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## Case study of assembly defects in manufactured products

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## **ABSTRACT**

### **CASE STUDY OF ASSEMBLY DEFECTS IN MANUFACTURED PRODUCTS**

by  
**Michael J. Withka**

Design for Quality Manufacturability (DFQM) is a design tool that empowers engineers to create designs that are easily and effectively transformed into manufactured products. The goal of this methodology is to make designers aware of design characteristics that may lead to product defects during the assembly process. Acknowledging the possibility of these defects will enable the designer to institute design modifications early in the design phase. The benefits realized in this approach are a reduction in the number of defects in the finished product, reduced product cycle times, a reduction in monitoring costs and a reduction in time-to-market.

This thesis supports the application of the DFQM methodology as a means of maintaining a competitive advantage within industry. The value of utilizing this approach is proven by the submitted case studies of quality defects. An automobile emergency brake, portable overhead projector, car door handle, hand soap dispenser, floppy disk drive and hand held hair dryer were analyzed using the DFQM classes of Manufacturing Quality Defects. Through this analysis, Influencing Factors and Factor Variables of the each design were isolated and suggestions for modifications were presented to eliminate these quality defects.

**CASE STUDY OF ASSEMBLY DEFECTS IN MANUFACTURED PRODUCTS**

by  
**Michael J. Withka**

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New Jersey Institute of Technology

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**of Master of Science in Manufacturing System Engineering**

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APPROVAL PAGE

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This thesis is dedicated in loving memory  
to sister Joan Appleyard.



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# CHAPTER 1

## INTRODUCTION

In manufacturing today, some of the most defining issues are those surrounding product quality. For the consumer, a quality product equates to owner satisfaction in terms of product functionality and longevity. For the manufacturer, producing quality products ensures a strong customer base and a competitive posture within industry. However, for the quality minded manufacturer, the maintenance of product quality is not a one time fixed cost. It requires a concerted effort by the entire organization to improve the way business is performed.

In the design room, improving quality pertains to supplying the manufacturing operation with a design that can be effectively transformed into a product that is free of defects. There is also an inherent need to reduce the cycle time needed to produce these high quality items. The solution is a design methodology that operates within the framework of traditional Design for Manufacturability guidelines, but from a quality perspective.

Design for Quality Manufacturability (DFQM) is a design approach that attempts to isolate design characteristics that foster quality defects during manufacturing. The goal of DFQM is to improve the design of a product as to reduce the number of design changes needed to achieve the desired level of quality while reducing the number of product defects realized during manufacturing.

### **1.1 Research Objectives**

The purpose of this study is the following:

1. To analyze selected assembled products for the purpose of identifying Primary Defects.
2. To apply the Design for Quality Manufacturability methodology in an effort to link Primary Defects to Influencing Factors within the product design, to assign Factor Variables to detail these Influencing Factors and provide the basis to suggest design improvements, and to determine the Specific Defects that may result from these Factor Variables for the purpose of assigning the appropriate Manufacturing Quality Defect class.
3. To identify the prevailing Manufacturing Quality Defects present in the case studies.

### **1.3 Summary of Research**

This thesis begins by establishing a design background by exploring some modern day design methodologies. Then, case studies are performed on six pre-selected assembled products. Once analyzed, the anticipated manufacturing quality defects are classified with respect to the DFQM defect classes. With the defects classified, conclusions are drawn as to the most commonly found quality defect.

Chapter 2 provides the foundation for the case studies. The Design for Manufacturability approach is discussed, as well as, the objectives of conceptualizing designs that are easily and effectively manufactured. The basic DFM design process of product realization is illustrated, showing an emphasis on design optimization.

With the DFM approach defined, two examples of DFM tools are given. The first, Boothroyd Dewhurst Industries (BDI) method, focuses on the DFM guidelines of reducing the number of parts in an assembly and designing them for easy handling and insertion. The BDI method evaluates each design by calculating the design efficiency and then indicates parts that are candidates for elimination.

The Axiomatic approach is a design philosophy that establishes a standard for a “good” design by using design axioms. The premise of the Axiomatic approach is to maintain the independence of all functional requirements of the design and to minimize the information content present in the manufacturing system.

With basic understanding of how product designs are improved, some quality engineering methods are discussed. Recognizing the need to engineer quality into every operation of a business, the concept of Total Quality Management is introduced. Total Quality Management (TQM) is an organization-wide program whose first goal is to define quality aspects affecting the business. With all pertinent quality issues revealed, TQM attempts to control quality. Areas of low quality are isolated and programs are developed to address these issues.

Within a TQM program, Quality Assurance is an area of operation that requires frequent improvement. Two methodologies, Taguchi’s method and Quality Function Deployment, are described as common approaches of infusing quality. Taguchi’s method is a design protocol that is applied to existing designs to optimize design and process parameters. Taguchi’s method evaluates product designs by calculating the potential loss imparted to society resulting from defective products.

Quality Function Deployment (QFD) is a quality assurance method that utilizes customer information for the purpose of translating consumer wants and needs into design targets. QFD uses “Houses of Quality” diagrams to illustrate the interaction of manufacturing characteristics such as consumer demands and current design attributes.

Design for Quality Manufacturability (DFQM) is a design tool that enables the designer to make early quality decisions concerning the end product. Unlike Taguchi’s method and Quality Function Deployment, the DFQM method recognizes that certain design features may inherently lead to product defects during manufacturing. Using a standard list of defect classes, the designer can fabricate a design with increased manufacturability.

In Chapter 3, case studies are performed on selected assembled products. Each study begins its analysis by identifying the functional requirements of the product. Next, a detailed description of assembly components, component interactions and the functional contributions of each component is provided. After analyzing the inner workings of each product, a list of Primary Defects is compiled. These defects are assumed product flaws that end user may experience. The Primary Defects are explored to determine which design features (Factor Variables) may contribute to the anticipated defect. With the Primary Defects and Factor Variables noted, design improvements were suggested. These improvements were proposed to reduce the likelihood that a Primary Defect will occur. An illustration of the relationships between the design Factor Variables and Primary Defects of the product is also included.



In Chapter 4, the Primary Defects isolated in each of the case studies are classified. This is accomplished by showing the predicted path from the Influencing Factor of the design to the projected Manufacturing Quality defect. First, the Factor Variable of each defect is mentioned. Next, a Specific Defect is assigned in accordance with the DFQM defect classes. Finally, the Manufacturing Quality Defect is stated as an effect of the Specific Defect.

In the Conclusion, the Manufacturing Quality Defects are totaled, as described in Chapter 4, and the relative expected frequency of the defects are discussed.

## CHAPTER 2

### REVIEW OF DESIGN FOR MANUFACTURABILITY

#### 2.1 Design for Manufacturability Defined

Design for Manufacturability (DFM) is a methodology that designates the product design phase as the first step in manufacturing. DFM provides the means to implement manufacturing decisions in the early stages of product development through the use of information. The objectives of the DFM [8, 9] approach are as follows:

1. To identify design concepts that are easy to manufacture.
2. To focus on component design for ease of manufacture.
3. To integrate manufacturing product design and process design to satisfy all product requirements.

This philosophy is applied to manufacturing operations by concentrating on two main areas: the DFM design approach and the DFM tools used to monitor the progress of the product design with respect to its objectives.

The basic DFM design approach, shown in **Figure 1**, begins with a proposed product concept, a proposed process plan and design goals. Next, product and process concepts are optimized to promote ease of manufacture. The third step focuses on simplifying the product design by utilizing product components that are easy to assemble (insertion and handling). The fourth step checks product and process conformance to verify that the product “fits” the process. The fifth step seeks to optimize the product function through refining design parameters with respect to design objectives. Each of the

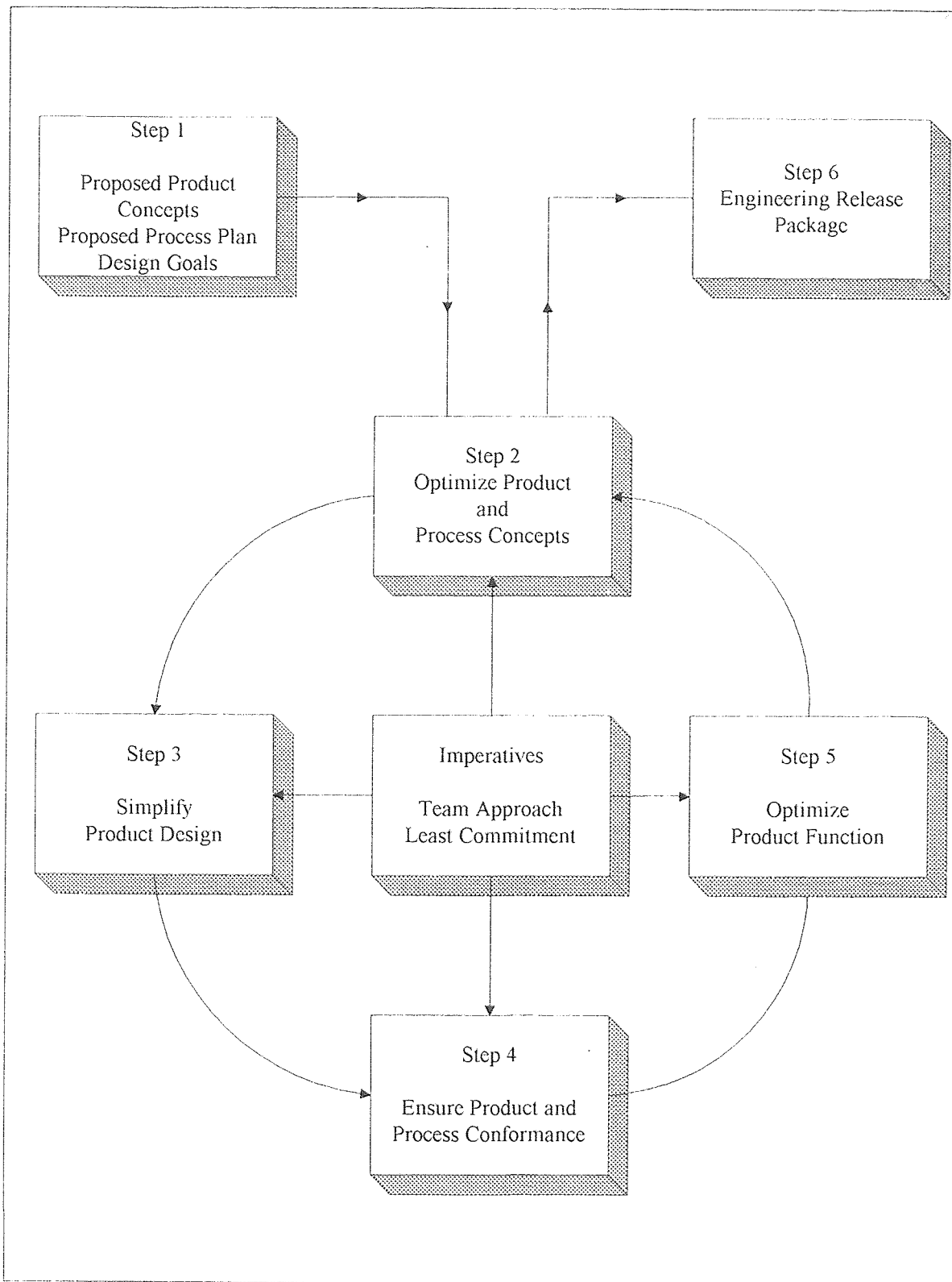


Figure 1 Typical DFM Process

five steps is continuously driven by imperatives built directly into the organization such as a team approach to engineering solutions and “Least Commitment”, an attitude that encourages open-minded problem solving. Finally, an engineering release package consisting of manufacturing recommendations and process plans is compiled for production.

Throughout the DFM design process, a standard list of guidelines are used to develop and refine product designs and process plans. The DFM guidelines are as follows:

1. Design for a minimum number of parts.
2. Develop a modular design.
3. Minimize part variations.
4. Design parts to be multi-functional.
5. Design parts for multi-use.
6. Design parts for easy fabrication.
7. Avoid separate fasteners.
8. Minimize assembly directions (design for “top down” assembly).
9. Maximize compliance (design for easy assembly).
10. Minimize handling.
11. Evaluate assembly methods.
12. Eliminate or simplify adjustments.

Design tools have been developed to help design teams to meet DFM objectives. There are a variety of design tools available to the designer, focusing on any one of several design issues. There is, however, one common element that is present in all of these design

tools and that is the need for product and process information. Information from all areas of manufacturing is necessary to address all pertinent design issues early on. Two design tools will be discussed: Boothroyd and Dewhurst Industries method [3] and the Axiomatic Approach [10].

### **2.1.1 Boothroyd Dewhurst Industries Method**

The Boothroyd Dewhurst Industries (BDI) method is concerned with reducing the cost of the end product by simplifying its design. The simplification process centers around the DFM guidelines of “reducing the number of parts in an assembly” and “designing parts that are easy to fabricate and assemble”. The BDI method contains the following generalized activities:

1. Selection of the assembly method.
2. Computation of the design efficiency.
3. Implementation of design improvements.

The selection of the assembly method is determined by a variety of factors. First, the annual production volume per shift, the number of parts in the assembly, the total number of parts necessary to produce all product styles and the pay back period need to be defined. Then, the ratio of product styles to the number of parts in the assembly is calculated. With this information, the most appropriate assembly can be selected using the BDI Assembly method chart. The following is a list of assembly methods as illustrated in **Figure 2**.

### ASSEMBLY METHOD SELECTION CHART 1-1

#### CONDITIONS FOR ECONOMIC APPLICATION OF VARIOUS ASSEMBLY SYSTEMS

PRODUCT WITH ONLY ONE STYLE  
(NT/NA = 1)

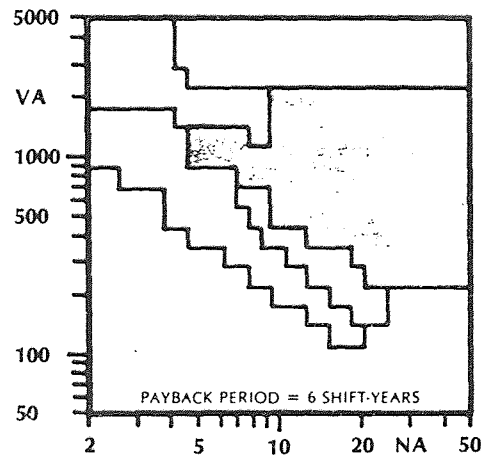
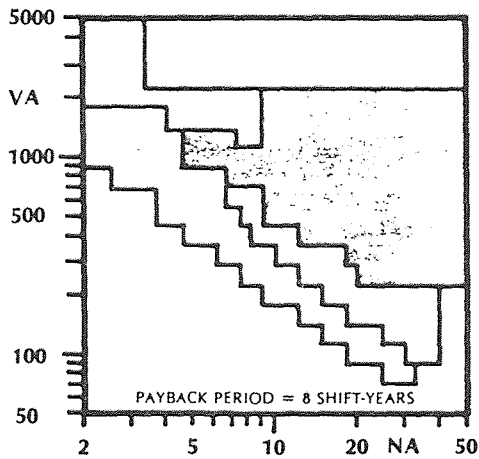
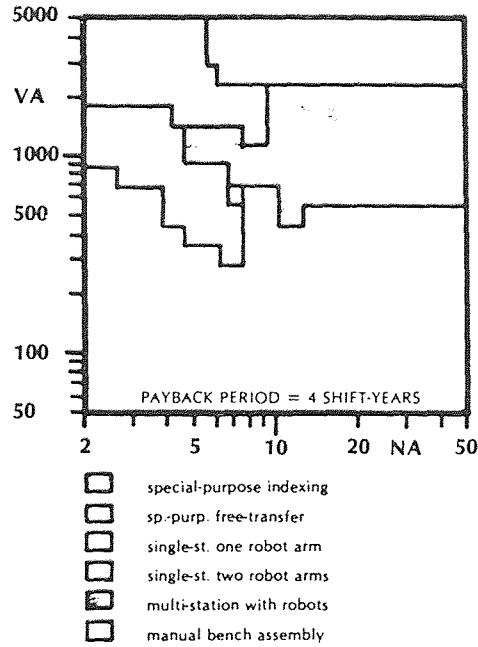
VA = annual production volume measured in thousands - the average number of assemblies of all styles produced during the equipment payback period

NA = number of parts in the assembly - the average number of parts or sub-assemblies to be assembled on assembly system

NT = total number of parts - the total number of parts or sub-assemblies from which various product styles can be assembled

(charts produced from micro-computer software developed by Boothroyd Dewhurst Inc.)

\*Note: Automatic systems are excluded unless system utilization is greater than 50%.



©1982, 1985, 1989 Boothroyd Dewhurst, Inc.

Figure 2 Assemble Method Selection Chart

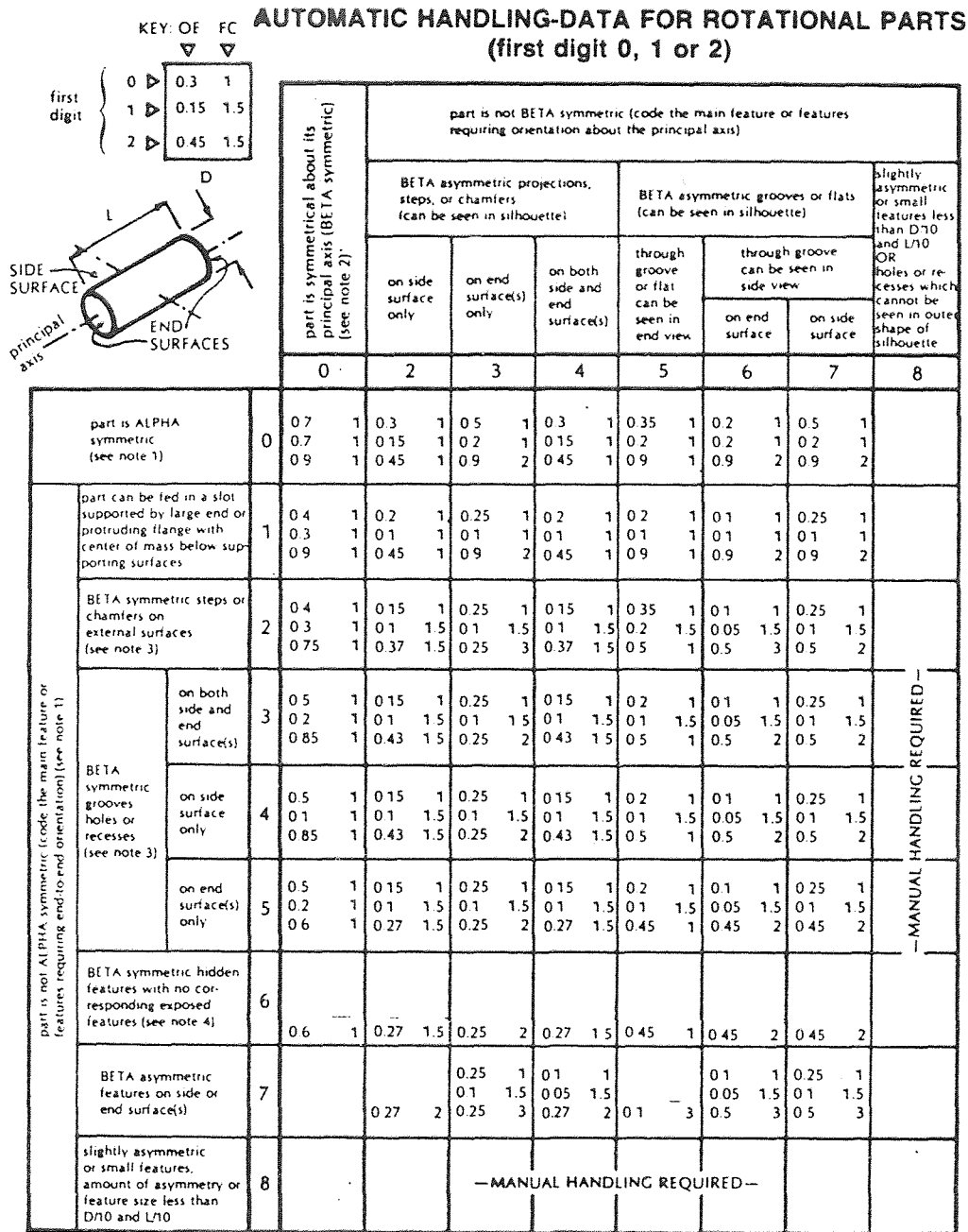
1. Manual assembly
2. Special purpose
  - a) Assembly is advanced by a synchronous indexing transfer device.
  - b) Assembly is advanced by free transfer device (non-synchronous).
3. Robotic assembly
  - a) Single work station is operated by one general-purpose robot arm.
  - b) Single work station is operated by two synchronized general-purpose robot arms.
  - c) Multiple work station free-transfer machine with two or more general purpose robot arms.

The BDI method evaluates each design solution through the comparison of design efficiencies. **Figure 3** shows a worksheet that was developed to aid the designer in systematically evaluating the physical characteristics of the design and how they effect handling and insertion operations. **Figure 4** is an example of a BDI chart that provides handling times for automated product assembly.

As mentioned before, BDI focuses on “reducing the number of parts in an assembly” and “designing parts that are easy to fabricate and assemble”. To accomplish these tasks, the approach suggests analyzing the theoretical minimum number of parts for candidates of elimination (parts with a “0” in column 9, **Figure 3**). The BDI method also suggests refining geometric characteristics in an effort to reduce insertion or handling times, thus reducing operation costs. The benefit of such modifications are evidenced through the recalculation of the design efficiency.







©1982, 1985, 1989 Boothroyd Dewhurst, Inc.

Figure 4 Automatic Handling-Data for Rotational Parts

### 2.1.2 Axiomatic Approach

The Axiomatic Approach to design attempts to provide a “good” design reference. In this approach, Functional Requirements (FR’s) of the design are defined. Design decisions are then made within the framework set by design axioms. Design axioms are universally accepted design principals based on common elements found in all “good” designs. The design axioms are defined as follows:

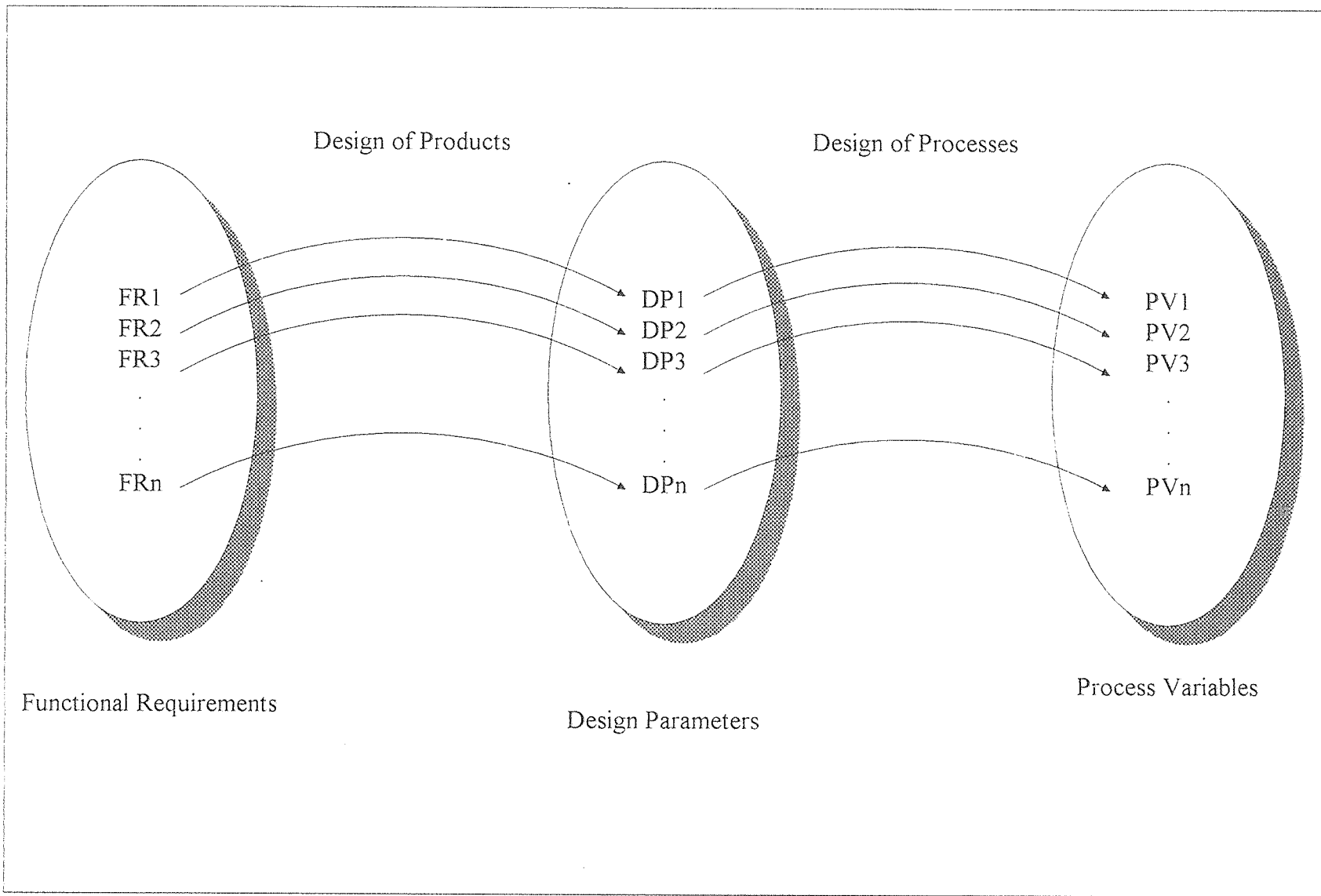
Axiom 1: Maintain the independence of all functional requirements (Independence Axiom).

Axiom 2: Minimize the information content (Information Axiom).

Design Parameters (DP’s) are aspects of the design that represent how each FR is to be satisfied. DP’s should be selected such that the FR’s remain independent of one another (Axiom 1). After the defining the FR’s and DP’s, a manufacturing process is selected to produce the desired product. The appropriate process will feature Process Variables (PV’s) that can support all of the previously defined DP’s. The relationships FR’s to DP’s and PV’s are shown in **Figure 5**.

Information pertaining to the design is illustrated in the forms of drawings, design equations, material specifications and operational instructions. Information is necessary for the operation of processing equipment, the control of material flow and the establishment of processing conditions. A manufacturing system can be simplified by minimizing the amount of information required to produce a desired product (Axiom 2). Information content is quantified by the following equation:

$$I = \text{Log}_2(1/p)$$



**Figure 5** Axiomatic Approach: Functional Requirements, Design Parameters and Process Variable Relationships

where  $p$  is the probability that the FR's are satisfied with the given amount of information (in bits). The probability that a FR is satisfied ( $p$ ) is calculated by:

$$p = (\text{range of values})/(\text{tolerance of values})$$

## 2.2 Quality Engineering

Quality can be defined as any design, process or business characteristic that prevents society from experiencing a loss as a result of a defective product. Manufacturing organizations, and businesses alike, have sought to engineer quality into their goods and services to reduce such losses. Quality engineering can then be described as a structured, organization-wide effort to improve the overall quality of a company and its products.

### 2.2.1 Total Quality Management

Total Quality Management (TQM) [1, 5] is an example of a organization-wide quality program. TQM has a three pronged approach to infuse quality. First, it defines quality as it pertains to the business at hand. Second, it isolates areas of low quality and third, it seeks to develop quality management programs to increase quality. Quality, or how a product or service measures up to pre-existing expectations, is defined by the following characteristics:

1. Functionality: complete execution of the products function.
2. Usability: how the product function is executed.
3. Reliability: product life and conformance.
4. Performance: the level at which the function is executed.

5. Serviceability: technical support available for the product.
6. Availability: supply of product available to the consumer.
7. Price: the cost to obtain and maintain the product to the consumer.

Low quality can result from failures in any of the aforementioned characteristics. When quality decreases, increased costs are experienced as efforts are made to improve and maintain quality. This cumulative cost, the Quality Management Cost (QMC), is defined as the price paid for 100% conforming products. QMC's are realized by companies through the implementation of programs to prevent and appraise low quality. The costs of prevention includes TQM implementation, process planning and training, whereas the cost of appraisal encompasses incoming/outgoing inspection, process inspection and customer surveys.

A high QMC can be detrimental to an firm by perpetuating low quality. Companies are sometimes unwilling to pay the entire cost for 100% quality. As a result, they frequently take short-cuts and attempt to break even at a point where the cost to implement quality measures matches the costs incurred by supplying low quality products to the consumer. Such costs, also referred to as Quality Failure Costs, are accumulated losses resulting from both internal (scrap, rework, downgrading and retesting) and external (product warranties, returned items, lost sales) sources. To reduce Quality Failure Costs, TQM programs are generally implemented in the following areas:

1. Supplier management
2. Quality assurance
3. Process control

4. Quality control
5. Customer/competition management

### 2.3 Taguchi's Method

Within the arena of quality engineering, there is an intense effort to assure product quality. As a result, several design philosophies have evolved to engineer high levels of quality directly into the product. Two such systems are Taguchi's method and Quality Function Deployment.

Taguchi's method [2, 4, 7] is a system which attempts to reduce the loss imparted to society resulting from defective products. This is accomplished by developing specifications and then producing designs and manufacturing operations capable of satisfying these specifications. The Taguchi methodology attempts to lower costs and increase productivity by improving the quality of existing product designs and processes. These improvements are realized by identifying variations that are controllable and developing a design that is more tolerant to variations (robust design).

The Taguchi method measures loss through the application of the Quality Loss Function (QLF). The QLF is a quadratic relationship between the financial loss and the functional specifications of the product design. The QLF is defined by the following:

$$L = k(y-m)^2$$

where L is the financial loss, y is the value response, m is the target value and k is the loss constant. The loss constant (k) is representative of Performance Variation. Performance variation is a variation from the functional specification which decreases the quality of a product, incurring additional costs. Therefore, the loss constant is determined by:

$$k = (\text{functional specifications})/(\text{production range})$$

With the quality loss determined, the Taguchi method concentrates on refining the design parameters. The goal is to control the mean values and variation about these values within the given design. The Signal-to-Noise Ratio presents the ratio of the mean to its standard deviation and is defined for three generalized applications.

Nominal-the-Best (Type N) involving physical dimensions such as voltages, amps, length:

$$S/N = 10\log_{10}[1/n(S_m - V_c)/V_c], \quad S_m = (\sum y_i)/n, \quad V_c = [\sum y_i^2 - (\sum y_i)^2/n]/n$$

where  $y_i$  is an observation and  $n$  is the number of observations.

Smaller-the-Better (Type S) for noise, contamination and hazardous material:

$$S/N_S = -10\log_{10}[1/n(\sum y_i^2)]$$

Bigger-the-Better (Type B) for strength and power:

$$S/N_B = -10\log_{10}[1/n\sum 1/y_i^2]$$

With the analysis tools in place, the Taguchi method applies orthogonal arrays to reduce the size of the experimental space. Linear graphs associated with each array are presented to illustrate the pattern between single factors (parameters) and two factor interactions within the design. With multi-factor designs, the use of orthogonal arrays allows the analysis of independent factors and then expands the search by examining the tolerances of each factor.

## 2.4 Quality Function Deployment

Another method of engineering quality directly into products is Quality Function Deployment [1, 5, 11]. QFD is a product development methodology that continuously integrates information from all manufacturing operations. The goal of QFD is to satisfy the

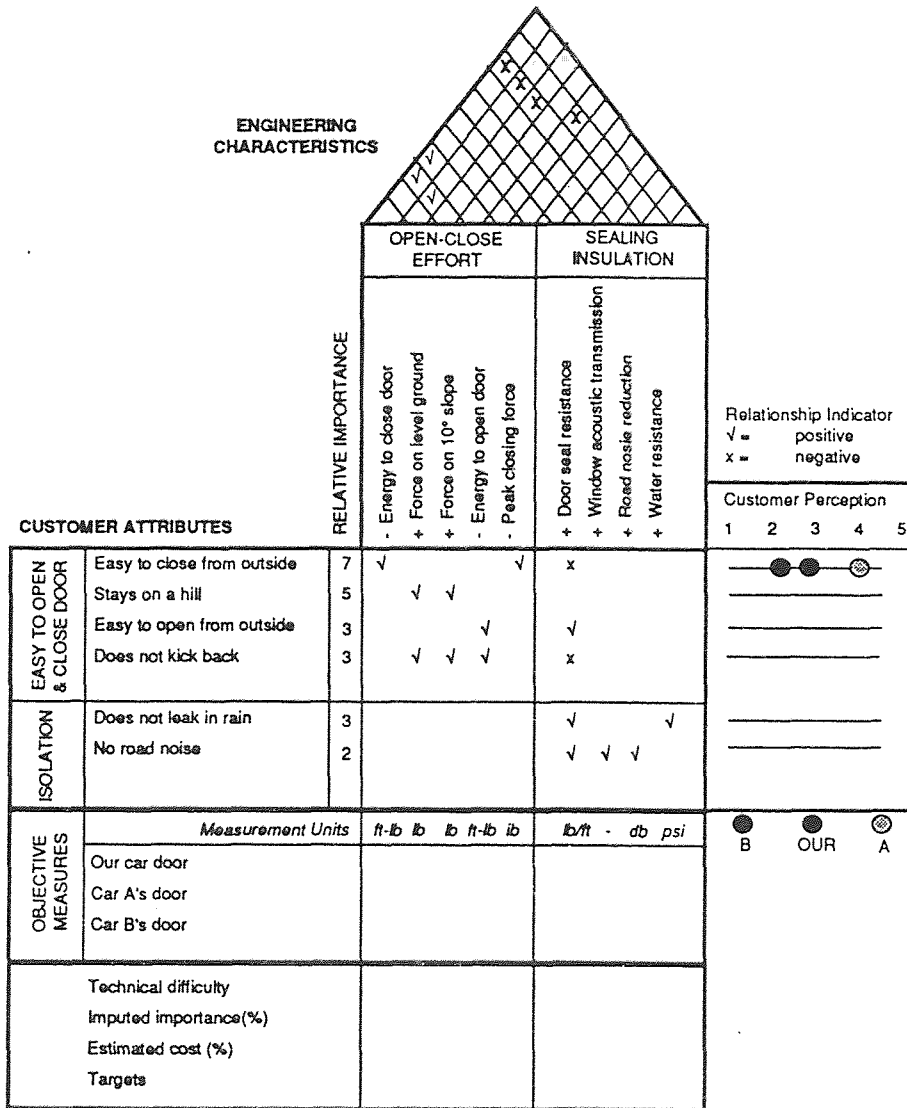
consumer by translating customer demands into design targets and quality assurance guidelines. QFD incorporates four matrices into the product development cycle. Each matrix, or “House of Quality”, assesses the relationship between two groups of manufacturing characteristics. Each “house” is successively linked, providing a direct path from determining customer wants and needs to instituting a production plan. The design of the end product is largely decided by the first “house” which relates customer demands with attributes of a proposed design.

QFD begins by surveying the market to determine consumer demands, quality issues and product selling features. **Figure 6** shows this information listed as Customer Attributes. Each attribute is assigned a weighted number to demonstrate its relative importance to society. The customers perception of how well each demand is satisfied by the companies product, as well as by those of the competition, is indicated using scaled values.

Next, a list of measurable design features or Engineering Characteristics is compiled. Each characteristic should be directly linked to at least one customer attribute. The relationships of customer attributes and engineering characteristics are depicted in the crosshatched region of the diagram. These relationships are described using a standard scale to indicate a positive or negative impact on one another. The engineering characteristics of the design are continuously benchmarked against those of the competition using measurable quantities in the Objective Measures section of the diagram.

Finally, the efforts exerted to produce the given product design or design modifications are relayed. The design team assesses the difficulty of producing the design





Source: J.R. Hauser and D. Clausing, "The House of Quality," Harvard Business Review, 1988, May-June

Figure 6 "House of Quality" Diagram

and then estimates the importance of each feature and the costs associated with integrating each into the design.

## 2.5 Design for Quality Manufacturability

Design for Quality Manufacturability (DFQM) [6] is a design tool that enables the user to produce designs that easily translate into manufactured products. The relative effort of translating a design, or the design's manufacturability, can be improved by understanding which attributes of the design are likely to spawn product defects during assembly. Improving the quality manufacturability of a design will reduce the costs incurred by traditional quality measures such as process control and sampling, as well as, reduce the product development cycle time and a product's time to market. **Figure 7** shows the basic DFQM structure for estimating the quality manufacturability of a design.

The DFQM method recognizes that there are design attributes or Influencing Factors within every design that are capable of generating defects during assembly operations. These Influencing Factors are present in the geometrical features of a part, material properties of a part, primary process by which a part is manufactured, fastening system, product assembly procedure, part interrelationships and tolerance interrelationships. These Influencing Factors are further broken down into sub-groups of Factor Variables. Factor Variables are specific design features that are directly related to one or more Specific Defect within the product.

Error Catalysts are actuating forces that produce Specific Defects when the appropriate Factor Variable is present. With information from Product Design and

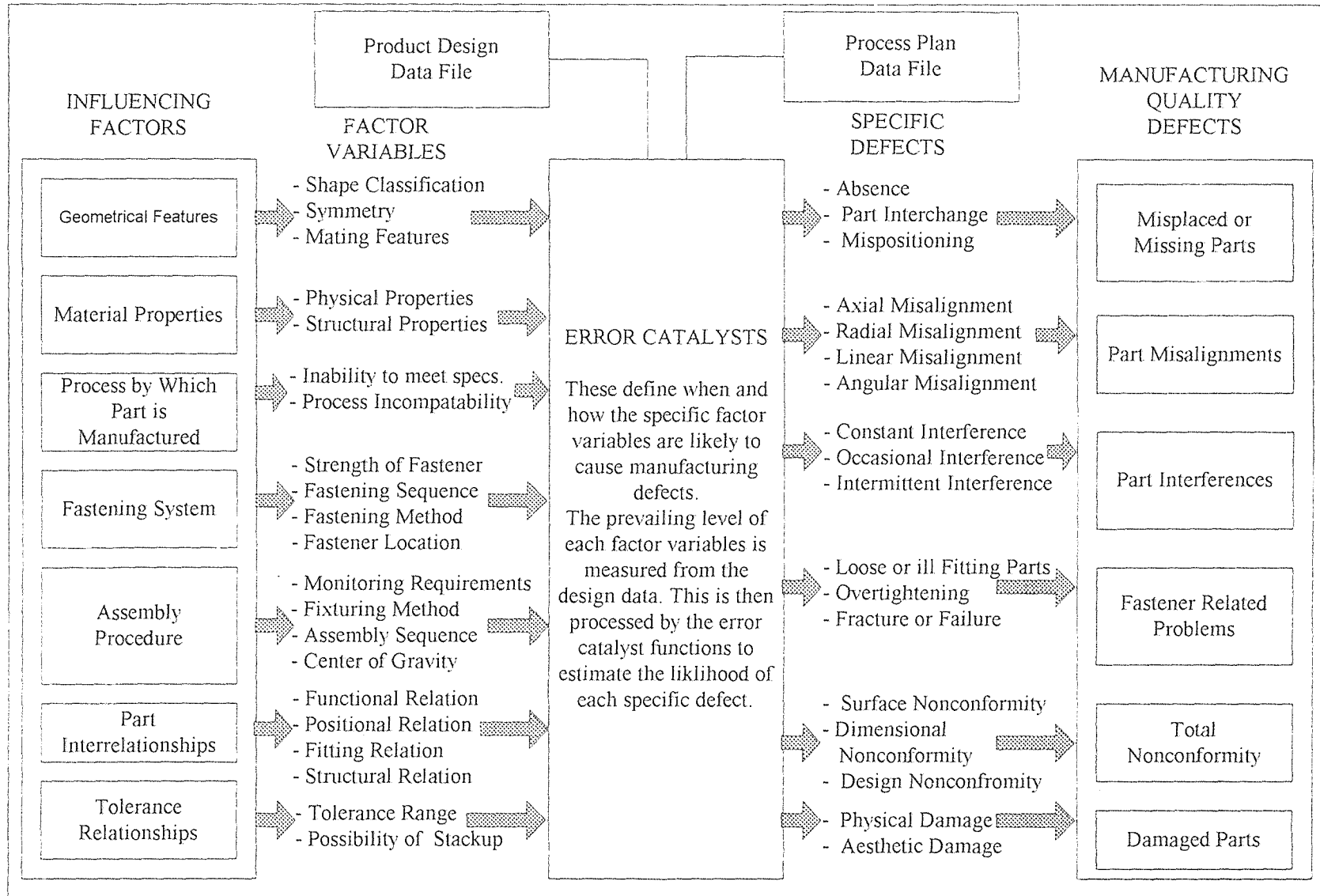


Figure 7 Estimating the Quality Manufacturability of a Design

Process Plan Data Files, Error Catalysts Functions approximate the likelihood that a Factor Variable will generate a Specific Defect.

Specific Defects are groups of related defects that may occur given a related Factor Variable. Although their causes may differ, Specific Defects within the same class will produce a common Manufacturing Quality Defect. Manufacturing Quality Defects are general classes of defects frequently found in assembled products. These defects are related to the processes by which a component is manufactured or assembled.

As the Error Catalyst Functions use information from the Product Design and Process Plan Data Files, the likelihood that a Factor Variable will produce a defect is calculated. With this information, designers can make early design modifications to reduce product development times and increase the overall quality of the end product.

## CHAPTER 3

### CASE STUDIES OF ASSEMBLY DEFECTS IN MANUFACTURED PRODUCTS

From a quality perspective, it is important to realize that a sound design does not always translate well into a manufactured product. The relative difficulty of translating the design into a product, or its manufacturability, is affected by a variety of influencing factors inherently present in all designs. The quality of a design's manufacturability can be increased if design decisions are made with an understanding of how these influencing factors affect the end product.

The following case studies will illustrate the application of Design for Quality Manufacturability for the purpose of improving the quality manufacturability of selected assembled products. The application begins by summarizing the functional requirements of the product and the component interactions within the assembly. Then, a list of primary defects that may occur in the finished product is compiled. The primary defects are analyzed to identify which influencing factors are capable of contributing to these defects. With the influencing factors known, design modifications are suggested to reduce the likelihood of the primary defects.

#### **3.1 Case Study 1: Emergency Brake**

##### **3.1.1 Functional Requirements**

The functional requirements of the emergency brake are as follows:

1. To provide brake force.
2. To maintain brake force.
3. To release brake force.

4. To indicate activation of brake.

### 3.1.2 Method of Function

The brake components, as shown in **Figure 8**, are secured to a steel platform, with the moving components having pivot points between the platform and cover bracket. The foot pedal assembly consists of the pedal lever, hold jack and geared pedal edge all of which pivot about a central rivet. The ratchet assembly, consisting of the geared ratchet drum, a drum spring, a release lever and a release lever spring, is similarly constrained by both the platform and cover bracket. There is also a rubber stop press fitted into the cover bracket to prevent the pedal lever from contacting the cover during brake disengagement.

The geared ratchet drum meshes with the geared pedal edge and prevents the pedal lever from disengaging the brake. The drum is inserted into the drum spring which is constrained by the intersection of the ratchet drum and platform. The free end of the spring interfaces with the release lever (to facilitate the release of the pedal lever). A spring tensions the release lever and is constrained by both the lever and a through hole in the cover bracket.

An indicator switch is fixed to the interior of the steel platform by a machine screw and a locating protrusion that mates with a through hole in the platform. The switch (normally closed) interfaces with the geared pedal edge when the pedal lever is in the released position. When engaged, the switch opens to indicate the absence of brake force. There is a plastic bracket snap fitted into the base to protect the indicator switch and exposed brake cable.



**Figure 8.1** Top View of Emergency Brake



**Figure 8.2** View of the Emergency Brake Ratchet Sub-Assembly

A channel in the pedal lever guides the brake cable from a through hole in the platform to the hold jack, where it is secured. The cable housing has a snap fit metal clasp that secures it to the platform. As the pedal lever is engaged, the hold jack pulls the cable along the channel, incrementally increasing the brake force.

### 3.1.2 Primary Defects

1. Brake jams.
2. Brake wire disengages.
3. Vibration while driving.
4. Increased human input force is needed to release or engage brake.
5. Brake force is not maintained.
6. Light will not extinguish.

### 3.1.3 Analysis of Primary Defect and Factor Variables

1. *Brake jams.*

The release lever spring mates with the release lever and cover bracket. If the spring is not constrained, it could dislodge and interfere with the motion of the geared ratchet drum. Also, mispositioning the ratchet during assembly or the geared pedal edge could cause the gear teeth to misalign and jam.

2. *Brake wire disengages.*

The brake cable slides in and out of the cable housing as it engages and disengages the wheel brake mechanism. If the cable is not fastened properly to the brake mechanism



(or if the cable is not lubricated properly), the cable may slacken and dislodge from the hold jack.

3. *Vibration while driving.*

The steel platform that secures the brake components is fastened to the frame of the vehicle by 3 bolts. If the fasteners are not located properly or if an inadequate number are used, the emergency brake may vibrate during vehicle operation.

The foot pedal assembly lever and ratchet assembly are fastened to the platform and cover bracket by rivets. If these rivets loosen, it could cause one or more components to vibrate during vehicle operation.

4. *Increased human input force is needed to release or engage brake.*

If the ratchet assembly or the foot pedal assembly is mispositioned, friction between mating surfaces may increase. These frictional forces must be overcome to engage or disengage the brake. Similarly, if the geared drum ratchet or geared pedal edge are inadequately lubricated, frictional forces between their mating surfaces may occur.

5. *Brake force is not maintained.*

The ratchet drum spring is constrained by the intersection of the geared ratchet drum and the platform. If the spring is not properly constrained, it will not secure the ratchet drum in the locked position. Without the drum locked, the brake force will decrease.

6. *Light will not extinguish.*

The geared pedal edge engages the indicator switch to indicate the absence of brake force. If the switch or the foot pedal assembly are not fastened securely, it may cause

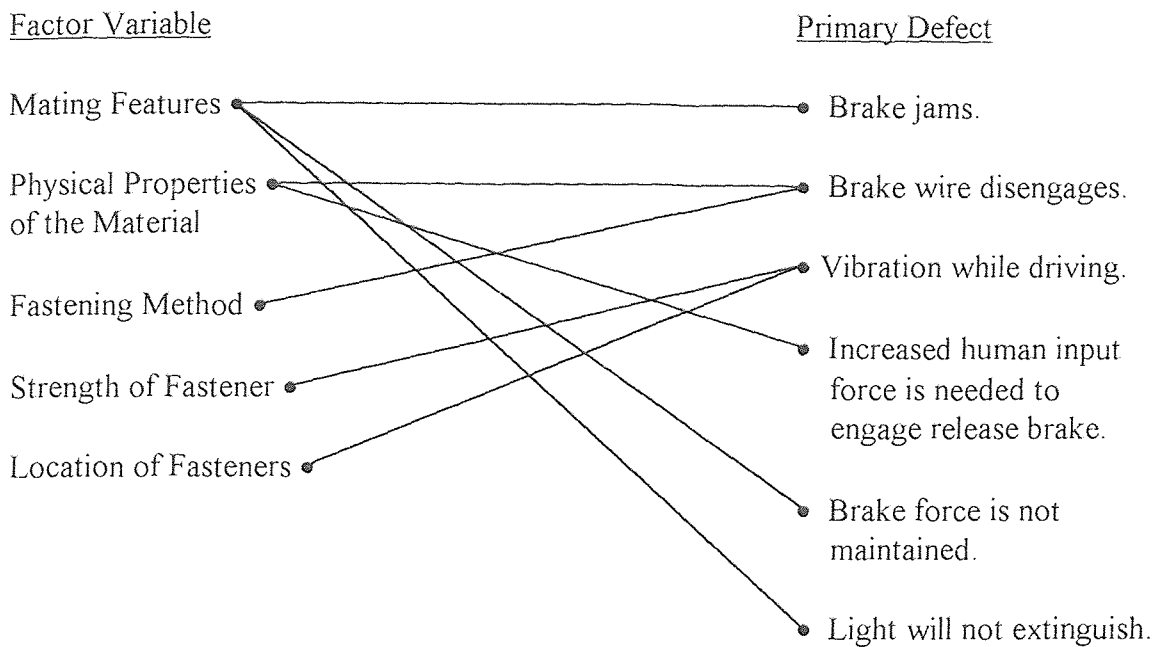
misalignment. Misalignment may prevent the switch from opening. This would continuously indicate the presence of brake force despite its absence.

### **3.1.5 Suggested Design Improvements**

1. Press fit the brake indicator into the platform to eliminate the possibility of misalignment with the geared pedal edge.
2. Contour the surface of the cover bracket as to force the pedal lever into a more precise position with respect to the ratchet assembly. This would prevent misalignment.
3. Redesign the constraints of the ratchet release lever spring to prevent dislodging and interference with geared surfaces.
4. Increase the number of fastening locations of the platform (to the vehicle) to reduce vibration during vehicle operation.
5. Add a metal snap fit cap to cover the hold jack. This would prevent the hold jack from dislodging.

### **3.1.6 Factor Variable\Primary Defect Relationships**

The following is a graphic representation of the relationships between Factor Variables within the design and Primary Defects that may appear during assembly. Some Primary defects may occur from a variety of Factor Variables, in one or more of the assembly components.



### 3.2 Case Study 2: Portable Overhead Projector

#### 3.2.1 Functional Requirements

The functional requirements of the portable overhead projector are defined as:

1. To redirect a horizontal image onto a vertical surface.
2. To produce a clear, enlarged image.
3. To fold and compact its components into a rectangular carrying case.

#### 3.2.2 Method of Function

The portable overhead projector assembly has two main areas of functionality: Portability and Projection. The following list of assembly components are grouped according to their functional contributions.

##### Portability Operation

1. Casing

- a) Handle
  - b) Cover
    - i) Latch
    - ii) Hinge
  - c) Projector body
  - d) Elevator
2. Mirror bracket
  3. Column and swing arm
  4. Projection Head

The portable projector, as shown in **Figure 9**, is contained within a compactable casing with an attached handle for carrying. The casing consists of a cover, projector body and an elevator. The hinged cover has a tensioned latch to secure the cover when closed. The cover also locks in the vertically open position to allow the extension of the projection head.

When the cover is opened, the column is vertically raised and locked into position. Simultaneously, the elevator extends through a through hole in the projector body, raising the entire assembly. In addition, a mirror bracket pivots to position the body mirror. The column pivots about the projector body and is locked vertically into place by a spring tensioned lever. The column is connected to the mirror bracket, by linkage, to facilitate the unfolding of the elevator and the positioning of the body mirror. The column is tensioned by a spring to maintain smooth folding and unfolding motions. A swing arm is



Figure 9.1 View of Compacted Overhead Projector

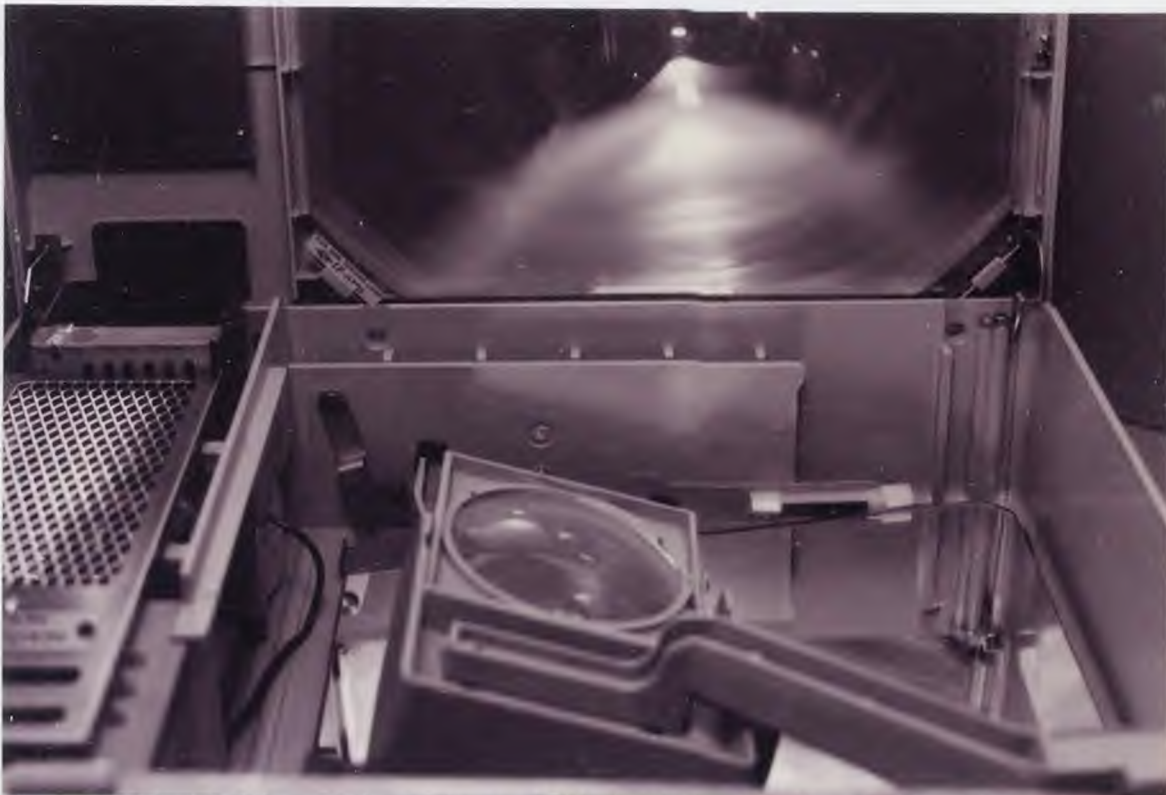


Figure 9.2 Inside View of the Projector With the Projection Head in Nested Position



**Figure 9.3** Inside View of the Projector Showing Mirror, Linkage, Elevator and Column



**Figure 9.4** Inside View of the Projector Showing Switch, Body Lens, Hinge and Elevator



**Figure 9.5** View of Overhead Projector Projection Head

attached to the end of the column with one pivot point. A metal stop on the swing arm maintains its position when extended.

The projection head, fastened to the other end of the swing arm, consists of a body, focus adjustment, platform, lens, lens mount and mirror. The mirror extends to the open position by pivoting about the lens mount (2 locations).

### Projection Operation

#### *Electrical*

1. Switch sub-assembly
2. Fan sub-assembly
3. Light sub-assembly
4. Printed circuit board (PCB)
5. Electrical cord rewind

#### *Mechanical*

1. Body mirror
2. Stage
  - a) Body lens
  - b) Glass plate
3. Projection head
  - a) Body and focus adjustment
  - b) Platform
  - c) Lens mount and lens
  - d) Mirror



#### 4. Bulb Changer

Once power is supplied to the projector, via retractable power cord, engaging the switch activates the lamp and fan. The lamp is responsible for highlighting images on a horizontal transparency, while the fan acts to cool the assembly components. The lamp and fan sub-assemblies are wired to a PC board.

A lens, in close proximity of the lamp, focuses light onto the body mirror (which is fastened to the mirror bracket) at the bottom of the projector body and redirects it to the cover. The cover has a through hole for the insertion of the stage. The stage consists of the body lens and a glass transparency plate (the body lens is mounted on the inside of the cover, the glass transparency plate is mounted on the outside). The transparency rests on the glass plate and is illuminated from below by the redirected light. The image is picked up by the lens in the projection head and is redirected by its mirror to provide a vertical image. The focus adjustment alters the focal length by raising or lowering the projection head platform.

#### **3.2.3 Primary Defects**

1. Cover does not open or close.
2. Projector components do not fold or unfold.
3. Image is not properly projected onto wall.
4. Image cannot be focused.

#### **3.2.4 Analysis of Factor Variables and Primary Defects**

1. *Cover does not open or close.*

The cover is secured by a tensioned lever while closed. This lever has two pivot protrusions that are anchored by the intersection of the cover and a mounting plate. When pulled, the lever displaces a metal latch that clears a mating surface of the projector body. The metal latch has an extension that mates with a through hole on the mounting plate. If the mating features between the metal latch and mounting plate are mispositioned, the latch will not interlock with the projector body to secure the cover.

The cover pivots about two protrusions fastened to the inside of the projector body. Two hinges with through holes are fastened to the cover and interface with these pivot protrusions. The tips of both hinges are constrained by two through holes in the projector body. If the tolerance relationship between the hinge and the projector body is violated, misalignment of the hinges and pivot protrusions may occur. This misalignment may cause a pinch point, preventing the cover from opening.

One of the hinges is connected to prop which holds the cover in the raised position. The prop has a channel that slides along a screw which is fastened to the interior of the projector body. If the tolerance relationship between the screw and the prop is violated, the prop may jam. With the prop stuck, the cover will not open or close.

## *2. Projector components will not fold or unfold.*

The elevator extends downward through the projector body during opening. The elevator forms box with a bottom, two fixed sides and two collapsible sides. The fixed sides contain four channels on their lower inside surfaces. Each set of opposing

channels mates with two pivots protrusions extending from its corresponding collapsible side. The collapsible sides also mate with the projector body using two pivot protrusions constrained by a metal plate and machine screw. If any of the pivot points or channels are out of tolerance or otherwise misaligned, the elevator may not fully extend.

The mirror bracket has four pivot points: two press fit pivot linkages secured to the collapsible sides of the elevator (adjacent to the fan and light sub-assemblies) and two plastic channels that mate with pivot protrusions extending from the pivot point of the elevator-collapsible side interface. Similarly, if any pivot points or channels are out of tolerance or misaligned, the bracket may not position the mirror. The mirror bracket also has a functional relationship with the elevator. Therefore, if the elevator malfunctions, the mirror bracket will also malfunction.

The column is pinned, by means of press fit, to the projector body. It has a press fitted linkage that connects the column to both collapsible sides. There is a spring that extends from the linkage near the base of the column to one of constraints (opposite of the fan and light sub-assemblies). The spring adds tension to the linkage, providing smooth folding and unfolding motions. Any tolerance variations of the pivot points may cause the linkage to bind, preventing the column from raising. Since the column is linked to the collapsible sides and the collapsible sides are linked to the mirror bracket, a three way functional relationship exists. If one of the three fail to open, the remaining two will also fail to open.

A tensioned lever extending from the projector body releases the column for opening, as well as, locks the column in the vertical position. The lever has one pivot point about the projector body (machine screw) and is tensioned by a spring running from a through hole in the lever to a mounting screw of the fan sub-assembly. The spring is fastened at these locations by crimping its ends. If these part surfaces fail to mate appropriately, the spring could dislodge. Without being tensioned, the lever would fail to hold the column in the vertical position. The linkage spring, responsible for tensioning the column, is also fastened by the crimping of its ends. If the spring were to dislodge at either end, it would interfere with motion of the linkage.

*Image is not properly projected on wall.*

The light sub-assembly consists of lamp, bulb changer, a reflector and a lens mounted on a common platform. The reflector is mounted, opposite the lens, on a vertical bracket by four metal clips. The clips are fastened to the reflector bracket with one machine screw. The bracket, in turn, is pinned to the sub-assembly platform. A pin is inserted into a spring and secured by two metal snap fit clasps. The spring is constrained by the platform and the reflector mount. If the metal clasps are mispositioned, the pin may dislodge causing the reflector to misalign with the lens. Misalignment would deliver an insufficient amount of light to highlight the transparency.

The lens is secured by a vertical mount that is fastened to the light sub-assembly platform by two machine screws. Four metal clips extending from the mount mate with the lens and hold it in position. The mating features of the parts may cause the lens to

dislodge during carrying. Without the lens in place, the light would not be magnified to the proper intensity for imaging.

The light sub-assembly also contains two projector bulbs. When a bulb burns out, the user replaces it by engaging the bulb changer lever. The lever slides the new bulb in front of the reflector and lens, supplying power to it. The old bulb is side stepped from the reflector and lens, removing it from the electrical circuit. The lever is fastened to the bulb fixtures with a channel that slides along a screw (fastened to the projector body). If the channel and screw mating features do not interface properly or if they are out of tolerance, the lever will not replace the old bulb causing no illumination for imaging.

The body lens is fastened to the inside of the cover by two plastic constraints and a metal snap fit clasp secured by machine screws. If the metal clasp is out of tolerance, the body lens may dislodge from the cover. The glass transparency plate is fastened to the outside of the cover by two plastic constraints and three metal snap fit clasps. The metal clasps are each positioned by one plastic post extending from the cover and are secured by one machine screw. If the posts are out of tolerance, the metal clasps will not flush mount against the cover. With the metal clasps mispositioned, the glass plate may dislodge.

The arm lens is positioned over a through hole in a mounting plate on the projection head platform and is secured by two plastic constraints and one plastic snap fit. If the lens or mounting plate does not mate properly or if they are out of tolerance, the lens may dislodge from the platform. Without the arm lens, the image will not be legible due to the incorrect magnification or orientation of the image.

#### 4. *Image cannot be focused.*

The body of the projection head is mounted to the end of the swing arm extending from the column. The platform pivots about the projection head body and is pinned in three locations with machine screws. A spring is inserted around one pivot and is constrained by the body and platform. There is a channel on the platform that mates with one end of a plastic link. The other end of the link is inserted into a through hole of the projection head body and fastened to the focus adjustment knob. The other end of the platform is connected to the mounting plate which supports both the arm lens and arm mirror. The mounting plate is secured to the platform at three pivot points by machine screws. The arm mirror pivots about the mounting plate in two locations by machine screws. The focus adjustment knob, platform, mounting plate and arm mirror are all secured by machine screws at their pivot points. This fastening system may introduce a defect due to the rotational forces applied to the screws. Any one of the components may become dislodged, preventing the focus of the image.

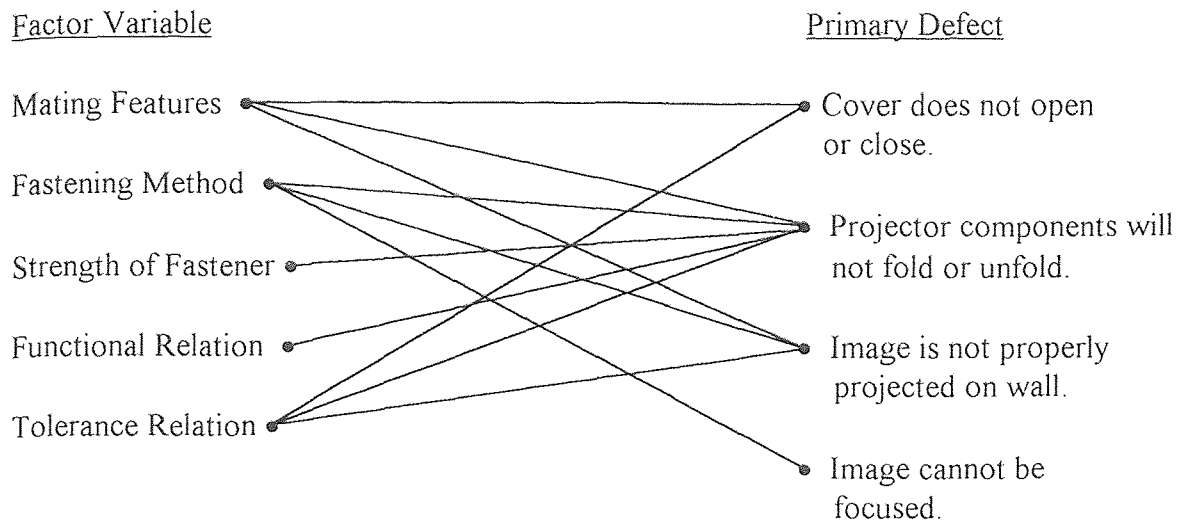
#### **3.2.5 Suggested Design Improvements**

1. The function of the metal latch should be incorporated with those of the lever. The lever should directly mate with the projector body to secure the cover. This would eliminate any defects due to the mispositioning of the metal latch.
2. The cover hinges should be press fitted to the pivot protrusions. The new hinge should be relocated in the projection body to eliminate any interference.

3. The prop should be replaced with a simpler free standing prop. This would eliminate the possibility of jamming.
4. The pivots used for the folding and unfolding of the projector components have plastic to metal contact. It is suggested to use a lubrication between all such mating surfaces to reduce friction and the possibility of hang up.
5. The springs used in the assembly have one or both ends fastened by crimping the ends about a through hole or protrusions. The springs should be fastened by machine screws to reduce the possibility of dislodging.
6. Plastic snap fits should replace the metal snap fit clasps responsible for securing the body lens and glass transparency plate to the cover. This would eliminate the possible misalignment with the plastic posts.
7. The projection head uses machine screws to provide pivot points for its components. It is suggested to replace these with press fit pins to prevent the dislodging of any components.

### **3.2.6 Factor Variable/Primary Defect Relationships**

The following is a graphic representation of the relationships between Factor Variables within the design and Primary Defects that may appear during assembly. Some Primary defects may occur from a variety of Factor Variables in one or more of the assembly components.



### 3.3 Case Study 3: Car Door Handle

#### 3.3.1 Functional Requirements

The functional requirements of the car door assembly are defined as:

1. To release the door latching mechanism to open door.
2. To unlock door using car key.
3. To lock door using car key.

#### 3.3.2 Method of Function

The car door handle assembly is assembled on the handle base as shown in **Figure 10**.

The door handle passes through the base via two parallel through holes and is pinned in the back. A press fit pin secures the door handle in two locations. An extension of the door handle contains a through hole with a plastic snap fit clasp responsible for connecting the door latching mechanism to the door handle.





**Figure 10** Car Door Handle Assembly With Lock Sub-Assembly

The handle base also has a circular through hole with a channel to position the lock sub-assembly. The channel has a through hole to snap fit the lock in place. An arm is secured to the shaft of the lock with a metal snap fit clasp. This arm has a through hole with an inserted plastic snap fit clasp to link the lock sub-assembly with the door latching mechanism.

The press fitted pin, which anchors the door handle to the handle base, is inserted through a spring which is constrained by both the handle base and the door handle extension. The spring returns the door handle to its initial (disengaged) position.

A rubber gasket, secured in four locations, seals the door handle assembly from the outside environment. The gasket is positioned over four protruding posts and is press fitted onto the back of the handle base.

There are rubber stops on the door handle and handle base which prevent direct contact between their outside surfaces. Two rectangular rubber stops are adhered to the door handle near the through holes. Two additional stops are press fitted into two through holes of the handle base.

### **3.3.3 Primary Defects**

1. Lifting door handle does not open the car door.
2. Handle does not return to initial position.
3. Lock cannot engage or disengage door latching mechanism.

### **3.3.4 Analysis of Primary Defects and Factor Variables**

1. *Lifting door handle does not open the car door.*

The door handle is fastened to the door latching mechanism using a plastic snap fit clasp. The clasp has considerable play with respect to the door handle and was effortlessly removed. The tolerancing relationship between the plastic snap fit clasp and the door handle could cause separation. In addition, the barb mating surface of the clasp could easily fracture causing part separation.

There is a rubber gasket press fitted onto the back of the handle base to protect the door handle assemble from the outside environment. If the gasket is applied after the pin is press fitted, it will interfere with the motion of the door handle.

2. *Handle does not return to initial position.*

The press fitted pin is inserted into a spring which is constrained by the extension of the door handle and the handle base. If the spring is mispositioned, it will not return the door handle to its original position.

The rubber gasket press fitted about the handle base may interfere with the motion of the door handle if an improper assembly sequence is followed.

3. *Lock cannot engage or disengage door latching mechanism.*

A metal snap fit clasp secures the lock shaft to the lock arm. The metal clasp has two through holes shaped as the cross-section of the shaft (one slightly larger to facilitate insertion, the other tighter fitting to facilitate locking). There is an extension of the metal clasp that simultaneously slides into a through hole of the arm as the clasp is locked. This prevents the clasp from sliding off the shaft. If the clasp is not aligned correctly, it will not lock onto the shaft. Consequently, the arm may dislodge from the lock sub-assembly.

The through hole that accepts the snap fit from the lock sub-assembly is relatively narrow (with respect to the interlocking protrusion from the lock). If the lock sub-assembly is not inserted to the correct depth within the handle base, the snap fit will not engage. When the door key is inserted, the lock sub-assembly may dislodge from the handle base.

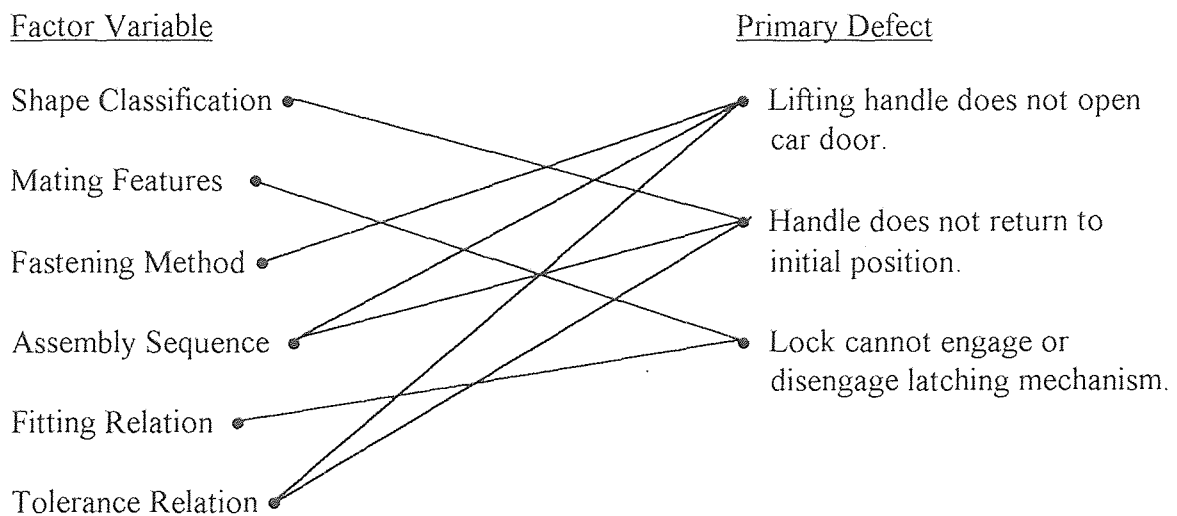
### **3.3.5 Suggested Design Improvements**

1. Incorporate the function of rubber handle stop into that of the rubber gasket. Rubber stops can serve as two fasteners for the gasket, while the balance of fastening is performed on the perimeter of the gasket. This approach will eliminate the need for the center portion of the gasket, thus reducing the likelihood of interference with the door handle.
2. Plastic fasteners should be replaced with high strength metal fasteners to prevent fatigue failure in the clasp. Metal fasteners may better maintain their inserted position within handle extension and lock arm.
3. Redesign the mating features of the spring and door handle. The spring should be redesigned to be symmetrical about its principal axis, having two ends with one 90 degree bend each. The extension of the door handle should have a slot to receive and position the spring. With these changes, the spring would properly interface with the door handle regardless of orientation.
4. The snap fit that secures the lock sub-assembly should be redesigned. A snap fit mechanism can be designed into the handle base that will not only secure the lock, but also ensure the lock sub-assembly is inserted to the appropriate depth.

5. The metal clasp which fastens the arm to the lock sub-assembly should be redesigned. The clasp shape should be conforming to the contours of the arm so that their mating features can act as a snap fit. If the clasp were rotated 90 degrees and then inserted, the end of the clasp would contact the arm. If the clasp was dimensioned correctly, this contact could serve as a snap fit to secure its position on the lock shaft. The extension of the clasp could then be eliminated, removing the possibility of misalignment.

### 3.3.6 Factor Variables/Primary Defect Relationships

The following is a graphic representation of the relationships between Factor Variables within the design and Primary Defects that may appear during assembly. Some Primary defects may occur from a variety of Factor Variables in one or more of the assembly components.



### 3.4 Case Study 4: Hand Soap Dispenser

#### 3.4.1 Functional Requirements

The functional requirements of the hand soap dispenser are defined as:

1. To dispense hand soap through human interface.
2. To open, allowing insertion of hand soap refill.
3. To close, providing support and containment of hand soap refill.
4. To mount to the wall.

#### 3.4.2 Method of Function

The hand soap dispenser casing consists of two interlocking shells as depicted in **Figure 11**. The front shell, or cover, is made of two parts joined by either adhesion or plastic weld. The upper portion of the shell has four snap fit fasteners responsible for fastening the top and sides to the back shell. The lower portion of the shell has two “legs” with protrusions which serve as pivots. The back shell serves as a platform for the entire assembly while maintaining the position of the hand soap refill box.

The dispensing unit is attached to the back shell by three snap fits and two slotted constraints. There is a mating feature between the back shell and dispensing unit that forms a through hole for the insertion of the pivot protrusions of the cover. The dispensing unit consists of nozzle holder (welded or adhered) that mates with the cover when the cover is closed. The resulting geometry positions and secures the rubber tube exiting the refill box.

There is also a dispensing lever that protrudes the surface of the dispensing unit. This lever swings about the top of the dispensing unit by means of two pivot protrusions.

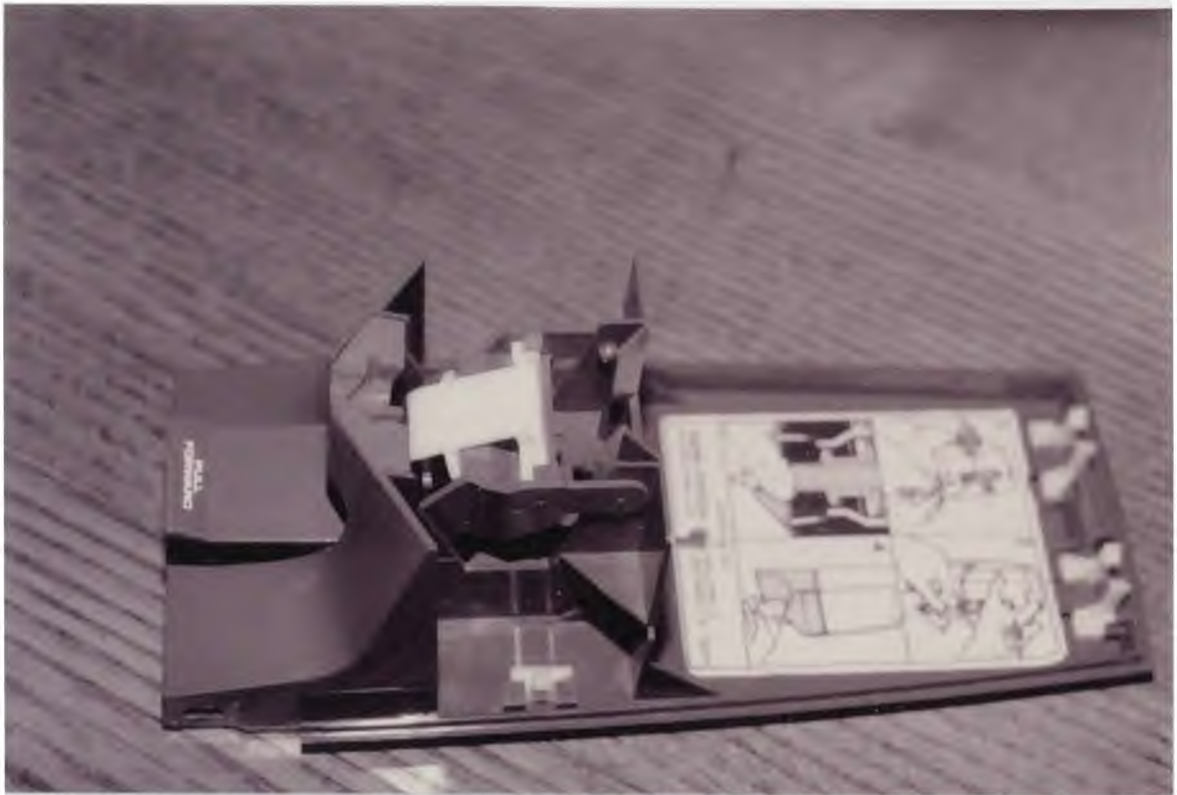


Figure 11.1 Hand Soap Dispenser Showing Rear Shell, Dispensing Unit and Lever

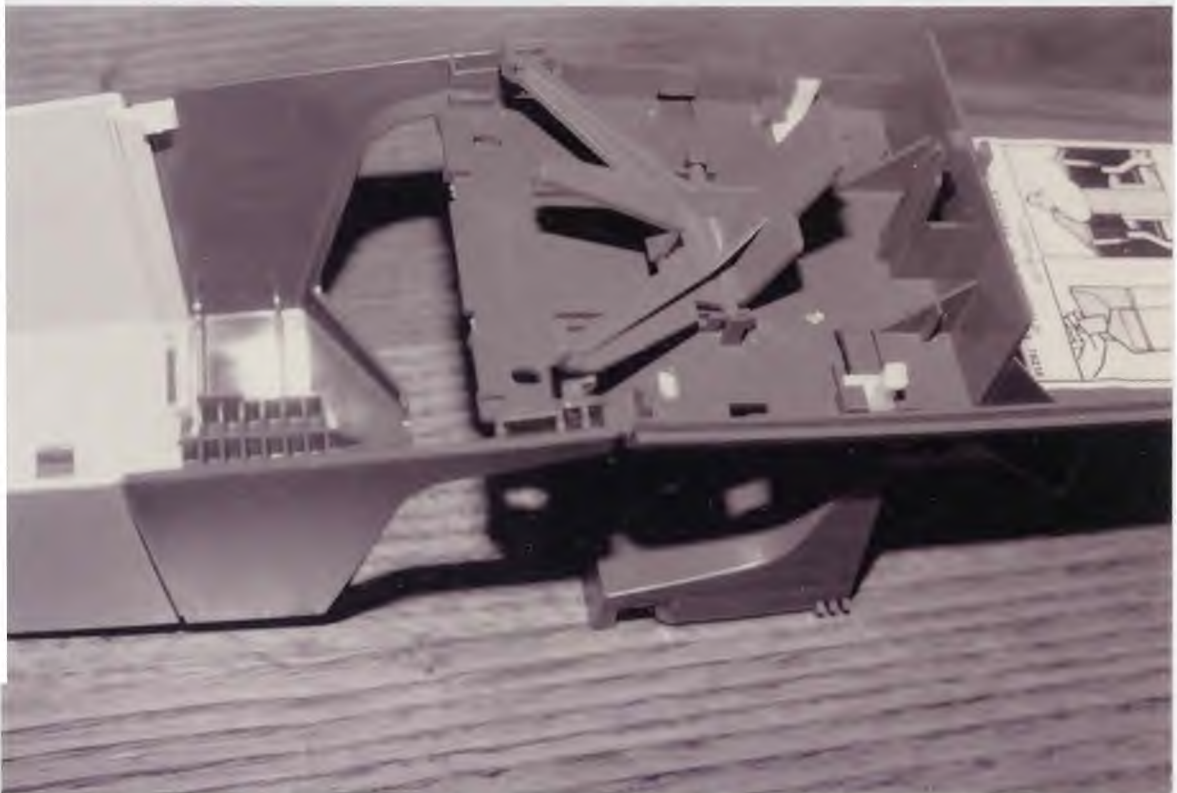
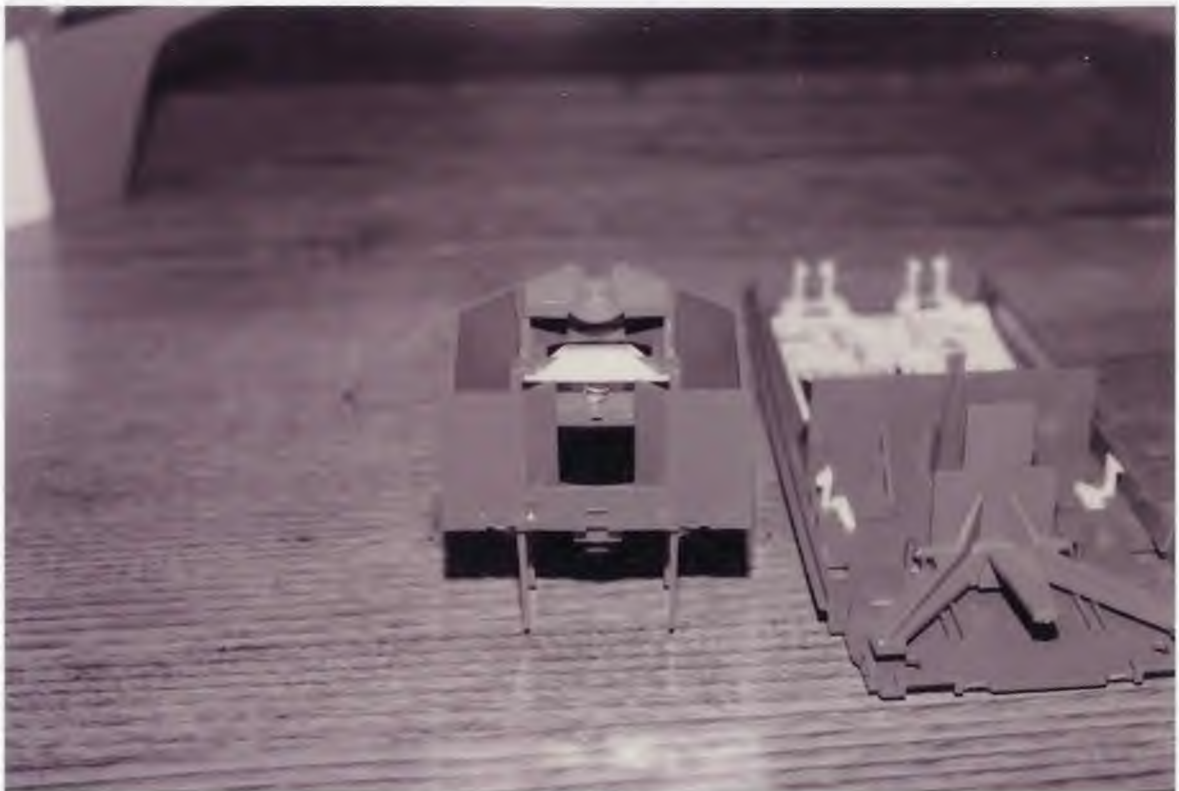


Figure 11.2 View of Hand Soap Dispenser Showing Cover and Cover Release Lever



**Figure 11.3** View of Hand Soap Dispenser Showing Nozzle Holder, Pressure Plate, Rear Shell and Cover Release Lever



The pressure plate on the dispensing lever engages the rubber tube of the refill box, pivoting about the lever by means of a snap fit pivot point. This plate experiences an upward spring force and is held in place by two snap fit constraints on the dispensing lever. As the lever is engaged, the pressure plate exerts a variable force along the rubber tube of the refill box. This variable force draws the soap through the nozzle for operator use.

The cover release lever has two pivot protrusions that are secured by two snap fits to the back shell. Engaging the lever raises it as to clear the protrusions of the cover, facilitating removal.

### **3.4.3 Primary Defects**

1. Cover will not open or close.
2. Cover cannot be removed for wall mounting.
3. Hand soap will not dispense.

### **3.4.4 Analysis of Primary Defects**

1. *Cover will not open or close.*

The fastening system of the casing consists of four snap fit clasps which secure the front shell to the back shell. Opening and closing the cover to insert the soap refill box may cause the plastic fasteners to fatigue, ultimately leading to fastener failure.

Fractured fasteners may prevent the casing from remaining closed.

The cover swings about the rear shell by means of two pivot protrusions that are inserted into a through hole formed by the mating features of the rear shell and dispensing unit. If the two parts are mispositioned or their tolerance relationship is violated, the through hole will be compromised. As a result, the pivot protrusions will not be constrained and the cover will be unable to pivot.

2. *Cover cannot be removed for wall mounting.*

The rear shell has four through holes for wall mounting the hand soap dispenser. Two of the four holes are only accessible by removing the cover. The cover is removed by engaging the cover release lever, allowing the pivot protrusions to slide out of the formed through hole. If an improper assembly sequence is followed, the pivot protrusions may not be positioned beneath the release lever. The resulting misalignment would not permit these protrusions from exiting the through hole for cover removal.

3. *Hand soap will not dispense.*

The nozzle holder portion of the dispensing unit mates with the interior of the cover to secure the rubber tube extending from the soap refill box. The nozzle holder is contoured and adhered to the dispensing unit. The part is geometrically constrained on two sides and contains no other positioning or securing feature. This lack of part restraint could contribute to mispositioning within the dispensing unit, causing a misalignment with the cover. If a misalignment occurs, the rubber tube will not be held in place. Without proper tube positioning, no soap will be delivered.

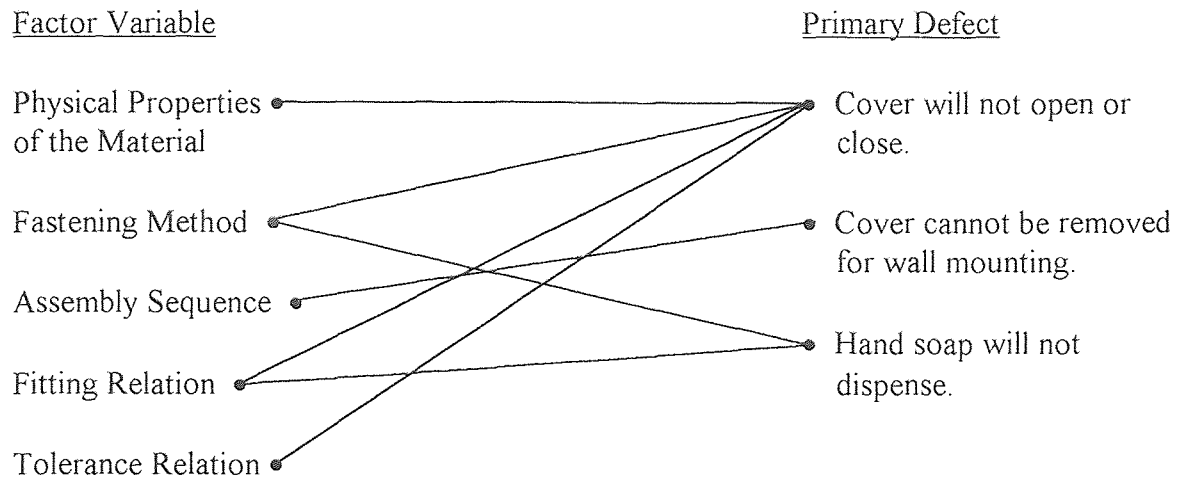
The pressure plate is constrained by the dispensing lever by virtue of two constraints and one snap fit pivot. A spring located between the dispensing lever and pressure plate maintains an upward force necessary to secure the plate. This force also incrementally dispenses the hand soap as the lever travels forward through user interface. The fastening method consists of a pivot point that can easily be disrupted during assembly, causing the misplacement or dislodging of the pressure plate and spring. Without these parts in place, no hand soap will be delivered to the user.

### **3.4.5 Suggested Design Improvements**

1. Eliminate the cover release lever. Cover could still be removed by just detaching the dispensing unit first. This would eliminate the possibility of a part interference.
2. The nozzle holder should snap fit to rear shell. This would eliminate mispositioning and a misplaced part defects.
3. Replace the snap fits that secure the cover with an opening mechanism. This would prevent the failure of snap fits during opening.

### **3.4.6 Factor Variables/Primary Defect Relationships**

The following is a graphic representation of the relationships between Factor Variables within the design and Primary Defects that may appear during assembly. Some Primary defects may occur from a variety of Factor Variables in one or more of the assembly components.



### 3.5 Case Study 5: 5.25 Inch Floppy Disk Drive

#### 3.5.1 Functional Requirements

1. To open for insertion or removal of 5.25 inch floppy disk.
2. To close to secure floppy disk.
3. To read information stored on floppy disk.
4. To write information for storage on floppy disk.

#### 3.5.2 Method of Function

The floppy drive assembly is housed in a case consisting of a top shell, enclosed on the top and on two sides, and a bottom shell that is enclosed in the back (refer to **Figure 12**). The bottom shell is fastened to the frame by four machine screws, while the top shell is secured to the bottom shell in a similar fashion.

The frame, which acts as an assembly platform, has a face plate mounted to it by four machine screws. This face plate has a wide through hole to allow the insertion of a 5.25 inch floppy disk, a cylindrical through hole for the protrusion of a “In Use” indicator

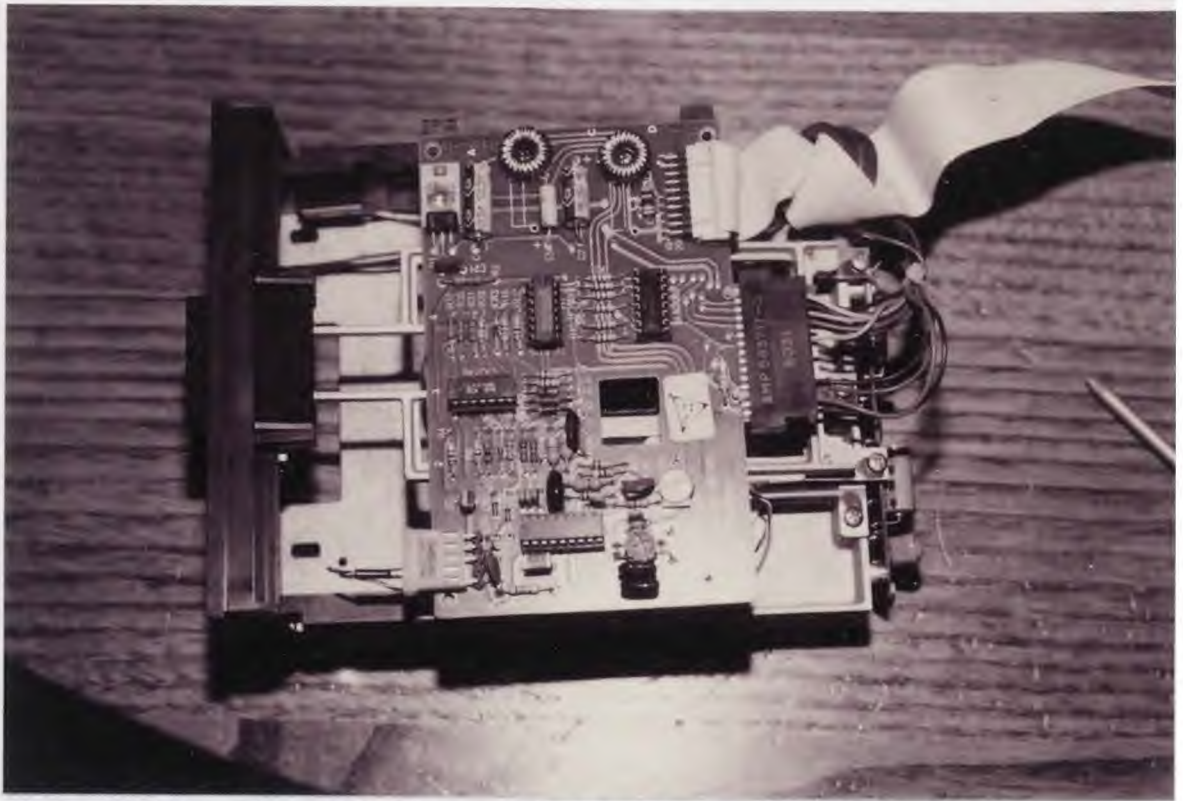


Figure 12.1 Top View of the Floppy Disk Drive Showing the PCB and Latch

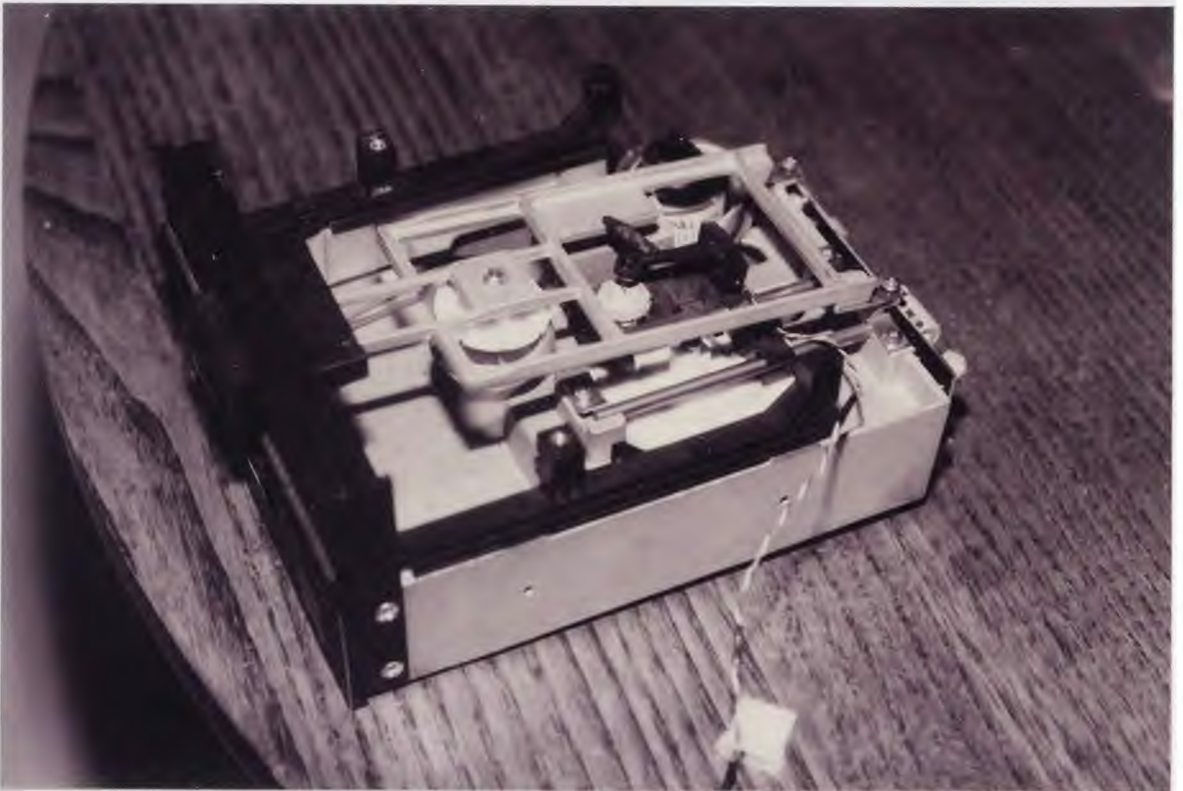
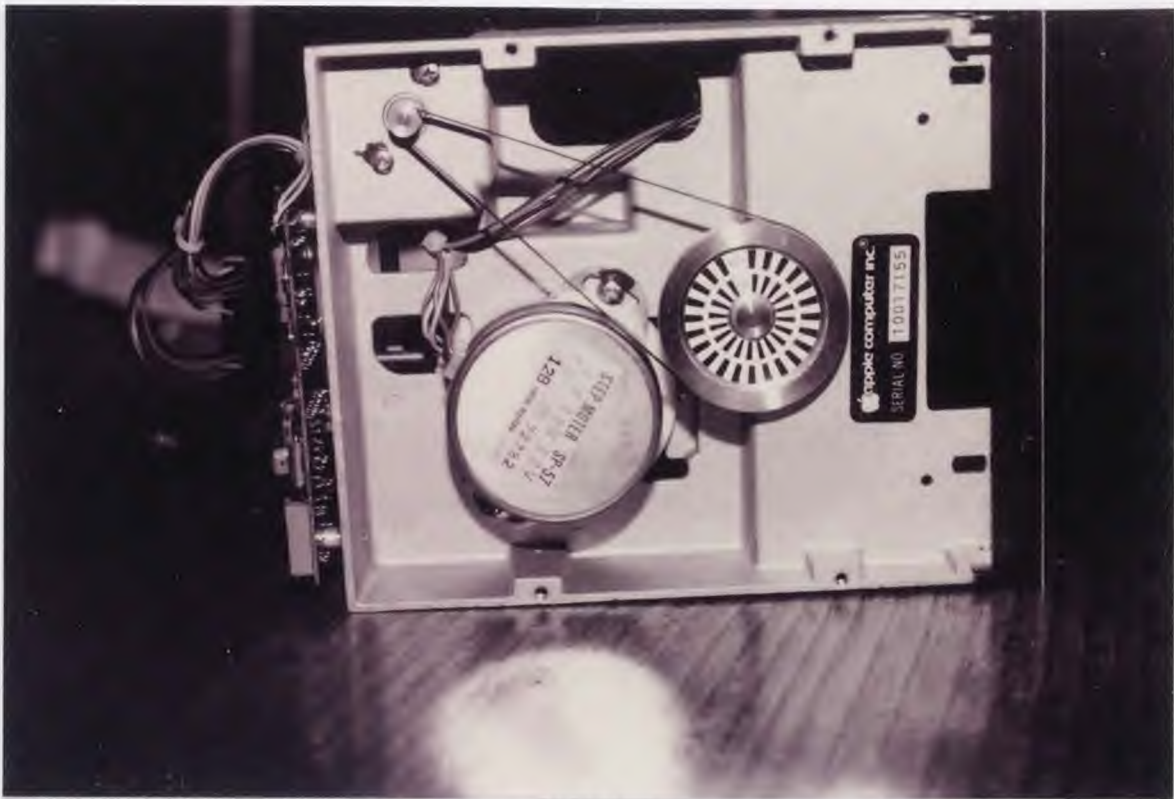


Figure 12.2 Floppy Disk Drive Showing Disk Clamp, Magnetic Head and Disk Guides



**Figure 12.3** Bottom View of the Floppy Disk Drive Showing the Turntable Flywheel, Flywheel Belt and Magnetic Head Step Motor

and a rectangular through hole for the latch which secures the disk during operation. The face plate also has two channels in the back that interface with the latch and guides it through its opening and closing motions.

There are two plastic strips adhered to the top of the frame that position the disk upon insertion. There are four posts (two of which are tapped) extending from these guides which support a PCB (PCB #1). The PCB is fastened to the posts by two machine screws and two slotted constraints. This PCB is electrically connected to the magnetic head, the magnetic head step motor, the “In Use” indicator, “disk loaded” switch and the turntable motor. The wire connecting PCB #1 and the magnetic head is pinched in place at two locations on the frame by two press-fits. A second PCB (PCB #2) is mounted on two posts at the rear of the frame (perpendicular to PCB #1). This PCB is electrically connected to PCB #1 and the turntable motor.

The turntable motor is fastened to the frame by two machine screws. This motor is linked to the turntable through a belt driven flywheel. The flywheel is connected to the turntable by means of a threaded shaft. The shaft spins on encased bearings fitted into a through hole in the frame.

The magnetic head step motor is fastened to the frame by two machine screws, accompanied with two washers. A shaft extends from the motor, through the frame, and is connected to a grooved guide wheel. The groove spirals from the outer edge of the wheel towards the center.

The magnetic head is mounted to the frame in four locations. Two guide rails rest on three frame supports and are secured by three angled metal clips, fastened by three

machine screws. A platform which supports the magnetic head, which is centrally located, slides along the rails. A stylus connected to the platform travels along the spiral groove of the guide wheel. A metal stop, connected to the magnetic head, interfaces with the shaft of the step motor and serves to limit the distance traversed by the magnetic head. This stop is fastened by a machine screw at one end and is anchored by a slotted constraint at the other end. There is a magnetic arm hinged on the platform that opposes the magnetic head (on the opposite side of the disk).

The disk clamp consists of a bracket that is fastened at one end by two pieces of spring steel (that are fastened to the frame by two machine screws). At the other end, the bracket is fastened by two machine screws to both the latch and a metal constraint that prevents the insertion of a disk while the unit is in operation. As the latch pivots and swivels into its closed position, the disk clamp lowers to secure the floppy disk. Simultaneously, the metal disk stop reaches its lowered position to prevent the insertion of another disk.

The “disk loaded” switch is positioned beneath one of the plastic disk guides and is fastened to the side of the frame by two machine screws and washers. The switch is engaged by the displacement of a plastic lever fashioned from the plastic disk guide.

### **3.5.3 Primary defects**

1. Latch jams in open or closed position.
2. Disk can not be inserted for reading or writing.
3. “In Use” indicator fails to acknowledge presence of inserted disk.



4. Disk does not spin for reading or writing.
5. Magnetic head fails to read or write.

#### **3.5.4 Analysis of Factor Variables and Primary Defects**

##### *1. Latch jams in open or closed position.*

The mating features between the latch and the face plate may cause binding. Binding within the channel of the face plate will inhibit the motion of the latch.

There are also functional relations between the latch and the disk clamp, and the latch and the metal disk stop. If the disk clamp is not anchored properly, it will interfere with the motion of the latch. If the metal disk stop is positioned incorrectly, it will hang up on the face plate and prevent the latch from closing. Mispositioning of the metal disk stop may occur if the latch is bent or loose.

##### *2. Disk can not be inserted for reading or writing*

The long, thin plastic disk guides are adhered to the top surface of the frame. The geometrical features, shape and mating features, may introduce mispositioning during adhesion. Also, misplaced bonding compound may obstruct disk insertion.

The lever which engages the “disk loaded” switch is fabricated out of the one plastic disk guides. If the lever fails, it may dislodge and block the path of an inserting disk.

If the disk clamp is not anchored securely to the spring steel during assembly, the clamp could physically block disk insertion.

##### *3. “In Use” indicator fails to acknowledge presence of inserted disk.*

As previously mentioned, the lever that engages the “disk loaded” switch is fashioned from the plastic disk guide. If the lever fails during assembly, it may dislodge. Without the lever in place, the switch cannot be activated to indicate the presence of a disk.

The mating features of the switch and frame can also affect the activation of the switch. The switch is mounted with two machine screws fasteners facilitated by two through holes in the frame. One of these holes is elongated for fine tuning the position of the switch. If the switch is not positioned properly, it may not make contact with the lever.

4. *Disk does not rotate consistently.*

There is a functional relationship between the turntable and disk clamp. If the disk clamp does not secure the disk against the turntable, the disk will not spin consistently.

The mating features between the belt and fly wheel, as well as, between the belt and turntable motor can affect the rotation of the turntable. If the belt slips, the disk will not rotate properly.

The fastening method of the shaft connecting the fly wheel and turntable can also impact disk rotation. Rotary motion may cause the threaded shaft to loosen at the turntable or motor. Eventually, the motor would fail to drive the turn table.

The mating features of the enclosed bearing and frame may cause the bearing to seat incorrectly. The resulting interference of bearing on the shaft could cause irregular rotational velocity of the disk.

5. *Magnetic head fails to read or write.*

The magnetic head is fastened to a platform that slides along two guide rails. These guide rails are constrained by the frame and three fastened metal clips. Should the metal clips bend, the guide rails may shift and interfere with the reciprocating motion of the platform.

The platform is propelled forward and backward by the indexing wheel. The platform has a metal stylus, fashioned from an angled piece of copper, that is fastened by a machine screw. The mating features of the wheel and stylus affect the motion of the platform. If the floppy drive is jarred, it is possible for stylus to leave the groove completely.

The indexing wheel is linked to the step motor by means of a threaded shaft. This fastening method may fail as the shaft rotates. Continual rotation may cause the shaft to “back out” of either the indexing wheel or the step motor.

There is a functional relationship between the opposing magnetic arm and the disk clamp. An extension of the bracket raises the magnetic arm as the disk clamp is disengaged. If the disk clamp jams, the opposing magnetic arm will not lower. Furthermore, this arm pivots about the platform by virtue of a pin that snap fits to the base of the arm. If this fastening system fails, the arm will not move as needed.

### **3.5.5 Suggested Design Improvements**

1. To prevent the latch from jamming, the pivot protrusions on the latch which interface with the channels of the face plate should be redesigned. Spring loaded protrusions should be used to provide some flexing within the channels. In addition, the method of

fastening the disk clamp to the frame should be altered. The mechanism should be pinned with either a threaded or press fitted pin, surrounded by a separate spring to disengage the disk clamp. This would prevent the clamp from jamming and interfering with the motion of the latch.

2. The plastic disk guides should be fashioned with snap fits that mate with the top surface of the frame. These snap fits would serve to adequately aligned and secure the guides, as well as, eliminate any obstructions due to misplaced adhesive. The added spring (mentioned above) would reliable disengage the disk clamp as to provide a clear path for disk insertion.

Eliminating the plastic lever could also prevent a possible obstruction. If the “disk loaded” switch were mounted so that the disk could directly engage the switch, the lever would not be needed in the assembly.

3. The drive belt that links the fly wheel to the turntable is flat and without contours. A timing belt should be used to more accurately synchronize the rotation of the turntable and motor. The flywheel should also be notched (resembling a gear) to accept this new surface geometry.

The enclosed bearings responsible for shaft rotation should have a plastic snap fit cover (with a centrally located through hole for the shaft) to fit over the through hole in the frame. This would ensure that the bearing was seated correctly.

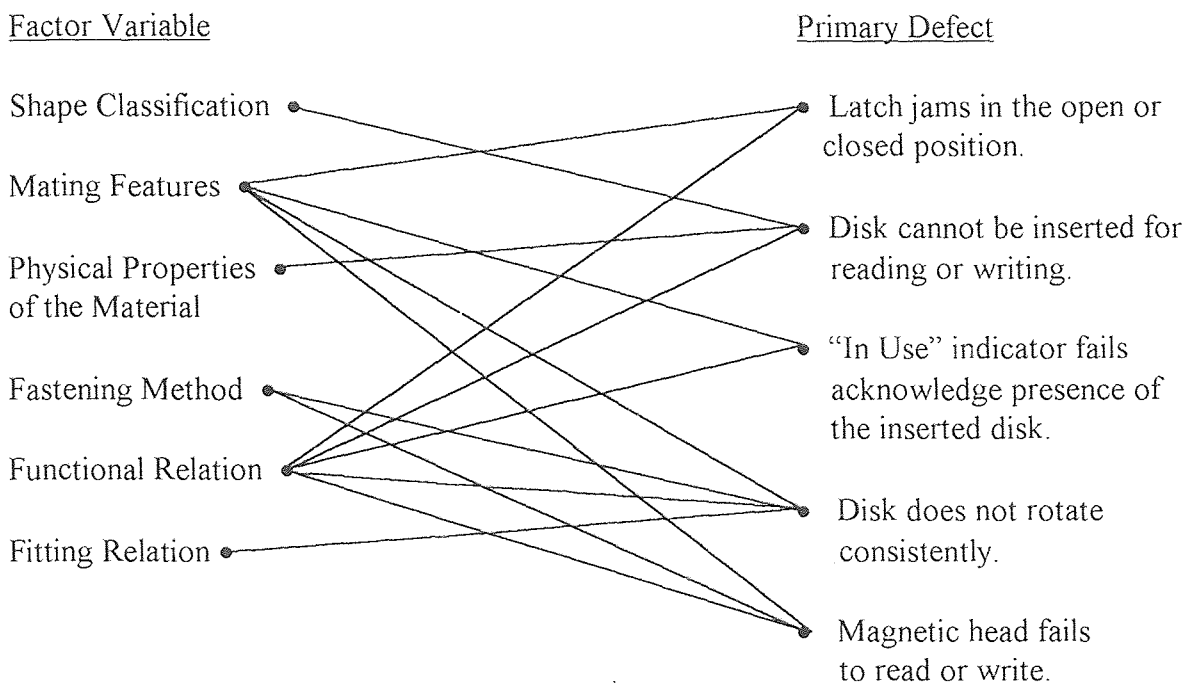
4. A snap fit cap should be designed to replace the metal clips that fasten the magnetic head guide rails. The cap would properly space the rails and secure them from movement by snap fitting into the frame.

The stylus should be more rigid to prevent it from jumping out of the groove due to jarring.

5. Redesign the pivot of the opposing magnetic arm with a press fit pin to prevent the arm from detaching.

### 3.5.6 Factor Variable/Primary Defect Relationship

The following is a graphic representation of the relationships between Factor Variables within the design and Primary Defects that may appear during assembly. Some Primary defects may occur from a variety of Factor Variables in one or more of the assembly components.



## 3.6 Case Study 6: Hair Dryer

### 3.6.1 Functional Requirements

1. To contain components.

2. To heat air.
3. To blow air.
4. To cool components.

### 3.6.2 Method of Function

The hair dryer consists of a two piece plastic shell, heater element, switch sub-assembly, fan sub-assembly, two wire framed fan filters, nozzle vent, wire ring constraint (heater element), hanger hook and power cord (refer to **Figure 13**).

The top piece of the shell has four threaded holes and one male, four female snap fits to secure both halves of the shell. There are two interior grooves: one to locate and position the nozzle vent and the other to locate and position the wire ring constraint. The nozzle vent is secured by one of two machine screws. There are two through holes that mate with identical holes on the bottom piece which positions the hanger hook and power cord. In addition, there is one of two holes that secures the hanger hook. There is a wire framed fan filter fastened to the interior of the top shell piece. The filter is secured by protruding plastic posts. These posts are inserted through the filter mesh and peened over by heat. There are three square through holes in which the switches protrude for user interface.

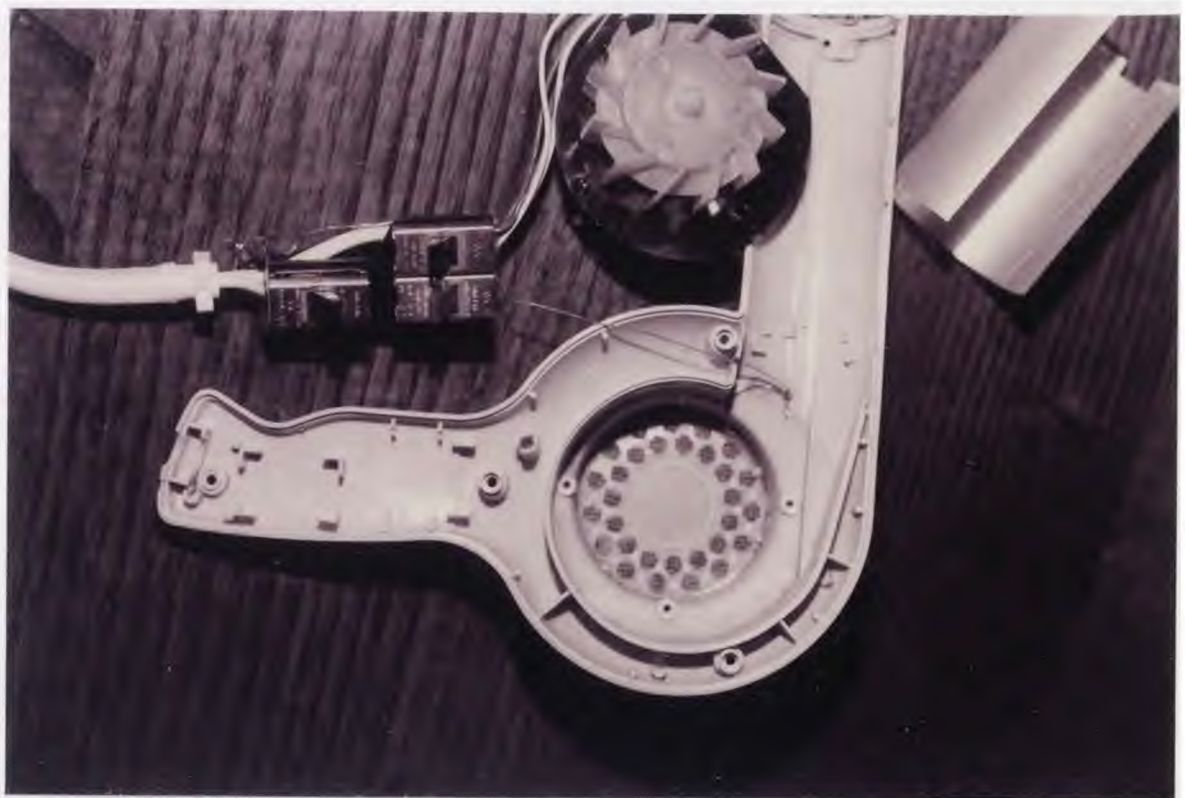
The bottom piece of the shell has nine protruding notched posts to locate and position the switch sub-assembly. The switches extend into the through holes of the top shell piece, securing them into position. There are two interior grooves: one to locate and position the nozzle vent and the other to locate and position the wire ring constraint. The



Figure 13.1 Inside View of Hand Held Hair Dryer



Figure 13.2 Hand Held Hair Dryer Showing the Top Shell, Fan Filters and Nozzle Vent



**Figure 13.3** Inside View of Hand Held Hair Dryer Showing the Bottom Shell, Switch Sub-Assembly and Fan Sub-Assembly



nozzle vent is secured by one of two machine screws and the wire ring constraint is secured by two heat-peened plastic posts. The fan sub-assembly is located by a cylindrical recess in the shell, positioned by a protruding constraint and secured by three machine screws (with three tapped holes). A wire framed fan filter is attached to the interior of the bottom piece by heat-peened plastic posts.

### **3.6.3 Primary Defects**

1. Shell does not close.
2. Fan does not blow air across heater element.
3. Heater element does not produce adequate heat.
4. Electricity is not delivered to components.

### **3.6.4 Analysis of Factor Variables and Primary Defects**

1. *Shell does not close.*

All of the components comprising the hair dryer are positioned by the contours of the shell interior surface. Any misalignment of the components will prevent the two shell halves from seating properly.

2. *Fan does not blow air across heater element.*

The fan is positioned within the shell by a cylindrical recess and is positioned by a protruding constraint. If the fan is mispositioned during fastening, the impeller may bind up on shell interior.

The wire framed fan filters are positioned by plastic posts on the interior of both shell pieces. They are then secured by peening the posts with heat. If the filter is mispositioned during fastening, it may entangle on the fan impeller.

3. *Heater element does not produce adequate heat.*

The heater element, shrouded by a heat resistant tube, is positioned by eight protrusions within the interior of the shell (four per half). If the wire ring constraint is not positioned correctly, it may come in contact with the heater element causing a short circuit or a heat sink.

4. *Electricity is not delivered to components.*

The power cord is contained by a through hole formed by the mating of both shell halves. The cord is shaped such that when positioned properly, it cannot slip out of the shell. If the power cord is not positioned properly, the soldered electrical connections to the switches and heater element are solely responsible for securing it within the shell. The soldered connections or wires may break if they are placed under tension.

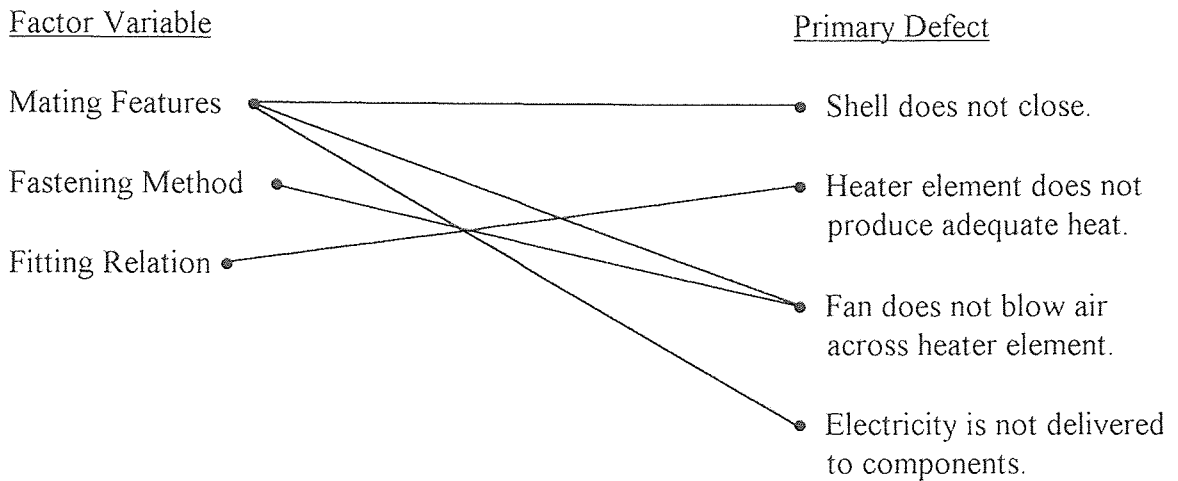
### **3.6.5 Suggested Design Improvements**

1. Redesign the shell with plastic snap fits to secure the wire framed fan filters. This would prevent incomplete fastening by posts, in turn, preventing dislodging of the filters.
2. Eliminate the wire ring constraint. If the length of the heat element shroud is increased as to butt against the nozzle vent, it would eliminate the possibility of a short circuit or heat sink due to a dislodged constraint ring.

3. Use a snap fit to secure the power cord within the shell. This would eliminate mispositioning during assembly and remove unnecessary stress on solder joints of components.

### 3.6.6 Factor Variable\Primary Defect Relationships

The following is a graphic representation of the relationships between Factor Variables within the design and Primary Defects that may appear during assembly. Some Primary defects may occur from a variety of Factor Variables in one or more of the assembly components.



## CHAPTER 4

### CLASSIFICATION OF MANUFACTURING QUALITY DEFECTS

Analysis of the selected assembled products isolated many design features that may eventually lead to quality defects. These defects are attributable to the particular Influencing Factors, as described by their Factor Variables, present in each product design. A summary of the Manufacturing Quality defects and Specific Defects, and their associated Factor Variables, for each case study is presented.

#### **4.1 Case Study 1: Emergency Brake**

##### **4.1.1 Brake Jam**

The Mating Features between the release lever spring and cover bracket may cause mispositioning of the spring, resulting in a Misplaced Part defect. Angular or Radial Misalignment of the ratchet or geared pedal edge could cause a Part Misalignment defect.

##### **4.1.2 Brake Wire Disengages**

The Fastening Method of the cable to the hold jack could cause a Loose Fitting part, thus facilitating a Fastener Related defect. The Absence of lubrication, perhaps as a result of its physical properties, may cause Mispositioning of the cable within the hold jack through friction. The defect may be classified as either a Misplaced Part or Missing Part defect.

##### **4.1.3 Vibration While Driving**

The Fastening Location and Strength of Fasteners, of both bolts and rivets, may cause ill-fitted components, leading to a Fastener Related defect.

#### **4.1.3 Increased Human Input is Needed to Release or Engage Brake**

The Fitting Relation of the ratchet and the foot pedal assemblies, with respect to the platform and cover bracket, may cause constant interference leading to a Part Interference Defect. The Absence of lubrication on the geared ratchet drum or geared pedal edge may increase frictional wear, resulting in a Missing Part Defect.

#### **4.1.4 Brake Force is not Maintained**

The Mating Features between the geared ratchet drum and the platform may cause the Mispositioning of the ratchet drum spring. A Misplaced Part Defect may create inconsistencies in the brake force.

#### **4.1.5 Light will not Extinguish**

The Mating Features of the indicator switch may cause Mispositioning with respect to the geared pedal edge. The result is a Misplaced Part defect.

### **4.2 Case Study 2: Portable Overhead Projector**

#### **4.2.1 Cover does not Open or Close**

The Mating Features of the metal latch and mounting plate may lead to the Mispositioning of the latch, preventing the cover from being secured. This causes a Misplaced Part defect.

The cover hinges extend through the back of the projector body. The Tolerance Relation of the hinges and the through holes on the projector body may lead to Dimensional Nonconformity, resulting in a Total Nonconformity defect.

The cover prop has a channel that slides around a screw fastened to the projector body. The Tolerance Relation of the parts may lead to Dimensional Nonconformity, resulting in a Total Nonconformity defect.

#### **4.2.2 Projector Components will not Fold or Unfold**

The elevator, responsible for raising the projector body during opening, consists of two fixed and two collapsible sides. The four sides have channels that mate with linkages. The Tolerance Relation of the linkages and channels may cause Dimensional Nonconformity, leading to a Total Nonconformity defect. Also, the Mating Features of these parts may cause Mispositioning, resulting in a Misplaced Part defect.

The linkage responsible for elevating the sides also facilitates the positioning of the mirror bracket. The Tolerance Relation of pivots and plastic channel on the bracket may cause Dimensional Nonconformity, resulting in a Total Nonconformity defect. Similarly, the Mating Features may lead to mispositioning, contributing to a Misplaced Part defect.

The column is connected to same linkage as previously mentioned. As in the case of the elevator and mirror bracket, the column may be subjected to a Total Nonconformity defect. Since the column, elevator and mirror bracket are interconnected, a three way Functional Relation exists. If one of the components fail, the remaining two will also fail. This relationship could cause a Part Interference defect to arise.

A lever extending from the projector body serves to lock and release the column. The lever pivots about the projector body and is tensioned by a spring. The spring is fastened to a hole in the column and is secured by a crimped end. If Fastening Method fails (or the Strength of the Fastener fails from crimping fatigue) it could introduce Occasional

Interference with the linkage during open or closing. The end result is a Part Interference defect.

#### **4.2.3 Image is not Properly Projected on Wall**

A pin, responsible for aligning and securing the lamp reflector, is locked into place by two metal snap fit rings. If this Fastening Method fails, the pin may become Loose Fitting, resulting in a Fastener Related defect. Furthermore, the loose pin may present a Misplaced Part defect since it shares Mating Features with the reflector.

The lamp mount is attached vertically to the projector body by two machine screws. Four metal clips fashioned from the surface of the mount serve to secure the lens. The Mating Features of the mount and lens may foster Mispositioning or an absent part, leading to a Misplaced or Missing Part defect. Failure of the metal clips in securing the lens can also be viewed as a Fastener Related defect.

The bulb changer lever has a channel that slides around a screw protruding from the projector body. The Mating Features of the two parts may contribute to Mispositioning and a Misplaced Part defect. In addition, the Tolerance Relation of each part may lead to Dimensional Nonconformity and a Total Nonconformity defect.

The body lens and glass transparency plate are fastened to the cover by plastic constraints and metal snap fit clasps. These metal snap fit clasps are aligned on the cover by protruding plastic posts. The Tolerance Relation of the posts and metal clasps could contribute to Dimensional Nonconformity and a Total Nonconformity defect. As related to the body lens and glass transparency plate, a Fastener Related defect may surface.

The arm lens is mounted to the projection head assembly using plastic constraints and one plastic snap fit clasp. The Mating Features of the lens and mounting surface may produce Mispositioning and a Misplaced Part defect. In addition, a Loose Fitting lens may manifest through the failure of the Fastening Method resulting in a Fastener Related defect.

#### **4.2.4 Image cannot be Focused**

The Fastening Method of the focus adjustment knob, projection head platform, mounting plate and arm mirror are subjected to rotational forces. The fasteners may leading to a Fastener Related defect.

### **4.3 Case Study 3: Car Door Handle**

#### **4.3.1 Lifting Door Handle does not Open Car Door**

The door handle is fastened to the door latching mechanism by an inserted plastic snap fit clasp. The Tolerance Relation of the clasp and door handle could introduce Dimensional Nonconformity, leading to a Total Nonconformity defect.

The plastic snap fit clasp contains a barb responsible for securing it to the door handle. This Fastening Method increases the likelihood of a Fracture, producing a Fastener Related defect.

There is a rubber gasket press fitted onto the back of the handle base. If an improper Assembly Sequence is followed, the gasket may Constantly Interfere with the handle. The result is a Part Interference defect.



### **4.3.3 Handle does not Return to Initial Position**

The handle pin is inserted into a cylindrical spring which tensions the door handle. The Tolerance Relation of the pin and spring could cause Dimensional Nonconformity and a Total Nonconformity defect.

The Shape Classification of the pin (not symmetrical) may cause Mispositioning, preventing the spring from interfacing with the door handle. The result is a Misplaced Part defect.

The rubber gasket is press fitted into the handle base before the handle is pinned. If an improper Assembly Sequence is followed, the gasket will Constantly Interfere with the motion of the door handle. The result is a Part Interference defect.

### **4.3.3 Lock cannot Engage or Disengage Door Latching Mechanism**

A metal snap fit clasp secures the lock arm to the lock shaft. The Mating Features of the lock arm and the metal clasp could result in Mispositioning, leading to a Misplaced Part defect.

The Fitting Relation of the lock sub-assembly and handle base may present an Absent part and a Missing Part defect.

## **Case Study 4: Hand Soap Dispenser**

### **4.4.1 Cover will not Open or Close**

The cover is secured by four plastic snap fit fasteners. Opening may cause Fastener Fracture, leading to a Fastener Related defect. The Factor Variable could be considered as either the Fastener Method or the Physical Properties of the material.

The Fitting Relation of the dispensing unit and rear shell may lead to Surface Nonconformity, preventing the cover pivot protrusions from being secured. The result is a Total Nonconformity defect. Also, the Tolerance Relation of both parts can be indicated as the Factor Variable. If they are out of tolerance, a Total Nonconformity defect will appear.

#### **4.4.2 Cover Cannot be Removed for Wall Mounting**

The cover release lever must be in the raised while the cover is being inserted. If an improper Assembly Sequence is followed, the cover will not be removable due to the Constant Interference introduced by the release lever. The result is a Part Interference defect.

#### **4.4.3 Hand Soap will not Dispense**

The Fitting Relation of the cover interior and the nozzle holder may prevent the rubber tube (extending from the soap refill box) to Misposition. This could result in a Misplaced Part defect.

The Fastening Method of the pressure plate and spring may fail during assembly. The Absence of these parts would lead to a Fastener Related Defect.

### **Case Study 5: 5.25 Inch Floppy Disk Drive**

#### **4.5.1 Latch Jams in the Open or Closed Position**

The Mating Features of the latch and the face plate may lead to Mispositioning, resulting in a Misplaced Part defect

There is a Functional Relation between the latch and the disk clamp. If the disk clamp is anchored improperly, it will Constantly interfere with the latch. The result is a Part Interference defect.

There is also a Functional Relation between the latch and the metal disk stop. If the metal disk stop experiences a Fastener Related defect (becomes Loose Fitting), it may hang up on the face plate. The metal latch would then Constantly Interfere with the motion of the latch, causing a Part Interference defect.

#### **4.4.2 Disk cannot be Inserted for Reading or Writing**

The Shape Classification of the disk guides, long and narrow, may introduce Mispositioning during adhesion. Mispositioning of the disk guides could cause a Misplaced Part defect.

The Material Properties of the plastic lever that engages the “disk loaded” switch may contribute to a fracture in the lever during assembly. If the lever becomes dislodged, it may Constantly Interfere with the plastic disk guides causing a Part Interference defect.

There is a Functional Relation between the disk guides and the disk clamp. If the disk clamp fails, it may interfere with disk insertion causing a Part Interference defect.

#### **4.4.3 “In Use” Indicator Fails to Acknowledge the Presence of an Inserted Disk**

As mentioned previously, the lever may fracture during assembly. An Absent part will lead to a Missing Part defect.

The Mating Features of the switch and the frame, combined with the Fastening Method, could produce a Mispositioned part, leading to a Misplaced Part defect.

#### **4.4.4 Disk does not Rotate Consistently**

There is a Functional Relation between the turntable and the disk clamp. If the disk clamp is not anchored properly, the disk will not be secured. This may be classified as a Mispositioned part and a Misplaced Part defect.

The Mating Features of the drive belt and the flywheel, and between the drive belt and the turntable motor, can also lead to a Mispositioning and a Misplaced Part defect.

The Fastening Method of a threaded shaft to both the flywheel and turntable may be affected by the rotational forces of rotary motion. If the shaft becomes Loose Fitting, a Fastener Related defect will appear.

The Fitting Relation of the enclosed bearing and the frame may cause the bearing to improperly seat (Mispositioned), causing a Misplaced Part defect.

#### **4.4.5 Magnetic Head Fails to Read or Write**

The Fastening Method of metal clips to constrain the guide rails may produce a Loose Fitting part and a Fastener Related defect.

The Mating Features of the metal stylus and grooved wheel may lead to Mispositioning if the unit is jarred, producing a Misplaced Part defect.

A threaded shaft is fastened to both the indexing wheel and the step motor. The Fastening Method may be compromised by the rotational forces experienced through the rotary motion of the shaft, causing a Fastener Related defect.

There is a Functional Relation between the opposing arm and the disk clamp. If the disk clamp fails, the arm will not lower. This Constant Interference will lead to a Part Interference defect.

A snap fitted pin serves to both secure and facilitate the pivot of the opposing arm. The Fastening Method of the pin may present a Loose Fitting part, contributing to a Fastener Related defect.

#### **4.6 Case Study 6: Hand Held Hair Dryer**

##### **4.6.1 Shell does not Close**

The Mating Features of the shell interior and the hair dryer components may lead to Mispositioning and a Misplaced Part defect.

##### **4.6.2 Fan does not Blow Air Across the Heater Element**

The Fitting Relation of the fan and the shell may lead to Constant Interference and a Part Interference defect.

The Fastening Method of the wire framed fan filters may produce a Loose Fitting part capable of entangling the fan impeller. The result is a Fastener Related defect.

##### **4.6.3 Heater Element does not Produce Adequate Heat**

The wire ring constraint is secured by melted plastic. If the ring is Mispositioned during fastening, a Misplace Part defect may occur. In addition, a short circuit involving the ring may re-melt the plastic (Fastening Method) resulting in a Fastener Related Defect.

##### **4.6.4 Electricity is not Delivered to Hair Dryer Components**

The Mating Features of the power cored and the shell may lead to the Mispositioning of the power cord. If the cord is not constrained properly, the soldered wires may separate causing a Misplaced Part defect.

## CHAPTER 5

### CONCLUSIONS

This thesis has proven the usefulness of the Design for Quality Manufacturability methodology as a design tool through reaching the stated research objectives of:

1. To analyze selected assembled products for the purpose of identifying primary defects.
2. To apply the Design for Quality Manufacturability methodology in an effort to link Primary Defects to Influencing Factors within the product design, to assign Factor Variables to detail these Influencing Factors and provide the basis to suggest design improvements, and to determine the Specific Defects that may result from these Factor Variables for the purpose of assigning the appropriate Manufacturing Quality Defect class.
3. To identify the prevailing Manufacturing Quality Defects present in the case studies.

In analyzing the selected assembled products, lists of proposed Primary Defects were compiled. These defects were successfully related to Influencing Factors of the design as previously outlined in **Figure 7**. Factor Variables were assigned to further detail the Influencing Factors and aid in the development of design modifications to reduce the frequency of Primary Defects. The Factor Variables were also used to identify the types of Specific Defects that may appear during assembly. The Specific Defects were then categorized under the appropriate Manufacturing Quality Defect class.

Of the 66 Manufacturing Quality Defects found, 27 were classified as Misplaced or Missing Part defects, 16 were classified as Fastener Related defects, 12 were classified as

Part Interference defects, 10 were classified as Total Nonconformity defects and 1 as a Part Misalignment defect. Damage Part defects were not assigned in this analysis since detailed manufacturing and process information was not available.

From this data, it is clear that prevailing number of Manufacturing Quality defects are classified as Misplaced or Missing Part defects. Fastener Related defects had the second highest total with 16. It is worth noting that Misplaced and Missing Part, Fastener Related and Part Interference defects occurred with the same relative frequency.

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