduces mundane work so that an engineer can handle a broader range of tasks.
- Communication between groups and simultaneous engineering can be facilitated through the transfer of computer files and electronic mail. The computer can assist the process of simultaneous engineering through expert systems that would examine a design and express expert concerns of a member of the product team. One thrust of the CMU and Fisher Guide project is such a Computer Aided Simultaneous Engineering (CASE).
- For U.S. auto makers Clark et al [3] find that the combination of
    - overlapping tasks and
    - ineffective formal communications in which large chunks of information are transmitted in large meetings

  result in large numbers of engineering change orders and reworking of designs because of surprises at various stages of the product cycle. CASE along with more effective engineering tools such as:
    - automatic tolerancing,
    - finite element modeling,
    - a knowledge base of previous test results to calibrate the finite element modeling

should reduce the number of surprises and design/test iterations.

Some manufacturers reduce their cost and lead time problems by limiting the variety of products. However GM has a corporate philosophy of product differentiation and product variety. Computer automation, flexible manufacturing, CAD, CAM, etc. offer the promise that when the TV commercial says "let us build a car for your", the computer systems don't gag but cheerfully accept a combinatorial explosion of options and styles and then efficiently design and schedule the production of just what the customer ordered.

## 5.6 Conclusions

For each product in the study, computer automation is estimated to reduce lead time to about a third of its current value. Tasks which introduce uncertainties in the estimate of the effect of computer automation and continue to take large amounts of time even with computer automation are:

- people to people interactions (e.g. negotiations with customers and agreeing on the meaning of analysis results),
- hand work (e.g. building prototypes and sample parts),
- testing (i.e. test simulation of a 10 year car life),
- tooling (both production and prototype tools).

These and other areas may have to be attacked with tools other than the computer such as organizational changes, management style, corporate culture, and new technologies. However the factor of three estimated reduction in time due to computer automation indicates that this tool should be a major actor in the effort to reduce lead time.

# 6. Drawings

## 6.1 Motivation

With automobile model changes occurring annually, the proliferation of engineering drawings is enormous. The number is so large that old drawings must either be destroyed or archived. When the former is adopted, what may prove to be valuable information is irretrievably lost. On the other hand, with some archiving techniques, attempts to search and/or restore archived materials may be so cumbersome as to render the archives of no value.

An exploratory study was undertaken to determine whether existing scanning and signal processing techniques could store information of this type, make it readily accessible, and thereby solve these problems.

## 6.2 The Study

Based primarily on hardware and software availability, a PC (personal computer) was selected as the platform for this study. During the course of this work production drawings ranging from size A to E were used.

The PC was an AT compatible with an 80286 CPU running at 10 MHz under MS-DOS. The machine had the full complement of 640 Kbytes of memory and was fitted with the more or less standard peripherals such as hard and floppy disk drives plus controller, keyboard, graphics video adapter, monochrome video display, mouse, parallel and serial ports. In addition, the machine was equipped with a number of special purpose peripherals. These included an interface board to a large size, high-precision scanner; digitizing boards; a high resolution, color video adapter; a large screen, high resolution color display; EMS memory.

After the bugs (or at least all the known ones) in the hardware and software were eliminated, the procedure to be followed proved to be quite simple. First a drawing is placed in the large size, high-precision scanner. As the image is scanned, the digitized output is automatically stored in a bit-mapped graphics format on the PC.

These graphic image files are, of course, quite large. They can be stored in much more compact form by using compression methods such as the Lempel-Ziv-Welch techniques. It is also advantageous to use such compressed forms when it is necessary to transfer the files from one machine to another in a networked environment.

Once the bit-mapped file of the digitized image has been stored on the PC, a variety of options are available. For example, by invoking a few simple commands, the image can be displayed on the high resolution color display attached to the PC. Moreover, the software provides a variety of other features which enables the image to be manipulated and modified. A zoom feature enabled any portion of the drawing to be magnified so that individual bits (pixels) can be examined. The image can also be modified at this high resolution level by turning individual bits on and off.

To demonstrate one of the other options available to the user working in a networked environment, a number of the files in the bit-mapped format were compressed by the techniques previously mentioned and transferred to a Microvax workstation running VMS. While the VMS software was not as versatile as that on the PC, the bit-mapped images could rapidly be accessed and displayed on the workstation console; the image could be zoomed in and out; and hard copies could be printed when needed. The bit-mapped format was also converted to the standard DEC Sixel format and printed on a DEC laser printer.

In addition to the method previously described of manipulating and modifying images at the bit level, scanned images can also be vectorized. Once vectorized, such images can be utilized in same ways as a conventional CAD drawing. One obvious way of producing a vectorized drawing from the bit-mapped one, is to trace it manually. The software we were using gave us this capability. However, we never utilized it in this manner, because the hardware and software on our PC platform enabled us to do this vectorization automatically.

The vectorization process was both CPU and memory intensive. It was at this stage in the study, that the limited memory capabilities provided by the MS-DOS operating system introduced problems. It was quite evident that this memory limitation made the vectorization step unreasonably long for any but rather small drawings. However, a very adequate solution was possible by installing EMS memory and utilizing it in the vectorization process. For this particular application all the EMS memory was configured as expanded memory.

Another variety of options is available to the user, once the drawing is vectorized. The software we were using on the PC had all the tools to manipulate and modify the vectorized drawing in a manner equivalent to what could be done with any standard CAD package. To further illustrate some of the options, a number of vectorized images were transformed into the industry standard DXF format. In this format, the drawings were imported into one of the well-known CAD packages. Once imported; these drawings could be handled just like drawings originally created with this package. We were able to demonstrate that despite many transformations, a hardcopy produced on a high quality pen plotter was essentially indistinguishable from the original.

Drawings converted to the industry standard DXF format, can also be transferred to the engineering resource information system (ERIS). In this manner, after a search of ERIS for a part with certain characteristics, the drawing for the part can be retrieved and displayed. An example of a drawing that has been retrieved and zoomed in on is given in Figures 6-1 and 6-2.

A drawback of the current automatic vectorization methods should be noted. When a person manually vectorizes a drawing, a straight line is represented by a single vector. When the computer does it, a straight line often becomes two or more vectors. This clearly leads to a vectorized version which is not as clean as that which a person could produce. However, this must be weighed against the time and effort for manual vectorization. Moreover, in the future we can look forward to the development of improved vectorization techniques.

## 6.3 Conclusions

Based on our results we find that conventional drawings can be successfully archived and retrieved by computer based methods. Moreover, there is another aspect of equal significance. The scanning and signal processing techniques we employed, enable conventional (non-CAD) drawings to be transformed, so that they can be imported by standard CAD packages. Thus, the the designer does not have to start from scratch when it is necessary to modify an old part. Instead he can access the archived version of the conventional part, import it into his CAD package, and then proceed to manipulate and modify it.

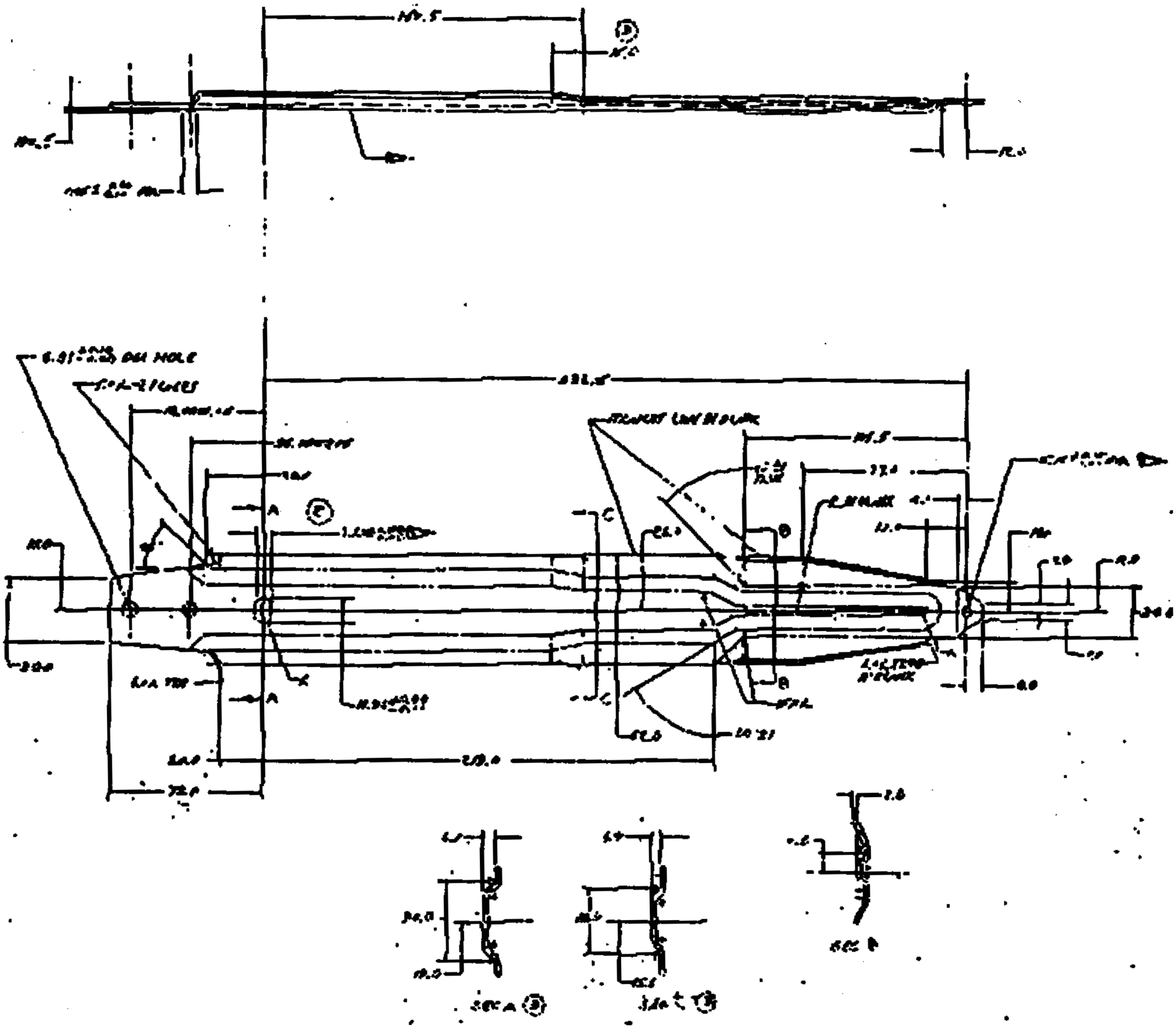


Figure 6-1: Drawing Retrieved from Data Base

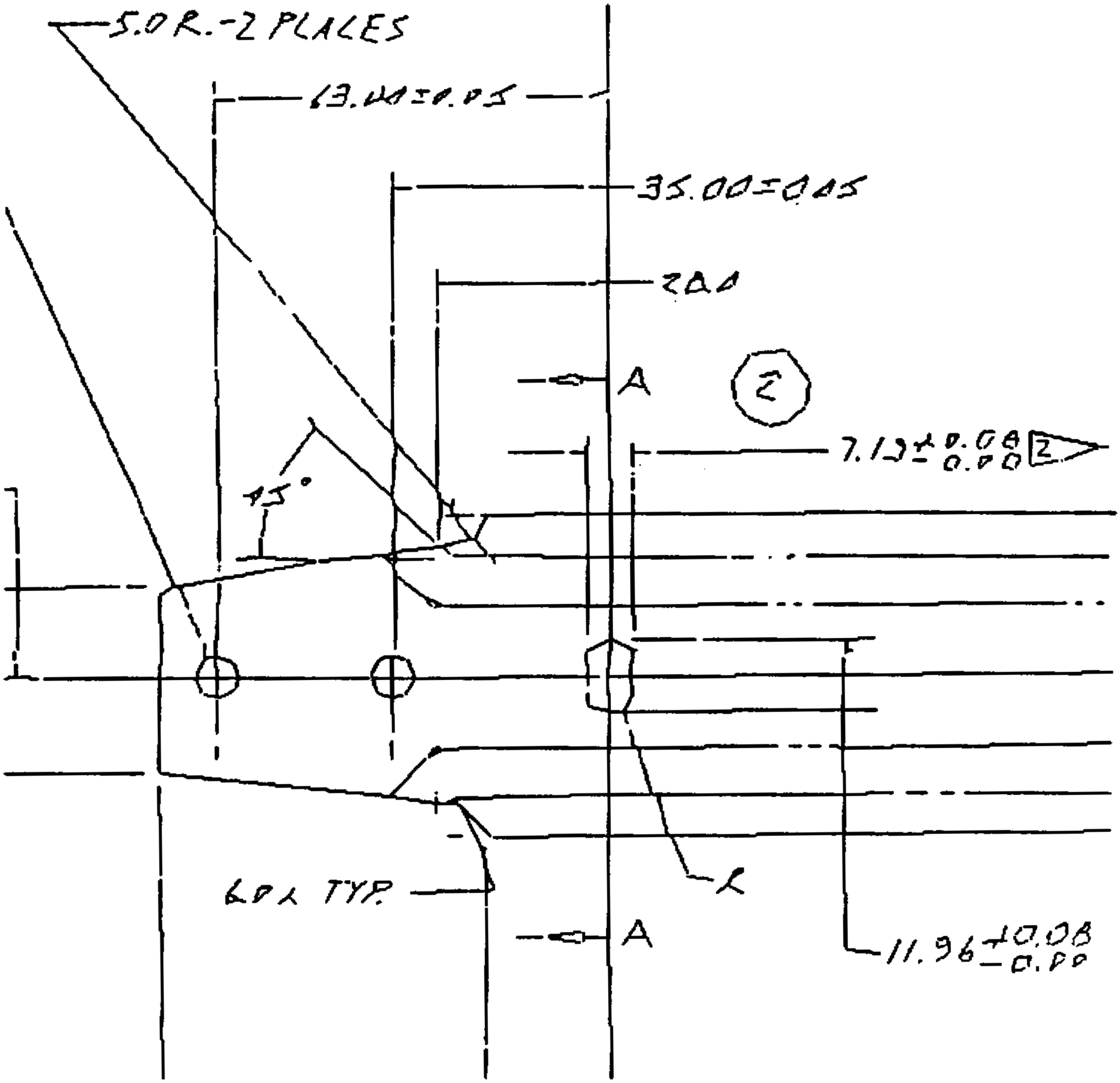



**Figure 6-2:** Zoom on a Section of the Drawing from Figure 6-1

# 7. Part Geometry

A window regulator is made principally from simple sheet-metal parts. The detailed geometry of these parts is represented in ERIS in two ways, a surface representation and a feature representation [2]. The surface representation is a hierarcnichal data structure in terms of primitive surfaces, edges, and design operations. The feature representation is also a herarchichal structure but in terms of manufacturing operations, such as the cutting and bending that occur during progressive-die stamping. Both representations contain complete detail of the geometry of the part. The feature representation is higher level and more abstract. In the feature representation, more information is contained in the definition of the primitive entity or feature and less information is contained in the data structure itself. A feature representation is easier to build, however it is not as general, cannot represent as wide a variety of parts as the surface representation. Transforming from the feature to the surface representation is straightforward, whereas transforming the other direction by extracting features from the surface representation is more difficult.

These representations can be used for design automation. Each representation contains parameters that can be modified to create a family of similar parts. These parameters could be chosen by a design synthesis program such as the stick model of Rehg et. al. [4], and the object oriented programming in the representation would create a part with those characteristics. The value of parametric design has been recognized, especially when an existing part is used as the basis of a routine redesign which generates a new member of a family of parts [5]. Khol [7] reports on parametric design coupled to two dimensional CAD for design of a V8 engine. Here the parametric design is coupled to a feature based representation.

The following sections outline the elements of both representations. More detailed discussion is given by Roth and Sapossnek [10].

## 7.1 Surface Representation

The surface representation is a tree structure that describes the evolution of the surface as geometric operations are performed. This evolution is meant to mimic the thought process of the engineer as he introspectively asked himself how he would design a liftarm.

### 7.1.1 Simplicity of Parts

The surface representation takes advantage of the simplicities of the parts which are considered. These simplicities are:

- The part is made of sheet metal; it has a constant thickness. So the geometry may be represented by the top surface. A solid can be generated by sweeping the top surface perpendicular to itself through a distance equal to the thickness.
- The drawings contain only straight lines and arcs of circles. So the surface can be constructed from patches of simple primitive surfaces.

### 7.1.2 Surface Entities

The hierarchy of entities used in the surface representation is given in Figure 7-1. A primitive surface may be a plane, sphere, cylinder, or torus. An edge may be straight or circular and may be an interface edge between two surfaces or a cut edge between a surface and empty space. Above the primitive surface in Figure 7-1 are simple complex and top surfaces to represent the evolution of the design (see below).

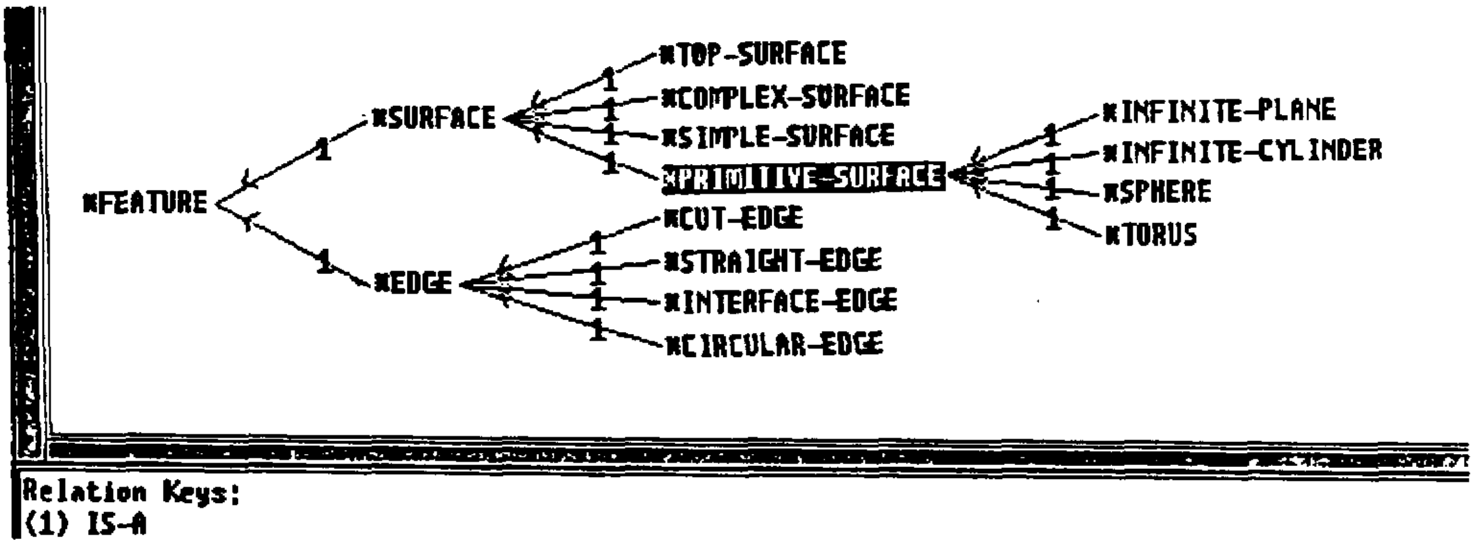



**Figure 7-1:** Entities Used in Creating a Surface Representation of a Simple Sheet Metal Part

### 7.1.3 Creation of the Surface Representation

The top surface of a part is built from a series of geometric operations of adding primitive surfaces and adding edges. A simple example is given in Figure 7-2. The lower half of this figure contains sketches of the surfaces as the design evolves from right to left. The light lines indicate infinite surfaces; the heavy lines indicate finite surfaces that have become bounded by cut edges or interface edges with other surfaces. The upper half of this figure shows the semantic network of schemas and links that represents the evolution of the design. The key to the relations expressed by the links between schemas is given at the bottom of the figure.

In this example, an infinite plane is chosen as the first primitive surface. Adding a cut edge gives a simple surface that is not quite so infinite. Then an intersecting plane is added followed by an interface edge to join the two planes. This is now a complex surface that consists of more than one primitive surface. When enough cut edges have been added so that the surface does not extend to infinity, the result is a top surface which represents an actual part.

The schemas in Figure 7-2 contain pointers to object oriented programs. Initially the quantitative description of the top surface is contained only in a few parameters in the top surface schema, e.g. the angle between planes. The hierarchy contains a qualitative topological description of surfaces and how they connect but no detailed quantitative specification of the surfaces; so the object can bend and stretch depending on the values of the top level parameters. The object oriented programs use these top level parameters to make the object a specific one, to calculate detailed parameters of the surfaces, e.g. the x, y, and z components of the surface normals and place these parameters into slots in the schemas representing the surfaces. The programs also do the appropriate intersections of surfaces and create new schemas for interface and cut edges along with the detailed quantitative slots describing each edge. Figure 7-3 illustrates the network for the top surface after execution of the object oriented programs. Two of the schemas are expanded at the bottom of Figure 7-3 to illustrate the slots that quantify the surfaces and edges.

A portion of a representation for an actual liftarm is illustrated in Figure 7-4 which shows four complex surface segments being combined into a top surface by the addition of the interface edges along which the surface segments intersect.

### 7.1.4 Parametric Variation

Parameters for adjusting the size of the liftarm are contained in the schema for its top surface. These parameters for the liftarm of Figure 7-4 are illustrated in the Palm Schema Editor box of Figure 7-5. Adjustments to the arm width, thickness, length, etc. are made prior to executing the object oriented programs listed in the compute slot of the top surface schema. The first of these programs does initialization. The second program executes all of the object oriented programs associated with the operations that go into creating the surface (operations related to the surface by a geometric-opreation-for link). The last two trim any cut or interface edges that might still extend to infinity. Two liftarms generated with two different values of the arm width are sketched as plan views in Figure 7-6.

Sector gears have also been represented using this method, and two generated with different parameters are illustrated in Figure 7-7.

## 7.2 Feature Representation

Representations in terms of features associated with operations in a progressive-die stamping process were created for the same liftarm as in the previous section. This progressive-die feature representation is somewhat more abstract than the surface representation and is easier to build, although it is more limited in the objects that it can represent. Its structure is a hierarchy of features and subfeatures of a part as opposed to the surface representation with its emphasis on the evolution of the design through a series of geometric operations. The feature representation is meant to mimic the response of the engineer as he introspectively asks himself what he sees in the liftarm.

### 7.2.1 Simplicity of Parts

In addition to the simplicities of functional sheet metal parts listed in the section on the surface representation, the progressive-die feature representation also assumes that the liftarm is not much different than the flat sheet metal from which it is created. This allows positions to be referred to the original undeformed x-y plane.

### 7.2.2 Progressive-Die Features

The hierarchy of entities or features used in the surface representation are given in Figure 7-8. These geometric features are meant to serve both a progressive-die feature representation as well as a modified surface representation and the transformation between them. However the modified surface representation has not yet been devised, so the part of the figure labeled surface-repn-feature is not currently active.

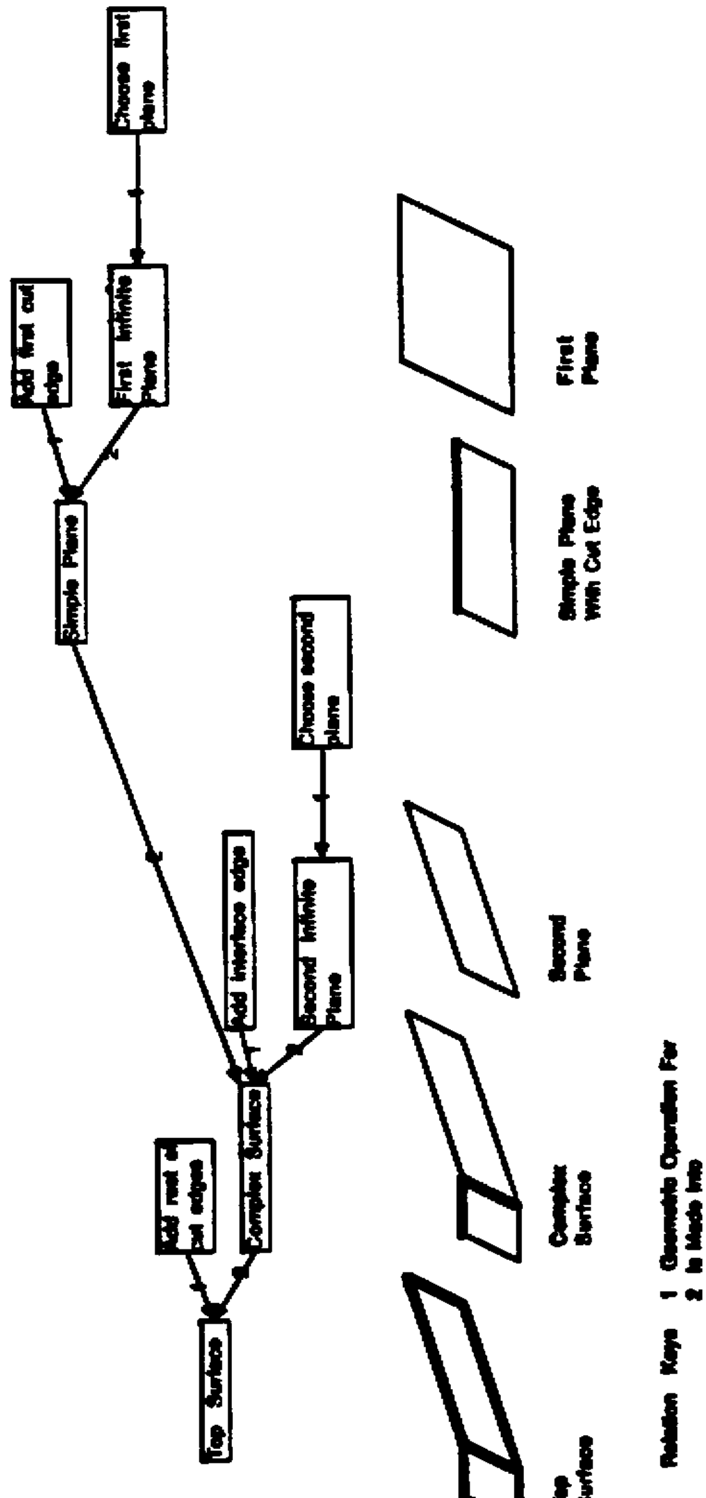



**Figure 7-2:** Surface Representation of the Evolution of a Simple Design

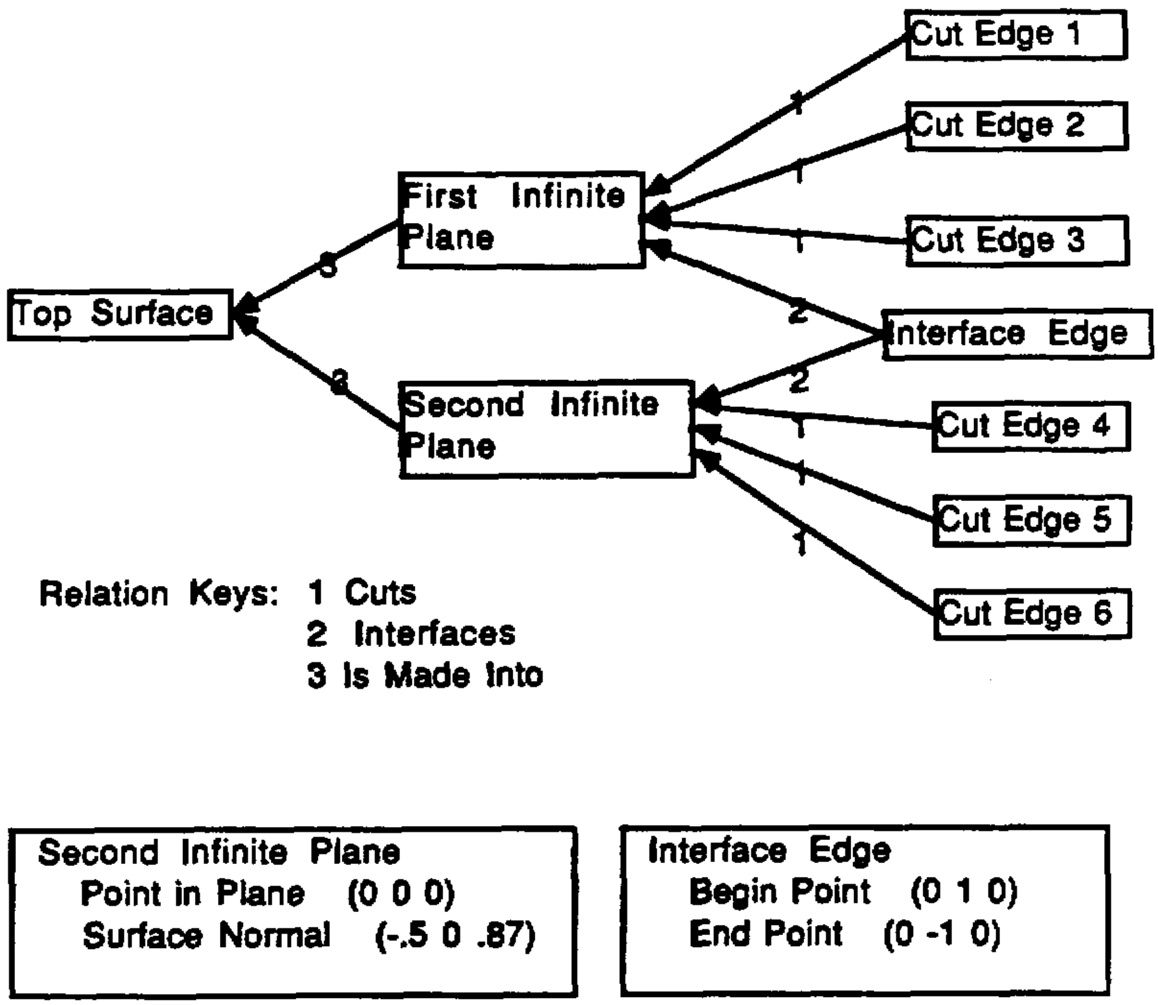



**Figure 7-3:** Surface Representation of a Simple Design After Evaluation

The progressive-die features used here are:

- Blank. The flat piece cut from the original sheet metal including the outer cut boundary and holes.
- Bend. Bending about a straight line axis.
- Draw. Pushing the metal perpendicular to the x-y plane in a region near a curve that is not straight.
- Wipe. Similar to a draw, but has a portion that becomes vertical and terminates on a cut boundary.
- Flange. Bending about more than one axis.
- Dart. A triangular brace between two planes.

A progressive-die feature has sub features which are curves made up of one or more edges. Edges may

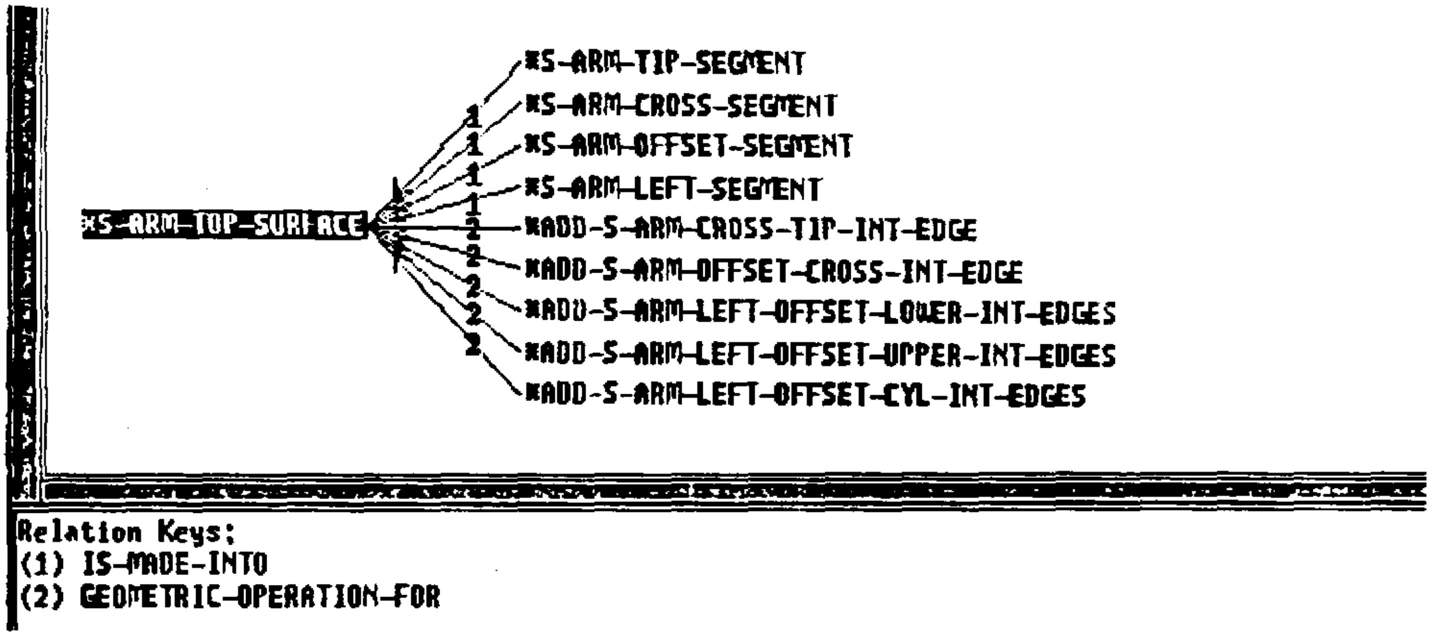


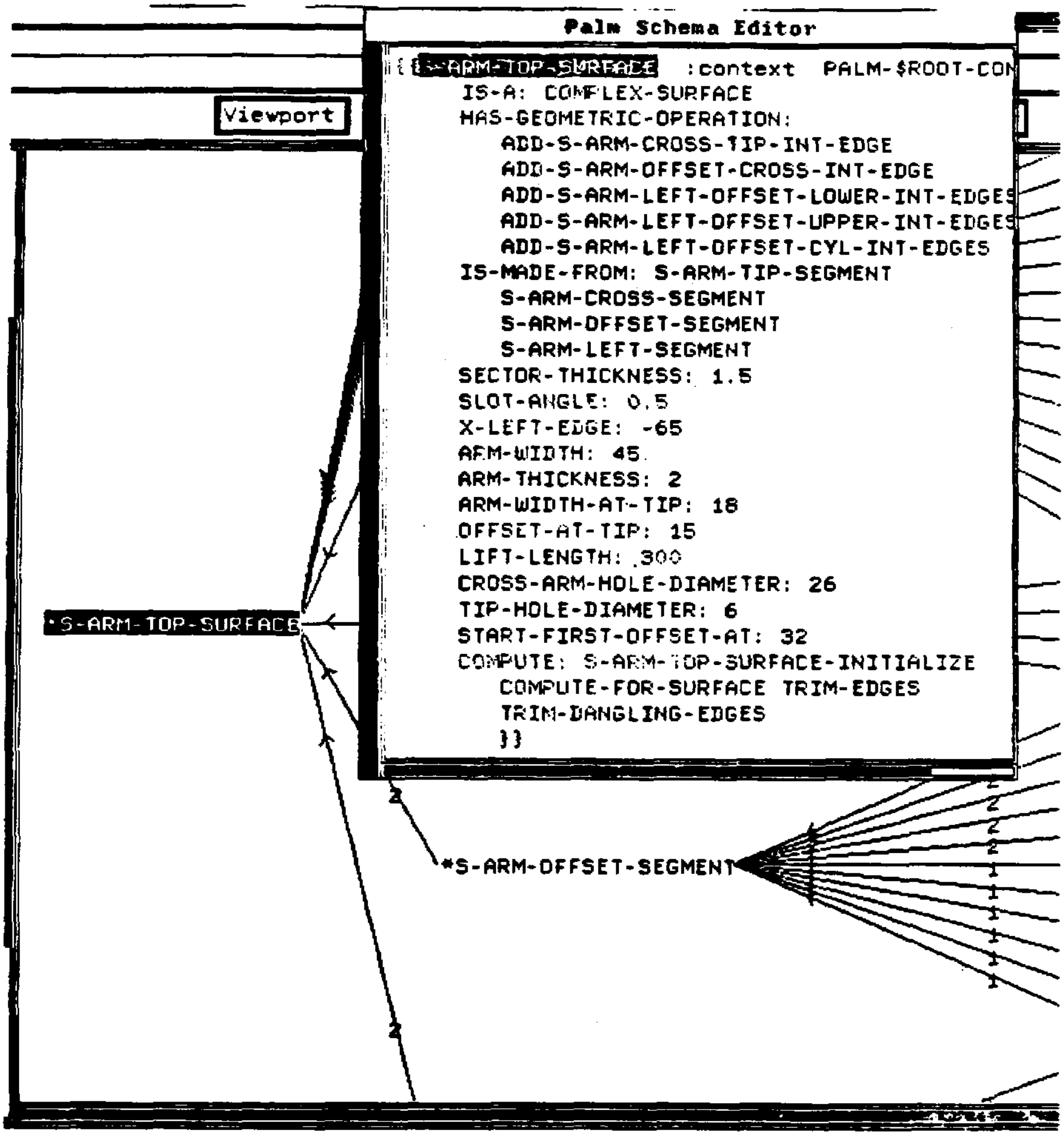

**Figure 7-4:** Creation of a Top Surface from Constituent Complex Surfaces

be either straight or circular. The curves may be either a closed loop or an open curve and may be either an interface between two surfaces or a cut curve which is a border between the surface and empty space.

### 7.2.3 Creation of the Feature Representation

Following ideas of Talukdar et. al. [11], a liftarm may be represented from different points of view, Figure 7-9. Here the points of view are the liftarm as a set of high level parameters, the liftarm as surfaces and the liftarm as a set of progressive-die features. Transformations allow a representation from one point of view to be created given the representation from another point of view; the feature representation is created by an object oriented transformation of the liftarm represented as parameters.

The transformation creates the entire tree structure representing the liftarm, Figure 7-10. The representation is a feature hierarchy [12] with the links between schemas being the has-feature relationship. The transformation first initializes additional parameters in terms of those already given. Then sub-feature schemas are created and linked to the higher level schema. The first level below the top one, Figure 7-10, contains entities of the type prog-die-repn-feature, i.e. blank, draw, bend. The schemas of these prog-die features contain slots which partially describe the feature, i.e. depth of the draw or angle of the bend. The next level contains sub features which complete the description of the prog-die feature. These sub features are curves which define an aspect of the prog-die feature, e.g. the cut outline of the blank. The leaf nodes of the tree are the individual edges that make up the curves of the next higher level.




Relation Keys:
(1) GEOMETRIC-OPERATION-FOR
(2) IS-MADE-INTO

**Figure 7-5:** Schema for the Top Surface of a Liftarm

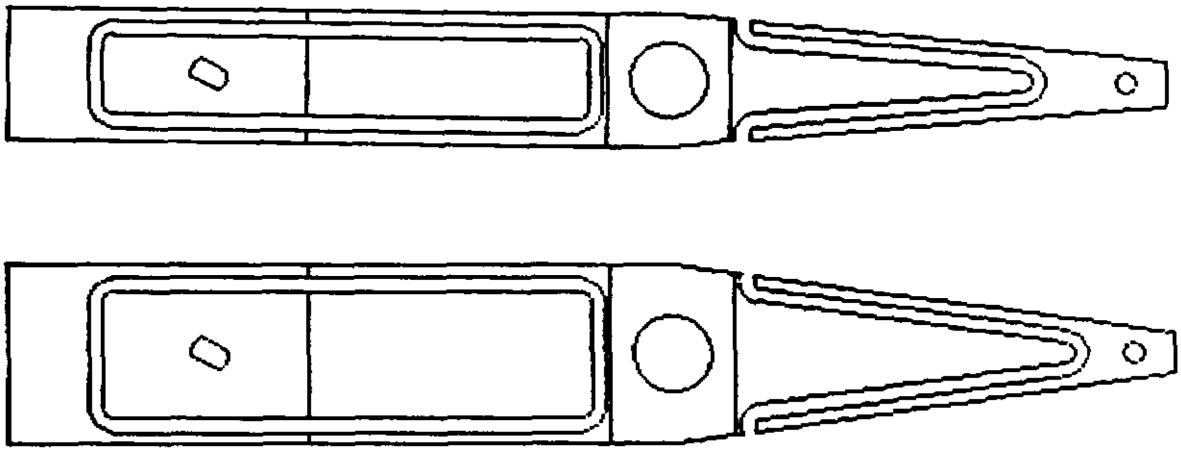


**Figure 7-6:** Two Liftarms Generated with Different Values of Arm Width

### 7.2.4 Parametric Variation

By adjusting the values of the representation of the liftarm as parameters prior to executing the transformation to the feature representation, variations in the liftarm are achieved, Figure 7-11. This figure is similar to Figure 7-6, however it is not an ordinary engineering drawing. In Figure 7-11 the lines all lie in the x-y plane; the heavy lines correspond to cut edges, while the light lines indicate the vicinity of features such as bends and draws. Two additional styles of liftarms are sketched in Figure 7-12. The bottom arm in this figure uses all six of the types of progressive-die features defined here. Its feature hierarchy is given in Figure 7-13.

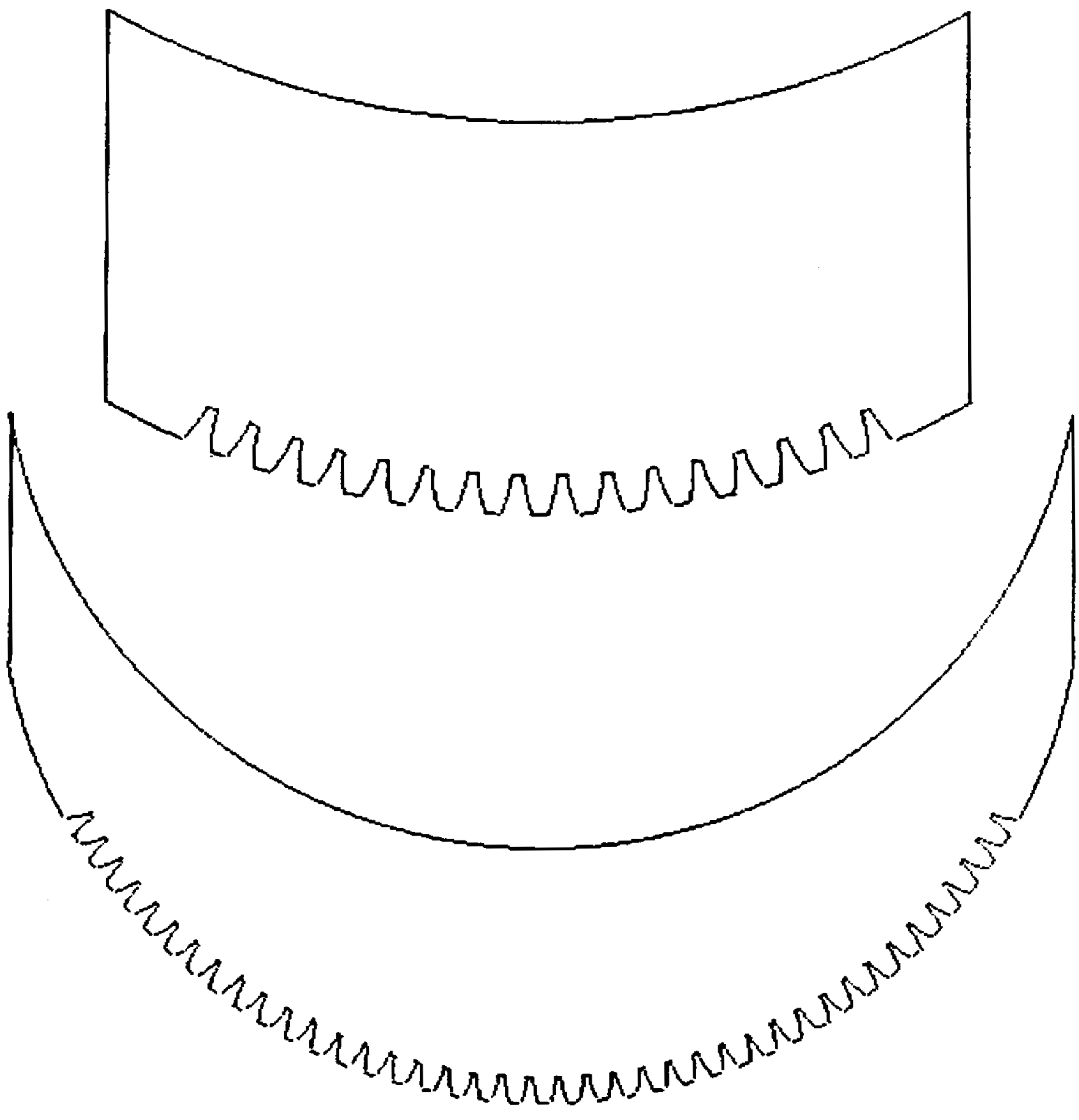


**Figure 7-7:** Two Sector Gears Generated with Different Parameter Values

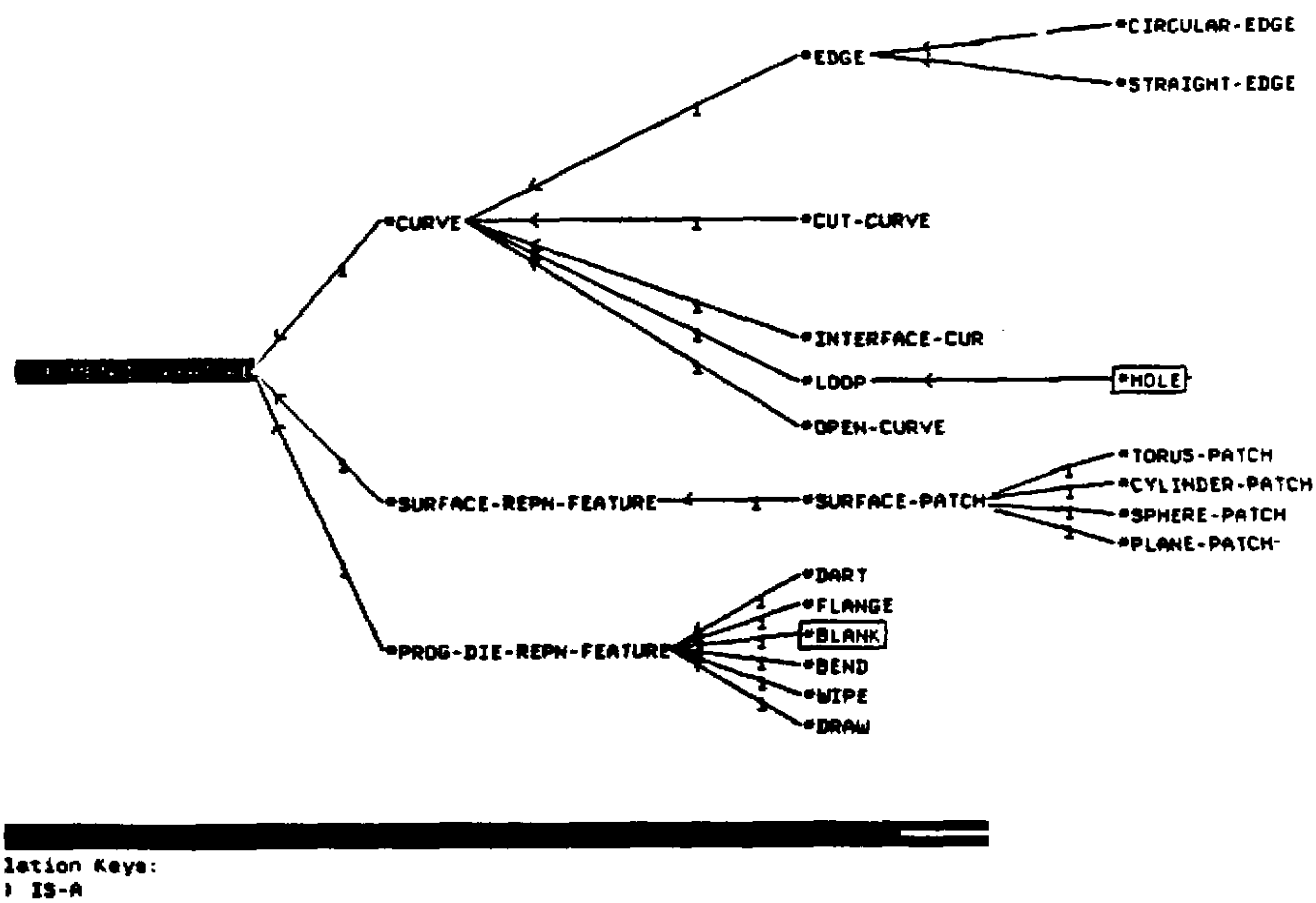



Figure 7-8: Progressive-Die Features for Representating a Simple Sheet Metal Part

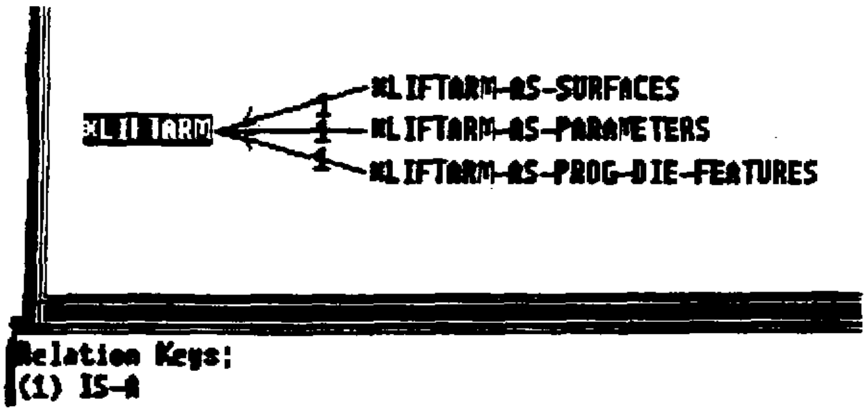



Figure 7-9: Classes of Representations of a Liftarm

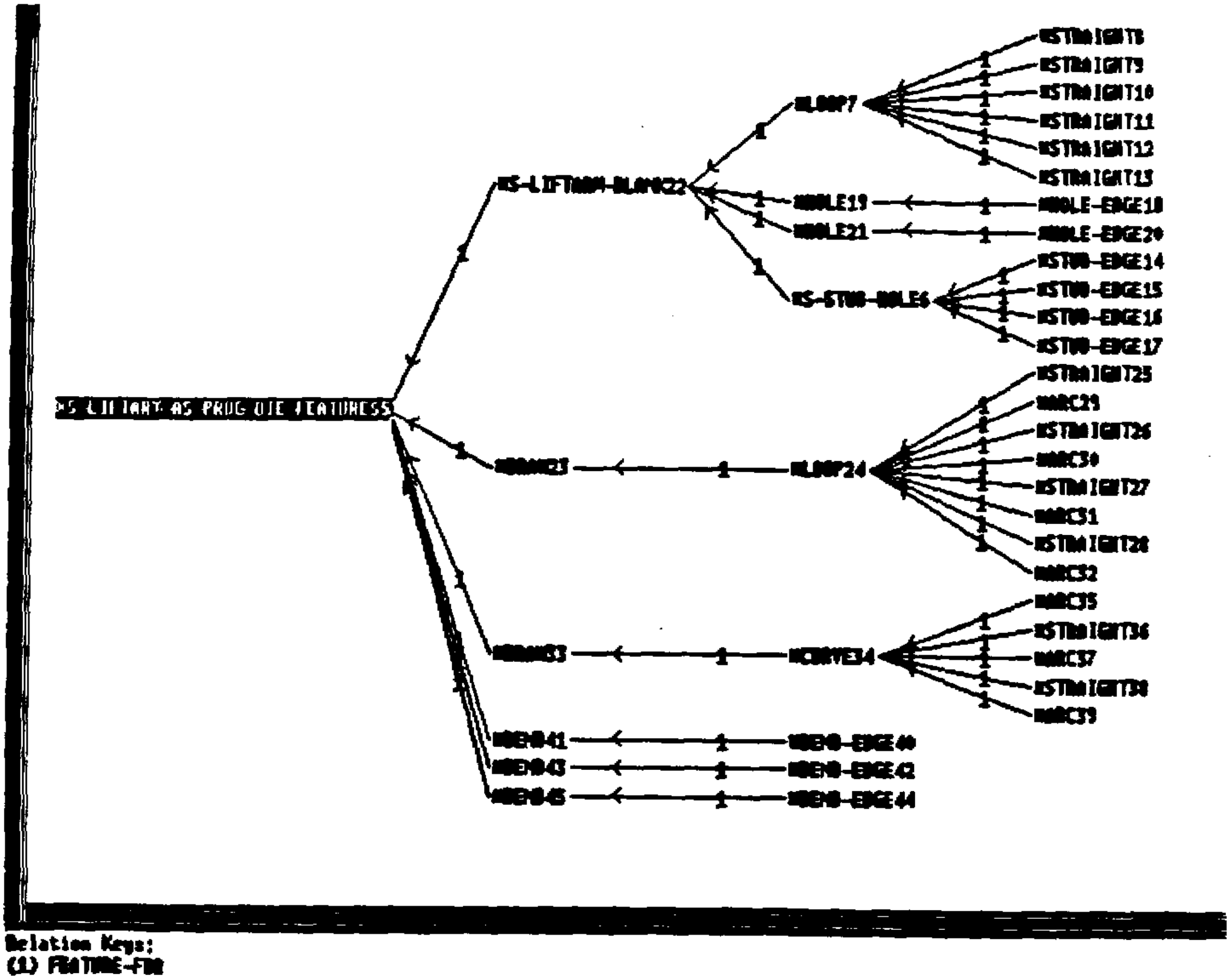



Figure 7-10: Feature Hierarchy for the Liftarms in Figure 7-11

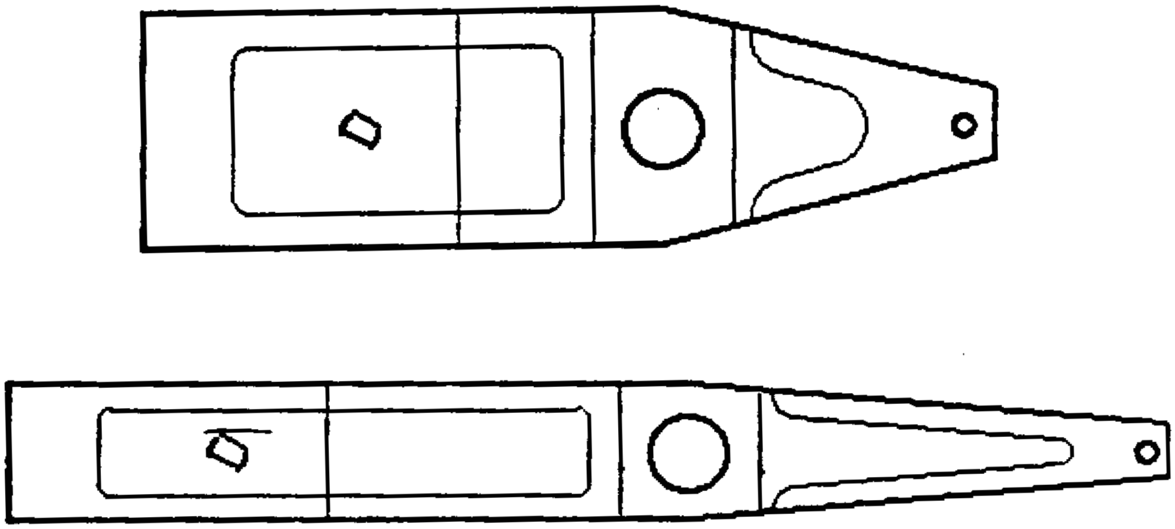


**Figure 7-11:** Sketch of Parametric Variation of the Liftarm Represented as Progressive-Die Features in Figure 7-10

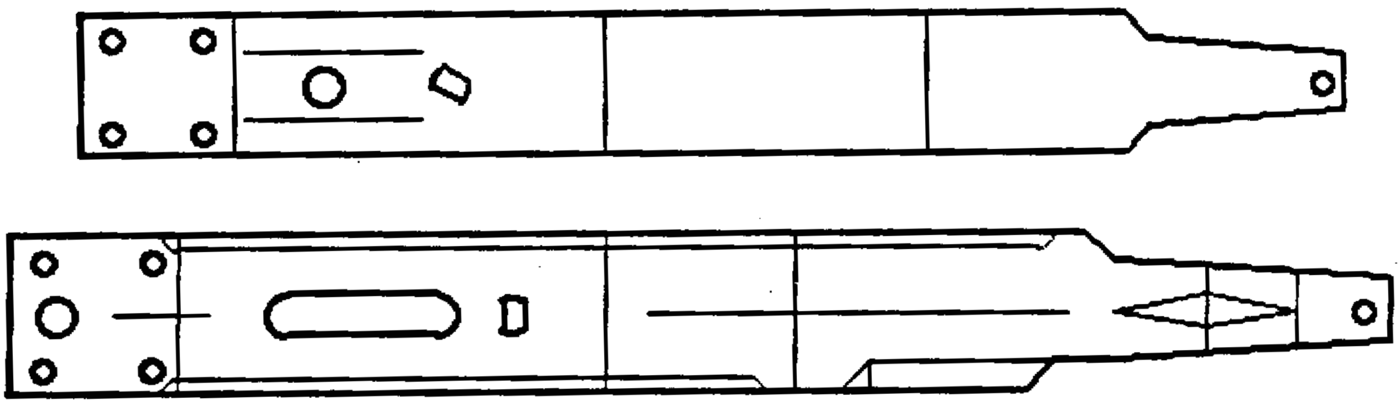


**Figure 7-12:** Sketch of Two Styles of Liftarm Represented as Progressive-Die Features

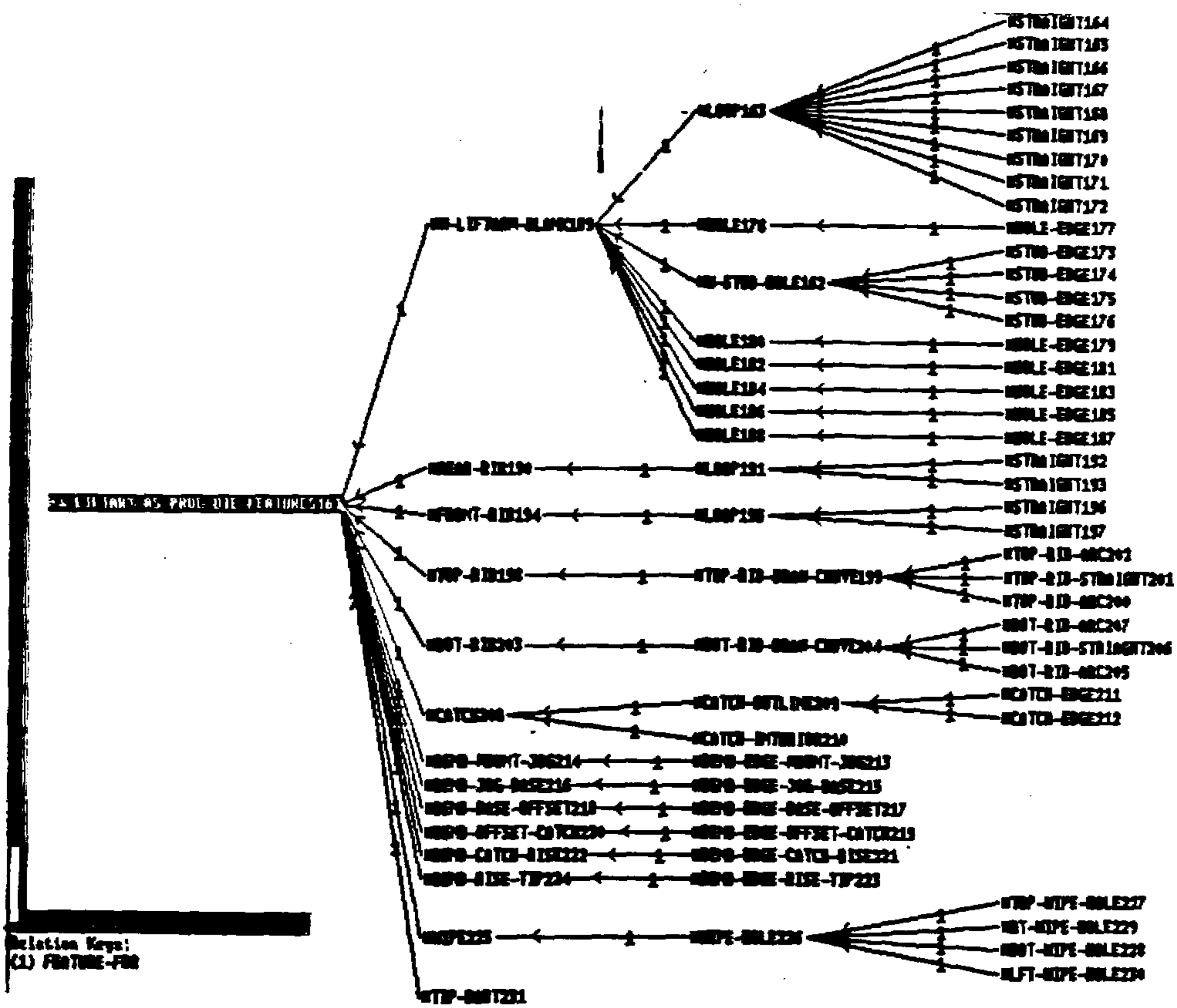


Figure 7-13: Feature Hierarchy for the Bottom Liftarm in Figure 7-12

# 8. Materials

ERIS contains information on the properties and uses of 53 materials employed by Fisher Guide and contains a materials critic which

- searches for materials with specified properties,
- helps with initial material selection,
- lists precautions to be exercised in the use of the materials in a design,
- and checks a design for sufficient materials strength

Materials are classified hierarchichally according to whether they are steels, plastics or lubricants, Figure 8-1. Instances of particular materials are linked to the parts in production by a made-from relationship. This information is used when checking a part for adequate material strength, cost, and precautions on the usage of the material.

The following sections describe the materials properties, the materials critic, and how outside data bases can be used to access a broader range of materials than those in current use at Fisher Guide.

## 8.1 Materials Properties

The schemas for a particular material contains information on its cost and on its mechanical, chemical, and processing properties. Properties are taken from the materials specifications and are in Standard International (SI) units.

### 8.1.1 Steel Properties

Properties are given in the schema for each steel. The ladle chemistry is in units of percent. Strength is in MPa. Cost information pertains to purchase of that steel at the manufacturing plant. Costs are given in dollars per kilogram starting with an average cost and continuing with a schedule of different costs for different thicknesses and widths of sheet.

### 8.1.2 Plastics Properties

The number of pieces of information for a plastic is larger than for a steel, so subcategories of mechanical and processing properties are defined. The schemas for these subcategories are linked to the schema for the plastic by a has-property relationship. The "@" symbol indicates the measurement condition for the property, i.e. the deflection temperature was measured to be 104 C at a stress of 1820 Pa.

## 8.2 Materials Critic

The materials critic helps with material selection, usage precautions, and failure mode analysis. Also a graphical editor is provided to facilitate modifications and additions to the data base.

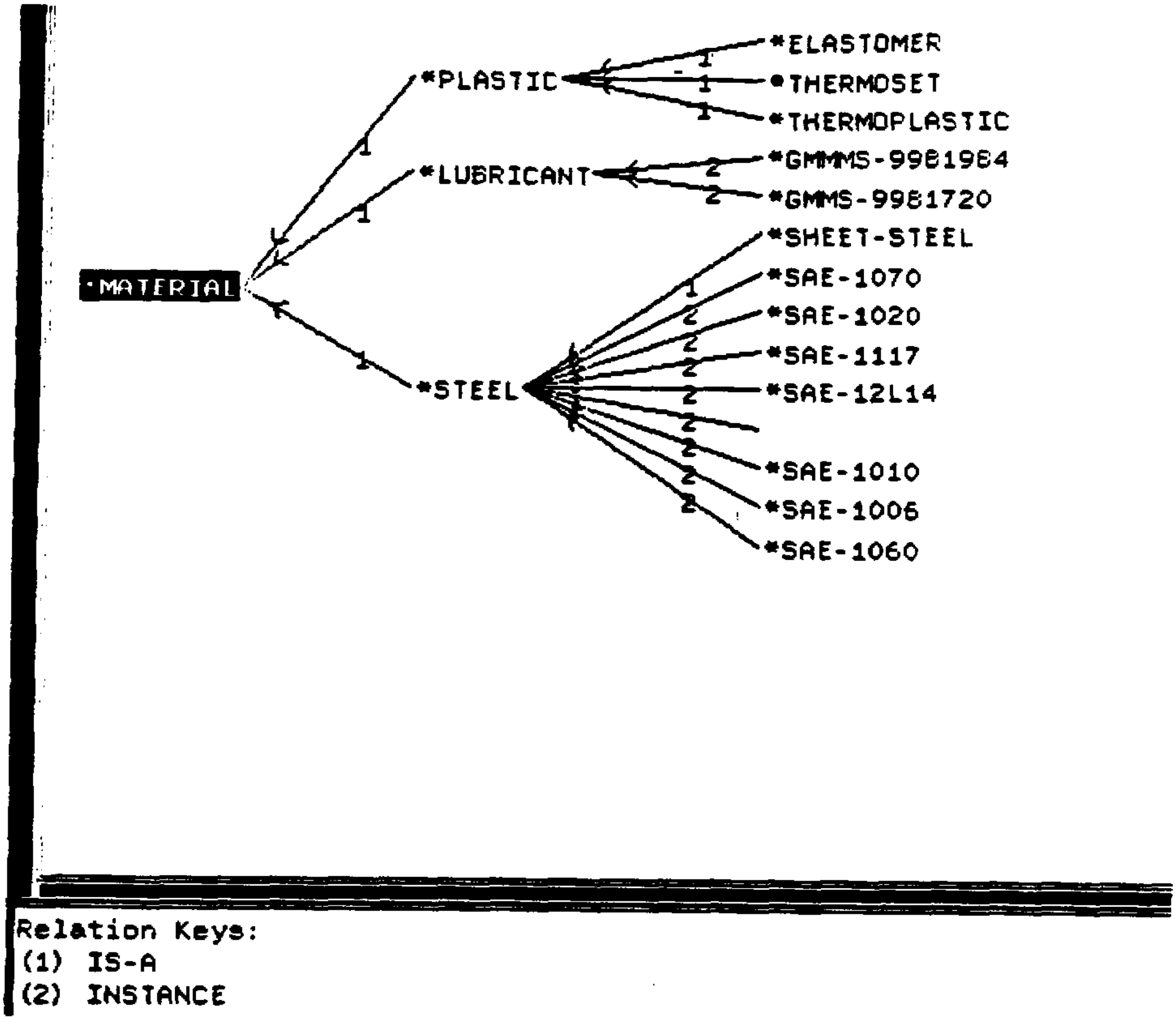



**Figure 8-1:** Materials Classification

### 8.2.1 Material Selection

The materials critic aids the designer in the selection of a material in two ways.

1. He can specify limits on various material properties (e.g. yield stress greater than 200 MPa), and the materials critic will list the materials which meet these specifications.

2. He can specify a type of part (e.g. a liftarm) and, the materials critic will list the materials that this part has been made from in the past.

### 8.2.2 Usage Precautions

Precautions must be taken in the use of certain materials, especially plastics. For example, when using nylon, sharp corners must be avoided because of notch sensitivity. The materials critic will display the precautions which must be used for the various materials in the design. The designer can examine precautions in the general categories of design, molding, bonding, and environment. As shown in Figure 8-2, the critic queries the designer as to whether he has considered a precaution, and if he has the critic records this so that it need not be reconsidered later.

```
For      2-20

Which makes the parts: ((MALE-ROLLER-FOR-LIFTARM-9826201 FEMALE-ROLLER-F(

The following precaution must be taken

***************************************************************
Parts should be designed to avoid sharp corners
and other stress risers because of notch sensitivity of nylon
***************************************************************

If you have verified that the design meets this precaution, enter your na
Otherwise enter a '/'.

Your name:

                                                            WELD-LINE-NY

NOTCH-SENSITIVITY-NYLON   WET-DRY-NYLON            ANNEALING-NYLON
THICK-SECTIONS-NYLON      LONG-TERM-NYLON          EXIT
```

**Figure 8-2:** Usage Precaution for Nylon

### 8.2.3 Failure Mode Analysis

The materials critic verifies customer specifications by determining the risk of failure in various modes during testing (e.g. risk of failure due to the liftarm bending during a spindle abuse test). This risk is displayed as a bar chart of the ratio of calculated to allowed stress for the various failure modes, see Figure 8-3. The failure mode analysis uses the specifications of the various tests that must be performed and the various failure modes that can occur. The representation of specifications and failure modes is described in chapter 9.

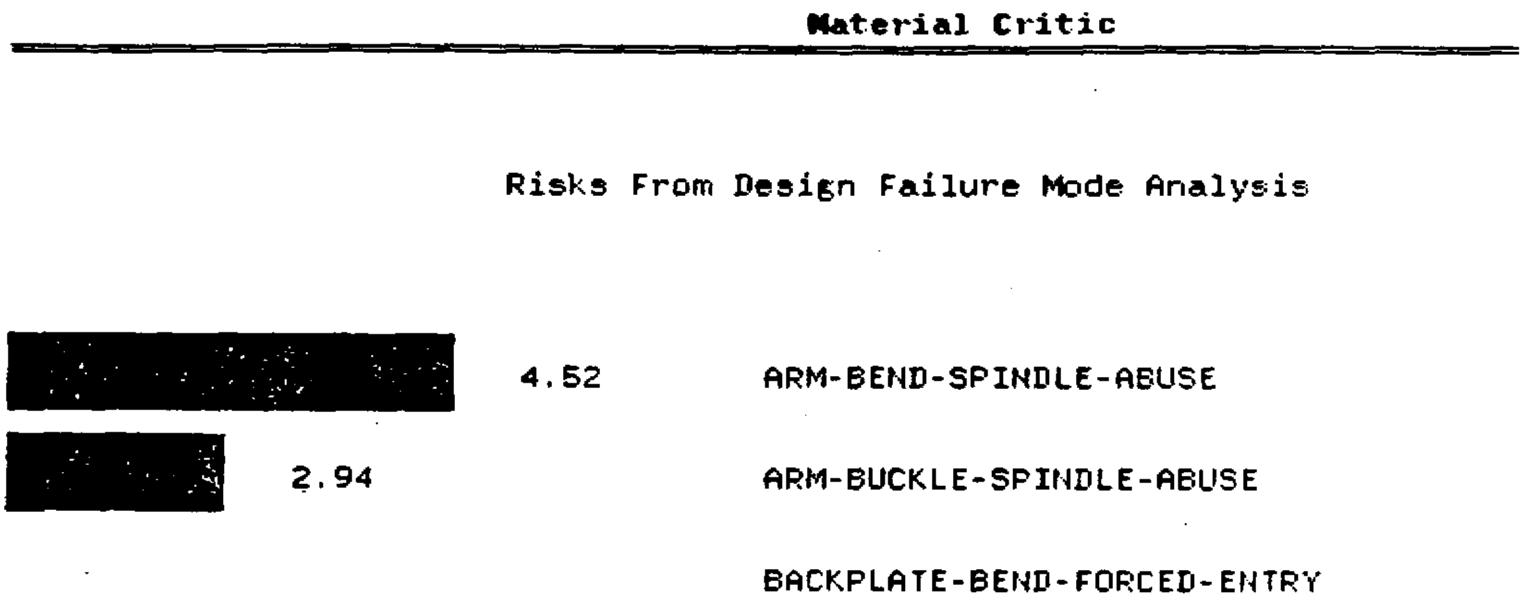



**Figure 8-3:** Risks from Design Failure Mode Analysis

## 8.3 Outside Data Bases

Part design frequently involves modification of an existing part. New and improved materials that the design engineer is not aware of may have been developed since the original part was designed. However, attempts to find better materials for a part are not usually made until a costly failure occurs or the revised specifications clearly indicate the old material will not do. The engineer may then ask the materials expert for assistance in selecting another material - much as he might do if designing a new part.

The materials expert responds to such requests by reviewing the part requirements and recasting them in terms of material properties, structure, formability, durability, and so on. The technical literature contains a wealth of such information. He also considers cost, availability, fabrication equipment required, etc. In the traditional approach the materials expert makes use of his training and experience, refers to handbooks and reference manuals which have partially digested the technical information, and refers to brochures issued by materials producers. Selected materials are tested until satisfactory ones are found. Better materials may be available, but time and cost constraints may prevent this traditional approach from finding them.

Computerized materials databases are now being developed which incorporate the wealth of technical and other information mentioned above. These databases make it easier for the design engineer and materials expert to find the new and improved materials modern technology has produced, and make the search so efficient that the best material can be found.

ERIS contains a limited materials database - only materials having Fisher Body Materials Specifications (FBMS) are included and only information that is in the FBMS is included. Nevertheless, it should be very useful to the window regulator designer since it contains the properties and uses of all the steels and plastics used in window regulators.

To show how even greater functionality could be easily added to our knowledge base, three other materials databases are described below.

### 8.3.1 Refereed Materials Database

A non-profit technical organization has produced and is maintaining a database which currently only includes information on metals . There are plans to expand it to cover non-metals. We have called it a refereed database, because the information it contains has been reviewed by experts for correctness and consistency. The database is distributed on floppy disks for use on a personal computer running the MS-DOS operating system.

The database contains information on chemical composition, product forms, industry designations, processing rankings (hardenability, formability, machinability, weldability, etc.), usage requirements (wear resistance, corrosion resistance, high strength, high toughness, etc.), material properties (mechanical, electrical, magnetic, environmental, etc.) and so on.

A user, knowing the common name (or other industry designation) of a metal, can retrieve all the information in the database on the metal and view it on the computer's video monitor. However, the real potential of the database is only exhibited when the user has a set of criteria which a material must satisfy. These criteria can be Boolean or particular values (less than or greater than particular values). The user then invokes a database search. A list of materials meeting the criteria is obtained. The list and all information on the members of the list can be examined on the monitor. Hardcopies can be printed.

The user can readily modify the database in a number of ways. For example, he can create a new database containing a specified subset of materials. He can add additional information to that already in the database for any particular material. He can also add new materials and information on them to the database.

In using the database a number of bugs and performance deficiencies were noted. Discussions with the database provider, indicated he would be correcting the bugs and would try to remedy the performance deficiencies.

The major drawback with this database is that it can only be used on a personal computer running MS-DOS and only accessed from the PC's monitor. This limitation is a probably a direct consequence of the software package/tools the provider used in creating this database.

Conversations with the database provider indicated he would like to port the database to other machines. If this was undertaken it would be most desirable to incorporate current trends in database design, viz., implementation in a networked environment. In such an environment, one machine is selected as the server - the large database files and most of the CPU intensive operations are performed on the server. The user, at his workstation, queries the database over the network. The server performs the search and only sends back information to the server which satisfies the user's criteria. Proposals have also been made to standardize how the database is queried - one which is gaining widespread recognization goes under the acronym SQL (for structured query language). However, it should be noted that improvements of this sort require considerable effort - as a non-profit organization, the database provider would probably look for industry funding as well as strong industry support and interest.

As an interim solution, we have found the following procedure to be a reasonable satisfactory way around the above-mentioned drawback: Once the materials search is finished, we store the list of materials and all the information on them to a flat (ascii) file on the PC. We then transfer this file from the PC to the user's workstation using hardware and software we installed on both the PC and the user's workstation. The user can then incorporate any new materials and new information resulting from the search into our knowledge base. A particular advantage of this method is that manual entry of information is avoided.

### 8.3.2 Plastic Materials Database

An industry based trade organization has produced a plastics materials database. Information in this database is producer supplied. The database contains entries for over 9,000 plastic materials. Access is via a modem and a locally dialed phone number. The database is stored on a DEC 10 mainframe. Users pay a yearly fee and connect time charges.

In addition to containing information on practically any plastic material property imaginable, it has information on many special features of interest to the plastics user, e.g., biodegradable, color stability, foamable. Searches can be performed by material type (e.g., thermoplastic, thermoset), by generic family (e.g., nylon, phenolic, polyester), by process type (e.g., continuous casting, injection molding), by chemical type, by fillers, and by appearance. The database also contains information on fabrication equipment and machinery, suppliers, pricing information, industry and product news, etc.

Hardware and software set-up on a workstation enable users to access and search this database. The software also enables the user to make a complete record of the session and store this record as a file (a log file) on the workstation. Thus the user has a permanent record of all the information returned by the search. The software on the workstation also enable the log file to edited. Hardcopies can be obtained by printing the entire log file or just printing selected or edited portions. Any or all of the information in the log file could be readily added to the knowledge base, while at the same time avoiding the errors introduced by manual data entry.

Discussion with the database provider indicated a willingness to cooperate in meeting specialized user needs. This might include addition of user materials specifications to the database (with limited access and confidentiality maintained); porting the database to a user workstation; installing suitable software on their mainframe to meet specialized user needs, and so on.

### 8.3.3 Producer Materials Database

One of the major plastic manufacturers has put together a database containing information on their products. What is rather unique about this database is that essentially all the information it contains is presented to the user in graphical form. Access to the database is provided to their customers and potential customers via a dialed phone number. The database is stored on a DEC Microvax 2000 workstation running VMS.

Since the information in this database is in graphical form, the user's monitor must be capable of displaying graphics and more particularly be compatible with the database's graphics format. The provider has chosen one of the more common graphic formats, so this presents no real problem for most workstations. In fact, we accessed this database from a DEC Microvax workstation running VMS and from workstations running a Unix version of X windows. Not only was it possible to display the graphics on the workstation consoles, but the graphic information could be saved and stored as files. Once stored as files, the graphics could later be redisplayed and even printed on hardcopy devices which could handle graphics input.

## 9. Specifications

The customer specifies regulator performance (e.g. the allowed number of handle turns and effort to raise the window) and specifies service conditions (e.g. the number of times the window will be raised and lowered and the ambient temperature range). Laboratory tests are performed to verify that specifications are met. ERIS contains schemas for these tests that are linked to the schema for the door by a specificied-test-for relation, Figure 9-1. The schemas contain descriptions of the tests including the test parameters, e.g. the torque for the spindle abuse test, Figure 9-1. The designer has enumerated the various modes of failure that can occur in each test, and schemas for these failure modes are linked to the schemas for the test by a failure-mode-for relation, Figure 9-2. The various failure modes and the parameters for the tests are used by the materials critic to calculate an expected risk of failure during testing.

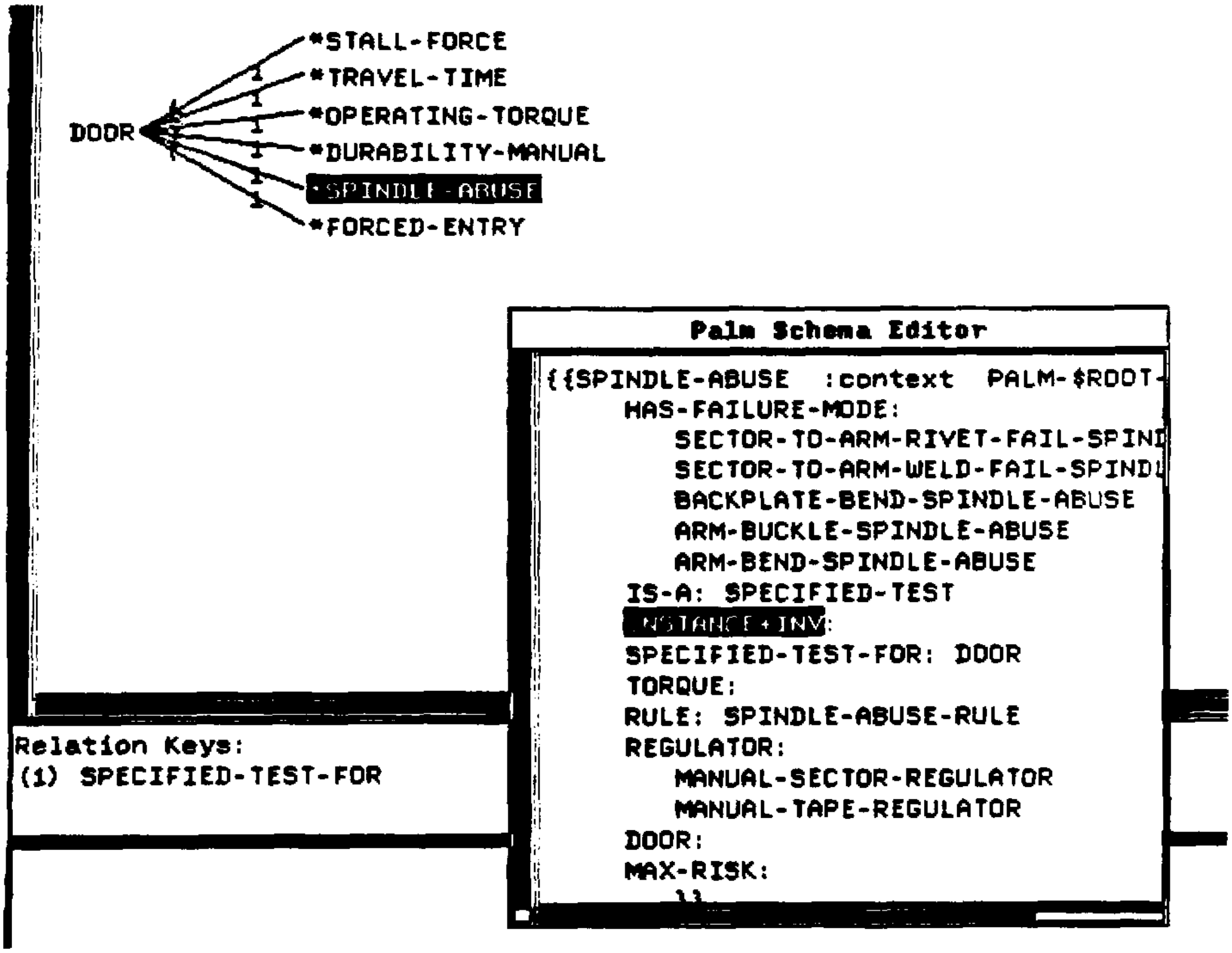



**Figure 9-1:** Tests Which a Regulator Must Pass

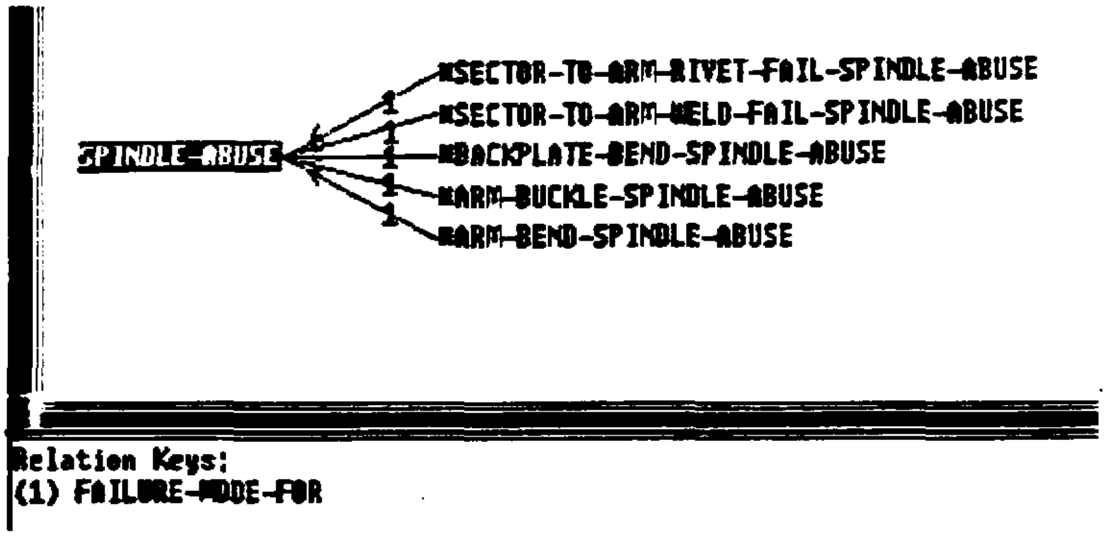



**Figure 9-2:** Failure Modes for the Spindle Abuse Test

## 10. Manufacturing

ERIS contains a semantic network representation of manufacturing processes. The manufacturing processes for a part are categorized, broken down into subprocesses, and ordered. Information such as time, cost, input, and output is stored for the various steps in a manufacturing process. This representation could be used to make estimates of labor cost for a new regulator that is similar to one already in production, or it could be used for process planning.

The processes used at Fisher Guide are placed into categories such as forming, assembly, and storage. A representation for the manufacture of a particular cross arm regulator is given by a hierarchy of the breakdown of the manufacturing process into subprocesses. The nodes of the hierarchy are instances of the process categories. The manufacturing process for an assembly generally breaks down into manufacturing processes for each subassembly within the assembly followed by an assembly process and a transport or storage. The manufacturing process for a basic part which has no subassemblies generally breaks down into forming followed by treating such as heat treatment and cleaning followed by transport or storage.

In addition to the break down of a process into sub processes, ordering of processes is represented through the use of a preceeds relationship. Preceeds refers to operations on a specific part, e.g. the spindle must be cleaned before it goes into the caster. Preceeds does not necessarily indicate the schedule of the days activities on the shop floor. Because parts can be stored, casting could be done using the stockpile of cleaned spindles, and spindles need not be cleaned before starting the caster. If a process is part of a line process, such as final assembly of the regulator, then the output of one process is directly input to the next with no storage in between. In this case, preceeds indicates the time ordering of activities on the shop floor.

## 11. Expert Systems

A small subset of the expert systems that could use the knowledge contained in ERIS has been written. Two are described in this report.

### 11.1 Materials Critic

The expert system built into ERIS for selecting materials and checking a design for adequate materials is described in the Sections 8.2.1, 8.2.2 and 8.2.3.

### 11.2 Choice of Regulator Style

A small expert system to choose the style of regulator that should be used for a given application has been written using the OPS [8] forward chaining rule based language. The system queries the user about the door (front or rear) and the type of glass guidance system (run channels or pin guides or flush glass). Then the system chooses a style of regulator using rules such as

- If a rear door with a pin guidance system, then use a tape regulator
- If flush glass, then use a cross arm sector regulator with a fixed point attachment for one arm.

### 11.3 Knowledge Based Materials Guide

The annual redesign of existing parts and the design of new parts results in the accumulation of an extensive body of knowledge by the design engineers, manufacturing engineers, production engineers, and materials experts. However, much of this knowledge in never effectively utilized, and is frequently lost because it is never documented. Moreover, even when this knowledge is not lost, it is still very difficult to find out who knows what. Problems of this sort can be effectively solved with a expert system which serves as a convenient and accessible source of the accumulated knowledge.

It is also evident that there are many problems in selecting materials - particularly plastic materials. For example, it has been reported that the methods currently employed in selecting plastics results in the wrong material being selected in about one out of every two cases. It is clear that a need exists for a powerful material selection expert system which can be used by the design engineer, materials expert and others involved in parts design, testing, and production.

After some study it was concluded that to adequately meet the need a set of powerful graphic knowledge management tools are required. This led to the selection of a set of tools that used rules and objects to represent knowledge, operated in a networked environment, made full use of a windowing system, had excellent graphic capabilities, and utilized fully developed inference mechanisms. Using these tools, the aim was to develop a materials guide - a knowledge based system which would enable the design engineer and other users to find the best material for a part. Another goal was to provide a materials guide with sufficient flexibility so that when there were special requirements for a part, these requirements could be easily incorporated into the material specifications. Some of the other ways we hoped the materials guide would assist the user are also described below.

Part location, part usage, environmental conditions, materials compatibility, product life requirements, safety and failure considerations, fabrication and processing requirements, cost, and other factors are utilized by the guide's rule-based knowledge representation to develop a set of specifications that enable the selection process to be optimized. The knowledge base is also used in the verification of design specifications, implementation of quality control procedures, design precautions, failure analysis, and so on.

Ease of use was considered to be an important element in developing the guide. This means that the expert system must have enough "smarts" so that it only prompts a user with a small number of inquiries in order to reach a conclusion. To do this, the guide divides material properties into very broad categories such as mechanical, physical, thermal, optical, electrical, and so on. By means of its "reasoning" capabilities and knowledge base, it determines which of the broad categories is pertinent to the part under consideration and confines its inquires to these. This not only provides an intelligent means of selecting materials, but also automates the process.

The output from the materials guide is a set of material properties, parameters, and other information tailored to make it easy to search databases for a suitable material.

## 12. Summary and Conclusions

- Hierarchichal semantic networks of frames are effective for representing a variety of engineering information:
    - Simple facts, e.g. the yield strength of a certain steel is 200 MPa
    - Classes of objects
        - a manual sector regulator is a type of regulator,
        - a liftarm is part of a backplate subassembly
    - Classes of processes
        - a progressive-die stamping is a type of part forming process,
        - the progressive-die process preceeds the riveting process for the liftarm
    - Descriptions of proceedures and specifications, e.g. the spindle abuse test is a specified test for a window regulator and is to be done with a certain torque.
    - Complex data structures that represent the geometry of a part, e.g. the rectangular draw is a feature of the liftarm.
- Parametric representation of geometry in terms of the features or surfaces of a part enables automatic redesign of an existing part to meet new specifications.
- Two geometric representations of sheet metal parts were created. One is in terms of progressive-die manufacturing operations and represents the features and subfeatures seen in the part. The other is in terms of surfaces and edges and represents the steps taken by the designer in creating the design. The latter representation has more generality, can represent a broader class of parts. The former is easier to build.
- Labor to produce and assemble regulators and the purchase price of raw materials (sheet steel) each account for a fourth of the cost of a regulator. Minimization of material used and reduction of labor input are major areas for cost containment. Large burden or overhead factors might be used to draw the conclusion that a dollar saved on direct labor leads to a ten dollar total cost savings; this is wrong.
- Machine maintenance and job setup is an area where moderate savings could be achieved through modernization.
- The modest cost for the design process indicates that the major payoff from improved design methods is in the improved and more timely design rather than the cost of designing.
- The representation in ERIS of the manufacturing process for a regulator in terms of subprocesses associated with the various subassemblies can be used to estimate costs for a similar regulator or to do process planning.
- Easily available information on parts in production allows use of carry over parts and retrieval of experience gained in development of those parts.
- After searching for a carry over part with appropriate characteristics, the drawing of the part found can be automatically displayed on the screen and a hard copy made so that the engineer can exercise judgement as to the suitability of the part.
- Automation of some design processes, i.e. material selection, failure mode analysis, selection of regulator style, and either choice of a carry over part or modification of an existing part, have been demonstrated using the ERIS knowledge base.
- The use of computer automation by itself and computer automation coupled to organizational changes could result in a factor of three reduction in the lead time between customer specification and a part in production.

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