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A METHODOLOGY FOR TOLERANCING, PROCESS EVALUATION AND CONTROL OF AUTOMOBILE BODY SUBASSEMBLY DESIGNS

by

Francis Eugene Plonka

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Industrial and Operations Engineering)
in The University of Michigan
1974

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ABSTRACT

A METHODOLOGY FOR TOLERANCING, PROCESS EVALUATION AND CONTROL OF AUTOMOBILE BODY SUBASSEMBLY DESIGNS

by
Francis Eugene Plonka

Co-Chairman: Walton M. Hancock, Prakash T. Sathe'

Process control studies in an automobile manufacturer's assembly plants, using inspection data to detect operations with defect rates exceeding ten percent, show that body assembly and related fitting and sealing operations require improvement. A study of body openings was performed that determined that the body assembly process was not producing all openings within engineering tolerances. Estimates of components of variance due to tool mastering, tool maintenance, control methods, and parts were then made, so that appropriate action could be selected. Deviations of opening surfaces from nominal were modeled in terms of tooling clearances, tool mastering biases and subassembly errors. Analysis showed that while the maintenance and mastering of tooling required improvement, the largest component of variance was due to subassembly deviations from nominal. Attempts to correct biases in openings by shimming tooling resulted in increased variation.

Subassembly measurements in checking fixtures are uncorrelated with the same measurements in the body, due to inadequate coordination of locating and clamping methods. Tolerances are not available for subassemblies, and thus potential problems in assembly tooling were not obvious in these fixtures. Examination of a subassembly process

showed that design dimensions could not be obtained with the deviations in the detail parts. Measurements of detail parts indicated that the sample ranges of deviations were small.

The conclusion of this research was that a method to tolerance engineering designs was needed for integrated control of the process from detail parts to body openings. A methodology is developed to systematically analyze a subassembly design in terms of the major manufacturing variables, i.e., tooling, parts and loading, at the preliminary design stages so that coordination is made possible through engineering design information. Functional equations are developed for subassembly surfaces, and are used to provide the probabilistic limits for surfaces and gaps between surfaces to be joined. This permits the evaluation of the design by structures, welding and sealing engineers.

Experiments are designed to verify the design assumptions when the parts are fabricated and to measure the process effects for the subassembly and body assembly processes. These experiments provide capability data that can be used for process control plans and to provide feedback to product and process design engineers. This permits reallocation of tolerances and early detection of problems that may require engineering and manufacturing action.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Professor Walton M. Hancock for his counsel throughout my graduate studies and his active participation in this research. My association with him has been both professionally and personally rewarding. I am grateful to Doctor Sathe for his encouragement and assistance during this research. The members of my doctoral committee provided guidance and advice for which I am appreciative. I would like to thank Professors Baum and Pollack for their "on site" review of the problem. The advice provided by Professors Chaffin and Datsko was invaluable.

I extend my sincere thanks for the financial support to the management of a major automobile manufacturer who prefer to remain anonymous. To the scores of employees of this corporation who have worked with me and given me their time, encouragement, and the benefit of their experience, I would like to say "Thank you".

Finally, this research would not be possible without the love and encouragement of my wife Betti, my daughter Lisa, and my son Frank. To them, I pledge my support for any dream they may wish to pursue.

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CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

This research is the result of a general investigation into the quality problems existing in the assembly plants of a major automobile manufacturer. The objectives of the investigation were: (1) to improve the quality of vehicles shipped to dealers, thereby reducing customer warranty charges; and (2) to reduce the in-plant repair costs incurred when operations were not performed correctly the first time.

The manufacturer uses an inspection and repair system shown schematically in Figure 1.1. In-process inspectors examine the operations performed within a department or section of the assembly line and write up any defects on an inspection ticket that travels with the car. Repair people are located after the inspection station where they read the ticket, perform the necessary repairs and certify on the inspection ticket if the repair has been successfully accomplished. At the end of the department, additional inspectors are located to verify or to "buy-off" the repair. Those vehicles that are not completely repaired are shunted to a repair facility for off-line repair and are not tallied in the production count until the repair is completed and certified.

An analysis of these inspection tickets showed that approximately sixty operations had defect rates greater than ten per cent of production. An experiment was performed with five teams, each consisting of three engineers, to determine the causes and to eliminate

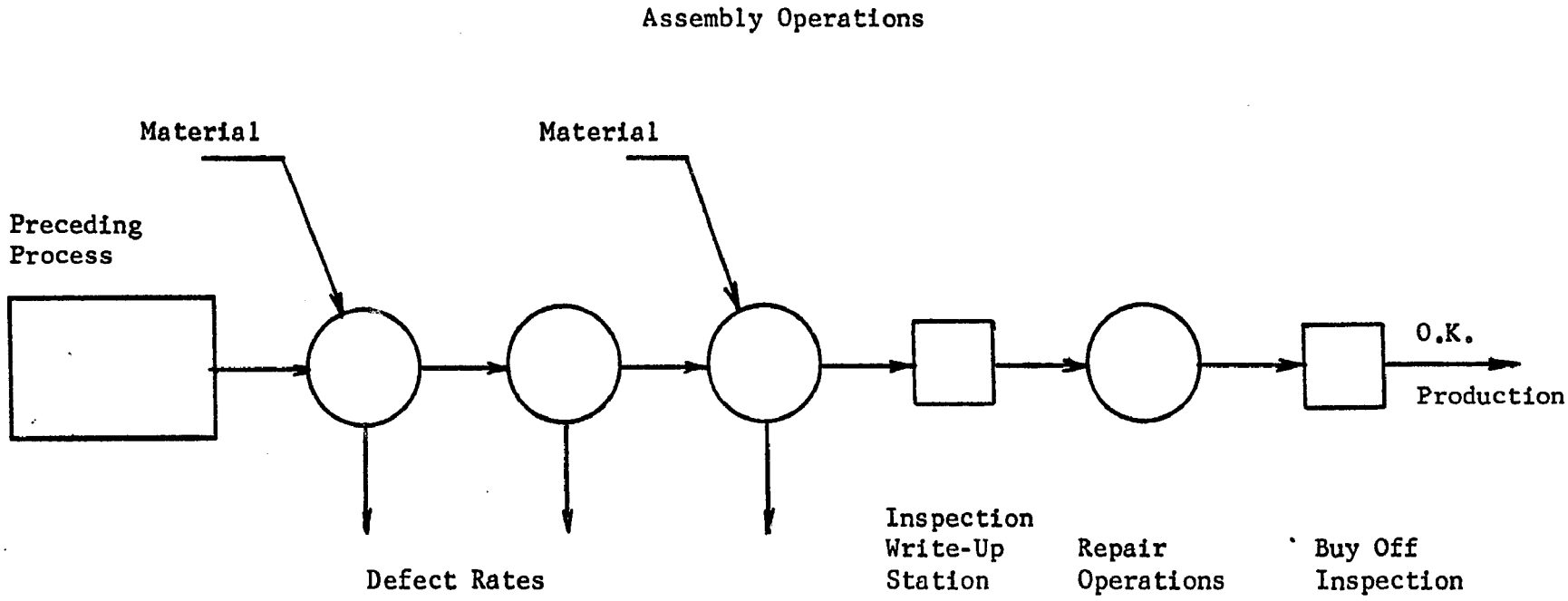


Figure 1.1 Schematic of the Inspection and Repair System

these high recurring defects. A sample report from one of the teams is shown in Figure 1.2. The following observations were made during the experiment:

1. Approximately two-thirds of the operations had inadequate process designs and control procedures.
2. A large number of the operations requiring process improvement were related to body assembly and sealing.
3. Investigations into the fitting of panels such as doors, decklids, hoods, windshields, and backlights showed that opening surfaces had high dimensional variability.
4. The sheet metal subassemblies that were assembled and welded to form the body did not have tolerance specifications for their surfaces.
5. Inspectors had more time when operations with high defect rates were improved. This permitted the detection and repair of the more random defects.

It became evident that, in order to eliminate the great majority of items, control over body dimensions must be obtained. The process of installing doors, windows and side glass and the sealing of these panels are dependent on the size of the openings, the repeatability of loading fixtures which locate from body surfaces and the size of the panel being installed. The effectiveness of seals around doors and window glass is dependent on body surfaces being maintained within specification.

The body assembly process was selected for further investigation. The procedures for measuring bodies and body openings were studied.

RECURRING DEFECTS

% DEFECTIVE FROM INSPECTION DATA

		Previous Week AVG.		Previous Week RANGE		Day of the Week 1		2		3		4	
Shift		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
FIT													
Door to Fender	LT	6	11	3-13	3-15	30	10	23	22	17	6	7	20
	RT	32	30	5-67	7-51	80	34	55	7	67	15	64	22
Front to Rear Door	LT	7	17	5-9	12-20	22	15	19	10	20	4	5	9
	RT	17	19	2-66	8-38	38	20	39	3	57	9	33	27
Door to Qtr Pnl	LT	4	11	1-7	10-15	20	15	15	11	17	4	1	8
	RT	16	18	1-59	5-38	40	17	40	6	52	9	41	57

Figure 1.2 Weekly Report of Recurring Defects - A Sample

The measurements for opening size were found to exceed engineering tolerances for large proportions of the bodies being produced. It was concluded that the body assembly process was not being adequately controlled and that the dimensional control of body surfaces was necessary if improvements in the fitting and sealing processes were to be realized.

1.2 STATEMENT OF THE PROBLEM

This research is concerned with the development of a methodology to dimensionally control the opening surfaces of car bodies fabricated by spot welding sheet metal subassemblies. It is hypothesized that the subassembly surfaces must be controlled within specified intervals about their design or nominal dimensions, if the opening surfaces are to be produced within engineering tolerances. A methodology to tolerance these surfaces is not available for sheet metal subassemblies. The design of opening sealing systems is predicated upon opening surfaces being controlled within tolerances. The appearance and fit of panels and mouldings require surfaces to be controlled dimensionally relative to each other. In addition, if the body is to be free of water and dust leaks, the joint surfaces that are welded must be dimensionally controlled.

The tolerancing problem for a product is further complicated because different organizational units design the product, design the process, and produce the product. This results in a large coordination problem between functions which, in the absence of realistic tolerances, leads to dimensional decisions being made that are not consistent with the design or the process.

The major processes in the fabrication of the detail parts, subassemblies and the body openings, and the final assembly sealing processes can be represented as a multistage serial process.

Figure 1.3 shows a generalized four stage process. Each stage has at least one input external stage variable or factor, designated by an input arrow, that it can influence only in an indirect way, and at least one input internal factor over which it has direct control. The output arrows represent the state variables which represent the output of the process. The process transforms the inputs, both internal and external, into an output with specified characteristics. Associated with each stage of the process and each set of characteristics of the factors is a defect rate and an associated cost. In the context of our problem, the body assembly process is represented by stage three. The external input variables represent the subassemblies that are assembled to produce body opening surfaces. The characteristics of these factors are the parameters of the distribution of the surface dimensions such as the average and the range. The internal input factor represents the calibration or setting of the assembly process and can influence the size of the body openings. The output vector represents the body openings. The cost vector is dependent on the combination of factors that results in a defect rate or a proportion of the openings that do not conform to engineering specifications.

The problem is to determine for the body assembly process the contribution of the internal factors, that the body assembly process controls, to the variability of the opening surfaces. If the desired conformance to the opening specifications can not be obtained economically, then the relationships between the subassembly surfaces and the

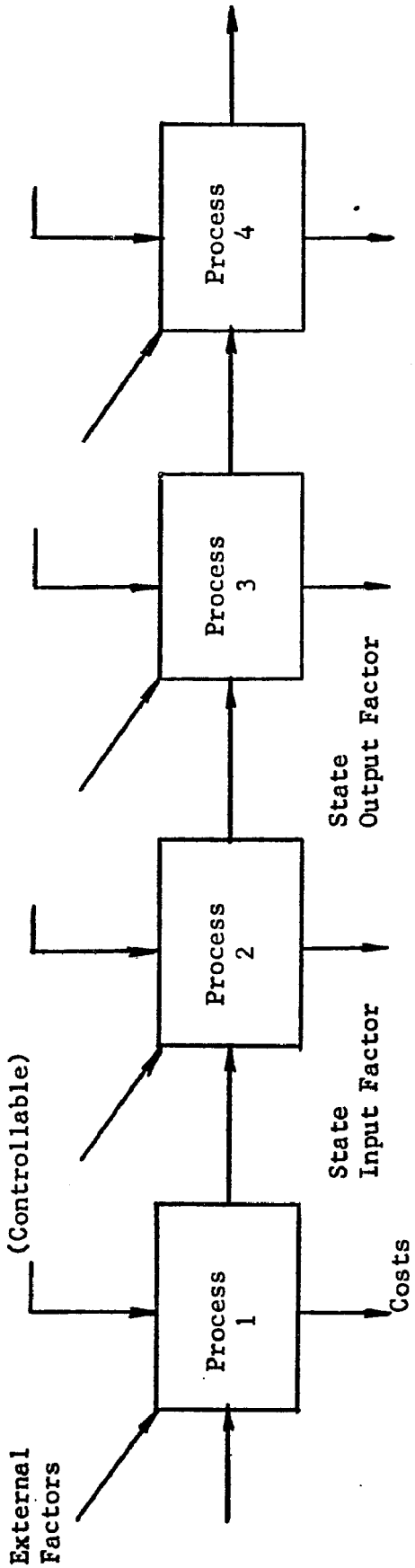


Figure 1.3 A Four Stage Serial Process Showing Internal and External Factors.

body opening surfaces must be determined. This analysis must be repeated for the subassembly and the detail part processes until economic and realistic specifications can be developed for each process such that the openings can be produced within engineering tolerances.

1.3 OBJECTIVES OF THE WORK

The objectives of this investigation are:

1. To identify the major process factors (internal and external), and to model the body subassembly and body assembly process in terms of these factors.
2. To design and conduct experiments in order to estimate the magnitude of the major process factors.
3. To develop a methodology to tolerance sheet metal subassembly and car body opening surfaces.
4. To use the tolerancing methodology and estimates of the major process factors to provide insights into evaluating product designs and process control procedures.

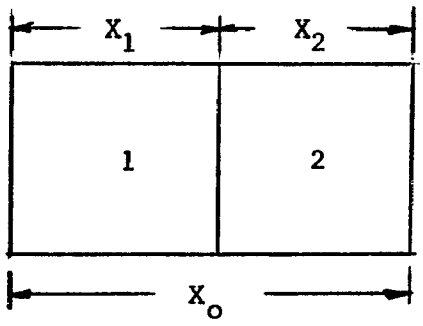
1.4 THE PERTINENT LITERATURE

This section contains a general description of the tolerancing problem and reviews the most significant papers written on tolerancing methodology.

1.4.1 THE GENERAL TOLERANCING PROBLEM

The general tolerancing problem will be described by means of a simple example in order to define terms and to introduce notation.

Consider the following assembly made from two blocks, 1 and 2:



The blocks are to be stacked together as shown so that the length of both blocks is to be X_o inches. This length X_o is the design or nominal length of the assembly. The design or nominal values for blocks 1 and 2 are X_1 and X_2, respectively. The functional relationship between the assembly characteristic X_o and the component characteristics X_1 and X_2 is expressed by the functional equation:

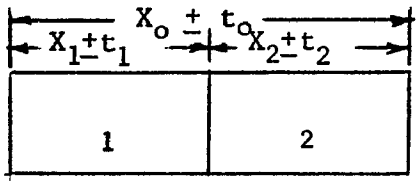
$$X_o = F(X_1, X_2) \qquad (1.1)$$

In our example, X_o is determined by:

$$X_o = X_1 + X_2 \qquad (1.2)$$

The length of blocks 1 and 2, however, cannot be made exactly to their nominal sizes and, therefore, the assembly cannot be made to dimension X_o. It is desirable that the actual assembly length x_o be held within a tolerance or a bandwidth of dimensions from $X_o - t_o$ to $X_o + t_o$ or, equivalently, $X_o - t_o \leq x_o \leq X_o + t_o$. If the nominal value X_o is subtracted from the actual value x_o, the difference $\Delta X_o = x_o - X_o$ is defined as the deviation from nominal. The tolerance statement can now be expressed by deviations from nominal, i.e. $|\Delta X_o| \leq t_o$ where $|\ |$ represents the absolute value of the deviation from nominal. This is equivalent to $-t_o \leq \Delta X_o \leq +t_o$. The $\pm t_o$ is an example of a bilateral tolerance because it departs in both directions from the nominal specification.

The value of t_o depends upon the tolerance values t_1 and t_2 that are assigned to components 1 and 2, respectively. These tolerances are usually represented as shown:



The influence of tolerances t_1 and t_2 on t_o can be interpreted two ways: (1) deterministically by the method of extremes, and (2) probabilistically where the probability distribution of the response x_o is predicted. Considering the method of extremes first, we have the following:

Maximum Value of X_o =

$$X_o + t_o = X_1 + X_2 + (t_1 + t_2)$$

Minimum Value of X_o =

$$X_o - t_o = X_1 + X_2 - (t_1 + t_2)$$

The tolerance equation for characteristic length X_o is determined by subtracting the minimum value of X_o from the maximum value:

$$X_o + t_o - (X_o - t_o) = X_1 + X_2 + (t_1 + t_2) - \left[(X_1 + X_2) - (t_1 + t_2)\right]$$

$$2t_o = 2t_1 + 2t_2$$

Simplifying, we have the following tolerance equation:

$$t_o = t_1 + t_2 \qquad (1.3)$$

The method of extremes permits the determination of the maximum and minimum limits for the response characteristic based on the component extreme limits. The advantage of this method is that it guarantees that the design will be within its limits even when the components are all at their extremes. The disadvantage is that the component variation must be very small and tends to be unrealistic.

Therefore, in order to solve the tolerance equation t_o, values of t_1 and t_2 are selected. It is evident that many combinations of t_1 and t_2 can be selected. The least cost tolerancing problem is to select that combination of t_1 and t_2 that results in the lowest manufacturing cost. It is then necessary to have estimates of the manufacturing cost for different values of tolerances t_1 and t_2. These cost relationships may be a set of estimates or there may exist a smooth curve indicating an infinite number of tolerance values, depending on the process. We define the cost relationships by $C_1\ (t_1)$ and $C_2\ (t_2)$, and $C_o\ (t_1, t_2)$. The problem can now be expressed by:

$$\text{Minimize } C_o = C_1\ (t_1) + C_2\ (t_2) \qquad (1.4)$$

subject to $t_1 + t_2 = t_o$

Considering the probabilistic approach to the problem, we would write the functional equation for the actual length x_o in terms of x_1, and x_2, i.e.,

$$x_o = x_1 + x_2 \qquad (1.5)$$

Taking the total derivative for the function $x_o = F\ (x_1, x_2)$ we have:

$$dx_o = \frac{\partial F}{\partial x_1}\ dx_1 + \frac{\partial F}{\partial x_2}\ dx_2 \qquad (1.6)$$

$$= dx_1 + dx_2$$

Substituting our notation for deviations from nominal for the small differentials, we have:

$$\Delta X_o = \Delta X_1 + \Delta X_2 \qquad (1.7)$$

We now have an expression for the deviations from nominal. The deviations from nominal are now assumed to be random variables that are distributed according to some probability density functions $f_1(\Delta X_1)$ and $f_2(\Delta X_2)$. Each distribution can be represented by its mean, variance,

skewness and kurtosis. The probabilistic approach requires the determination of the density function of the response deviation ΔX_o which we denote by $f_o(\Delta X_o)$. The use of this approach requires a probabilistic statement concerning the tolerance of the assembly dimension. An example of this is:

$$P(-t_o \leq \Delta X_o \leq t_o) = 1-e$$

which signifies that only a small proportion of the product will have an assembly dimension outside the interval $X_o \pm t_o$. The probabilistic method is based on the classical equations for the propagation of errors which permits the resultant tolerance to be computed from:

$$t_o = [(t_1^2 + t_2^2)]^{1/2} \qquad (1.8)$$

where t_o is the resultant tolerance and t_1, t_2 are the component tolerances. If $t_1 = t_2 = T$ then (1.8) permits a tolerance $t_o = \sqrt{2}T$ versus $t_o = 2T$. The probabilistic method depends on the assumption that the individual component tolerances are independent with the means set at the nominal dimensions. The probability of all components having extreme values occurring simultaneously is very small.

1.4.2 TOLERANCING METHODOLOGY

The first comprehensive work on tolerancing was written by Gilson (16). The author emphasizes the importance of tolerances as a coordinating link between design and production. He advocates the use of realistic tolerances based on process capability and added probabilistically, rather than adding maximum and minimum limits to determine the extreme limits of the response dimension. The author introduces the concept of a semi-circular probability density function as a compromise between the extremes of the uniform and normal density functions for the component deviations from nominal.

The development of the tolerance equation facilitates the allocation of tolerances to the components in order to satisfy the desired tolerance for the assembly characteristic. The methods for forming these tolerance equations for engineering design analysis have been described by Fortini (15), Gladman (17), Mansoor (24), Ashbridge (1), and Bennett and Gupta (3). Use of probabilistic methods is described by Johnson (22), Fortini (15), Spotts (29), Evans (9), Gladman (17), Bennett (2), and Mansoor (24). The probabilistic method requires that the probability distribution of the response be determined from the distributions of the component characteristics which are combined according to the functional equation. The response distribution is described in terms of its first four cumulants. Burr (5) gives formulas for the calculation of skewness and kurtosis of the response distribution when the components are additive to determine if the response probability distribution is normal. Shooman (28) provides tables to determine the form of the response probability distribution, and the formula for the mean and variance for the more common functional equations and component probability distributions. The author also discusses the linearizing of nonlinear tolerance functions by taking first order Taylor Series expansions.

Tukey (31), (32), (33), has developed formulas for the non linear case which give the first four moments of the response as a function of the first four moments of the distribution of the components.

Evans (10) has developed a Monte Carlo technique called Multiplex Sampling that is especially adapted to the tolerancing problem. It is used when the tolerancing equation can not be expressed analytically but is known only experimentally. This technique has the advantage of

determining the parameters of the response distribution for many different values of parameters of the components with substantially fewer trials. The alternative to this procedure would be a simulation run for each combination of component parameter values.

Evans (11), (13), (14), has used quadrature formulas to numerically approximate the multiple integrals that are formed when the first four moments are expressed analytically. The moments are then used to determine the probability of the response variable being within tolerance limits. He applies this technique first to components that are independent and normally distributed in the first two papers, and finally when the variables are dependent and not normally distributed.

Given the ability to predict the probability distribution parameters i.e., mean, variance, etc., of the response variable as a function of the component probability distributions, the same response can be obtained by different combinations. In order to determine the combination that is most desirable, the problem must be formulated as a least cost or maximum profit problem. Pike and Silverberg (26) formulated the tolerancing problem as a maximum profit or value problem. They applied this procedure to an open kinematic chain, the Scott-Russell Sine linkage. They obtained the minimum variance combination of component tolerances for different values of manufacturing cost using the criterion: an optimal assignment exists when each component contributes an equal reduction in variance to the design. The maximum value design is selected from the profit curve obtained from the difference between the value curve and the cost curve.

Evans (9) has formulated a minimum cost problem where total cost

consists of the cost of original manufacture plus the cost of salvage. The design contains identical units whose responses are additive and a percentage of the design must be within predetermined limits. The units can be made from different components which permit different responses and different costs. His analysis allows him to set rejection limits on each unit such that the set of units satisfy the quality constraint and the minimum cost unit is obtained. Other minimum cost formulations are Latta (23), Moy (25), Edel and Auer (8), Hillier (20), and Bennett and Gupta (3), (4). The work of Bennett and Gupta is not probabilistic but determines the minimum cost assignment of tolerance based on extreme values. The approach uses Lagrange multipliers in order to minimize the cost and satisfy the constraint: the sum of the component tolerances equals the response tolerance. The second paper considers the case when a component is used in more than one response relationship.

The effectiveness of any tolerancing methodology depends on the degree of compliance with the component tolerance specifications by manufacturing. Adherence to these specifications is controlled by process control plans, or sampling inspection plans depending on whether the components are produced or purchased. It is also expected that the parameters of the component distributions will change during the life of the product. Such changes may take the form of shifts in the process mean due to tool wear, machine setting, and material differences, or increase of the process variance due to machine wear. Some of these changes are inevitable and the tolerancing procedure should take them into consideration. Other changes, which are undesirable, should be detected by the appropriate control procedure.

Burr (6) develops a model for deviations from nominal of a component part as a sum of the deviations from an instantaneous mean, the process mean, and the design or nominal value. He uses the design mean and the tolerances to develop control limits for $\bar{X}$ and R charts. The objective here is to insure that the distribution is being controlled. Burr proposes the use of a sampling plan based on samples of size 10, and two process control plans based on samples of size 5 to detect changes in the mean and the range. The first process control plan detects undesirable changes in the mean and the range, and the second detects consistent or gradual changes in the process level. The plans are not optimal in any sense, but were selected on the basis of their applicability to many different processes.

Evans (12), considers the case where changes to the mean have equally likely chances of occurring. He assumes that the component tolerances are controlled by a variable sampling plan, and that N components form the assembly. Lots that are bad will be detected according to the operating characteristic curve of the plan and the out-of-tolerance product will be sorted. He computes the density function for the mean of the lots which are accepted by the test and used in the assembly. This permits the determination of the percentage of assemblies within limits as a function of the sample size for the plan.

1.5 CONTRIBUTION OF THE RESEARCH

The contribution of this work is synonymous with the research objectives. There has been no published work concerning the tolerancing of sheet metal component surfaces. Tolerances have not been available for sheet metal subassembly surfaces that can be used by manufacturing.

Because of the complex geometrical relationships between the detail parts and the difficulty in predicting the consequences of errors on the subassembly and body opening surfaces, a successful application is not possible unless the entire procedure is outlined for the responsible functions. This research provides a methodology to determine the surface tolerances for designs.

The research also constitutes an application of process modeling to the automobile body assembly process in order to design a process control system. The components of variance have been estimated for the major process factors and experiments conducted to correlate predicted and actual process transformations.

1.6 ORDER OF REPORTING

The next two chapters describe the environment of the problem, the modeling of the process, and the procedure to estimate the process factors. Chapter II describes the process and the organization structure that existed at the time the study was initiated. Chapter III describes the analysis that was performed in order to determine the largest component of variance. Chapter IV describes the steps of the algorithm that were developed in order to tolerance and evaluate a sheet metal design. The methodology is also applied to a subassembly design. Chapter V discusses the cost of allocating tolerances and formulates the least cost tolerancing problem. Chapter VI summarizes the research and offers suggestions for further work.

CHAPTER II

ENVIRONMENT OF THE PROBLEM

2.1 INTRODUCTION

This chapter describes the body assembly process and the major panel fitting and sealing processes. The systems used to measure the dimensional characteristics of the bodies with respect to their nominal design dimensions are discussed. The use of this information and the controls employed by quality control personnel are presented. Mathematical models are developed for body surface measurements in terms of the major process factors. Body measurement data are compared to engineering design tolerances. Finally, the organization structure that existed at the time of the study for those functions that designed the product and the process and supplied the parts are discussed.

2.2 DESCRIPTION OF THE PHYSICAL PROCESS

The automobile body building process employed by this manufacturer is referred to as a "gate line" process. This process has 45 framing gates and 60 framing trucks. A gate is a large welding fixture with clamps to hold sheet metal components which make up one side of the body. Figure 2.1 illustrates a gate frame, framing truck and car body. The gate "frames" the door openings, the rear fender and wheelhouse assembly. The framing truck holds the front and rear floorpans. Figure 2.2 illustrates the framed body and the major subassemblies. A body is framed when the two gates are joined with a framing truck by clamps and tie bars. Assemblies that bridge the body sides are added. These include the cowl top, windshield and backlight headers, upper and lower deck panels, and the rear window package shelf. These members are welded

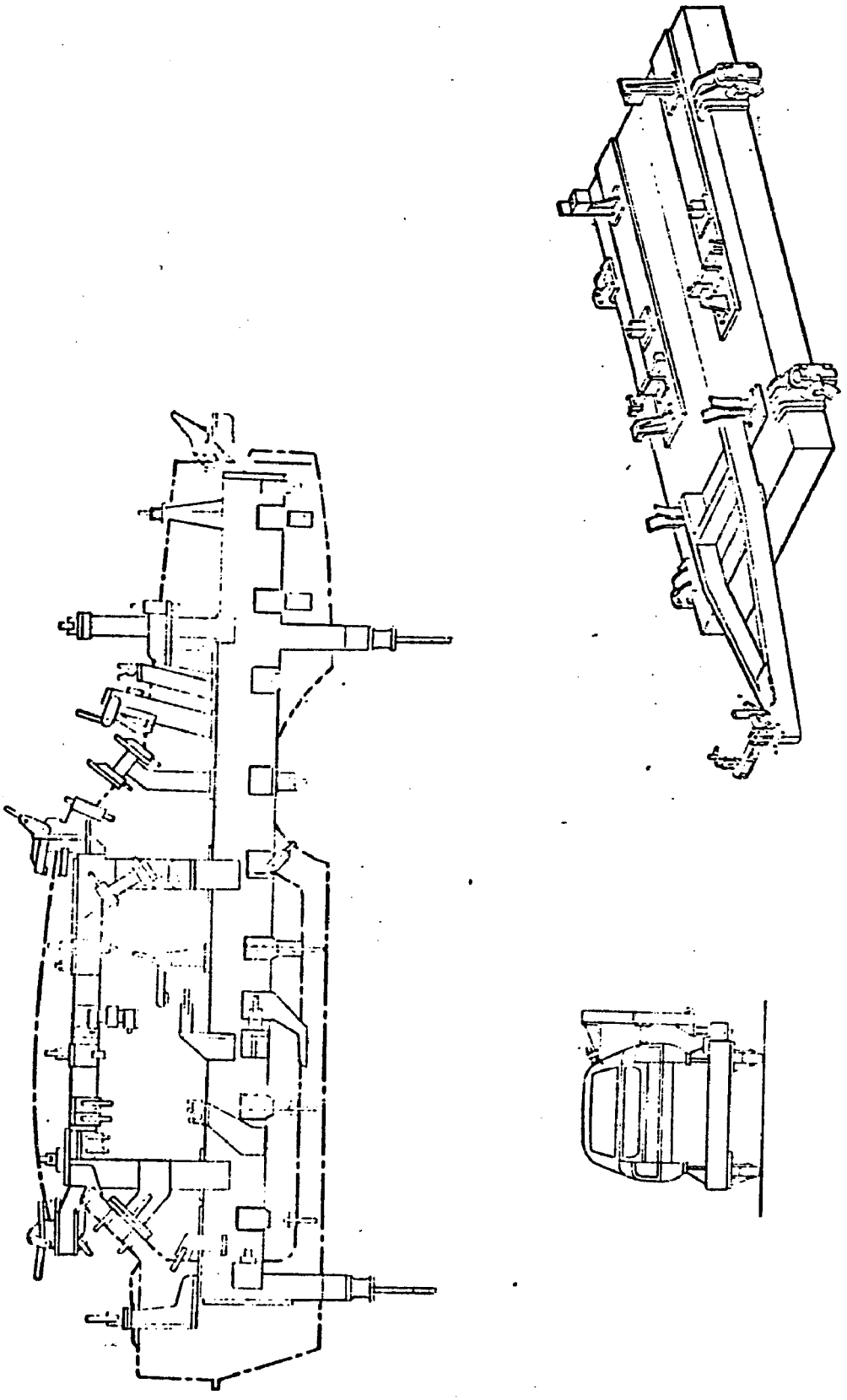


Figure 2.1 Typical Gate Fixture and Framing Truck

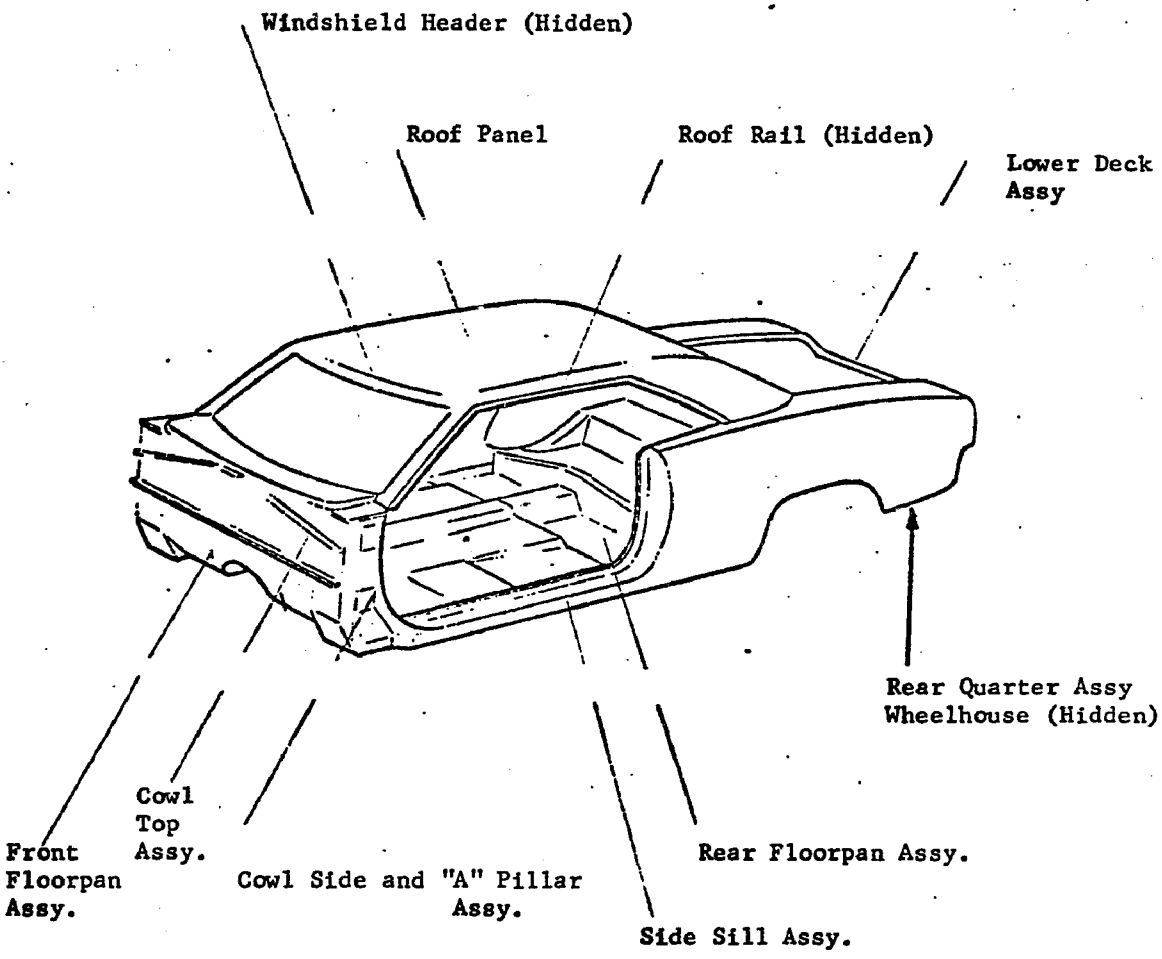


Figure 2.2 Framed Body and Major Subassemblies

to the floorpan and sides. The roof panel is added and spot welded to the windshield and backlight header. The openings of interest, the door, window,and backlight are "framed" at this point in the process. Figure 2.3 is a schematic of the process flow for the body framing line.

The detailed parts and subassemblies are located in the gates at principal locating points. These points are referenced to three planes: Front O plane, Bottom O plane, and Centerline. All tooling and parts are referenced to these planes. Figure 2.4 illustrates the locations of some points and shows the reference planes. The gates have machined blocks representing the female contours of the body surface that they locate. The floorpans have locating holes and sockets and are held to the framing truck with "hold down" bolts.

The assembly plant body shop receives all parts from the corporation's stamping plants. These parts include subassemblies that the plant uses directly in the body and component parts which are welded into subassemblies. The body that is assembled by this manufacturer is of unitized welded construction. Immediately following the gate separation, the body continues to travel on the framing truck through the respot area. The spot welds that were not applied because of tooling are performed here. Small stampings, such as gussets and clips, are also welded at this stage of the process. The body is transferred from the framing truck to a trim truck. The bodies that have major gaps or damage are transferred to a repair area. Bodies that are acceptable proceed to the door hanging, fender installation, hood and deck lid setting operations.

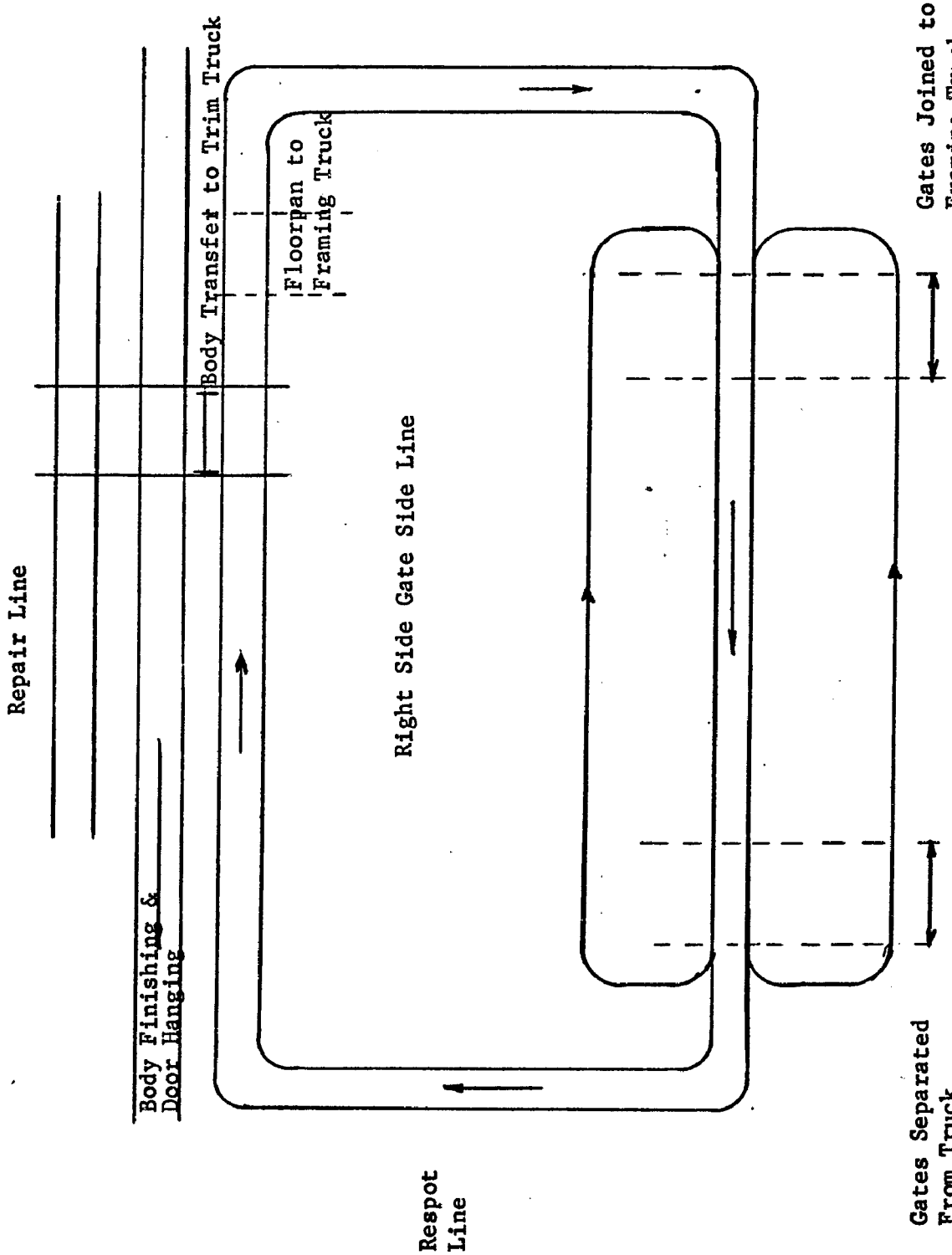


Figure 2.3 Schematic of Body Framing Process

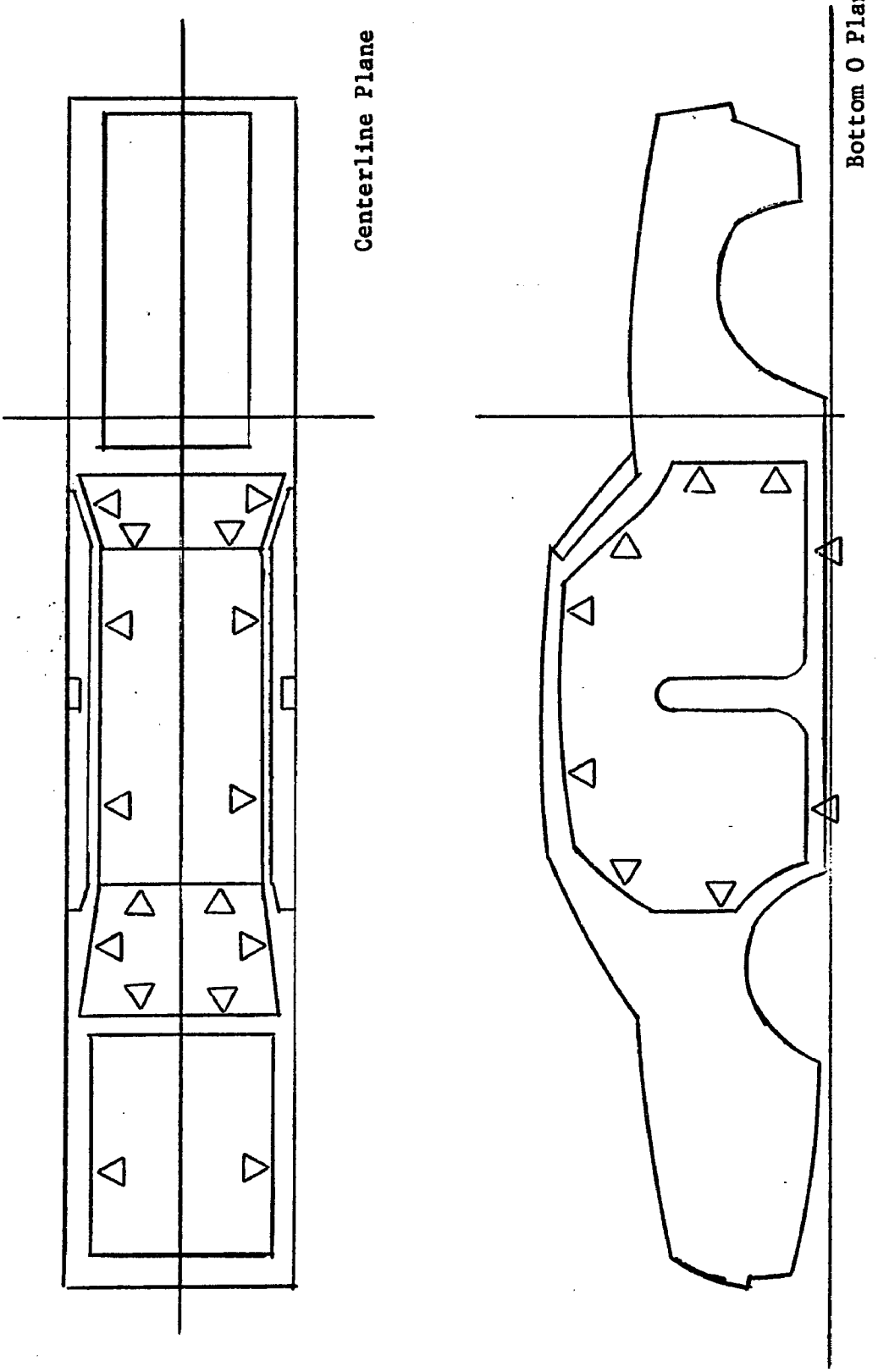


Figure 2.4 Location of Tool Locating Blocks for Body Openings

The door installation is performed by two operators per door using a fixture. The doors are loaded into the fixture which locates from holes and points on the body. While the door is being held in the opening, the other operator then inserts bolts and fastens the door hinges to the 'A' pillar and 'B' pillars according to the body style. The quality of the door fit at this point depends on the variability of the opening, the locating points for the fixture and its repeatability, and the variability of the doors and hinges. Immediately following this operation are operators with rubber hammers that examine the door fit and make adjustments by applying pressure or force to the door and hinge at different points. When the door fit is considered satisfactory, the hinge bolts are torqued down.

The next operations performed in the body shop are fender installation, deck lid and hood installation. Figure 2.5 illustrates the major processes schematically. All through this production area, seal is applied to holes, seams, and gaps to prevent water from leaking into the car. The front fenders are loaded into an installation fixture which locates the fenders using the body and truck as points of reference. The hood opening is, therefore, a consequence of the body and truck variability and the repeatability of the fixture. The mechanisms for the hood and deck lid are installed next, being followed immediately by the hood and deck lid. These panels are also adjusted for fit. The bodies are then subjected to a series of soldering, grinding and finishing operations to prepare them for paint application. Panels are adjusted again by repairmen further down the line. The bodies are inspected and repaired prior to shipment to the paint department.

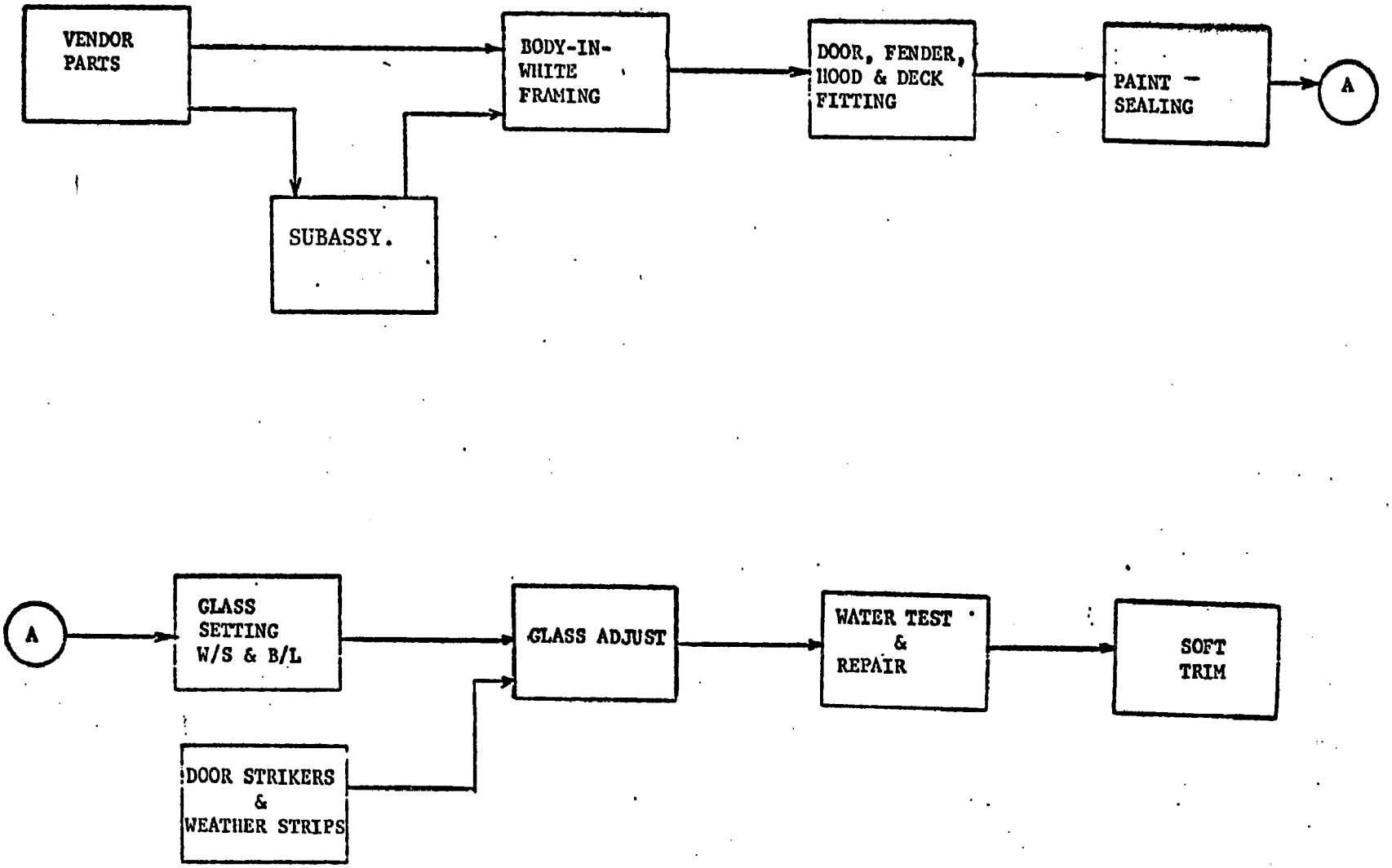


Figure 2.5 Schematic of the Major Processes for Body Assembly

Application of hard trim items, such as mouldings, glass, weatherstrips, etc., are done next in the trim department. Operations pertinent to the sealability of the body begin with the installation of windshield and backlight moulding clips. Proper installation of these clips, in addition to opening size, is important to prevent windshield and backlight leaks and glass breakage. The openings for windshields and backlights are prepared next by priming them with a paint, and then installing a butyl rubber tape. The backlight and windshield are installed and compressed with a fixture. Irregular contours of these openings result in poor compression of the butyl tape which may result in water leaks and extensive repairs. The mouldings around these openings are installed next. Rubber weatherstrips are applied to the deck opening and the doors. Hardtop models have a weatherstrip retainer applied to the roof rail on upper door openings. The installation and adjustment of the door lock striker is also performed in this department. Door glass and mechanisms are installed in sedan doors, hardtop doors and rear quarter panels. The hardtop models require an adjustment after installation to achieve a proper fit of the glass and good compression against the weatherstrip.

The body is then subjected to a water test as it moves through a pressurized booth for a prescribed interval of time. The body at most plants does not have soft trim, such as seats, carpeting or trim panels, installed at this point of the process. Water leaks are detected by an inspector who "rides" the car through the test booth. In some facilities, "black light" is used to identify water leaks from outside the body after it emerges from the test booth. The inspector marks the area of the leak on an inspection ticket which travels with

the body. He then marks or tallies the leaks on a chart to determine if any trends are occurring. Cars then proceed to a line repair and soft trim installation. Repairmen read the tickets to determine what leaks and proceed to stop the leak using rubber or plastic sealer. A second water test booth has inspectors "riding" cars to "buy-off" or accept the repair. Those bodies that are not repaired and accepted by this system must proceed down the line for soft trim installation. At the end of this line, cars are driven to a repair area for off-line tear down and repair. Repairs in this area necessitate the removal of trim panels to detect the source of the leak.

2.3 DESCRIPTION OF MEASUREMENT SYSTEM

There are two major sources of measurements concerning the assembled body: the surface plate and plug gauges.

The surface plate is a large machined metal plate with mounting details to hold the body in a fixed relationship to the three reference planes. Measuring equipment is attached to the plate which permits readings to be taken in each coordinate plane. The principal locating points on the assembly body are measured and compared to the nominal or target dimensions. The deviation from nominal is recorded for each point. The complete assessment of all gate and truck combinations can only be done over an extended period of time.

The second method of obtaining information concerning the dimensional performance of the process is through the use of plug gauges which act as glass or door panel simulators. These gauges are cumbersome to use on a moving line. In addition, they are used in conjunction with feeler gauges to obtain a numerical reading.

The plants have checking fixtures to evaluate the dimensional characteristics of the subassemblies that are made by them. The checking fixtures clamp the assembly against certain surfaces or "net" blocks. The surfaces to be measured have targets that have been calibrated to a nominal model. The targets are normal to the surface and are offset by 1/8 inches. This permits the use of feeler gauges to measure deviations from nominal in both directions. Checking fixtures are also available for the larger subassemblies such as the 'A' pillar and the cowl top. The subassembly surfaces are not toleranced. Considerable knowledge is required to determine if deviations from nominal are acceptable.

2.4 PRESENT CONTROL SYSTEM AND PROCESS PERFORMANCE

This section describes very briefly the type of control system for body quality and related processes that was employed by the assembly plant being studied. The performance of body openings to specification and other quality indicators are also discussed.

2.4.1 PRESENT CONTROL SYSTEM

The Quality Control Department consists of the Quality Engineering function, the Inspection Department, and a Material and Salvage function. Quality Engineering specifies the inspection operations to be performed by inspectors in each production department. Critical inspection write-ups that cause a loss of production counts of acceptable vehicles are usually tallied in each department by the inspectors. Quality Engineering also conducts audits of different processes in each productive department,

such as adherence to torque specifications, Federal safety and weld specifications, etc. The Material section is charged with the responsibility for the quality of incoming materials. This function performs little or no dimensional sampling of incoming material. Its primary activity is to evaluate the quality of parts for visible defects and to write defective material reports. The body-in-white quality control function is under the supervision of a leader for each shift. The body shop leader is charged with the responsibility of authorizing adjustments to body shop tooling. Adjustments to gates and subassembly fixtures are made by tool maintenance only after written orders from quality are received. The adjustments to the gate are based on history obtained from surface plate measurements of car bodies. The auditors perform plug checks of windshield and backlight openings and other checks for the gate line on a daily basis. The major activity of this section is trouble shooting. Calls from production concerning problems with tooling or parts are investigated by the leader and his engineers. The leaders are also required to investigate body influence on conditions further downstream in the process that are brought to their attention by their superiors.

Subassemblies and parts are measured only when problems occur. The dimensional conformance of doors, rear quarter panels, and floorpans can only be checked in fixtures at the supplier's plant. Levels of control for subassemblies varied at different plants.

The control of water and dust leaks has been assigned to a Senior Quality Engineer. His activities usually consist of observing vehicles

in the repair hole for water leaks after the line water test and observing how sealing operations are performed in the body and trim departments. He does not have access to body opening information when trying to identify causes of leaks. He also samples a number of vehicles per shift by putting them through a static water test. Cars that leak are also worked on until the cause of the leak can be detected and the condition can be corrected.

The corporation has a final customer acceptance audit that it conducts on a sample of two cars per day in each assembly plant. This audit works on a demerit system. Defects are given 3, 5, or 10 demerits according to an established procedure. This "Corporate Audit" also samples cars daily for their performance in the static water test. These cars are also evaluated for causes of the leaks. The audit is given a great amount of attention by the plants, considering the small sample of cars examined daily. The audit items are typical of those things that customers will return for warranty correction. Experience with the items that are written up by inspectors indicate that problems exist that have not been solved. Solution of these quality failures would prevent their appearance on the audit cars and also allow the inspection and repair system to cope with random quality failures more effectively.

2.4.2 PROCESS PERFORMANCE

The quality indicators that are maintained by the body shop quality control section were reviewed. The more important indicators are:

Surface Plate Checks

Deck Lid Spacing Audit

Hood Spacing Audits

Windshield Opening Size

Backlight Opening Size

Figure 2.6, which summarizes the deviations from nominal of the principal locating surfaces in the body, indicates that approximately thirty per cent of the readings exceeded .100 inches. These readings represent where the tooling placed the subassembly surfaces in the finished body. Because these surfaces represent opening surfaces, the readings indicate that a large percentage of the openings are not being maintained within their engineering tolerances.

Examination of the quality indicators for water leaks also showed a high incidence of process failures. Figure 2.7 illustrates the large number of cars with hardtop body style that had water leaks. The inability to correct or repair these leaks was evidenced by their occurrence on the Corporate Audit results and the warranty expense reports.

The next section discusses the analysis that was performed on the body measurement data obtained from the surface plate measurements.

2.5 ANALYSIS OF BODY MEASUREMENT DATA

This section describes the analysis of the principal locating point data collected from the bodies measured on the surface plate. Models are developed to describe the sources of error that contribute to a deviation from nominal of a principal locating point (plp) in each coordinate plane. The samples are reduced to determine the mean bias and variability of the measurements for the plp's. As no tolerances are available for plp's, the data are further reduced by taking differences of measurements for plp's to obtain opening size relationships. These

ITEM NO. BODY-IN-WHITE

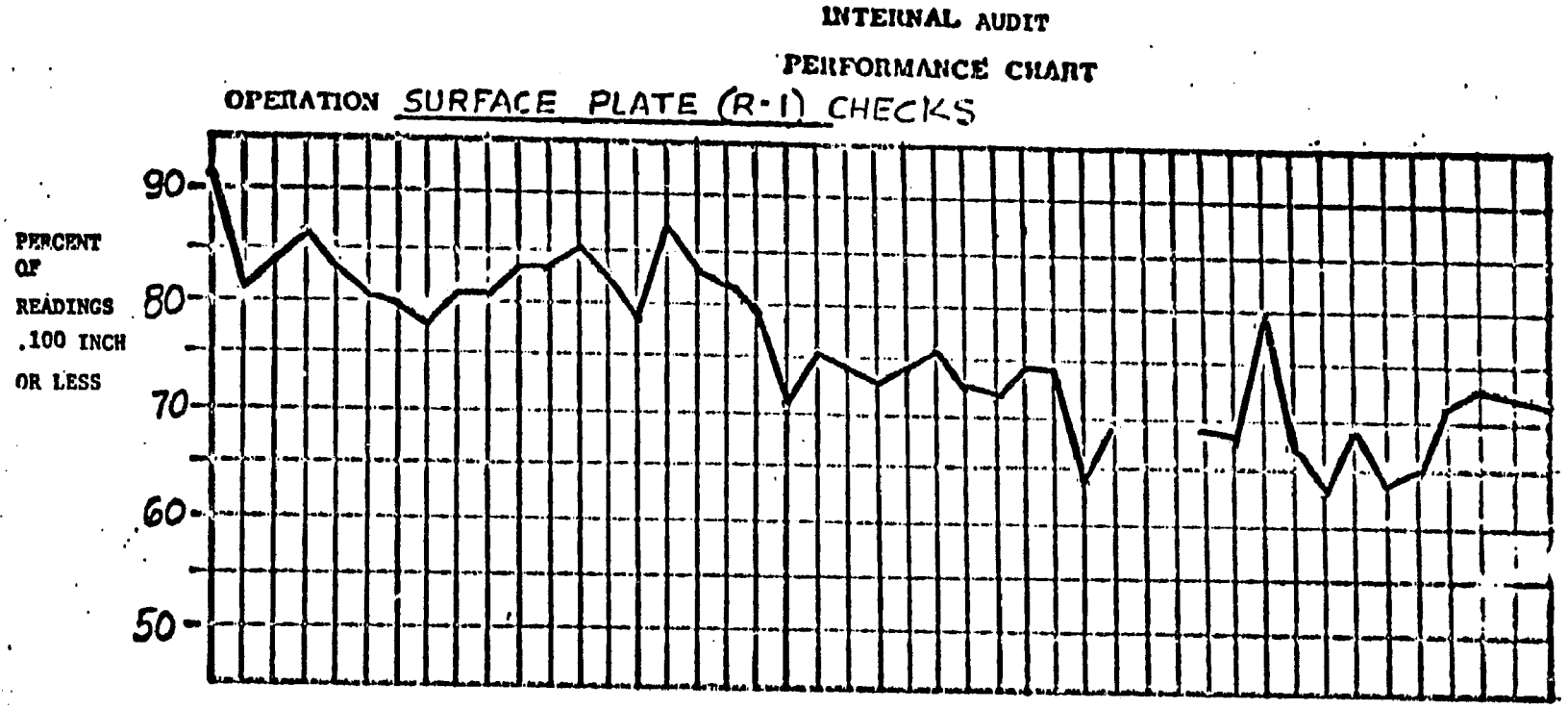


Figure 2.6 Chart of Surface Plate Measurements. Percent of Readings .100 In or Less

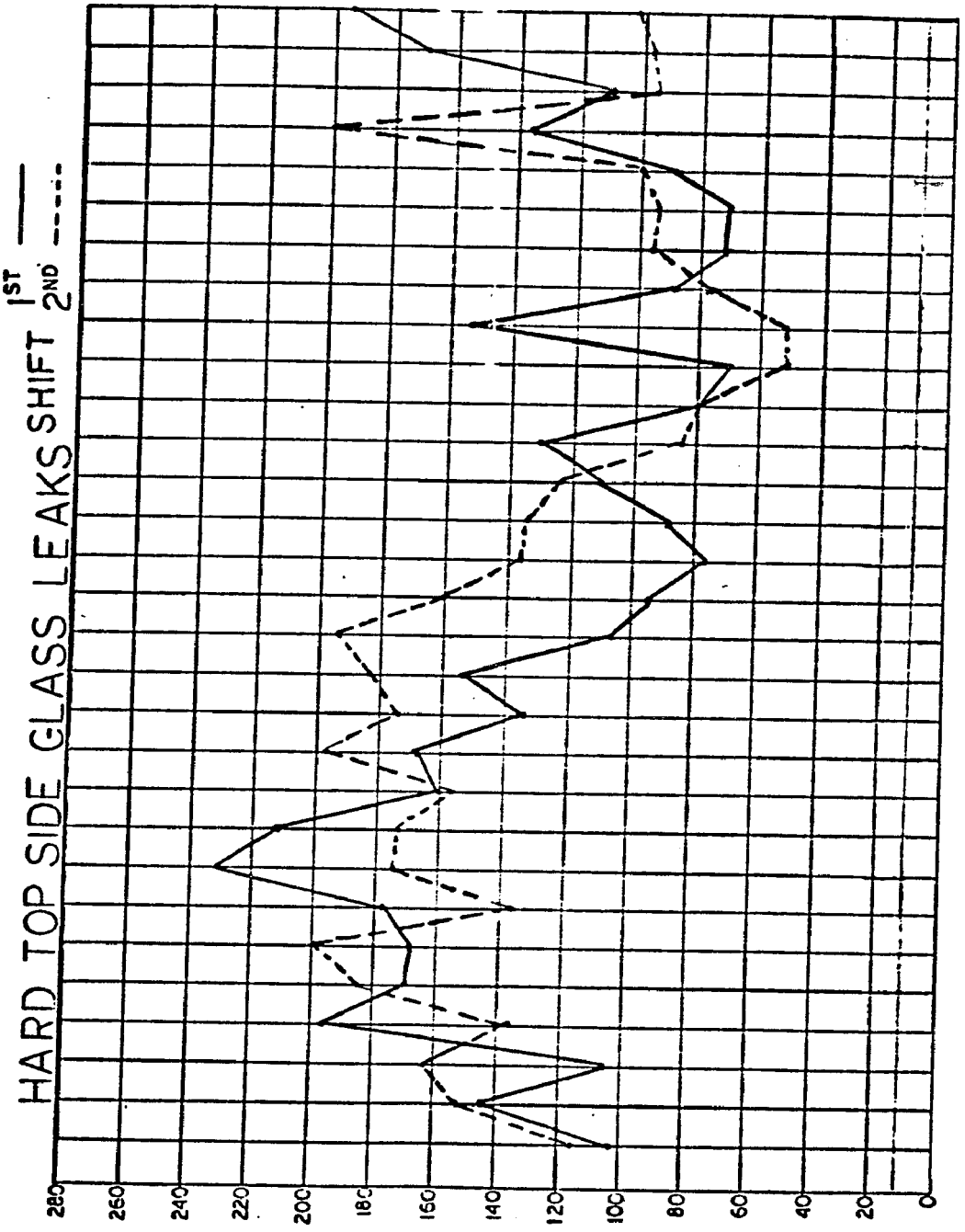


Figure 2.7 Graph of Number of Cars Having Water Leaks

measurements are compared with tolerances which exist for opening sizes to determine if the process is capable of meeting engineering specifications.

2.5.1 MATHEMATICAL MODELS FOR PRINCIPAL LOCATING POINTS

All principal locating points on an automobile body are referenced with respect to the three planes as illustrated in figure 2.4. These points represent where the subassembly is held in the gate during the assembly process. The point is defined by passing a plane parallel to one of the reference planes at a prescribed distance. The point is then located at the intersection of the plane and a character or contour line on the sheet metal. The coordinates with respect to the other two planes are compared with the nominal dimensions and the deviations from nominal recorded. The mathematical model represents this deviation as the sum of the identifiable deviations due to clearances and gaps between parts and tool members, mastering of gate locating block units and framing trucks, and unexplained variability in each coordinate plane. The unexplained variability for each principal locating point (plp) measurement is denoted by e which includes the variation in the process due to parts, part distortion from welding and clamping, and random measurement errors. In the case of deviations with respect to the centerline plane, there is an additional component of variability, the offset of the gate frame from perpendicular. This offset is a function of the gate leg, tie bar anchors, tie bars, floorpan width, and framing truck system that holds the two gate frames with respect to the base, the framing truck. These elements are shown in figure 2.8. The models for plp's with respect to each plane are:

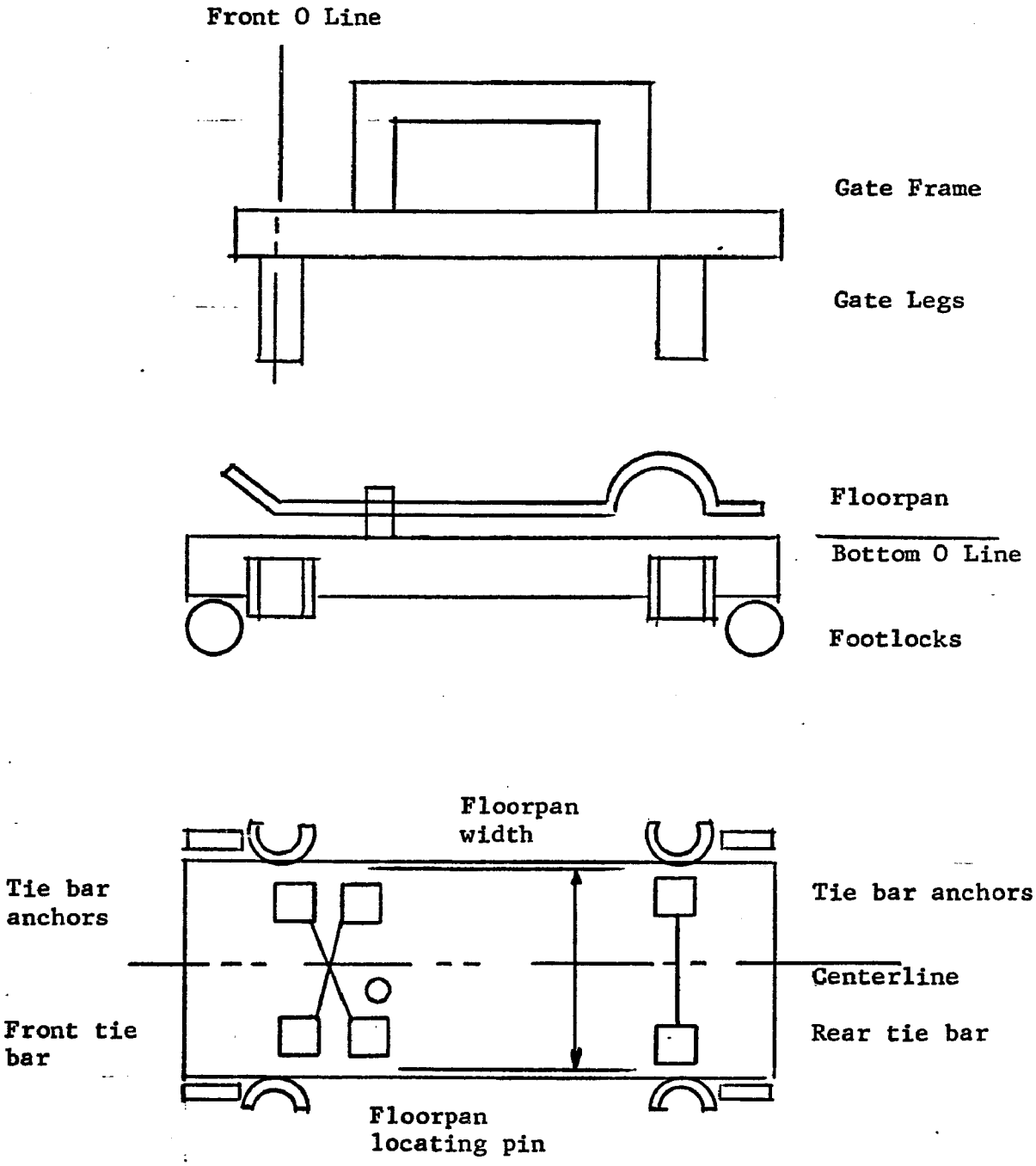


Figure 2.8 Tooling Elements of the Framing Process

$$d_{ijn}^{(k)A} = u_n + v_n + w_n^{kA} + G_i^{kA} + T_j + e_{ijn}^{kA} \quad \text{Front 0 Plane} \quad (2.1)$$

$$d_{ijn}^{(k)A} = w_n^{kA} + G_i^{kA} + \frac{D}{D}^{k} T_j + e_{ijn}^{kA} \quad \text{Bottom 0 Plane} \quad (2.2)$$

$$d_{ijn}^{(k)A} = u_n + v_n + w_n^{kA} + G_i^{kA} + e_{ijn}^{kA} + \frac{D}{D}^{kA} F_n(x_1, x_2, T1, x_4, x_5, P, T2) \quad (2.3)$$

Centerline Plane Front

$$d_{ijn}^{k(A)} = u_n + v_n + w_n^{kA} + G^{kA} + e_{ijn}^{kA} + \frac{D}{D}^{kA} F_n(x_6, T3, x_7, P, T2) \quad (2.4)$$

Centerline Plane Rear.

where

i is an index denoting the ith gate.

j is an index denoting the jth framing truck.

k is an index denoting the kth plp on the body.

A denotes the side of the body i.e., left side or right side.

n is an index denoting the nth observation and indicates that the symbol that it subscripts is a random variable.

$d_{ijn}^{(k)A}$ denotes the deviation from nominal of a principal locating point as measured in inches in a coordinate plane.

u_n denotes the clearance between the floorpan and the locating pin that locates the floorpan relative to the centerline and front 0 plane.

v_n denotes the clearance between the gate leg and the front 0 locator on the framing truck for deviations with respect to the front 0 plane. For centerline readings it represents the gap that could exist between the gate leg and the centerline stop.

w_n denotes the gap that is observed between the part and the locating block in the gate.

G_i^{kA} represents a bias from nominal of the locating block which represents a mastering deviation.

T_j represents bias in the distance from the front 0 footlock stop to the floorpan locating pin for front 0 readings. For bottom 0 readings, it represents any bias that may occur from the bottom 0 floorpan locator to the elevation of the framing truck footlock bottom 0 locators.

e_{ijn}^{kA} represents any unexplained variation or random error attributable to part variability and measurement errors.

D represents the nominal distance between gate leg centers on a gate for bottom 0 readings. For centerline readings, it represents the nominal distance from the lowest centerline stop in the footlock mechanism to the dimension of the plp where the offset from perpendicular of the gate frame is measured.

D^k represents the front 0 distance to the plp from the front footlock centerline for bottom 0 readings; and for centerline readings, it represents the distance from the lower centerline stop on the framing truck to the height of the plp.

$F_n(x_1,x_2,T1,x_4,x_5,P,T2)$ represents the offset of the gate frame from perpendicular in the vicinity of the front tie bars.

It is a function of the following variables:

x_1 represents the deviation from nominal of the upper tie bar anchors.

x_2 represents the deviation from nominal of the lower tie bar anchors.

T1 represents any bias in the centerline truck stops.

x_4,x_5 represents any bias in the upper and lower tie bars, respectively.

P represents deviation from nominal of the floorpan width.

T2 represents any bias from nominal of the floorpan centerline pin locators on the framing truck to centerline.

The terms for the offset from perpendicular in the vicinity of the rear tie bars are:

x_6 represents deviation from nominal in the rear tie bar anchor.

T3 denotes bias in the rear centerline stops.

x_7 represents error from nominal in the rear tie bar length.

The above expressions indicate the variables that can influence the readings in each plane. The number of variables also points to the importance of mastering the tooling and maintaining it in acceptable condition.

2.5.2 ANALYSIS OF PRINCIPAL LOCATING POINT DATA

Principal locating points were measured for 67 bodies of a year's production of a particular body style. The average deviation from nominal and the standard deviation about this average deviation were computed for each plp.

The sample averages and standard deviations for each plane are plotted as histograms in figure 2.9. The histograms for sample averages indicate little success in centering at zero the plp deviations from nominal in the centerline and bottom 0 coordinates. The range of the sample means is also quite large, indicating that these surfaces are not being positioned in the body correctly. The histograms for the standard deviations also indicate that almost all deviations have a standard deviation greater than .050 inches. The natural process variation ($\pm$ 3 standard

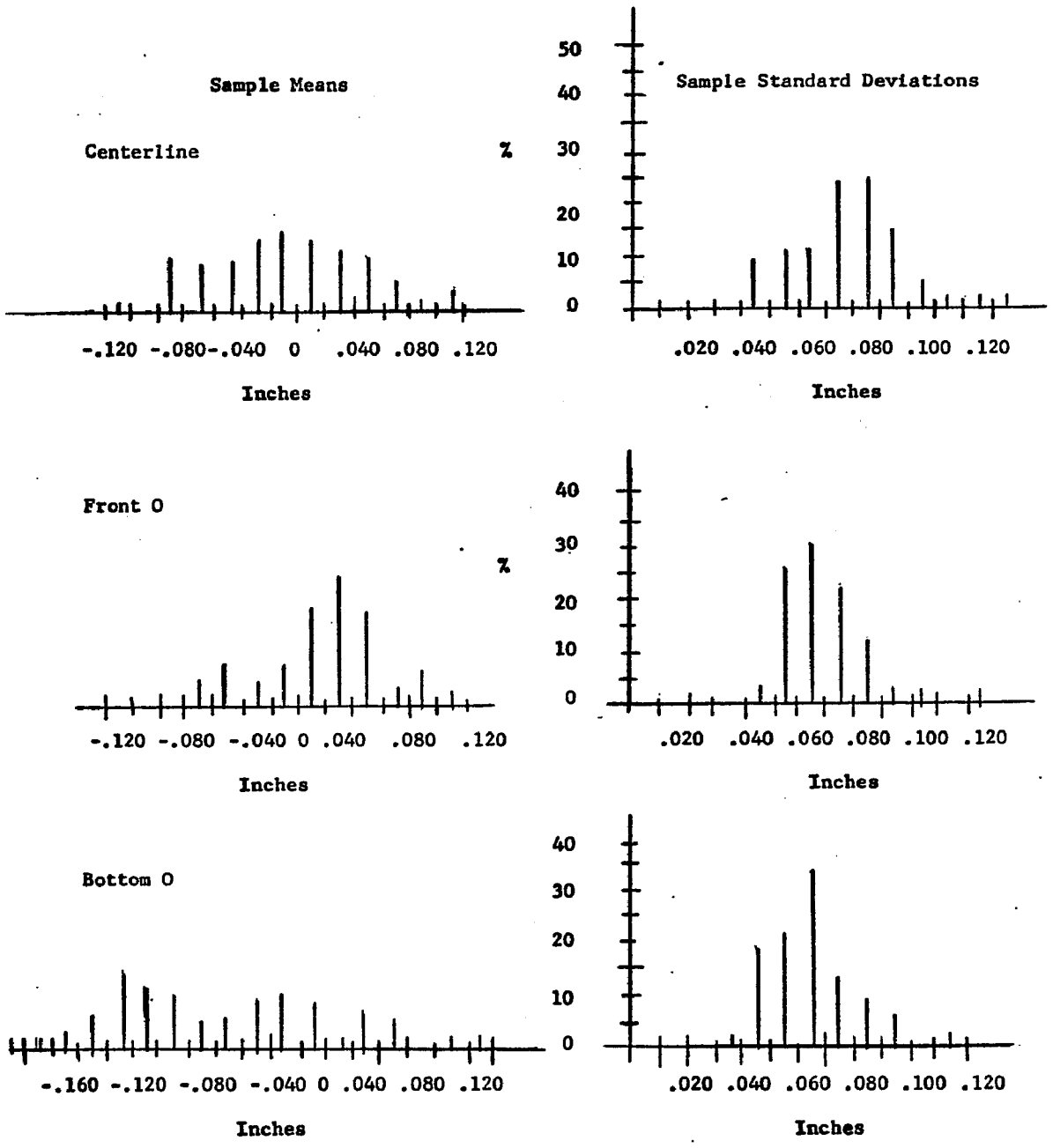


Figure 2.9 Histograms of Sample Means and Standard Deviations for Deviations (d_{ijn}) of Principal Locating Points

deviations) is greater than $\pm$ .150 inches. Appendix A contains a goodness of fit test, and a significance test for skewness and kurtosis. The conclusion is that the deviations are normally distributed when there are no large part distortions or dominating tool effects present.

The plp's that make up the opening sizes are grouped by their applicable allowable standard deviations in Table 2.1. The allowable standard deviations were obtained by allocating one-half of the tolerance specification to each plp and dividing by the number of standard deviations, six. A tolerance interval of six standard deviations contains 99.7 per cent of a normally distributed population. For example: $\pm$ .120 represents a tolerance interval of .240 inches for the opening or .120 inches for the plp. The allowable standard deviation is .120 $\div$ 6 = .020 inches. Table 2.1 shows that the actual standard deviations are greater than the allowable standard deviations.

2.5.3 ANALYSIS OF OPENING RELATIONSHIPS

Differences of plp's are taken in each plane so that the tool band and truck effects denoted by v_n and T_j are eliminated from the front O and bottom O readings.

The equations obtained after subtracting plp deviations in each plane, i.e., $R_{ijn} = d_{ijn}^{k} - d_{ijn}^{l}$, are:

Front O Plane

$$R_{ijn} = w_n^{k} - w_n^{l} + G_i^{k} - G_i^{l} + e_{ijn}^{k} - e_{ijn}^{l} \qquad (2.5)$$

Bottom O Plane

$$R_{ijn} = w_n^{k} - w_n^{l} + G_i^{k} - G_i^{l} + \left(\frac{D^{k}-D^{l}}{D}\right)T_j + e_{ijn}^{k} - e_{ijn}^{l}, \qquad (2.6)$$

TABLE 2.1
SAMPLE MEANS AND STANDARD DEVIATIONS FOR PRINCIPAL LOCATING POINT MEASUREMENTS

Opening	Pip	Left		Right		Allowable Standard Deviation
		$\bar{x}$	s	$\bar{x}$	s	
Front O Plane						
Door Width	114 A Pillar	.006	.092	-.006	.095	.028
	313 C Pillar	-.045	.083	.003	.066	.028
Centerline Plane						
Sill Front	150L - 150R	-.050	.051	.041	.051	.028
Sill Rear	154L - 154R	-.020	.047	.065	.047	.028
Quarter Panel	305L - 305R	-.080	.068	-.003	.073	.028
Roofrail Front	202L - 202R	-.060	.080	-.001	.083	.028
Roofrail Rear	210L - 210R	-.081	.080	-.077	.094	.028
Deck	436L - 436R	.028	.077	-.046	.073	.014
Back light width	418L - 418R	-.030	.083	-.019	.081	.014
Windshield width	108L - 108R	-.069	.097	.021	.102	.014
Bottom O Plane						
Door Height Rear						
	154 Sill	.040	.046	.041	.049	.014
	210 Roofrail	-.069	.056	.012	.046	.014
Door Height Front						
	150 Sill	.064	.065	.066	.060	.014
	202 Roofrail	-.003	.052	.039	.051	.014
Front O Plane						
Backlight Depth						
	502 Roof	.011	.063	.043	.058	.011
	521 Upper Deck	.117	.077	.050	.069	.011
Windshield Depth						
	4 Cowl Top	-.044	.061	.032	.072	.011
	35 Roof	.028	.049	.071	.055	.011
Bottom O Plane						
Backlight Height						
	502 Roof	-.008	.070	-.029	.067	.011
	521 Upper Deck	-.100	.059	-.159	.075	.011
Windshield Height						
	4 Cowl Top	-.086	.055	-.074	.049	.011
	35 Roof	-.038	.072	.008	.079	.011

and as $D^k - D^l$ is very close to 0,

$$R_{ijn} = w_n^k - w_n^l + G_i^k - G_i^l + e_{ijn}^k - e_{ijn}^l \qquad (2.7)$$

Centerline

$$R_{ijn} = w_n^{kL} - w_n^{kR} + G_i^L - G_i^R + e_{ijn}^{kL} - e_{ijn}^{kR} + \frac{Dk}{D} F_{ijn}(x_1, x_2, T1, x_4, x_5, p, T2) \qquad (2.8)$$

$F_{ijn}(x_1, x_2, T1, x_4, x_5, p, T2)$ is the deviation from nominal of the width between gate frames at the point of measurement.

These equations show that for front 0 and bottom 0 relationships the truck bias term is eliminated, and for centerline the distance between gate frames includes all of the variables described earlier. The w_n^k terms are the gaps between the metal and the plp locating block and can be observed and measured while the body is being built. The $G_i^k - G_i^l$ is mastering error that may exist in the two plp locator blocks that comprise the opening. Centerline relationships are dependent on the truck as it influences the distance between gates by the relationships T1 and T2. The x_1, x_2, x_4 and x_5 deviations are associated with the tie bar anchors and tie bars which are connected to the gate. The tie bars ordinarily remain with the gate, unless maintenance is performed on them at which time they are exchanged.

The mean, standard deviation about the mean, opening tolerance specification, and the ratio of 6 standard deviations to the tolerance band are shown in Table 2.2 for the openings of the 67 bodies. This table shows that no opening relationship has a capability ratio (6 standard deviations ÷ allowance) of less than one. Also, the average deviations for the opening sizes are not equal to zero which adds to

TABLE 2.2

SAMPLE MEANS, STANDARD DEVIATIONS AND CAPABILITY RATIOS FOR BODY OPENINGS

Opening Relationship		Deviation Mean $\bar{x}$	Deviation Standard Dev. S	Tolerance $\pm$ T	Capability Ratio $3S \div T$
Front 0 Plane					
Windshield Depth	Left	.073	.054	$\pm$ .045	3.6
	Right	.040	.054	$\pm$ .045	3.6
Backlight Depth	Left				
	Right				
Door Width Upper	Left	.051	.079	$\pm$ .120	2.0
	Right	.024	.091	$\pm$ .120	2.3
Bottom 0 Plane					
Door Height Rear	Left	-.025	.055	$\pm$ .060	2.8
	Right	.047	.064	$\pm$ .060	3.2
Door Height Front	Left	.067	.071	$\pm$ .060	3.6
	Right	.101	.074	$\pm$ .060	3.7
Windshield Height	Left	.046	.069	$\pm$ .045	4.6
	Right	.071	.088	$\pm$ .045	5.9
Backlight Height	Left	.091	.079	$\pm$ .045	5.3
	Right	.152	.067	$\pm$ .045	4.5
Centerline Plane					
Sill Width Front		-.015	.063	$\pm$ .120	1.6
Sill Width Rear		.040	.047	$\pm$ .120	1.2
Quarter Panel Width		-.085	.068	$\pm$ .120	1.7
Deck Opening Width		-.017	.056	$\pm$ .060	2.8
Backlight Width		-.049	.075	$\pm$ .060	3.8
Windshield Width		-.032	.092	$\pm$ .060	4.6
Roofrail Width Front		-.062	.082	$\pm$ .120	2.1
Roofrail Width Rear		-.151	.083	$\pm$ .120	4.2

the number of openings being greater than the desired tolerance.

2.6 ORGANIZATION STRUCTURE

This section describes the organization of the process design and fixture design staffs for different components of the body. Figure 2.10 summarizes these organizations and their outputs with respect to the plant organization. The plant receives all parts and process designs from other organizations. It is responsible for the operation and the maintenance of the equipment and assembly tools. The weld fixtures for body assembly, the side gates, are mastered by the plant using a master gauge that is assumed to be correct. In the absence of objective standards and specifications, it is extremely difficult to determine why the process is not capable. Suppliers of stamped parts can argue that the tooling is not properly mastered or maintained, and assembly tooling designers argue the parts are not correct. Unfortunately, examples of the above claims exist, which further complicate deciding upon the most appropriate action to build bodies within specification.

2.7 CONCLUSION

A review of the dimensional performance indicators of the plant and the opening relationship data show clearly that body openings are not being produced within design tolerances. The seal designs are predicated on these tolerances and the data for leaks indicate difficulty in sealing the body. The plant, in an effort to control these openings, adjusts the tooling by an amount equal to the average readings.

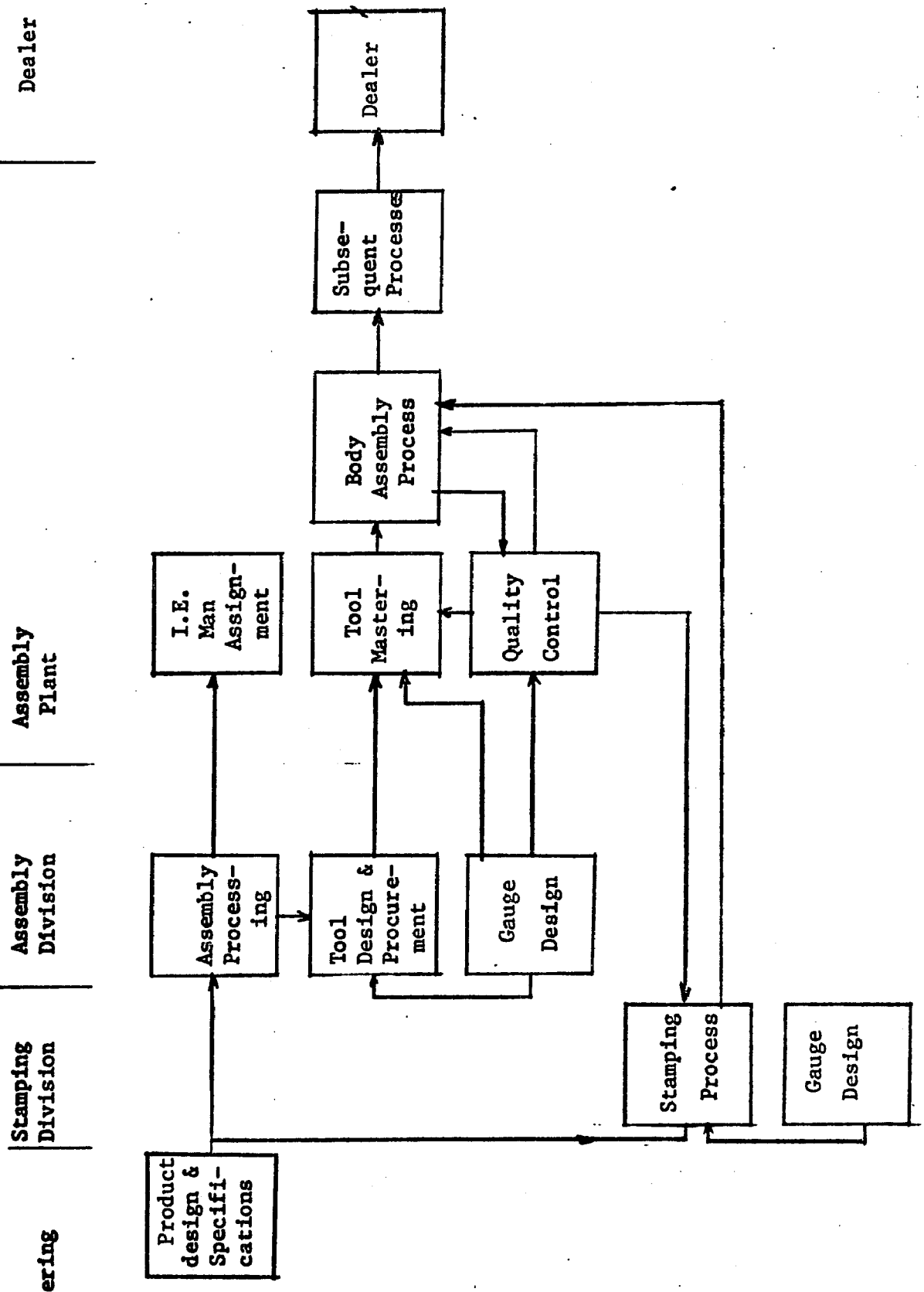


Figure 2.10 Flow of Tools, Material and Information

The sample averages indicate that this adjustment does not always produce the desired effect. The variation of the process is much larger than the allowable tolerances. The study of the organization indicates that the plant has little control over the design of the process, the design of the fixtures for gauging, or the quality of the parts and subassemblies it receives. In addition, subassembly tolerances are not available for control purposes. Without standards the burden of producing a body within tolerance is placed on the plant.

The next chapter describes the results of an experiment to determine if the process is capable of producing a body with openings within engineering tolerances. The experiment was designed to obtain one set of tooling that was mastered with no plant adjustments. The bodies were observed to verify that the required process was being followed. If the bodies were significantly closer to nominal than the production bodies and within tolerance, it would be concluded that the problem was one of assembly plant control. If the bodies were not closer to nominal, the research plan was to further analyze the process and determine the components of variance so that the appropriate study direction could be taken.

CHAPTER III

PROCESS CAPABILITY AND COMPONENTS OF VARIANCE

3.1 INTRODUCTION TO THE ANALYSIS

This chapter describes the analysis that was performed to determine the most effective process control procedures in order to produce body opening sizes within design tolerances. The body fabrication and automobile assembly processes consist of four major processes or stages: (1) stamping of detail parts, (2) subassembly fabrication, (3) body assembly, and (4) body sealing and panel fitting operations. Figure 3.1 summarizes these steps and the internal and external factors that represent the major process factors. The internal factors for the body assembly process are the maintenance and mastering of assembly tooling. The external factors include the subassemblies, the subassembly checking fixtures, the assembly process design and the subassembly locating and clamping system, the gate mastering fixture, and the mastering of the framing trucks. The symbols for these factors are defined in the previous chapter. These factors indicate the large number of variables from different organizations that must be controlled.

The general approach used to determine the contribution of the internal and external factors to body opening surface variability is:

1. Determine the performance of the process to specification. If acceptable stop, otherwise, proceed to step 2.
2. Identify the internal and external factors for the process. Internal factors are under the control of the organization responsible for the process. External factors are beyond the control of the organization and can only be influenced

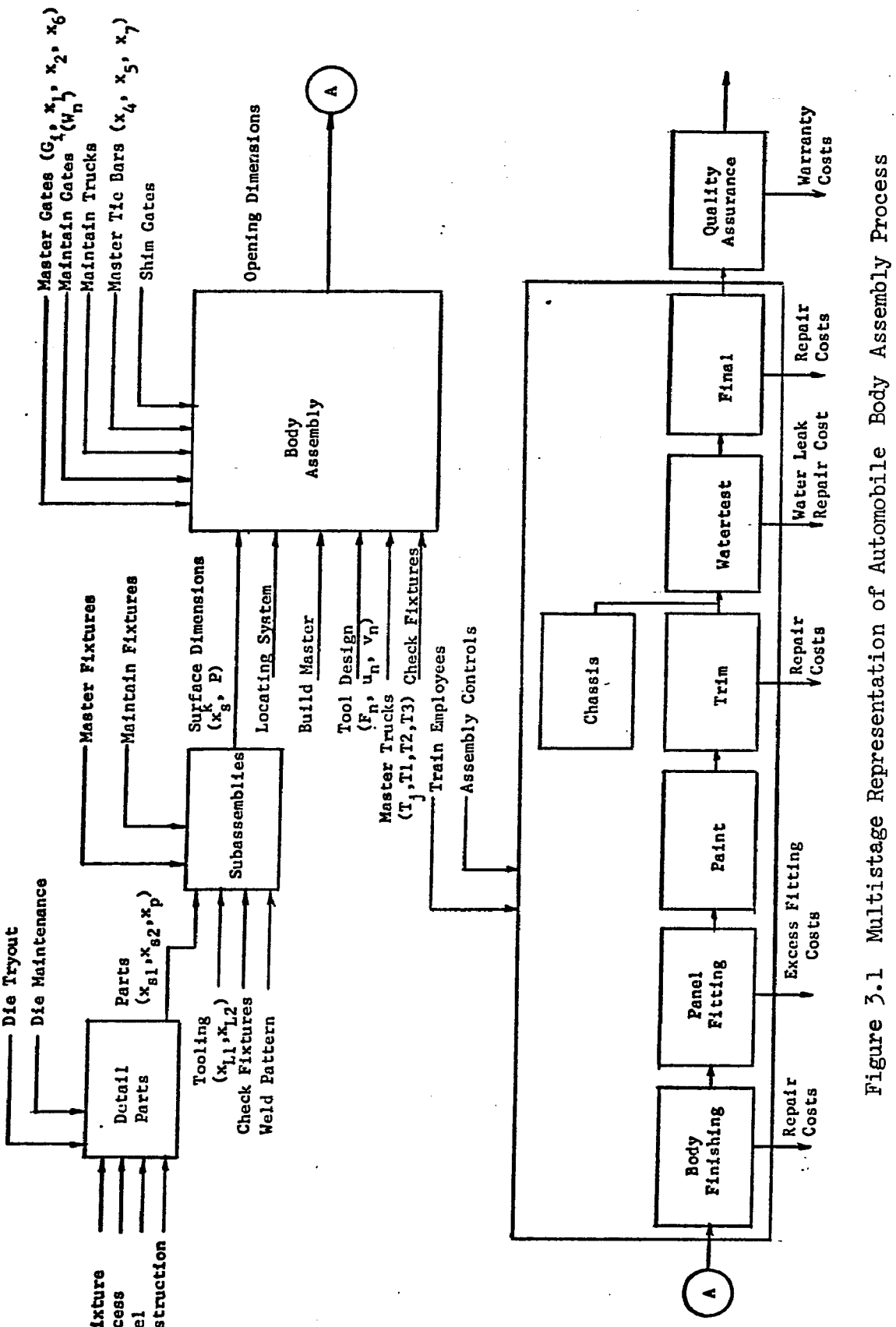


Figure 3.1 Multistage Representation of Automobile Body Assembly Process

indirectly.

3. Estimate the contribution of the internal factors to the variability of the process output characteristics.
4. Correct the most important internal factors.
5. Perform a capability study using the current values of the external factors. If process produces to specification, then control internal factors, otherwise go to step 6.
6. Determine the influence of external factors on process performance. Determine the specification for the external factors that produce product within specification.
7. Repeat steps 1 through 6 for the process of the external factor being investigated.

Application of this procedure to the body assembly process resulted in the following analyses:

1. A component of variance analysis to determine the contribution of the gate mastering procedures to the variance of body openings.
2. An analysis of means to identify those assembly tooling units, i.e., the gates, that are significantly different from the entire tooling population.
3. A capability study using mastered tooling to determine if openings can be produced within the prescribed opening tolerances.
4. An analysis of variance for significant differences between body framing trucks.
5. Determining the influence of subassembly variability on the measured body points.

6. Estimating the bandwidth of the measurements that can be expected from the tooling.

The analysis of the subassembly process was confined to measuring detail parts and performing a capability study for an "A" pillar subassembly.

3.2 CAPABILITY STUDY - EXPERIMENTAL BODIES

An experiment was performed where 11 bodies were built on one set of gates using one framing truck. The framing truck and the gate were both mastered. A new set of nominal tie bars was obtained. The bodies were built from production parts. All bodies built were carefully checked, and any departure or gaps between the locating stops and the metal were noted. At gate marriage, extra precautions were taken to guarantee that the footlocks on the framing truck were tightly locked. The production gates contained seven tool deviations. These deviations changed the position of the locating blocks from where they were initially mastered. These deviations were placed in an effort to correct any bias in the readings that were obtained from the routine body measurement procedures. During the course of the experiment, a deviation was placed in one side of the gates to draw the rear quarter panel in closer to centerline. It was concluded that the tooling was not locating the panel correctly.

Figure 3.2 shows some results of the study by plotting the opening size deviations from nominal versus the tolerance for each opening relationship. These plots show that the openings that are set primarily by the tooling are capable of being produced within tolerance. These include the following openings:

Door Width Upper

Door Height Rear

The remaining relationships were not produced within their tolerances.

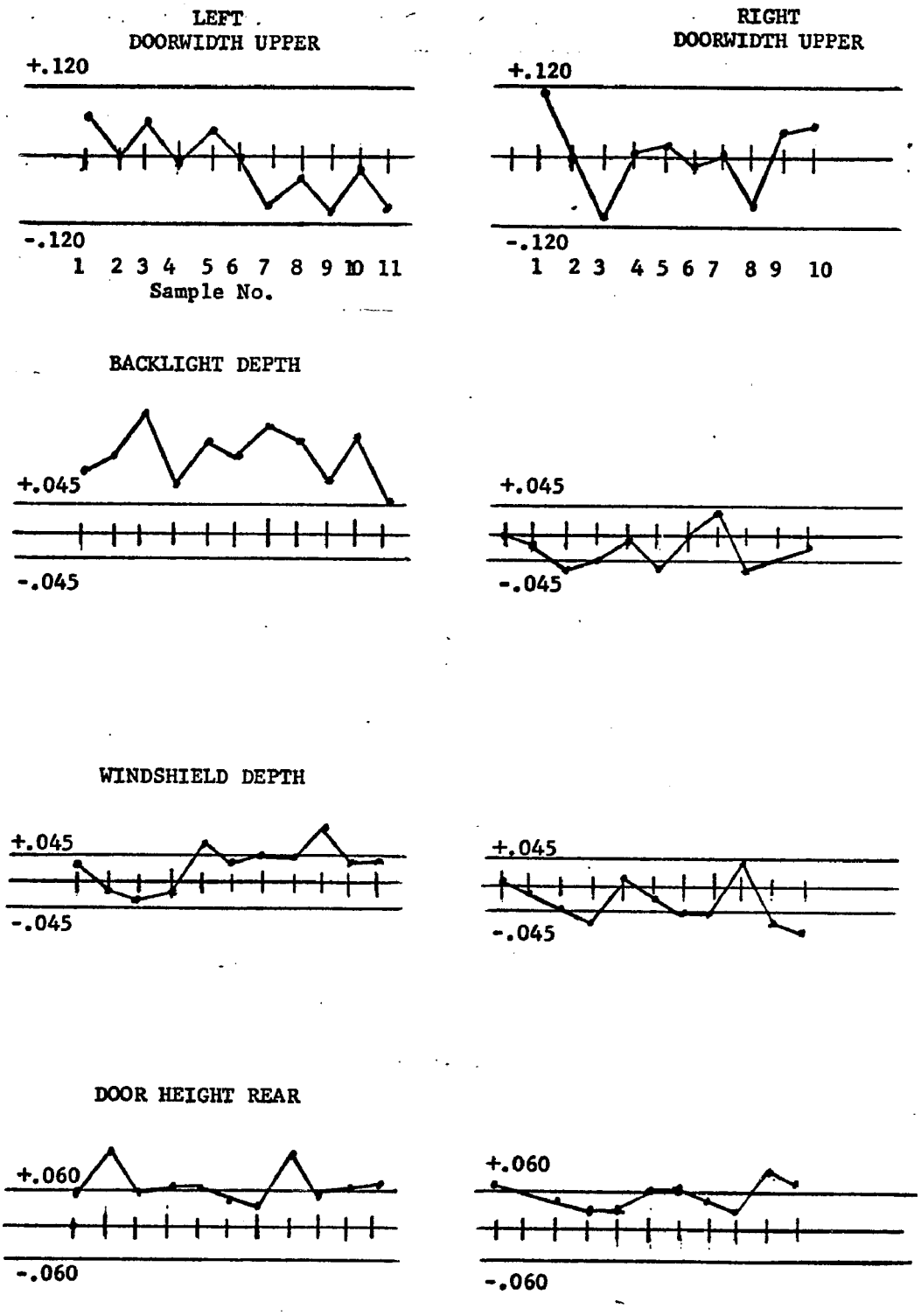


Figure 3.2 Plot of Opening Relationships for Eleven Experimental Bodies

These relationships are either the result of two or more subassemblies being joined together, or are centerline relationships at the higher elevations of the body. An example of the former is the windshield height which consists of the cowl top surface that is assembled to the "A" Pillar, and the surface of the roof that mates to the upper "A" Pillar. The latter relationships are the backlight, windshield, and roof rail widths. These bodies were tracked through the system and evaluated for water leaks. In all but one case, when the door glass was properly adjusted, the bodies were water tight in the door area. The exception was a body that had inboard roof rails and an outboard center pillar. This body leaked water because of poor compression of the door glass against the roof rail weather strip.

EXPERIMENTAL VERSUS PRODUCTION BODIES

Appendix B contains a comparison and a test of hypothesis for the means and variances between the production and test bodies.

Table 3.1 illustrates how the significant differences are classified. The smaller mean deviation for the production bodies appears to be made at the expense of a larger variance. The relationships for door height and windshield height indicate that an attempt to shift the mean was accompanied by an increase in variance. These are cases where stacking occurs. Raising the sills must be accompanied by raising the "A" and "B" pillars because they mate with the sill. Lowering the cowl top results in interference with the floorpan and the "A" Pillar.

EXPERIMENTAL VERSUS PLANT NO. 2 BODIES

A sample of surface plate readings for 11 bodies from a second

TABLE 3.1

CLASSIFICATION OF SIGNIFICANT DIFFERENCES FOR MEANS AND VARIANCES OF OPENING SIZES BETWEEN EXPERIMENTAL AND PRODUCTION BODIES

	$\bar{x}$ prod			
	Smaller	Same	Larger	Total
s^2 prod same	2	0	3	5
s^2 prod larger	4	2	1	7
Total	6	2	4	12

assembly plant was reduced. The comparison and tests of hypothesis for the means and variances are contained in Appendix B. Six of the twenty-two relationships had significant differences for the variances, four of which were larger for plant number 2. This compares with eight from the first plant. Nine of the twenty relationships had significantly different means, six of which were smaller than the experimental bodies.

Table 3.2 classifies the differences. Comparing the two plants, it is apparent that plant 2 has centered the process without increasing the variance as much as the first plant. The conclusion is that changes to the second plant's tooling were made with a greater understanding of the body construction. The maintenance of the tooling is also superior for the second plant.

CONCLUSIONS

The following conclusions were drawn from the analysis of opening relationships:

1. All openings are not capable of being built within the specified tolerances with the current run production subassemblies and mastered tooling.
2. Deviations to the tooling can increase the variance where the parts that are moved form butt joints with other subassemblies that are not moved an equivalent amount.
3. Comparison with bodies built in another plant that individually adjusts each gate based on measurements showed better centering of the process. The variance of the relationships for the second plant was essentially the same as the experimental bodies.
4. Bodies that had door openings within tolerance were found to be

TABLE 3.2

CLASSIFICATION OF SIGNIFICANT DIFFERENCES FOR MEANS AND VARIANCES OF OPENING SIZES BETWEEN EXPERIMENTAL AND PRODUCTION BODIES FROM THE SECOND PLANT

		$\bar{x}$ prod			
		Smaller	Same	Larger	Total
$s^2_{prod_2}$	Smaller			1	1
	Same	3	1	1	5
	Larger	3	1		4
Total		6	2	2	10

water tight when the door fit and glass adjust operations were performed properly.

3.3 TOOLING VARIATIONS

This section describes the methods that were used to indirectly determine the amount of assembly tooling variation. This variation is defined as the amount of deviation of the gate side from its mastered position. This deviation is due to: the clearance between the gate leg and the truck locating blocks or stops, v_n; mastering errors in the truck T_j; and the offset of the gate side from centerline due to tie bar variation,

F_n (x_1, x_2, T1, x_4, x_5, P, T2) and F_n (x_6, T3, x_7, P, T2).

Using the models in Chapter II, the tooling band can be defined as:

Front O $$v_n + T_j \qquad (3.1)$$

Bottom O $$\frac{D}{D}^{k} \; T_j \qquad (3.2)$$

Centerline Plane

Front $$v_n + \frac{D}{D}^{k} F_n (x_1, x_2, T1, x_4, x_5, P, T2) \qquad (3.3)$$

Rear $$v_n + \frac{D}{D}^{k} F_n (x_6, T3, x_7, P, T2) \qquad (3.4)$$

3.3.1 FRONT O PLANE

In order to estimate the influence of the tooling and measurement system on the plp readings, the data from the eleven experimental bodies were analyzed. Figure 3.3 shows the deviations obtained from the Front O plane. Plp 170 left was selected because no part distortion was observed. It was concluded that with the process behaving normally, the readings on the surface plate can be expected to fall from -.040 to +.030 in. from nominal. This would include the following errors:

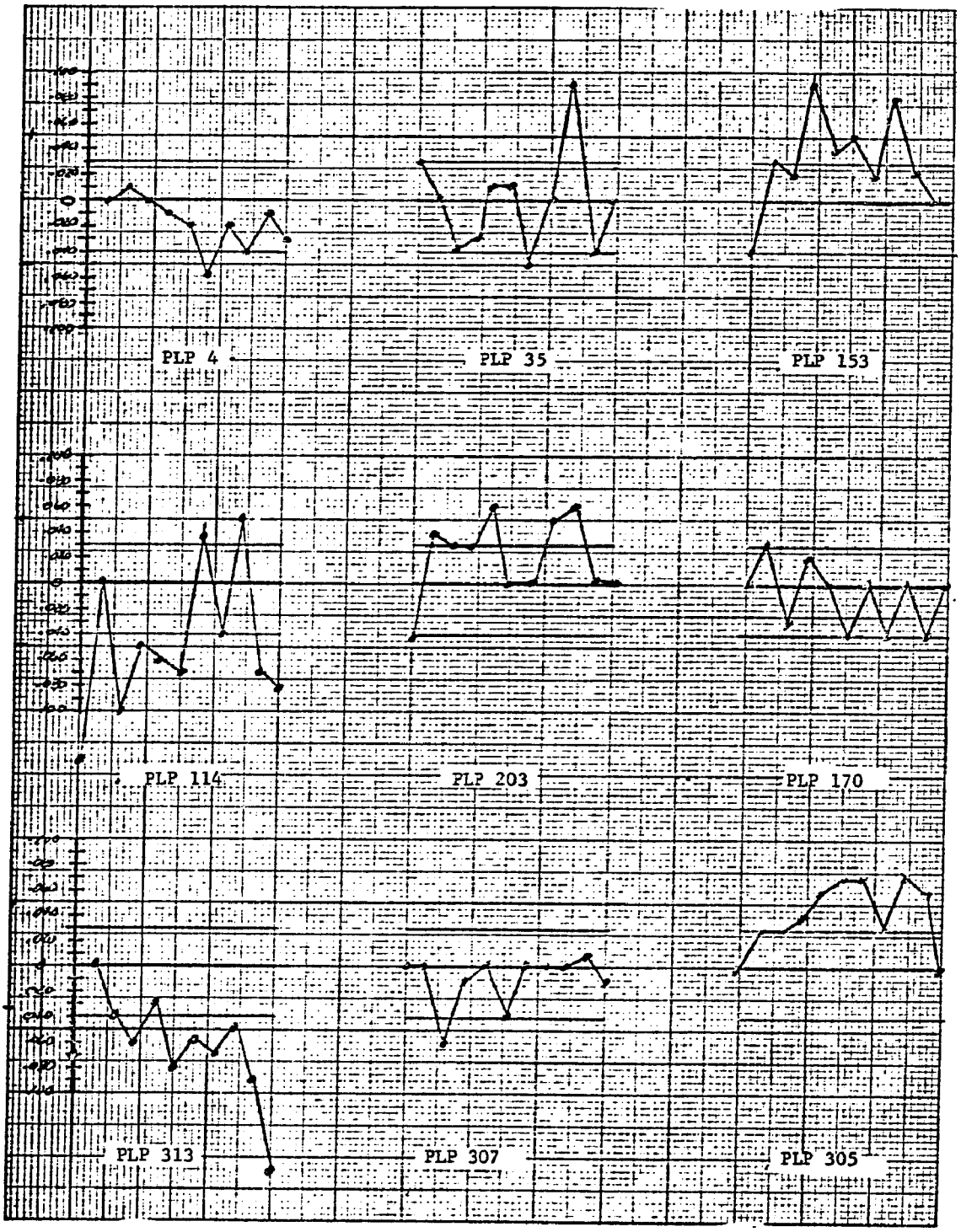


Figure 3.3 Front O Plane Deviations from Nominal for Eleven Experimental Bodies

1. Clearance between floorpan bracket hole and locating pin, u_n.
2. Clearance between gate leg and front O stops on the framing truck v_n.
3. Truck bias, T_j.
4. Measurement error, e_{ijn}.

The range is .070 in. and, assuming a normal distribution and 99.7% confidence interval, the standard deviation can be estimated at $\frac{.070}{6}$ = .011 in. Therefore, readings for plp's in the front O plane that fall outside this range had assignable causes. These would include the following:

1. Metal not up against the locating block,
2. Bias in the locating block due to mastering,
3. Part deviation.

3.3.2 CENTERLINE PLANE

The tooling band for centerline was estimated by plotting the deviations from nominal for plp's, in the vicinity of the front and rear tie bars, that are at different elevations on the body. The offset of the gate line frame from perpendicular was estimated by passing a least squares estimate through the points. Figure 3.4 shows the plots of the plp's and the best fit line.

The following ranges were estimated for points along the roof rail. The standard deviation was estimated from $\sigma = \frac{\text{Range}}{6}$

Point	From	To	Range	σ
202L	-.050	-.170	.120	.020
202R	+.010	-.150	.160	.027
210L	-.030	-.170	.140	.023
210R	-.080	+.040	.120	.020

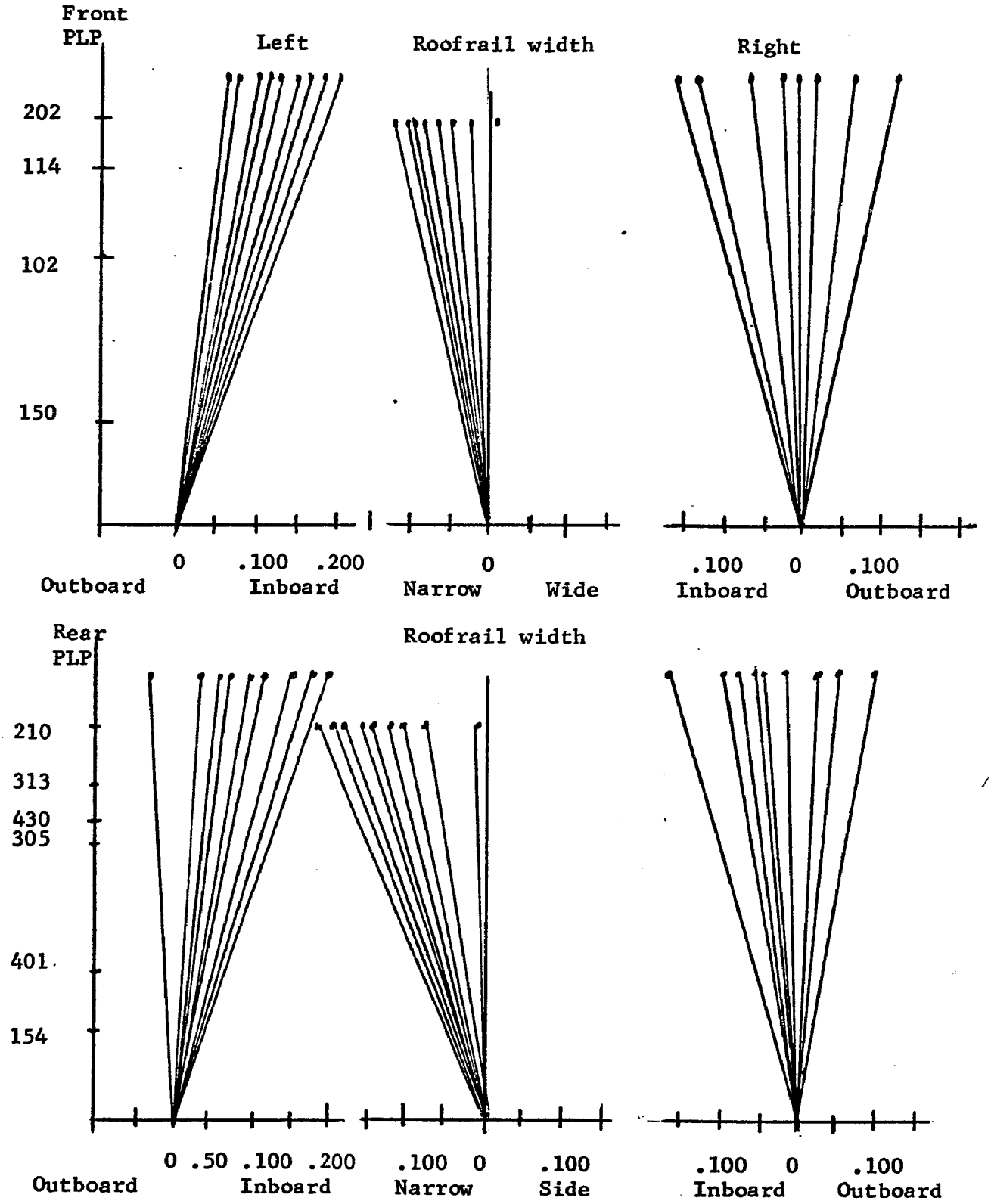


Figure 3.4 Deviations from Nominal of Centerline Plp's and of Roofrail Width for Eleven Experimental Bodies

The standard deviation of plp's at different elevations can be estimated from the following:

$$\sigma(d_{ij}^{k}) = \left[\sigma^2 (e_{ij}^{k}) + \left(\frac{D}{D}^{k}\right)^2 \quad \sigma^2(F(x_1, x_2, T1, x_4, x_5, P, T2)\right]^{1/2}$$

Figure 3.4 also shows the difference between the gate frames plotted between the left and right side plots. The average offset for this distance was .0925 in. with a range of .100 in. and a standard deviation S = .029 in. Observations on the framing line showed that,with normal operator foot pressure on gate leg clamps, the gate legs are not up against the stops. A sample of 57 gates on the left and 60 gates on the right was taken. An experiment was performed using balls of sealer placed between the gate leg and the footlock stops. They were removed when the gates were separated from the truck. The following averages and ranges were obtained:

	Sample Size	Mean	Range
Left front top centerline stop	57	.072	.025 to .150
Right top centerline stop	60	.054	.010 to .125
Left Rear top centerline stop	15	.040	.010 to .060
Right Rear top centerline stop	20	.055	.020 to .110

The conclusion is that the gate frames pivot about the lower stop and the footlocks require maintenance. Therefore, the centerline perpendicularity and distance between the gate frames is controlled by the tie bar lengths and anchors.

A sample of 14 tie bars selected at random on the line showed the following:

Mean deviation	.012 in.
Range	-.050 to .075 = .125 in.

Nine tie bars were found to be greater in length than nominal and

five were shorter than nominal. The conclusion is that tie bar length has not been maintained within specification.

An experiment to measure the variation of the centerline distance between the left and right side gate frames at the top of the frame was performed. In total, fifty gates were measured on the line after the gate marriage operation. The results of this experiment indicated that high variability at the top of the gate frame existed. The mean deviation was +.021 in. with a range from -.060 to +.125 in. Nine gates had a width between frames less than nominal, eight at nominal, and thirty-three were greater than nominal.

The conclusions drawn from the experiments are:

1. The distance between the gate frames is determined by the tie bar length with present footlock condition.
2. The tie bar lengths have excess variation. Greater control of these lengths is necessary.
3. Standards for acceptable centerline variation should be established empirically using tooling that has been mastered and maintained to specification.

3.3.3 FRAMING TRUCK EFFECTS

A one way analysis of variance was performed for selected plp's to determine if significant truck effects, T_j, existed. A significant difference was obtained between trucks in the front O readings for plp 170 under the asumption that all the gates were mastered properly. No significant effect was found in the bottom O deviations. Therefore, there is a normal variation within a gate truck combination as a consequence of system clearance and gate mastering. In addition, there is a significant truck effect that influences the front O readings. A

significant difference was also obtained for the same plp, when all truck data was pooled and left side readings were compared with right side readings. The indication is that the left side truck front O locators are further aft than the right side. A significant difference was also detected between the left and right side bottom O locators with the left side being lower than the right side.

These conclusions are indirect based on the measurement of surfaces in the body. They point to the necessity of having a direct method of checking and mastering trucks that can be easily used by plant tooling personnel. Direct measurements of framing trucks showed larger deviations for some locators.

3.4 COMPONENTS OF VARIANCE

3.4.1 INTRODUCTION

The differences between the production sample and the experimental sample suggest that the greater variance of the former may be due to mastering errors. An analysis of variance was performed to determine if significant differences existed between bodies from different gates, and to estimate the components of variance. An analysis of means was also performed to detect those gates that have a significantly different mean. The within gate variance for each relationship was tested to determine if it was significantly different from the variance obtained from the experimental bodies. The components of variance are defined by the major process factors. Estimates are given for mastering variance when an effective mastering program is used. This mastering variance and any tooling variance are subtracted from the total allowable variance to estimate the remaining variance that can be allocated to parts and subassemblies.

3.4.2 ANALYSIS OF VARIANCE FOR GATE EFFECTS

A one way analysis of variance was performed for the 67 observations to determine if significant gate effects existed. This analysis, applied to the front O and bottom O relationships, is equivalent to testing for a significant gate effect from the overall mean. The relationship model for these planes is:

$$R_{ijn}^{k} = G_i^k - G_i^l + e_{ijn}^k - e_{ijn}^l \qquad (3.5)$$

where k and l denote the plp's in the relationship, assuming the truck effect is negligible. The corresponding ANOVA model is:

$$R_{ijn} = G_i^{k-1} + e_{ijn}^{k-1} \qquad (3.6)$$

When this model is applied to the centerline relationships, i.e.,

$$R_{ijn} = G_i^L - G_i^R + e_{ijn}^{kL} - e_{ijn}^{kR} + \frac{D^k}{D} F_{ijn}(x_1, x_2, T1, x_4, x_5, P, T2) \qquad (3.7)$$

any gate effect includes the tie bar and tie bar anchor errors. The unexplained variation would include the influence of floorpan errors and truck errors. Isolation of these effects would require replications of gates on trucks using floorpans of known dimensions. Because of the large number of gate truck combinations, a sufficient number of replications on gates and trucks was not available.

Table 3.3 summarizes the results of the ANOVA and shows the relationships that had a significant gate effect. At the 5% significance level, 2 of the 6 front O relationships and 5 of the 8 centerline relationships had significant gate effects. The exhibit also gives the components of variance. Those relationships that have a significant gate effect also have the percentage of total variance in excess of 20%.

TABLE 3.3

COMPONENTS OF VARIANCE ANALYSIS FOR OPENING RELATIONSHIPS

RELATIONSHIP		$\bar{x}$	BETWEEN GATE σ	BETWEEN GATE % of Tot. Var.	WITHIN GATE σ	WITHIN GATE % of Tot. Var.	TOTAL σ	F VALUE	GATE EFFECT?
Front O									
Windshield Depth	L	.072	.007	2	.053	98	.054	1.09	No
	R	.040	.028	26	.047	74	.054	2.20	Yes
Backlight Depth	L	.107	.025	13	.065	87	.069	1.65	No
	R	.002	.023	19	.048	81	.053	1.78	No
Door Width Upper	L	-.051	.036	21	.071	79	.079	2.14	Yes
	R	.024	.000	0	.091	100	.091	.50	No
Centerline									
Backlight Width		-.049	.049	42	.058	58	.075	3.50	Yes
Roof Rail Width	AFT	-.151	.028	12	.078	89	.084	1.52	No
Roof Rail Width Fore		-.062	.038	21	.073	79	.081	1.88	No
Sill Width AFT		.040	.032	46	.035	54	.047	4.12	Yes
Sill Width Fore		.015	.029	21	.056	79	.062	2.00	Yes
Quarter Panel Width		-.085	.031	21	.061	79	.068	1.90	Yes
Windshield Width		-.032	.056	36	.074	64	.092	2.90	Yes
Deck Opening		-.017	.010	3	.055	97	.056	1.12	No
Bottom O									
Backlight Height	L	.091	.055	48	.058	52	.079	4.95	Yes
	R	.153	.017	7	.065	93	.067	1.23	No
Windshield Height	L	.046	.032	22	.062	78	.069	2.20	Yes
	R	.071	.036	17	.080	83	.088	1.72	No
Door Height Front	L	.067	.003	0	.070	100	.071	1.01	No
	R	.101	.046	37	.060	63	.074	3.02	Yes
Door Height Rear	L	-.025	.036	42	.042	58	.055	4.11	Yes
	R	.048	.029	20	.057	80	.064	1.80	No

3.4.3 ANALYSIS OF MEANS

A graphical approach to the means for each relationship was applied based on a procedure by Schilling (27). The treatment means are plotted, in control chart fashion, with upper and lower decision limits that indicate statistical and engineering significance. The procedure permits identification of those treatments or gates that are significantly different from the population. The control limits are computed as $\bar{x} \pm \sigma_e h_a \sqrt{q} / \sqrt{n}$ (3.8) where:

$\bar{x}$ represents the overall relationship mean

σ_e is an estimate of the within gate standard deviation

q is the degrees of freedom associated with the number of gates

n is the total number of observations in the experiment

h_a is a factor obtained from a table of values in the paper for a, the type I risk; k, the number of means to be compared; and the degrees of freedom for errors in σ_e . The factor h_a is derived from the bounds for the studentized maximum absolute deviate H_a using the relationship

$$H_a = h_a \sqrt{k-1} / \sqrt{k} \qquad (3.9)$$

The results of the analysis are shown in Figure 3.5

Gates with significantly different means also have a significant gate effect from an analysis of variance, with the exception of the relationship for backlight depth left. The following relationships had a point outside the control limits: windshield depth right, and door height front right. Investigation showed that the means were based on only one observation.

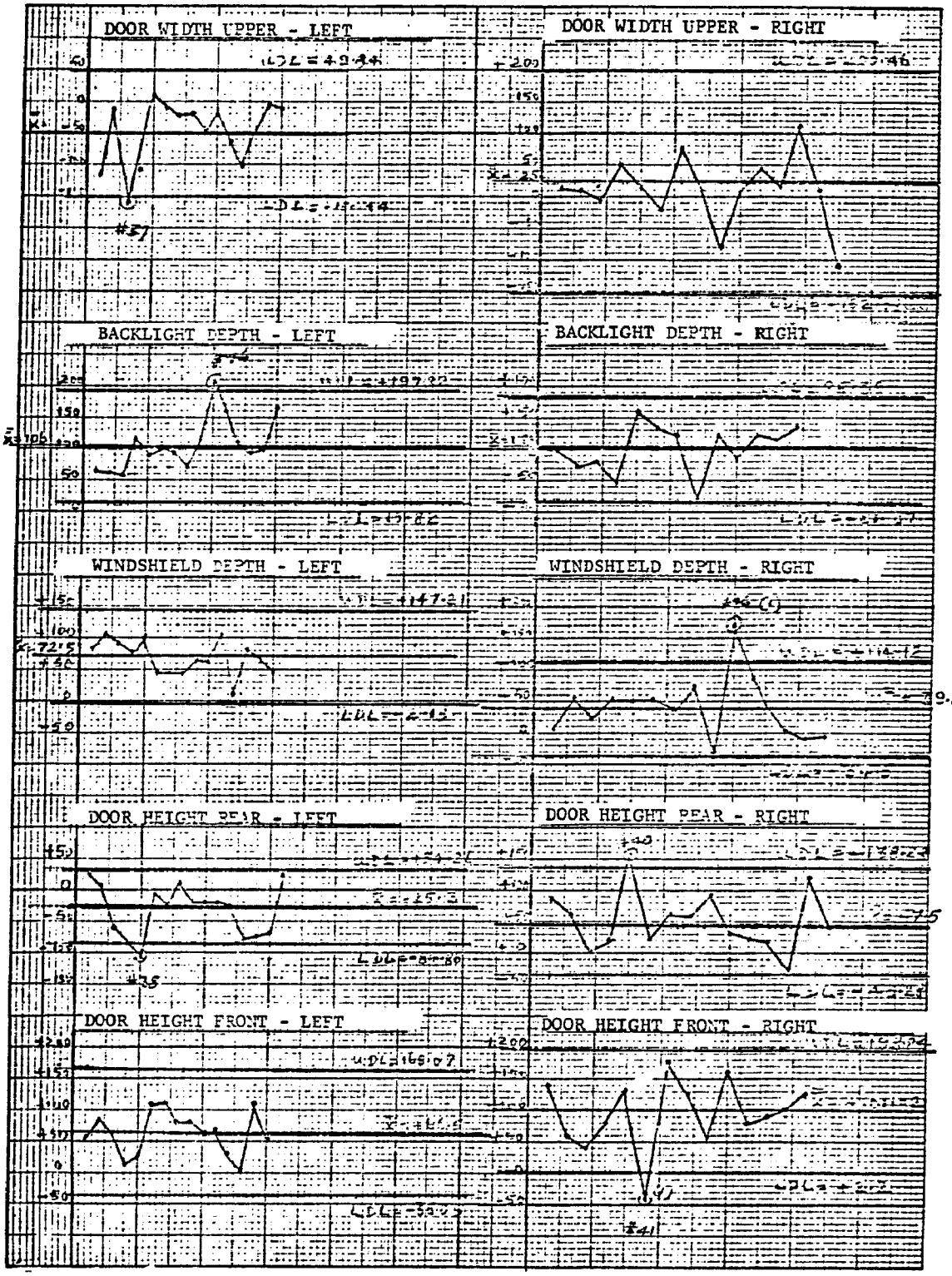


Figure 3.5 Analysis of Means for Openings from Different Gates

The analysis provides an excellent device for showing graphically which gates may require mastering. The method is impractical because of the large samples required for the analysis and the limited facility to measure bodies.

3.4.4 WITHIN GATE VARIANCE

The within gate variance was compared with the variance of the eleven experimental bodies. Table 3.4 contains a comparison of the standard deviations and the results of a test of hypothesis for variances.

The following relationships had significantly smaller variance with the mastered gate and truck: windshield height right, door height front left and right, door height rear right and roof rail width fore. The mastered gate contained no tool deviations from nominal. The production gates had tool deviations that influenced the position of subassemblies that made up the above openings. The components moved, and the pertinent openings are:

TABLE 3.4

TESTS OF HYPOTHESIS FOR DIFFERENCES BETWEEN OPENING VARIANCES, PRODUCTION WITHIN GATE VARIANCE AND EXPERIMENTAL BODIES

RELATIONSHIP	LEFT		RIGHT		Ho: $S_1^2 = S_2^2$	
	PRODUCTION S_1	GATE 43 S_2	PRODUCTION S_1	GATE 43 S_2	Left	Right
Windshield Depth	53.38	35.6	46.8	38.1	*2.24 Yes	1.50 Yes
Backlight Depth	64.5	47.4	47.8	32.8	1.85 Yes	2.12 Yes
Door Width Upr	70.9	58.2	99.85	62.2	1.48 Yes	2.58 Yes
Backlight Width	57.5	95.5			0.362 Yes	
Windshield Width	74.0	53.8			1.892 Yes	
Deck Opening	55.10	34.7			2.52 Yes	
Backlight Height	58.0	92.5	64.7	60.9	.393 Yes	1.32 Yes
Windshield Height	61.8	39.7	80.3	45.5	2.43 Yes	3.1 No
Door Height Frt	70.4	26.9	60.0	39.5	6.86 No	2.30 No
Door Height Rear	42.0	29.4	57.0	25.8	2.03 Yes	4.88 No
Roof Rail Width A	78.0	57.9			1.81 Yes	
Roof Rail Width F	73.0	40.4			3.26 No	
Sill Width Aft	35.0	45.0			.60 Yes	
Sill Width Fore	56.0	43.0			1.70 Yes	
Quarter Panel	61.0	54.0			1.28 Yes	

* Represents $S_1^2 \div S_2^2$

All standard deviations x 10^{-3}

COMPONENT	TOOL DEVIATION (Inches)	OPENING
A Pillar	.060 outboard left and right	Windshield width Roof rail width fore
	.120 forward	Door opening.
Sill	.120 up left	Door height front and rear.
	.060 up right	Door height front and rear.
Cowl Top	.060 down left and right	Windshield height.

The conclusion is that the deviations have increased the variance of their related openings.

3.4.5 COMPONENTS OF VARIANCE

The components of variance that have been identified for a principal locating point in any plane are represented graphically in Figure 3.6.

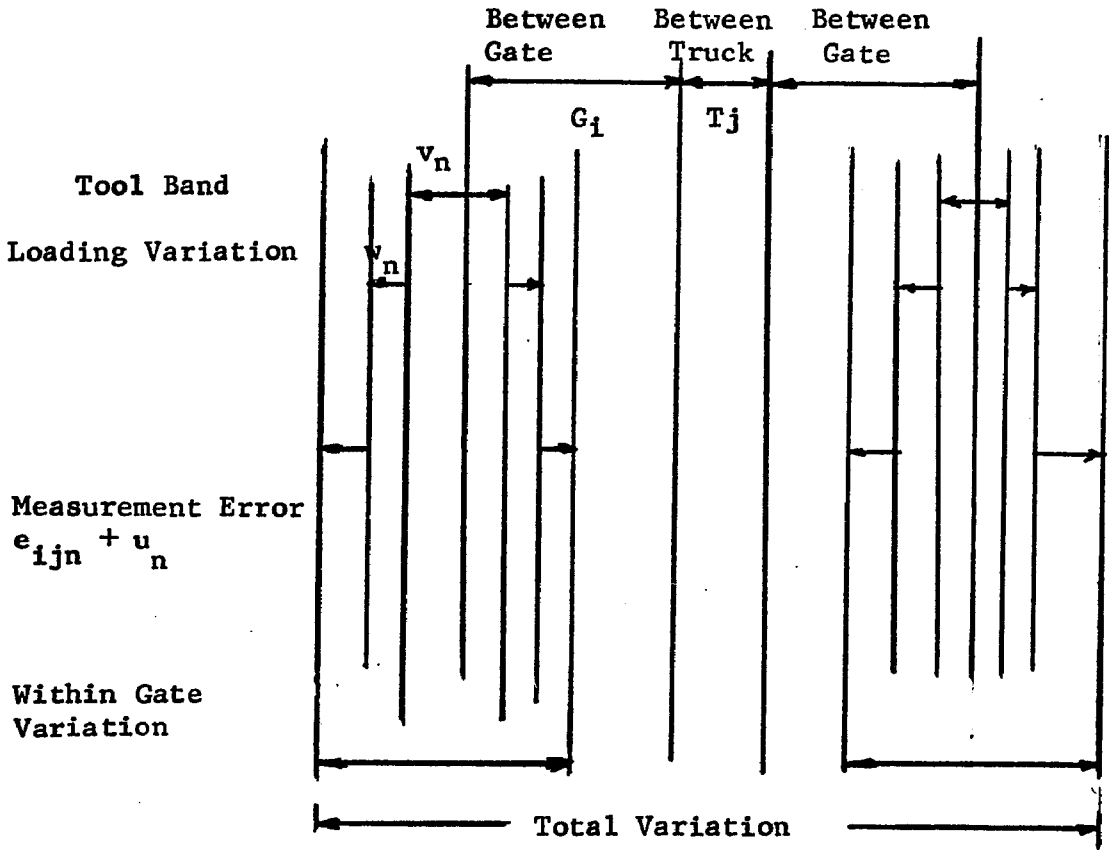


Figure 3.6 Components of Variance Principal Locating Points

The between truck variation is the error, T_j, that can be attributed to mastering of truck relationships in each plane.

The between gate variation is the difference between plp stops from one gate to another, G_i. The standard that has been applied to mastering is a total variation of .013 inches.

The tool band represents the variation in measurements as a consequence of the clearances between the footlock and gate legs in the front 0 plane, v_n. In the centerline relationships, it represents the gate offset from perpendicular, F_n.

The loading variation represents the errors encountered in positioning the parts in the gate against the locating blocks, w_n. The clearance between the floorpan and its tooling locators is denoted by u_n.

The within gate variation represents the variation in deviations from nominal of the principal locating points. It includes: the tool band, the loading variation due to improper tuning of the clamps, overall maintenance condition of the tooling, errors due to measurement, and the floorpan clearance.

The components of variance for relationships are depicted graphically in Figure 3.7. The differences between the two representations are:

1. The between truck variation is deleted.
2. The tool band for front 0 and bottom 0 relationships is deleted.
3. The tool band for centerline relationships remains and represents the variation between gate frames as a result of the tie bar, gate, and framing truck system.

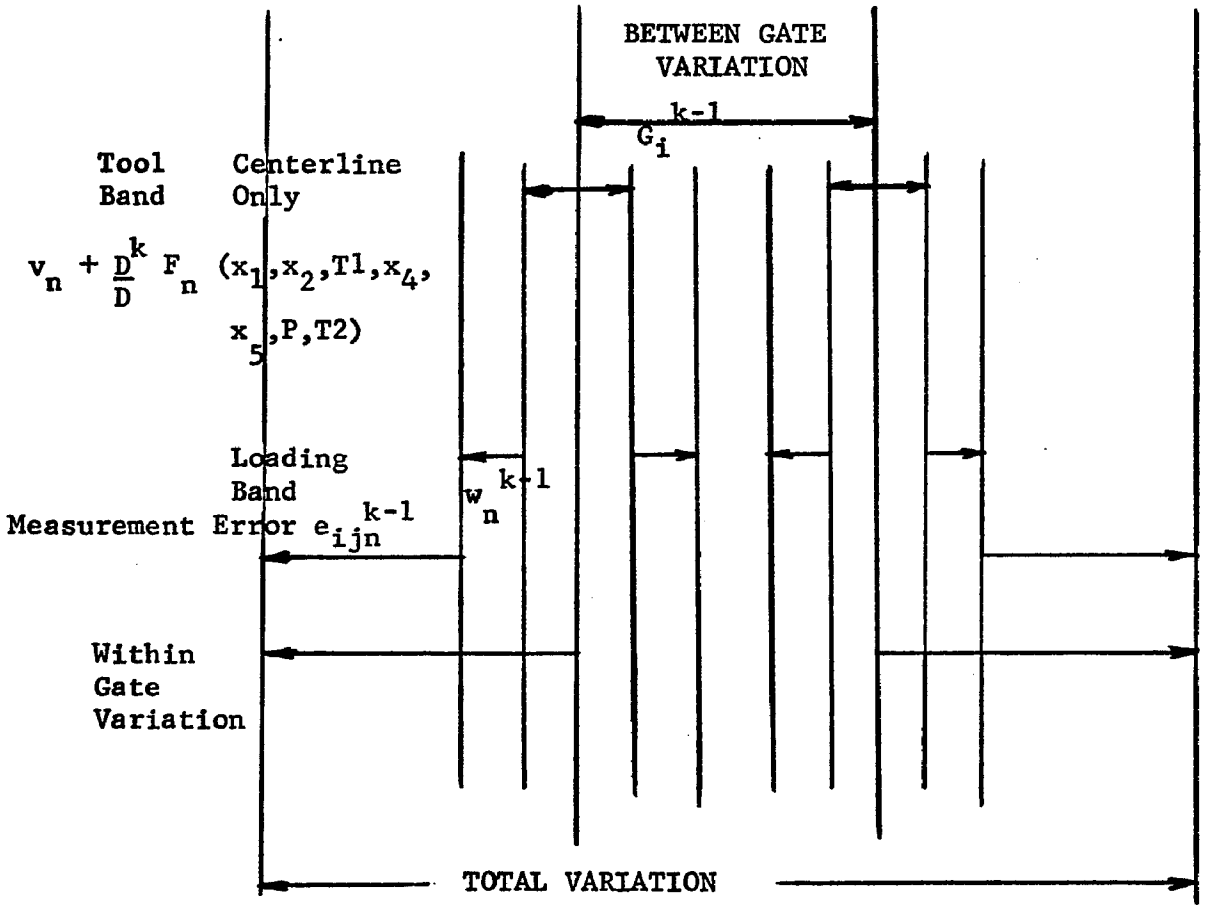


Figure 3.7 Components of Variance Relationships

The between gate variance is a measure of performance of the gate mastering program in the plant. The within gate variance is,essentially, the variation in subassemblies and parts. It also includes the general condition of the gate line. Because the gate system is unforgiving, any part or subassembly deviations result in their deflection. The clamps are subjected to large forces which lead to their degradation. The deviations placed in the gate locators to shift the mean of the process have been shown, earlier, to increase the variance of those openings, unless careful analysis is made of the body design and the tooling. The parts may change in subsequent runs and go undetected by the assembly plant. The-experimental bodies built on the mastered tooling contained parts from one run, and therefore, did not include between run variance. The variance from this experiment can be used as a lower bound estimate on the influence of parts. The difference between the estimate for parts and total variance is the component the assembly plant tries to control. Table 3.5 summarizes the components as standard deviations. Column 1 shows the standard deviation obtained from the between gate variance. Column 2 is the standard deviation obtained from the within gate variance. Column 3 is the standard deviation obtained from the eleven experimental bodies. It represents a lower bound estimate of the parts. Those relationships where the eleven bodies show a significantly smaller variance are denoted by an ** in Column 3.

Column 6 indicates the tolerance specifications for the opening relationships.

Column 4 of this table is an estimate of the attainable mastering and process variability that can be expected with a strong mastering and maintenance program. The estimate for front O and bottom O relationships

TABLE 3.5

ACTUAL AND ALLOWABLE COMPONENT STANDARD DEVIATIONS OF BODY OPENING RELATIONSHIPS

RELATIONSHIP		Standard Deviation of Actual: Gate Mastering	Standard Deviation of Actual: Within Gate	Standard Deviation of Actual: Experimental Bodies	Attain Mastering and Process Std. Dev.	Allowable Part Std. Dev. (± Spec)	Print Specification
		Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6
Gate Tool Units							
R-3 Door Width	L	.036	.071	.058	.006	.040(±.120)	± .120
	R	0	.100	.062	.006	.040(±.120)	± .120
R-16 Door Height Front	L	.003	.070	.027**	.006	.019(±.057)	± .060
	R	.046	.060	.040**	.006	.019(±.057)	± .060
R-17 Door Height Rear	L	.036	.042	.029	.006	.019(±.057)	± .060
	R	.029	.057	.026**	.006	.019(±.057)	± .060
Swing Units							
R-1 W/S Depth	L	.007	.053	.036	.006	.014(±.042)	± .045*
	R	.028	.047	.038	.006	.014(±.042)	± .045
R-2 B/L Depth	L	.025	.065	.047	.006	.014(±.042)	± .045*
	R	.023	.048	.033	.006	.014(±.042)	± .045
R-15 W/S Height	L	.032	.062	.040	.006	.014(±.042)	± .045*
	R	.037	.080	.046**	.006	.014(±.042)	± .045
Centerline							
Gate Tool Units							
R-7 Roof Rail Width	AFT	.028	.078	.058	.031	.025(±.075)	± .120*
R-8 Roof Rail Width	Fore	.038	.073	.040**	.031	.025(±.075)	± .120*
R-9 Roof Rail Width	AFT	.032	.035	.045	.010	.039(±.117)	± .120*
R-10 Sill Width	Fore	.029	.056	.043	.010	.039(±.117)	± .120*
R-11 Quarter Panel Width		.031	.061	.054	.027	.030(±.090)	± .120*
R-R W/S Width		.056	.074	.054	.027	0 (± 0)	± .060
Swing Units							
R-13 Deck Opening		.010	.055	.035	.006	.019(±.057)	± .060

*Specifications derived from component prints.

** Denotes a significantly smaller variance

can be derived as follows:

	Band	σ
Acceptable mastering error for a plp	0-.015	.0025
	0-.015	.0025
Acceptable loading error	0-.020	.0033
	0-.020	.0033

Total standard deviation = $(.0025^2 + .0025^2 + .0033^2 + .0033^2)^{1/2} = .006$

For centerline relationships, the standard deviation of the centerline width of the roof rail is estimated at $\sigma = .030$ inches. Therefore, $\sigma = (.0025^2 + .0025^2 + .0033^2 + .0033^2 + .030^2)^{1/2} = .031$. This standard deviation can be computed for relationships at other elevations on the gate frame by multiplying .030 inches by the constant determined from the ratios of the heights.

Column 5 represents the component of variance expressed as a standard deviation that is allowable for parts. It was obtained by subtracting the variance for mastering and process from the variance permitted from the tolerance band. For the relationship door width, the following calculations were used:

Tolerance $\pm$ .120

Tolerance range +.120 - (-.120) = .240

Print standard deviation = $\frac{240}{6}$ = .040

Allowable part standard deviation

$= (.040^2 - .006^2)^{1/2} = .040$

The allowable part specification is shown in Column 5 in parenthesis. It is $\pm$ 3 (allowable part standard deviation). This allowable part standard deviation must be allocated to each principal locating point and must be further divided between parts where stacking occurs. It must also be noted

that the allowable part standard deviation for centerline relationships becomes smaller the higher the elevation on the body.

3.4.6 CONCLUSIONS

The following conclusions have been drawn from observations and from the analysis:

1. The major component of variance is the within gate variance. It is hypothesized that this is due to part and subassembly variability.
2. The subassembly checking fixtures do not have tolerances for surfaces. This is necessary if subassemblies are to be controlled at their source of fabrication.
3. The assembly plant does not have the ability to effectively respond to subassembly conditions. The changes to the gateline on the basis of surface plate readings without a thorough analysis of the subassembly and tooling, increases the variance.
4. The use of surface plate information is inadequate for process control purposes because of the small sample size and the interval between samples. More direct methods of making process decisions between parts and tooling are necessary. The use of qualified parts to be loaded in the gates would permit the immediate identification of the problem.
5. An effective mastering and maintenance program should be designed and implemented.
6. Standards for acceptable centerline variation should be determined for the system using gates, tie bars, and footlocks in excellent condition.

The next section describes the principles of locating and tolerancing subassemblies in the gate, and experiments to determine the influence of subassembly deviations from nominal on the body dimensions.

3.5 THE INFLUENCE OF SUBASSEMBLY VARIANCE

The models developed in Chapter II apply to any point on the body where a measurement is made to determine the deviation from nominal. In the previous section of this chapter, it was concluded that the largest component of variance was within the gate. The between gate component of variance was estimated and indirect methods were used to estimate the tooling variation. This section of the chapter describes the subassembly holding and clamping system in the assembly tooling and the relationship between subassemblies in the body. These relationships are defined and added to the models for measurement points to explain the influence of subassemblies on the body. Samples of subassemblies were obtained and measured in fixtures to determine their deviations from nominal. An experiment is described where bodies are built from these subassemblies. The same relationships are later measured and correlated to determine the predictability of the subassembly dimension in the body.

3.5.1 GATE LOCATION AND CLAMPING SYSTEM

Parts and subassemblies are located and held in the gates using blocks and clamps. The locating blocks define the principal points. Each principal locating point has a corresponding clamp or pusher to hold the metal. Each subassembly must have sufficient locators in each plane to locate the assembly in the body tooling and to prevent any translation or rotation.

For a rigid rectangular shaped object, good work piece control principles (Eary and Johnson (7)) require the use of a 3-2-1 system of locators, i.e., 3 locators on the largest surface define a plane, 2 locators on the second largest surface define the second plane and prevent any rotation, and 1 locator for the remaining surface prevents translation. Holding forces opposite these locators hold the subassembly rigidly in position. Additional locators for a rigid body contribute to increased positioning variability as differences in parts and tool mastering result in different combinations of the locators being used.

Sheet metal panels that are non-rigid and flexible require additional locators and supports so that the natural shape of the panel is maintained during the welding of the members. The quarter panel or rear fender is an example of a flexible panel that requires supports. When more locators than those necessary for a rigid body are used, the sequence used to apply the holding forces by closing the clamps becomes critical for good dimensional control. Those points that frame openings or where dimensions are critical must have their clamps closed first. This fixes the position of the part in the tooling and prevents movement of the panel in that coordinate. This removes a degree of freedom. When the remaining degrees of freedom are removed, the subassembly is located with respect to all three reference coordinates. These locators will be referred to as the critical locating points. If this sequence is not rigidly adhered to, the part will not be located in the tooling properly because existing clamping forces prevent movement. Therefore, after the critical locating point clamps are closed, additional clamps and locating points that are closed have the effect of:

1. Restraining the point against the stop so that weld gun forces will not move the part.
2. Aligning mating surfaces so that welds maybe properly placed.
3. Providing shape or mechanical support to the subassembly.

The locating blocks in the gate are mastered to a nominal body and are unforgiving when parts that are not nominal are loaded into the gate. Subassembly dimensional errors result in deflecting the part to conform to the principal locating blocks. The forces applied to the clamps depend on the relative stiffness of the component and the error in the part relative to the critical locating blocks. The result of these deviations is difficult to predict, as the energy stored must be relieved somehow. It becomes necessary to control the dimensions of the more rigid members. The gate when properly mastered can be used as a checking fixture and errors can be detected while closely restraining clamps. A gap between the metal and the stop indicates a part deviation and requires clamp effort to deflect the part and to force it against the stop. The spring back can be detected by opening the clamps after welding and observing the movement of the part surfaces.

3.5.2 SUBASSEMBLY RELATIONSHIPS

The process sequence determines the order of the parts that are loaded into the gate. The critical locating points and clamps position the part in the fixture. Secondary or restraining clamps hold the part against their locators. If the parts held during welding are dimensionally correct, then subsequent parts can be loaded and their mating surfaces will fit closely together. Welds can be placed with minimal distortion.

Dimensional errors in parts can introduce loading problems. Parts cannot be positioned properly against their stops because of interference. These dimensions are referred to as loading relationships. If the mating parts meet with a slip joint, then the effect of any part deviation is minimized and the parts are independent. When parts mate as a butt joint, then dimensional stacking exists. This results in parts locating improperly in the body, as one part locates with respect to the others. Gaps between mating parts result in distortion of the joint and weak welds, which can result in sealing and structural problems. These dimensional deviations are evident in the gate as gaps or deflections necessary to close clamps. The following notation is used to describe the relationship between points as a result of mating part deviations:

$$d_s = d_p + d_{p,s} \quad d_{s,p} + e_s \qquad (3.10)$$

where d_s is the deviation of a secondary point from nominal. It is secondary because it is influenced by another mating surface. d_p is the deviation from nominal of the critical locating point of the primary part which is loaded first. $d_{p,s}$ is the deviation from nominal in the primary part from where it is held to where it mates with the secondary part surface.

$d_{s,p}$ is the corresponding deviation of the secondary part in the relationship from the secondary plp to where it mates with the primary subassembly.

e_s is the unexplained error in the secondary plp which is a consequence of part distortion from welding and clamping forces, and measurement error. The model for a secondary principal locating point can be expressed by:

$$d^s_{ijn} = u_n + v_n + G_i + T_j + e^p_{ijn} + d_{p,s\ n} + d_{s,pn} + e_{s\ n}$$

$$= d^p_{ijn} + d_{p,s\ n} + d_{s,p\ n} + e_{sn} \qquad (3.11)$$

"A" PILLAR ANALYSIS

In order to demonstrate the principles discussed above, the loading and clamping of the "A" pillar subassembly will be reviewed. The "A" pillar is a sheet metal subassembly that frames the front door and windshield openings. The locators and clamps for the "A" pillar are shown in Figure 3.8.

The triangles represent the principal locating points that locate the component in the gates. The squares represent locating blocks that locate and provide support for the pillar. The arrows represent the holding forces of the clamps. The integers associated with each arrow denote the sequence that the clamps are to be closed. It is obvious from this figure that there are an excessive number of locators and clamps on this subassembly. The pillar is a very rigid component and, because errors are inevitable, the excess clamping forces distort the subassembly in an unpredictable fashion and increase the variability of its surfaces in the gate. Observations made when closing the clamp against 106 FO indicate the pillar slides about 106 FO because it can not be compressed enough to be held against the stop. In addition, the mating surfaces with other components were distorted.

The checking fixture that was designed to measure the "A" pillar surfaces did not have the same clamping forces and locators as the gate. This made communications between the supplier plant and the assembly plant extremely difficult. The position the pillar takes when loaded into the gate cannot be simulated in the fixture.

Figure 3.9 shows a location and holding system with fewer clamps. The three centerline locators form a plane, locating a one piece

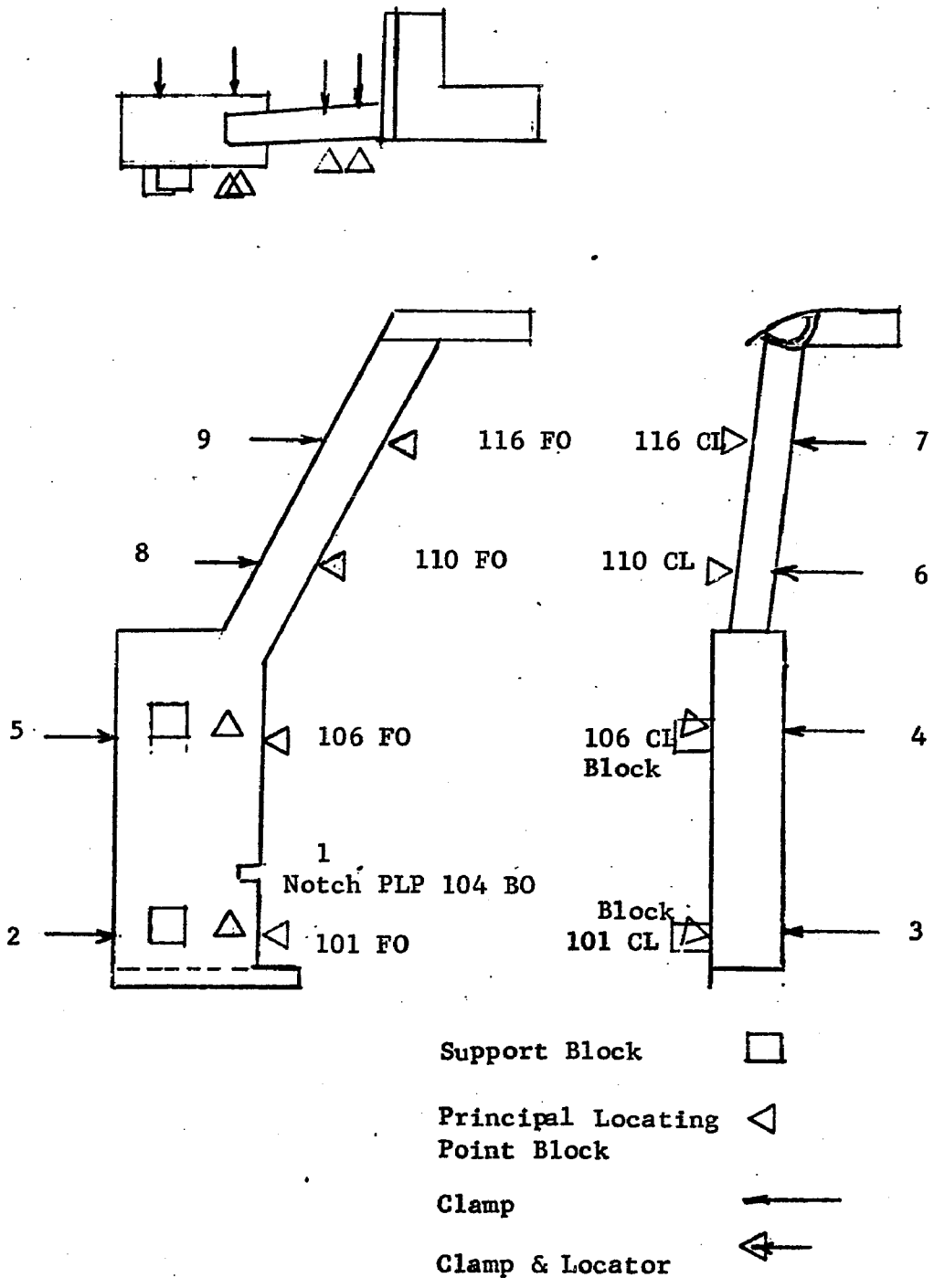


Figure 3.8 Present Loading of "A" Pillar

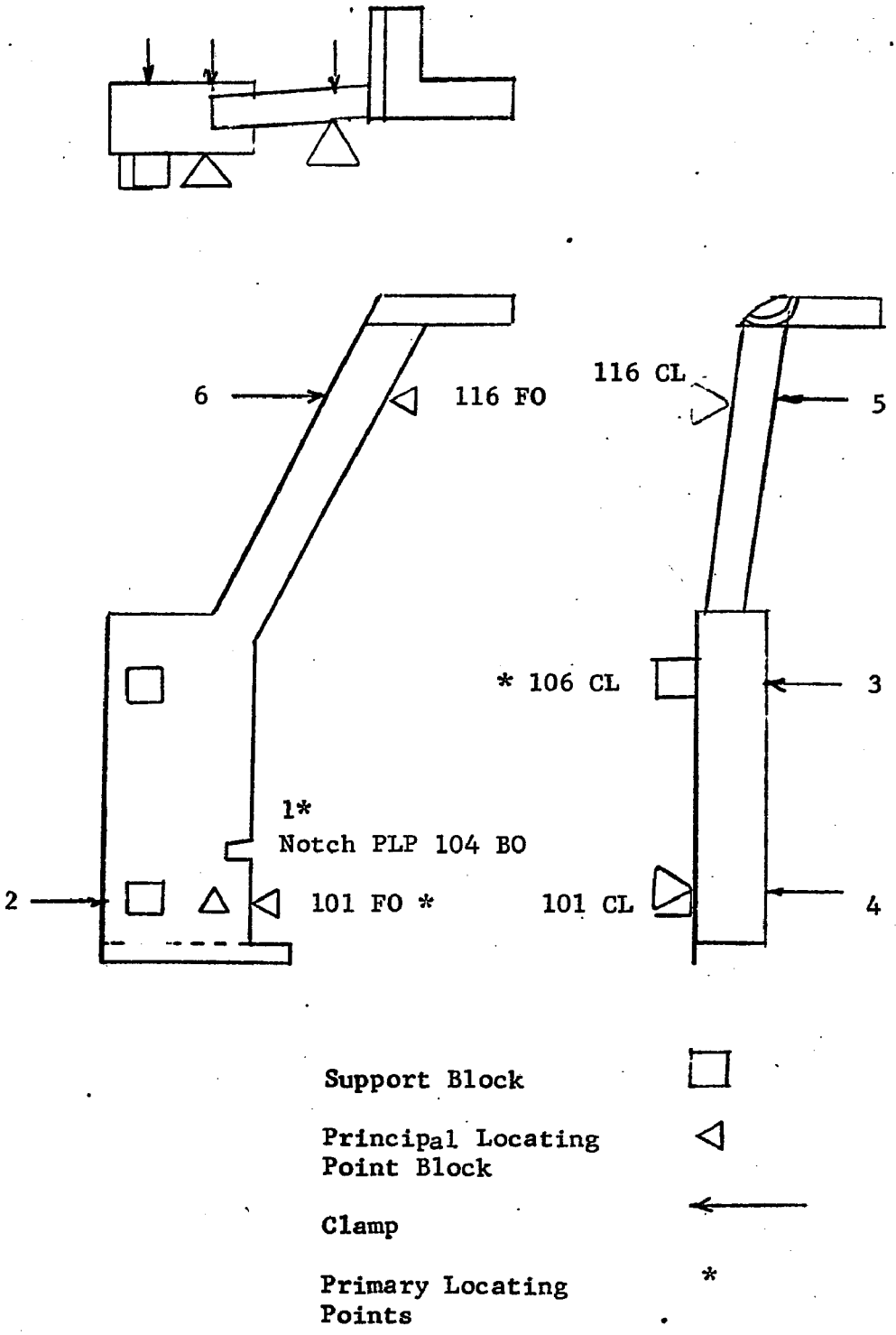


Figure 3.9 Proposed Loading of "A" Pillar

stamped surface. The bottom 0 position is determined by the notch, and the position of the pillar with respect to the front 0 plane is determined by two locators 101 and 116. The "A" pillar is therefore located in the tooling and any errors in the assembly are relative to the natural position it holds in the gate. This location system will minimize the variation in dimensions due to loading variation. The clamping sequence used with this system should be:

1. Position the "A" pillar on the notch against the two front 0 stops. One degree of freedom with respect to the bottom 0 plane has been removed.
2. Close the lower clamp opposite plp 101 FO. A second degree of freedom has been removed with respect to the front 0 plane.
3. Close the clamp opposite plp 106 CL. The remaining degree of freedom with respect to the centerline plane is removed.

   These principal locating points have been designated as the primary locating points as they locate the component in the tooling. All other locating points are designated as restraining plp's and are secondary. The remaining secondary clamps are closed next.
4. Close the clamp opposite plp 101 CL.
5. Close the clamp opposite 116 CL. Any inboard error in the "A" pillar relative to the lower member will be visible as a gap between the metal and the locating block.
6. The clamp opposite plp 116 FO is closed last.

The "A" pillar and its mating parts are shown in Figure 3.10. The parts that mate to the "A" pillar in the gate are the sill, the roof rail, and the inner cowl side panel. At gate marriage the two sides are mated to the floorpan, the roof header is joined to the upper "A" Post, and the cowl top rests on the "A" pillar. Further in the process, a gusset or reinforcement

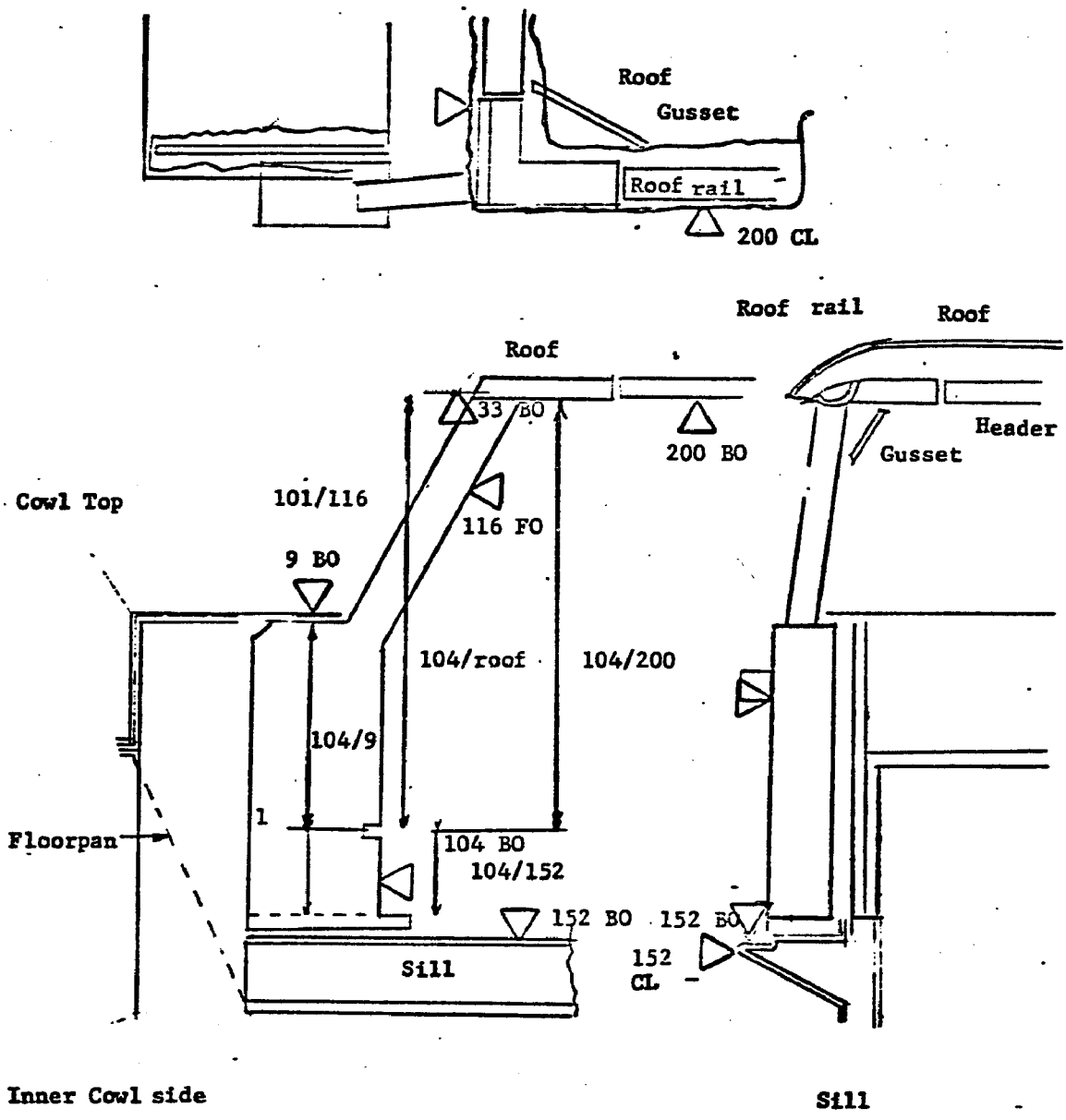


Figure 3.10 "A" Pillar and Mating Parts

plate is added to reinforce the header, "A" pillar, and roof rail joint. The last mating part to the "A" pillar is the roof. Some of the important dimensions from the primary locating points to the surfaces that mate with these parts have been identified in Figure 3.11. In addition to these relationships, there are other relationships that are important to the loading of mating parts. If these relationships are not correct, the parts cannot be loaded properly so that the tool concept works. The result is increased variability and excess repairs. It becomes very important that the checking fixture locating and clamping systems and sequence be identical to that used in the gate, so that deviations from nominal and their consequences be recognized.

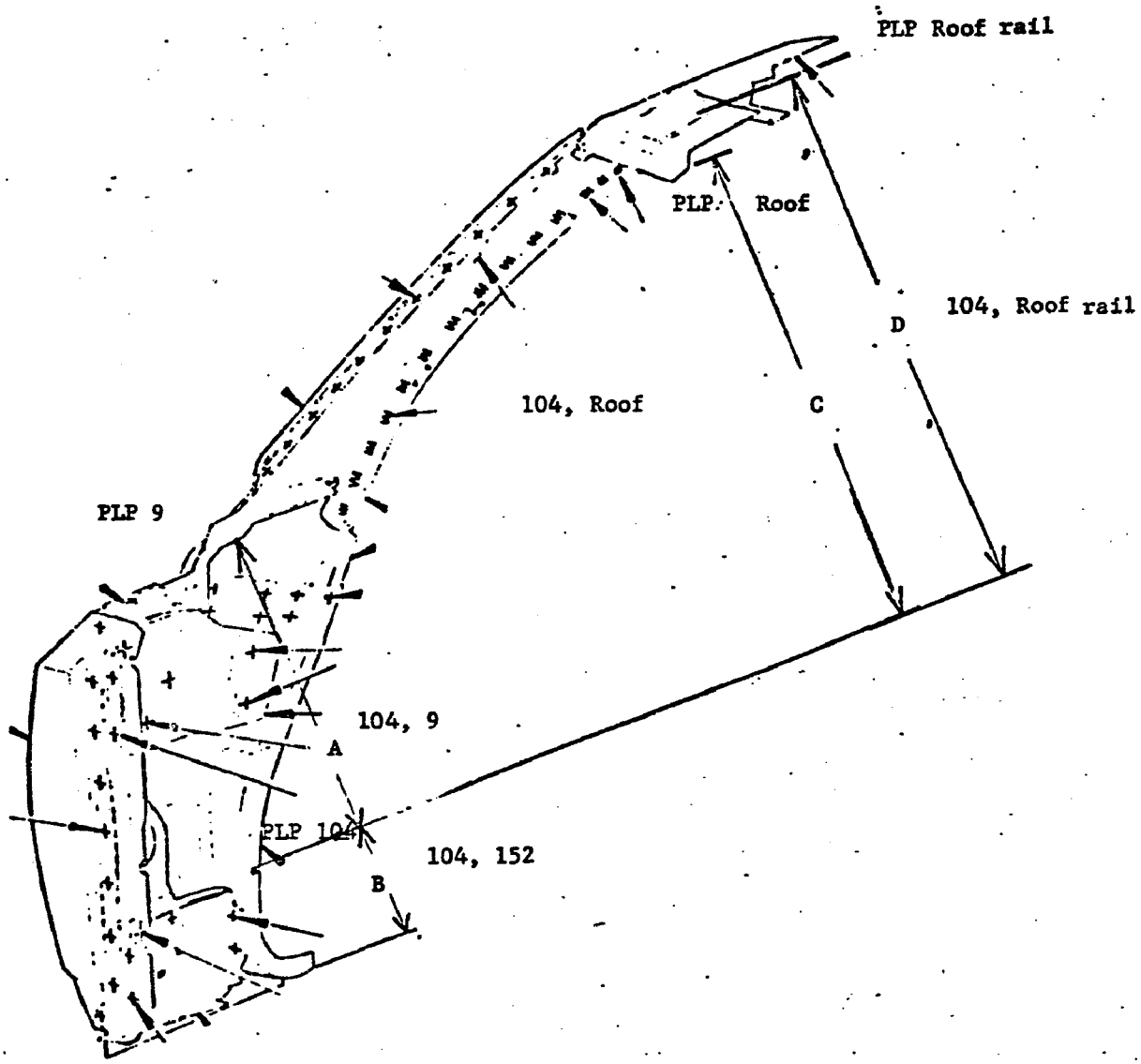
The following parts and their principal locating points are influenced by relationships from the primary locating points on the "A" pillar:

A pillar

Primary locating points	104 BO 106 CL 101 FO
Secondary locating points	116 FO 101 CL 116 CL

Mating principal locating points

Roof Rail	200 BO 200 CL
Sill	152 BO 152 CL
Cowl Top	4 BO 4 FO 9 BO
Roof Header	35 BO
Roof	33 BO



DIMENSION A - COWL TOP MATING
DIMENSION B - SILL MATING
DIMENSION C - ROOF MATING
DIMENSION D - ROOFRAIL MATING

Figure 3.11 "A" Pillar Relationships and Principal Locating Points

Data from 25 bodies were analyzed to determine if the points measured on the "A" Pillar and points on mating parts that are stacked to the "A" Pillar surfaces agree with the relationship (3.11).

$$d^{s}_{ijn} = d^{p}_{ijn} + d_{p,s,n} + d_{s,p,n} + e_{s,n}$$

The variance of d^{s}_{ijn} can be expressed as

$$\text{Var}\left(d^{s}_{ijn}\right) = \text{Var}\left(d^{p}_{ijn}\right) + \text{Var}\left(d_{p,s,n}\right) + \text{Var}\left(d_{s,p,n}\right) + \text{Var}\left(e_{s,n}\right) \qquad (3.12)$$

Therefore $$\text{Var}\left(d^{s}_{ijn}\right) > \text{Var}\left(d^{p}_{ijn}\right) \qquad (3.13)$$

and $$\sigma\left(d^{s}_{ijn}\right) > \sigma\left(d^{p}_{ijn}\right) \qquad (3.14)$$

In Table 3.6 the primary locating point, i.e., d^{p}_{ijn}, for the A pillar is 101 CL, and the secondary plp's are 106, 110 and 116 CL.

TABLE 3.6

SAMPLE STANDARD DEVIATIONS FOR "A" PILLAR CENTERLINE PLP'S FROM A SAMPLE OF 25 BODIES

PLP	LEFT	RIGHT
101	.036	.036
106	.055	.048
110	.065	.049
116	.070	.081

The point 106 is on the same part and plp 110 and 116 are on the same subassembly but on a different sheet metal part. In this case:

$$d^{106}_{ijn} = d^{101}_{ijn} + d_{101,106} + e_{106}$$

$$d^{110}_{ijn} = d^{101}_{ijn} + d_{101,110} + e_{110}$$

$$d^{116}_{ijn} = d^{101}_{ijn} + d_{101,116} + e_{116}$$

The secondary standard deviation is greater than the primary standard deviation for each point, i.e.,

$$\sigma_{106} > \sigma_{101}$$

$$\sigma_{110} > \sigma_{101}$$

$$\sigma_{116} > \sigma_{101}$$

3.6 EXPERIMENT TO ESTIMATE SUBASSEMBLY EFFECTS

This section of the chapter describes an experiment to estimate the influence of subassembly deviations from nominal on body dimensions. The subassembly data collected and the results of the experiment are presented.

3.6.1 EXPERIMENTAL PROCEDURE

The objective of the experiment was to determine how much of the variation of a measured point on the body could be explained by the variation in the subassemblies. The coordinate deviation from nominal of a point is the sum of the deviations of the subassembly relationships between it and the principal points that locate them in the tooling. This was expressed by (3.11) $d^{s}_{ijn} = d^{p}_{ijn} + d_{p,s} + d_{s,p} + e_{s,n}$. The difference between the two points in the body can then be expressed by $d^{s}_{ijn} - d^{p}_{ijn} = d_{p,s} + d_{s,p} + e_{s,n}$ (3.15)

where: $d^{s}_{ijn} - d^{p}_{ijn}$ is the difference between the two points in one coordinate direction;

$d_{p,s}$ is the component of the deviation from nominal of the primary subassembly from d^{p}_{ijn} to where it mates with the secondary subassembly;

$d_{s,p}$ is the component of the deviation from nominal of the point of interest on the secondary subassembly.

$e_{s,n}$ is the experimental error which contains the process effects due to distortion from clamping and weld gun

forces, thermal distortion, and measurement error.

Most relationships studied were measured in the vicinity of the mating surface. In that case $d_{s,p} = o$ and $d^{s}_{ijn} - d^{p}_{ijn} = d_{p,s} + e_{s,n}$. The subassembly deviation from nominal should correlate with the same relationship in the body. All experiments were performed in the same tooling which was carefully mastered. When checking fixtures are used to measure part relationships the deviations are measured perpendicular to the surface of the metal. A procedure to resolve these deviations so that comparisons can be made to surface plate data is contained in Appendix C.

A summary of the procedure to predict the deviation of body opening surfaces from the deviations of the subassemblies which form these openings is outlined below:

1. Identify the relationships on each subassembly that are critical to forming an opening.

   These relationships are the distances from the principal locating surfaces to the surfaces which mate to the adjoining subassembly.

2. Measure the critical relationship by placing the primary subassembly into its checking fixture. Net the subassembly to the principal locating surfaces. Measure the deviation of the mating surface from nominal, perpendicular to the metal surface. Record deviations.

3. Place the primary subassembly into the sidegate fixture. Net the subassembly to the principal locating surfaces.

4. Choose an opening surface on a secondary subassembly whose position is controlled by mating to the primary subassembly.

5. Measure the deviation of the opening surface with respect to the mating surface to the primary subassembly by placing the secondary subassembly into its checking fixture. Net the subassembly at the mating surface to the primary subassembly. Record deviations perpendicular to the surface.
6. Load the secondary subassembly into the sidegate fixture. Net the secondary subassembly to the primary subassembly at the common mating surface measured in 2 above.
7. Build the body.
8. Load body into the checking fixture, locating it with respect to its principal locating surfaces.
9. Measure the position of the opening surface chosen in 4 above. Measure the deviation from nominal perpendicular to the surface. Record deviation.
10. Replicate steps 2 through 9 N times.
11. For each combination of primary and secondary subassembly deviations, compute the predicted position of the secondary subassembly opening surface.

    This predicted value is a function of the dimensional deviation of the subassemblies which form the opening.
12. Compare 11, the predicted value, with 9, the actual value for each combination.

    High correlation between the predicted and actual should result. Any numerical differences between the two numbers should be caused by process effects and experimental error.

EXAMPLES OF EXPERIMENTAL PROCEDURE

The experimental procedure was applied to a sample of four "A" pillars. Figure 3.11 shows the part relationships that were measured prior to assembly and the plp's on mating subassemblies that were measured after the body was assembled.

For this example the primary plp is 104, the bottom O locating notch. The equation for the secondary plp's are:

$$d_{roof} = d_{104} + d_{104,roof} + e_{roof}$$

$$d_{roof\ rail} = d_{104} + d_{104,\ roof\ rail} + e_{roof\ rail}$$

$$d_9 = d_{104} + d_{104,9} + e_9$$

$$d_{152} = d_{104} + d_{104,152} + e_{152}$$

A sample of measurements from four bodies for the height of the roof is summarized in Table 3.7.

TABLE 3.7

MEASUREMENTS OF "A" PILLAR DEVIATIONS IN CHECKING FIXTURES AND IN ASSEMBLED BODIES

	DEVIATIONS IN THE BODY			"A" PILLAR DEVIATIONS	
	(1)	(2)	(3)=(1)-(2)	(4)	(5)=(3)-(4)
BODY	d_{roof}	d_{104}	$d_{roof}-d_{104}$	$d_{104,roof}$	e_{roof}
1	-.120	-.080	-.040	-.032	-.006
2	-.110	-.090	-.020	+.030	-.050
3	-.060	-.090	+.030	+.017	+.013
4	-.180	-.110	-.070	-.026	-.044
Sample Average	-.118	-.093	-.025	-.003	-.0218
Standard Deviation	.0493	.0126	.042	.0315	.0303

Column 3 of Table 3.7 represents the actual distance from the notch to the roof measured in the body in the bottom O coordinate direction.

Column 4 is the same distance that is measured in the checking fixture.

Column 5 readings are the difference between columns 4 and 3 readings and represent the process effects of assembling the roof to the "A" pillar and any measurement errors. Correlating the values in Column 3 and Column 4, we obtain the coefficient, $r = .70$ and $r^2 = .49$. Therefore, the dimensional variation of the "A" pillar explains 49% of the variation of the roof height. The remaining variation is unexplained and it includes the effects of clamping and welding of mating parts on the subassembly, which could change the roof height measurements.

The next section describes the results of this experiment for selected surfaces in the body.

3.6.2 RESULTS OF EXPERIMENT

Table 3.8 contains the correlation coefficient for each relationship obtained by correlating the coordinate distance of the relationship in the finished body versus the relationship coordinate distance measured in the subassembly by checking fixtures. Hypothesizing a linear relationship between the predicted and actual, the correlation coefficients are very low. This indicates that the relationships are changing in the body after they are assembled and welded. The major reasons for this failure of the experiment to show higher correlations were found to be:

1. The checking fixture holding systems are not identical to the gate holding systems. This was particularly evident for the "A" pillar. This resulted in the deviation measured in the checking fixture being

TABLE 3.8

CORRELATION OF BODY RELATIONSHIPS WITH CORRESPONDING SUBASSEMBLY RELATIONSHIPS

BODY RELATIONSHIP	SUBASSEMBLIES INCLUDED	SIDE OF BODY L	SIDE OF BODY R	CORRELATION PARTS VERSUS BODY
Quarter Panel Front O to Backlight Fence	Quarter Panel	X		.61
	Upper Deck Panel		X	-.24
"A" Pillar Bottom O to Cowl Top Mating Surface	"A" Pillar	X		.67
	Cowl Top		X	.32
"A" Pillar Bottom O to Roof Front	"A" Pillar	X		.10
	Roof		X	-.23
"A" Pillar Bottom O to Roof Rail	"A" Pillar	X		.09
	Roof Rail		X	.17
"A" Pillar Centerline to Roof Rail	"A" Pillar	X		.35
	Roof Rail		X	.41
"A" Pillar Bottom O to Sill	"A" Pillar	X		.12
	Sill		X	.23
"A" Pillar Centerline to Sill	"A" Pillar	X		.35
			X	.30
Wheelhouse Bottom O to Roof	Wheelhouse	X		.77
	Roof		X	.50
Wheelhouse Centerline to Roof Rail	Wheelhouse	X		.068
	Roof Rail		X	.095

different from the deviation in the gate due to the different subassembly responses to the clamping. Relationships C and D for the "A" pillar in figure 3.11 were changed because a spot weld was applied in the gate. A gap existed between the surfaces being welded. Therefore, the "A" pillar was measured in a checking fixture with the gap. The "A" pillar in the gate had the gap closed which distorted relationships C and D.

2. In some cases, the parts were not permitted to be stacked according to design because of interference at another surface. This also resulted in not realizing the predicted value. The cowl top mates to the cowl side at six surfaces that can influence the stacking of the relationships.
3. The gate locators are unforgiving and clamping distorts the surface locally.
4. The weld guns and pressure cause local changes to the subassembly which influence the predicted relationship.
5. Stresses are transmitted from the forces required to close gaps at other weld joints.

3.7 SUBASSEMBLY CAPABILITY

The same principles that were used to determine subassembly effects in the body can be applied to the detail parts and subassemblies. A sample of component parts for an "A" pillar subassembly were selected and measured. Figure 3.12 shows an exploded view of the components parts that are contained in the "A" pillar assembly.

The relationships on the detail parts that make up the "A" pillar shown in figure 3.12 are listed here:

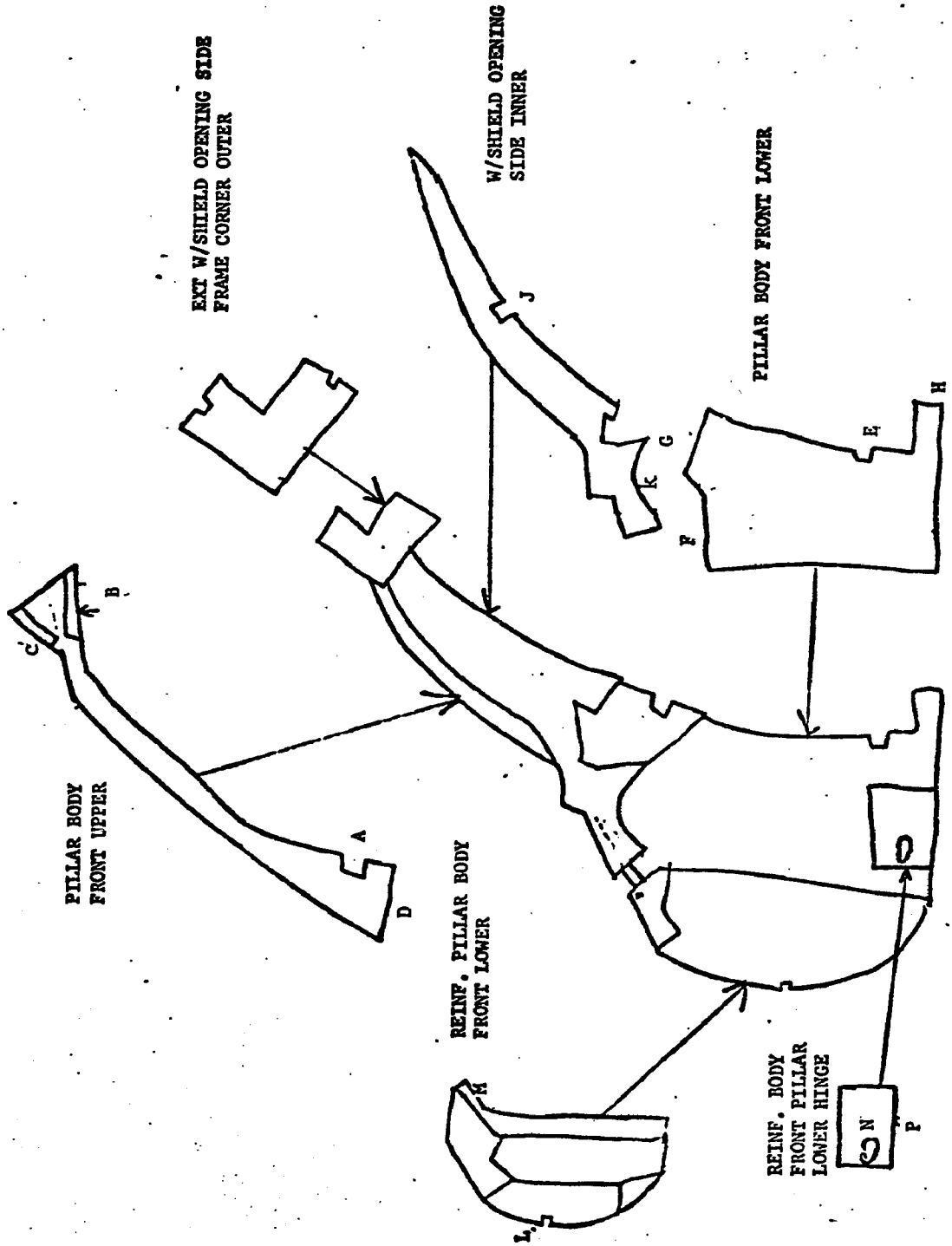


Figure 3.12 "A" Pillar Component Parts

Pillar body front upper.

Centerline of notch A to roof rail mating surface B.

Centerline of notch A to ext-w/shield mating surface C.

Centerline of notch A to pillar body front lower mating surface D.

Pillar Body front lower.

Centerline of notch E to w/shield opening side inner mating surface F.

Centerline of notch E to pillar body front upper mating surface G.

Centerline of notch E to sill mating surface H.

Windshield opening side inner.

Centerline of notch J to pillar body front lower mating surface K.

Reinf-pillar body front lower.

Centerline of notch L to pillar body front lower mating surface M.

Reinf-Body front pillar lower hinge.

Centerline of gauge hole N to sill mating surface P.

Table 3.9 contains the sample mean and range for selected relationships of "A" pillar detail parts.

The same parts were also cycled through the machine welder and their subassembly relationships are shown in table 3.10. The experimental procedure was not performed because the locators in the machine welders that locate each part with respect to another are not mastered to a nominal model. In order to correlate relationships, the distance between tooling locators would have to be known. The data clearly shows that the

TABLE 3.9

SAMPLE MEAN AND RANGE OF "A" PILLAR COMPONENT PART RELATIONSHIPS

DETAIL PART RELATIONSHIPS	DEVIATIONS FROM NOMINAL			
	LEFT SIDE		RIGHT SIDE	
	MEAN	RANGE	MEAN	RANGE
PILLAR BODY FRONT LOWER				
From Bottom O notch to Sill Surface H			.015	.000
From Bottom O notch to W/shield Opening Side Inr Surface F	.000	.000	-.030	.000
Centerline to Pillar Body Front Upr Mating Surface G				
Target B	-.069	.015	.024	.015
C	-.009	.015	.000	.000
F	-.036	.015	+.045	.000
PILLAR BODY FRONT UPPER				
Centerline of Tooling notch A to Ext-W/shield mating surface C				
Target D	+.036	.030	-.015	.060
E	-.045	.030	-.057	.060
F	-.119	.030	+.094	.030
G	-.027	.015	-.006	.030
Centerline of Tooling notch A to Pillar Body Front Lower				
Mating Surface D				
Target A	+.018	.015	0	0
B	+.045	.060	.007	.015
C	.015	.045	.066	.015

Sample Size = 5

TABLE 3.10

SAMPLE MEAN AND RANGE OF "A" PILLAR RELATIONSHIPS

SUBASSEMBLY RELATIONSHIP	DEVIATIONS FROM NOMINAL	
	MEAN	RANGE
"A" PILLAR - RIGHT SIDE		
From Bottom O notch to Sill Surface J2	.015	.030
From Centerline to Sill Surface J1	-.030	.105
From Bottom O notch to Cowl Top Surface	-.060	.090
From Bottom O notch to Roof Rail Surface	-.019	.050
From Bottom O notch to Roof Surface	+.104	.045
From Centerline to Roof Rail at Cap Centerline	.054	.030

mean or average part deviation for some surfaces are considerable, although the variance, as reflected by the range, is small for most part relationships. A further difficulty was noticed with the detail part checking fixtures. The surfaces that were net, and that located the part in the checking fixture, did not agree with the surfaces in the tooling and subassembly. Consequently, it was difficult to collect part data that could be added together to predict the surface in the subassembly.

It was concluded that subassembly process capability is dependent on the control of part surfaces. Figure 3.13 shows a histogram of sample means and ranges for the detail part relationships of the "A" pillar. It is evident that the ranges are small, i.e., 73% are less than .015 inches and 90% are less than .030 inches.

The sample means show a larger dispersion. The variability of the subassembly process is the result of the interaction of part errors and weld forces. Attempts to shape the parts or subassemblies in the tooling have the effect of transmitting errors to other surfaces. The absence of gauging surfaces and realistic tolerances on important stacking and mating surfaces makes the control of detail parts very subjective.

3.8 CONCLUSIONS

The conclusions resulting from the analysis performed in this chapter are:

1. The major component of variance for the side gate process is the within gate variance which is due to subassembly deviations from nominal.
2. Specifications are needed concerning the dimensional performance of assembly tooling.

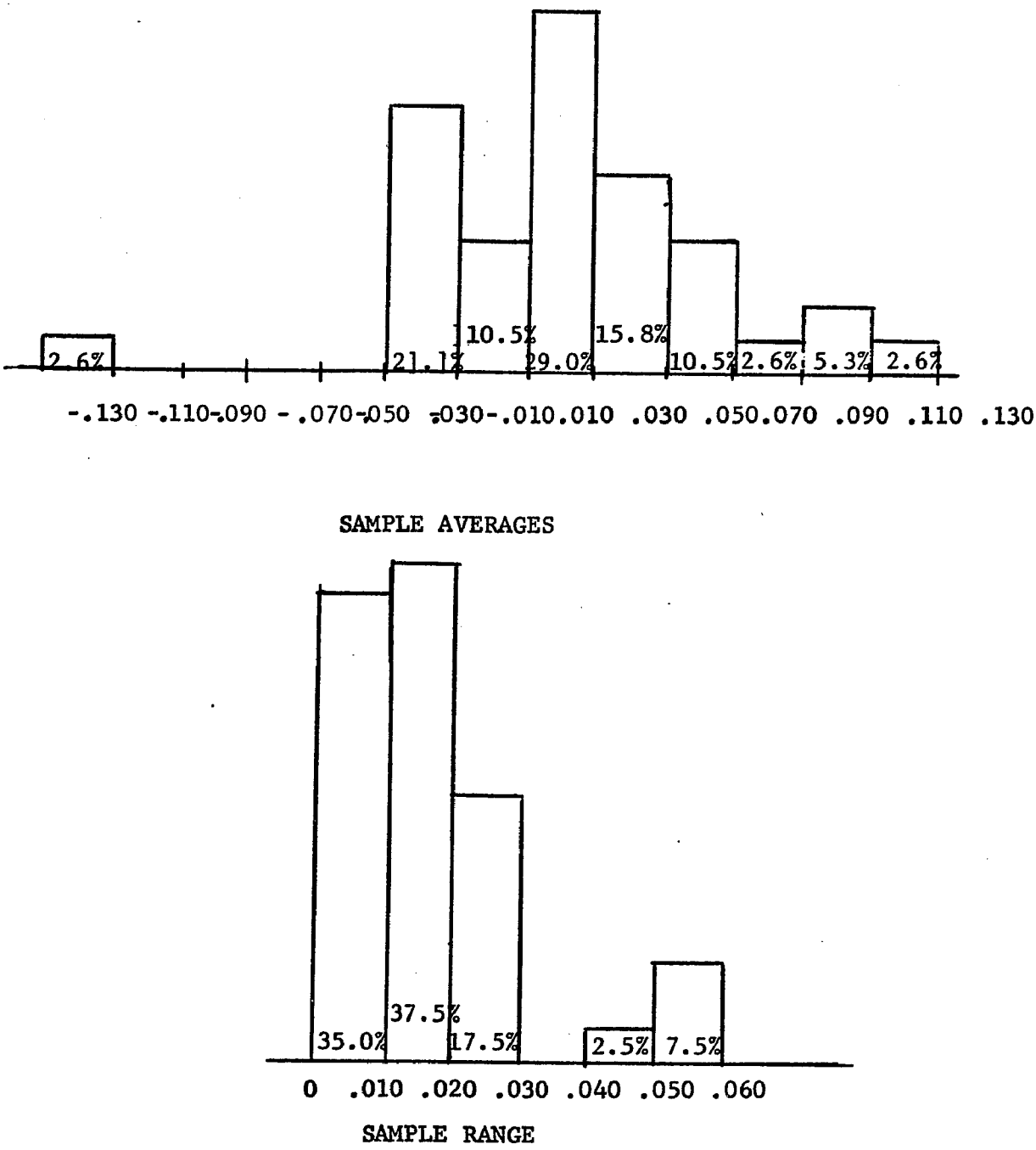


Figure 3.13 Histograms of Sample Means and Ranges "A" Pillar Detail Parts

3. Direct methods should be provided to determine the condition of gate, trucks, and other assembly tooling.
4. The emphasis of assembly plant personnel should be on maintenance of welding fixtures.
5. Changes to assembly tooling should be carefully controlled as tooling deviations increase the variability of openings.
6. The appropriate point of control for body openings is detail part dimensions and the mastering of subassembly tooling.
7. The sealability of body openings has been demonstrated when openings are produced within design specifications.
8. The effectiveness of subsequent sealing and assembly operations should be evaluated using bodies that have openings within specification.
9. The design of detail part and subassembly checking fixtures should be coordinated with the subassembly and body assembly process.
10. Stacking and mating surfaces for detail parts and subassemblies should be realistically toleranced consistent with functional gauging methods.
11. All other surfaces that prevent the tooling from placing parts together on desired stacking surfaces should be toleranced for desired clearances.

The next chapter describes a procedure for evaluating and tolerancing a subassembly and body structure design.

CHAPTER IV

METHODOLOGY FOR THE TOLERANCING, PROCESS EVALUATION AND CONTROL OF SHEET METAL CAR BODY STRUCTURE DESIGNS

4.1 INTRODUCTION

This chapter describes an algorithm to tolerance sheet metal parts and subassembly designs based on the capability of the stamping process. The main objective of the procedure is to predict the dimensional variation of surfaces in the car body. This is accomplished by tolerancing sub-assemblies, recognizing the interaction between tooling and mating surfaces, to eliminate interference preventing the desired location. The methodology requires agreement, at the design stage, between engineering and manufacturing on the assembly sequence and gauging surfaces so that coordination is possible throughout the process design stage. The methodology includes steps for the design of capability studies for dimensional review and process control limits. This chapter outlines the steps of the methodology and describes an application to a sheet metal design. There are four sections to the chapter:

1. Pre-tolerancing analysis
2. Tolerance analysis and process review
3. Post launch analysis
4. "A" pillar example

4.2 PRE-TOLERANCING ANALYSIS

This section of the chapter discusses the analysis that is required before functional equations can be developed for the design. This analysis requires: the location of every detail part and subassembly in the body with respect to tool location surfaces and mating surfaces of other parts;

the capability of the assembly and subassembly tooling to locate subassemblies in the gate, and parts relative to each other, respectively; the selection of surfaces and sections on these surfaces necessary for the design of checking fixtures; and a preliminary die process and estimate of the dimensional capability for the surfaces to be toleranced and controlled.

4.2.1 DETERMINATION OF THE DESIGN PATH FOR THE STRUCTURE

This phase of the procedure specifies the assembly sequence for the body components, the surfaces on each component that locate it in body position and the surfaces that are restrained during welding, the assembly sequence for detail parts in a subassembly, and the major stacking and intermediate surfaces necessary to locate parts in the tooling. The purpose is to specify how each part will be located in body position and whether the part will be located with respect to another part surface, called stacking, or by some combination of stacking and tool location. The detailed steps of the procedure are listed below:

Step 1 For all components and subassemblies in the body structure perform the following steps:

Step 1.1 Define the assembly sequence.

Step 1.2 Determine the subassembly reference surfaces that locate it in the assembly tooling. This applies to the principal locating surfaces that geometrically locate the component. It does not include those surfaces that are clamped for mechanical support.

Step 1.3 Determine the surfaces that will be clamped and restrained for mechanical support to a mastered locating block. It is important to identify these surfaces to control the degree of error between the part and the block that causes distortion

when clamped.

Step 1.4 Identify the major stacking surfaces which locate other body components. These surfaces are selected on the basis of the structure and rigidity of the mating components.

Step 2 For each major subassembly perform the following steps:

Step 2.1 Determine the assembly sequence and the predominant stacking surfaces for detail parts in the design.

Step 2.2 Identify the gauging surfaces for each part that are compatible with the reference (principal locating) surfaces and the stacking surfaces. The gauging surfaces locate the part in its checking fixture. They should agree with the method of assembly so that the contribution of deviations from nominal to the subassembly can be read directly.

Step 2.3 Identify intermediate tool surfaces based on the preliminary process and holding concept. In those cases where the part is not located at its gauge surface because of process requirements, but is located at a secondary surface, these surfaces must be measured and controlled so that the process performs as intended. An example of this occurs when two parts are loosely assembled by a notch on one part and a tab on the second part. The position and size of both of these features must be toleranced so that the two parts may be positioned in the correct relationship to one another.

Step 2.4 Determine the sequence of dimensional relationships for each surface that is to be toleranced and controlled, between it and the subassembly reference, stacking, and tooling surfaces.

This is equivalent to identifying the functional path for each surface. This permits the development of equations relating the errors at a surface to the errors in the detail parts and errors in tool locators.

4.2.2 ESTIMATION OF TOOL CAPABILITY

This phase of the procedure estimates the degree of variability that can be expected from the tooling for a preliminary assembly process. These estimates can be based on past experience with similar holding concepts and manufacturing engineering standards regarding the mastering of the tooling. Experiments for estimating these variables will be presented in the preproduction phase of the procedure. The required steps are:

Step 3.1 Obtain estimates for gate side tooling variability. This refers to the tool band that was estimated by indirect methods in the last chapter. An experiment for a direct method of estimation is described later. This estimates the variability of the gate frames from their mastered position. The locating surfaces are mastered to a model of the nominal surfaces of the body, referred to as the build master. The gate sides are locked to this master and to framing trucks in the same manner. The tool band then describes the variation of the gate sides from their mastered position in each coordinate axis as they are locked to different trucks.

Step 3.2 Obtain estimates for the mastering variability of the gate locating blocks for each subassembly. These deviations from nominal are measured normal to the surface of the

nominal surface. The permissible variation is usually covered by tooling specifications. This variation is in addition to the tool variability in the previous step.

Step 3.3 Obtain estimates for the relative loading error and its direction between parts for each subassembly. The variation depends on the locating concept used. A positive locating system such as a surface block and a clamp would have a normal mastering tolerance, whereas a part that is located between two stationary blocks by trapping the part would have a predictable range of variation. These estimates recognize that a range of mismatch can be expected between two parts.

4.2.3 CHECKING FIXTURE ANALYSIS

The tolerancing procedure requires a definition of the surface to be toleranced. The parts are made and checked with respect to a die model. Deviations from nominal are measured at targets normal to the surface of the model. Similarly with subassemblies, a checking fixture is designed and the targets are calibrated to a set of models that are stacked together to obtain the nominal surfaces. The surface is then checked at the targets at different sections along the surface. The gauging surfaces, stacking surfaces, tooling surfaces, mating and opening surfaces have been defined in the previous steps of the procedure. This phase of the procedure requires the following step:

Step 4.1 Define the sections, points and breaklines on all functional surfaces to be toleranced.

4.2.4 PRELIMINARY DIE PROCESS AND ESTIMATION OF PART VARIABILITY

The objective of this analysis is a preliminary die process for the parts in the design and an estimation of the maximum and minimum limits

for each detail part surface identified in step 2.4 and further defined in step 4.1.

Step 4.2 Estimate part deviation intervals for:

(a) Stacking surfaces with respect to reference and gauge surfaces.

(b) Mating and opening surfaces with respect to gauge surfaces.

(c) Reference and gauge surfaces with respect to master or intermediate tooling surfaces.

4.3 TOLERANCING ANALYSIS AND PROCESS REVIEW

This section of the chapter describes the tolerancing of subassemblies as separate units and as surfaces in the body. The procedure includes the modeling of the stacking between two parts in a subassembly and the computation of gaps and interferences at mating surfaces. This permits a review of the design structurally when surfaces are restrained to locating blocks, and when gaps are closed by welding. The quality of weld and sealability of the joint can be evaluated from the prediction of the gaps at joints. The tolerancing of more than two parts and the tolerancing of surfaces in the body is an extension of this procedure.

4.3.1 SUBASSEMBLY TOLERANCING

The steps of the procedure to tolerance a subassembly are listed in this section including a discussion of each step. The objective of this procedure is to determine a tolerance band for the important surfaces of the assembly at the sections and points identified for the design of checking fixtures. In addition, a prediction of the interference at other surfaces in the subassembly is made, so that appropriate clearances can be designed into individual part surfaces.

Steps 2 and 4 of the procedure have defined the design path for the detail parts and a deviation interval for the functional surfaces. Step 3.3 has estimated the direction and amount of loading variation that can be expected based on the preliminary process. This step is concerned with the stacking of two detail parts in order to tolerance the subassembly. The steps for tolerancing the subassembly surfaces are listed below:

Step 5.1 Develop dimensional models for each surface as a function of the design path and process variables.

This step requires a review of the design path for the subassembly. The part with the gate reference surfaces is selected and defined as the primary part. These reference surfaces define the origin for the subassembly and the second part is toleranced with respect to the primary part. The secondary part is then stacked according to the design to the predominant mating surface. A second stacking surface (three are required if the surfaces are orthogonal) is then selected to fix the position of the secondary part. There may be more than two surfaces to be satisfied by the design. The criterion for selection should be minimal distortion to the design, i.e., satisfy those surfaces that contribute the most to the structure of the design. An expression for the coordinates of movement of the secondary part can be written as a function of the deviations from nominal of these surfaces.

The surfaces, although they are touching, can be improperly located on the predominant mating surface. These errors in location may be due to mastering errors in the tooling blocks

that locate the two parts in a particular direction, or they may be due to the process design which "traps" the part. These errors are defined as loading errors, whereas the errors in the previous paragraph are defined as stacking errors.

The method of checking a subassembly is reviewed briefly in order to explain the response of a surface to the above errors of stacking and loading. The checking fixtures are calibrated by adjusting a cross section of the surface to a model of the nominal surface. The readings can be obtained by two methods: the first using a feeler check and the second using a flush pin check. The former requires that the target be offset by an amount, in order to read deviations in both directions. A subassembly, located at the reference surfaces, is clamped in the fixture. A surface measurement is obtained by inserting feeler gauges until the perpendicular distance from the target to the metal surface is obtained. The deviation from nominal is $\frac{A}{2} - x_o$ where x_o is the feeler gauge thickness and A is the offset. The second method uses a steel pin where the deviation from nominal is read directly.

In both cases the reading represents the perpendicular distance from the nominal point of the surface to the actual metal surface. The response of the tolerance equation is the deviation of the surface in a direction that is normal or perpendicular to the nominal point. The independent variables of the tolerance equation are the errors of the stacking surfaces and the loading errors in the plane of the predominant stacking surface.

In order to model the problem and to develop the tolerance equations for the subassembly, the following assumptions are made:

1. All surfaces are approximated by a plane tangent to the surface at the point where the feeler check or response is to be evaluated.
2. All errors in surfaces are assumed to be normal to the tangent plane and of constant magnitude for the entire surface. This amounts to limits for the surface which are normal deviations to the surface at all points.
3. All movements to the parts due to stacking and loading are assumed to be translations only.
4. All loading errors are assumed to lie in a plane that approximates the predominant stacking surface. The plane is selected as that plane which most likely represents the motion of the secondary part when it is joined by clamping and welding to the primary part. The direction of the loading error is assumed to be along a line normal to the locating stop, form, or block.

The stacking surfaces cause the secondary part to be translated. In addition the loading errors are assumed to cause a translation in the plane of the predominant stacking surface. The result of these translations can be expressed in terms of the coordinate change to the secondary part. A surface deviation from nominal on a secondary part can then be expressed as the sum of the vector equivalent, normal to the surface, of the coordinate motion plus the deviation of the surface on the secondary part itself. The deviation from nominal on a primary part surface is the deviation from nominal of the surface itself. The procedure requires the coefficients of the normal vector to the tangent plane for each surface point to be

toleranced. This permits the determination of the coordinates due to stacking and the resultant deviation from nominal for any coordinate translation. In addition the coordinates as a function of any loading errors are required.

The following example will demonstrate a model to tolerance a sub-assembly surface. Consider the plan and side view of the simple sub-assembly in figure 4.1.

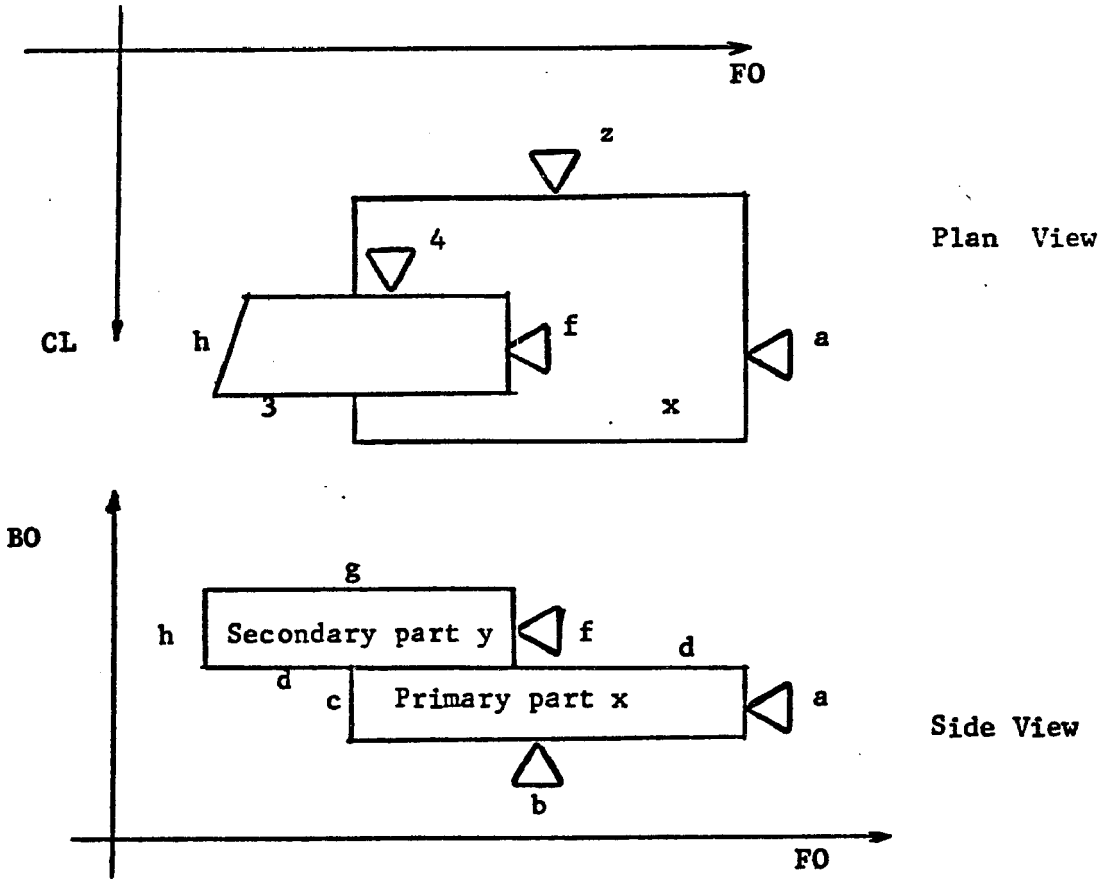


Figure 4.1 A Simple Subassembly Showing Gauge and Tool Surfaces

Part x is the primary part and has reference surfaces a, b, z. These surfaces are all orthogonal and parallel to the coordinate axes. The predominant stacking surface for part x is surface d. There is no other stacking surface that fixes the position of part y, which has gauge

surfaces d, f and 4 and no reference or restraining surfaces. Surfaces f and 4 are located in the subassembly by tooling blocks. They contribute to the mismatch between parts x and y and therefore these mastering errors are referred to as loading errors. Surfaces d, f, and 4 are also orthogonal and parallel to the coordinate axis. The surfaces to be toleranced are h, g, and 3. Surfaces g and 3 are parallel to the bottom O and centerline planes,respectively. Surface h is an oblique surface and has components in the front O and centerline directions.

Step 5.2 Determine the equations and the coefficients for loading and part errors on the stacking surfaces.

The purpose of this step is to determine equations for the coordinates of motion of the secondary part due to loading and stacking errors. The coordinates in the FO, CL and BO axes must be expressed as a function of the deviations from nominal at the stacking surfaces and the deviations from nominal of the locators on the stacking surface. Returning to our example, we introduce the following notation:

$x_{f;a}$ represents the loading or mastering deviation from nominal, measured normal to the surface of the surface or locator f, with respect to the surface a;

$x_{4;z}$ represents the loading or mastering deviation from nominal of the surface or locator 4 with respect to the surface z;

$x_{d;a,b,z}$ represents the stacking deviation from nominal of surface d on part x with respect to the reference surfaces a, b and z;

$\vec{K}=(K^{FO},K^{CL},K^{BO})$ is a vector whose components represent the coordinate values of a unit shift in the stacking plane in a direction perpendicular to surface f;

$\vec{L}=(L^{FO},L^{CL},L^{BO})$ is a vector whose components represent the coordinate value of a unit shift in the stacking plane in a direction perpendicular to surface 4;

$\vec{M}=(M^{FO},M^{CL},M^{BO})$ is a vector whose components represent the coordinate values of a unit deviation from nominal of the stacking plane measured normal to the nominal surface;

$\vec{T}=(T^{FO},T^{CL},T^{BO})$ is a vector whose components represent the coordinates of part y due to translations.

$\vec{T}$ can then be expressed as a function of $x_{f;a}$, $x_{4;z}$ and $x_{d;a,b,z}$ as follows:

$$(T^{FO},T^{CL},T^{BO})=(K^{FO},K^{CL},K^{BO})\ x_{f;a} + (L^{FO},L^{CL},L^{BO})\ x_{4;2} + (M^{FO},M^{CL},M^{BO})x_{d;a,b,z} \quad (4.1)$$

Using vector notation for $\vec{T}$, $\vec{K}$, $\vec{L}$ and $\vec{M}$

$$\vec{T} = \vec{K}\ x_{f;a} + \vec{L}\ x_{4;z} + \vec{M}\ x_{d;a,b,z} \quad (4.2)$$

Step 5.3 Determine the functional equations for all surfaces. Equations for surfaces on the primary part are the deviation from nominal of the surface x_p. The equation for any surface i on the secondary part can be expressed as

$$x_s^i = x_{s,p}^i + x_p^i \quad (4.3)$$

where

x_s^i denotes the deviation normal to the surface i on the secondary part in the subassembly,

$x_{s,p}^i$ denotes the deviation normal to the surface i on the secondary surface with respect to its gauge surfaces, and

x_p^i denotes the deviation normal to the surface i on the secondary surface as a result of the primary part.

In order to determine the response x_p^i of the coordinate movements due to stacking and loading, the coefficients of the vector normal to the tangent plane are required. We denote

this by the vector

$$\vec{N}_i = (N_i^{FO}, N_i^{CL}, N_i^{BO})$$

The deviation of the secondary surface from nominal can be written as

$$x_s^i = x_{s,p}^i + \vec{N}_i \cdot \vec{T} \tag{4.5}$$

where $\vec{N}_i \cdot \vec{T}$ is the dot product of two vectors, i.e.,

$$\vec{N}_i \cdot \vec{T} = (N_i^{FO}, N_i^{CL}, N_i^{BO}) \cdot (T^{FO}, T^{CL}, T^{BO}) = N_i^{FO} T^{FO} + N_i^{CL} T^{CL} + N_i^{BO} T^{BO} \tag{4.6}$$

Applying this notation to our example, we can express the deviation from nominal of surface h as follows:

$$x_{h;a,b,z} = x_{h;f,d,4} + \vec{N}_h \cdot \vec{K}x_{f;a} + \vec{N}_h \cdot \vec{L}x_{4;z} + \vec{N}_h \cdot \vec{M}\, x_{d;a,b,z} \tag{4.7}$$

where:

$x_{h;a,b,z}$ is the deviation from nominal of surface h in the subassembly,

$x_{h;f,d,4}$ is the deviation from nominal of surface h in the detail part,

$\vec{N}_h \cdot \vec{K}x_{f;a}$ is the deviation from nominal of surface h due to loading or mastering of surface f,

$\vec{N}_h \cdot \vec{L}x_{4;z}$ is the deviation from nominal of surface h due to loading or mastering of surface 4, and

$\vec{N}_h \cdot \vec{K}x_{d;a,b,z}$ is the deviation from nominal of surface h due to stacking at surface d on the primary part with respect to its gauge or reference surfaces a,b,z.

Similarly the functional equations for surface g and surface 3 can be written:

$$x_{g;a,b,z} = x_{g;f,d,4} + \vec{N}_g \cdot \vec{K}_{f;a} x_{f;a} + \vec{N}_g \cdot \vec{L}_{4;z} x_{4;z} + \vec{N}_g \cdot \vec{M}_{d;a,b,z} x_{d;a,b,z} \tag{4.8}$$

$$x_{3;a,b,z} = x_{3;f,d,4} + \vec{N}_3 \cdot \vec{K}_{f;a} x_{f;a} + \vec{N}_3 \cdot \vec{L}_{4;z} x_{4;z} + \vec{N}_3 \cdot \vec{M}_{d;a,b,z} x_{d;a,b,z} \tag{4.9}$$

In our example

$\hat{K} = (K^{FO}, K^{CL}, K^{BO}) = (1,0,0)$

$\hat{L} = (L^{FO}, L^{CL}, L^{BO}) = (0,1,0)$

$\hat{M} = (M^{FO}, M^{CL}, M^{BO}) = (0,0,1)$

$\hat{N}_h = (N^{FO}, N^{CL}, N^{BO}) = (\cos(90-\alpha), 0, \sin(90-\alpha))$

where α is the angle that surface h makes with the centerline plane

$\hat{N}_g = (0,0,1) \quad \hat{N}_3 = (0,1,0)$

An example is developed in section 4.5 for the case where there are two stacking surfaces which are oblique, i.e., not parallel to one of the coordinate axis. The expressions for gaps are developed, similarly, with the exception that they are the difference between mating surfaces and can be written as

$$x_G = x_a - x_b \tag{4.10}$$

where: x_G is the deviation of the gap,

x_a is the deviation from nominal of surface a and

x_b is the deviation from nominal of surface b,

when x_G is greater than 0 a gap exists, and when

x_G is less than 0 interference exists.

Step 5.4 Define the distributions and parameters for each variable in the functional equation.

The previous step developed the functional equation for the deviations from nominal of a surface and the size of a gap, in terms of the deviations from nominal in the stacking surfaces and loading errors. This step of the procedure estimates the type of probability distribution and parameters that the individual part and tooling deviations are expected to have.

The next step of the procedure uses these estimates to determine the distribution of the response (the deviation from nominal of the surface) and establishes tolerance limits based on a probability requirement.

The functional equation for the surfaces has the general form

$$x_s^i = x_{s,p}^i + f(x_{s1}, x_{s2}, x_{L1}, x_{L2}) \tag{4.11}$$

where the function is determined by the geometry of the design and the process, and x_{s1}, x_{s2} denote random variables due to stacking on the primary part, x_{L1}, x_{L2} denote random variables due to loading and mastering.

Assuming that the functional relationship is linear, then (4.11) can be expressed as:

$$x_s^i = x_{s,p}^i + a_1 x_{s1} + a_2 x_{s2} + a_3 x_{L1} + a_4 x_{L2} \tag{4.12}$$

The moments of the response variable can be determined from the moments of the individual variables by the following well known linear propagation of errors formula:

$$E(x_s^i) = E(x_p^i) + a_1 E(x_{s1}) + a_2 E(x_{s2}) + a_3 E(x_{L1}) + a_4 E(x_{L2}) \tag{4.13}$$

$$Var(x_s^i) = Var(x_p^i) + Var(a_1(x_{s1})) + Var(a_2(x_{s2})) + Var(a_3(x_{L1})) + Var(a_4(x_{L2})) \tag{4.14}$$

Assuming that x_p^i, x_{s1}, x_{L1}, x_{L2} are independent, we have

$$\sigma^2(x_s^i) = \sigma^2(x_p^i) + a_1^2 \sigma^2(x_{s1}) + a_2^2 \sigma^2(x_{s2}) + a_3^2 \sigma^2(x_{L1}) + a_4^2 \sigma^2(x_{L2}) \tag{4.15}$$

The standard deviation is the square root of the variance, therefore

$$\sigma(x_s^i) = \left(\sigma^2(x_p^i) + a_1^2 \sigma^2(x_{s1}) + a_2^2 \sigma^2(x_{s2}) + a_3^2 \sigma^2(x_{L1}) + a_4^2 \sigma^2(x_{L2}) \right)^{\frac{1}{2}} \tag{4.16}$$

If the variables x_{s1}, x_{s2} are correlated, Schooman (28) provides the following formula for $\sigma^2(x_s^i)$:

$$\sigma^2(x_s^i) = \sigma^2(x_p^i) + a_1^2 \sigma^2(x_{s1}) + a_2^2 \sigma^2(x_{s2}) + a_3^2 \sigma^2(x_{L1}) + 2a_1 a_2 \mathrm{cov}(x_{s1}, x_{s2}) \tag{4.17}$$

With four or five independent random variables the normal

distribution is a good approximation to the distribution of the response x_s^i (Burr (5)). Because little information is available on the distributions of surface deviations and loading errors at the present and because the sums of random variables approaches normality with increasing variables, it is assumed that the distributions are normal. The data collected on parts show that the standard deviation is rather small compared to the average or mean deviation from nominal. This data represents samples from one stamping run of parts. The average may change from one run to another due to different metal thickness, die wear and set up differences.

Burr (6) proposes the following model for the deviation from nominal of a measured characteristic:

$$x - M_o = (x - M) + (M - M_m) + (M_m - M_o) \qquad (4.18)$$

where: x is the measured characteristic of the part and

x is a random variable with mean M and standard deviation σ_x,

M_o is the desired nominal mean (the middle of the specification range), and

M is the instantaneous mean of the process that would occur during a run. M is also a random variable and has a mean M_m and standard deviation σ_m.

Therefore:

$x-M_o$ is the deviation of the dimension from its desired nominal,

$(x-M)$ is the deviation of the dimension from its current instantaneous mean,

$(M-M_m)$ is the deviation of the instantaneous mean from the expected or process mean, and

(M_m-M_o) is the deviation of the process mean from the nominal or desired dimension.

Taking the expected value and the variance for the model we have:

$$E(x-M_o) = E(x-M)+E(M-M_m)+E(M_m-M_o)$$

$$= E(M_m) - M_o = M_m-M_o \qquad (4.19)$$

$$E(x-M_o)^2 = \sigma_x^2+\sigma_m^2 + (M_m - M_o)^2 \qquad (4.20)$$

Applying this model to our problem, the mean of the deviations is the mean of the overall process less the nominal value. It is desirable that this be equal to zero, but this is not always possible. The variance is the sum of the within run variance σ_x^2 and the between run variance σ_m^2 (4.21). Therefore the parameters that require estimation are the expected bias to the surface $E(M_m)-M_o$ and the total variance about the process bias $\sigma^2(x-M_m) = \sigma_x^2 + \sigma_m^2$.

Step 5.5 Compute the parameters and the tolerance limits for each surface to be toleranced.

The tolerance limits for the surface can be computed from the functional equation and the linear propagation of error equations for the mean and standard deviation. The mean is computed from

(4.13)

$$E(x_s^i) = E(x_p^i) + a_1E(x_{s1}) + a_2E(x_{s2}) + a_3E(x_{L1})$$

and the standard deviation from (4.16) or (4.17)

$$\sigma(x_s^i) = (\sigma^2(x_p^i) + a_1^2\sigma^2(x_{s1}) + a_2^2\sigma^2(x_{s2}) + a_3^2\sigma^2(x_{L1}))^{1/2} \quad (4.16)$$

The tolerance limits can be computed as

$$E(x_s^i) \pm 3\,\sigma(x_s^i) \quad (4.22)$$

Assuming the normal distribution, these tolerance limits will include approximately 99% of the assemblies.

The same procedure can be applied to those surfaces that must be welded together. The extremes or tolerance limits of the gap or interference are computed.

The following steps of the procedure determine the clearances necessary to obtain the desired location of parts, and review the joints for weldability and sealability.

Step 6.1 Determine the class of fit at mating surfaces to be welded in the subassembly.

The procedure has assumed that the predominant stacking surfaces will be joined and welded in the subassembly tooling. The procedure has also determined the distribution of gaps for all other surfaces to be joined in the subassembly process. This step determines the class of fit between the mating surfaces to be closed. It is desirable to have the smallest possible gaps and yet permit the parts to stack as designed. This step realizes that due to the geometry of the design and the degree of flexibility of the sheet metal that some interference is

permissible and in some cases desirable. In other cases the slightest amount of interference will prevent the parts from mating as designed in the process. Therefore each surface that is to be joined must have the permissible degree of interference specified.

Step 6.2 Compute the design clearance corresponding to the permissible interference, and the maximum gap expected at each weld joint.

The gap at a surface is defined as a random variable

$$x_G = x_a - x_b \qquad (4.9)$$

The mean and standard deviation of this gap distribution are:

$$E(x_G) = E(x_a) - E(x_b) \qquad (4.23)$$

$$\sigma(x_G) = (\sigma^2(x_a) + \sigma^2(x_b))^{1/2} \qquad (4.24)$$

The maximum and minimum limits for the gap are determined by

$$x_G^{max} = E(x_G) + 3\sigma(x_G) \qquad (4.25)$$

$$x_G^{min} = E(x_G) - 3\sigma(x_G) \qquad (4.26)$$

where $x_G \geq 0$ implies gap

and $x_G < 0$ implies interference

This is shown in figure 4.2.

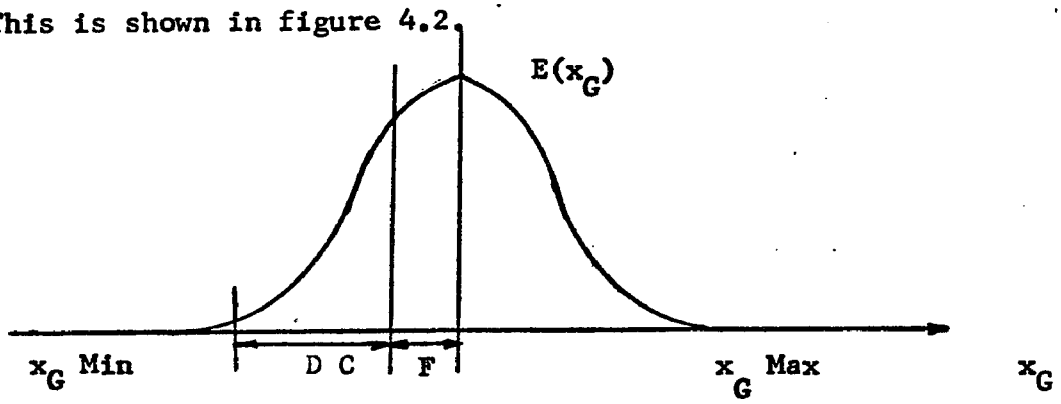


Figure 4.2 Maximum and Minimum Gaps, Design Clearance and Permissible Interference.

The design clearance when interference is evident is computed as:

$$DC = \begin{cases} -(F + x_G^{min}) & \text{when } F + x_G^{min} < 0 \\ 0 & \text{otherwise} \end{cases} \quad (4.27)$$

where DC denotes the required design clearance

F denotes permissible interference

The maximum amount of gap is now computed as:

$$DC + x_G^{max} \quad (4.28)$$

Step 6.3 Evaluate the effect on the structure of clamping restraining surfaces and closing maximum gaps at weld joints.

The design at this step of the procedure has all important surfaces toleranced. The maximum gaps have been calculated for surfaces to be joined in the subassembly process. The evaluation of the subassembly from a manufacturing viewpoint must be performed. The surfaces that were toleranced included those that are to be held in the assembly process. Because the assembly fixture is set to a model, the tooling is unforgiving. Any errors result in deflections which influence other surface dimensions. These surface deviations must be judged for their acceptability. In addition, the gaps at weld joints must be capable of being drawn together and spotwelded. If the gaps are too large, then the forces distort the subassembly. If the surfaces cannot be brought together, the welds will be weak. The process and product design must meet these requirements if an acceptable product is to be made.

Step 6.4 If the design is acceptable, the detail part tolerances and subassembly tolerances should be marked on detail and assembly drawings. If the design and process are not acceptable, then Steps 3, 4, 5, and 6 are repeated until gaps and distortions are acceptable or the design is changed.

4.3.2 TOLERANCING SUBASSEMBLIES IN BODY POSITION

The objectives of the following steps of the procedure are to tolerance the body opening surfaces and to estimate the gaps expected in the final assembly tooling, in order that the design and process may be evaluated. The same methodology applies as outlined in Steps 5 and 6 with the addition of the capability of the assembly tooling.

Step 7.1 Tolerance subassembly surfaces using the estimate of tool capability from Steps 3.1 and 3.2 and the subassembly tolerance parameters from Step 5.4.

The subassembly was toleranced with respect to the reference surfaces. The mastering errors in Step 3.2 refer to the changes in the reference surface locating blocks. The mastering of each block is independent of the other blocks. When the subassembly is located against another subassembly, a stacking error is also realized. This stacking error is a function of the subassembly surface and its mastering errors. The tool band in Step 3.1 represents the coordinate shift of all the reference surfaces, as the gate side holds all the mastered locators. The coordinates of the gate side to framing truck are measured directly. It is assumed that these coordinate translations are independent of each other.

In an example we have the functional equations for the deviation from nominal for surface h expressed by:

$$x_{h;a,b,z} = x_{h;\,f,d,4,} + \vec{N}_h \cdot \vec{K}\, x_{f;a} + \vec{N}_h \cdot \vec{L}\, x_{4;z} + \vec{N}_h \cdot \vec{M}\, x_{d;a,b,z} \tag{4.7}$$

The mean and standard deviation are expressed by:

$$E(x_{h;a,b,z}) = E(x_{h;f;d;4}) + \vec{N}_h \cdot \vec{K}\, E(x_{f;a}) + \vec{N}_h \cdot \vec{L}\, E(x_{4;z}) + \vec{N}_h \cdot \vec{M}\, E(x_{d;a,b,z}) \tag{4.29}$$

$$\sigma(x_{h;a,b,z}) = (\sigma^2(x_{h;f,d,4}) + (\vec{N}_h \cdot \vec{K})^2\, \sigma^2(x_{f;a}) + (\vec{N}_h \cdot \vec{L})^2\, \sigma^2(x_{4;z}) + (\vec{N}_h \cdot \vec{M})^2\, \sigma^2(x_{d;a,b,z}))^{1/2} \tag{4.30}$$

Figure 4.3 depicts the simple subassembly in body position

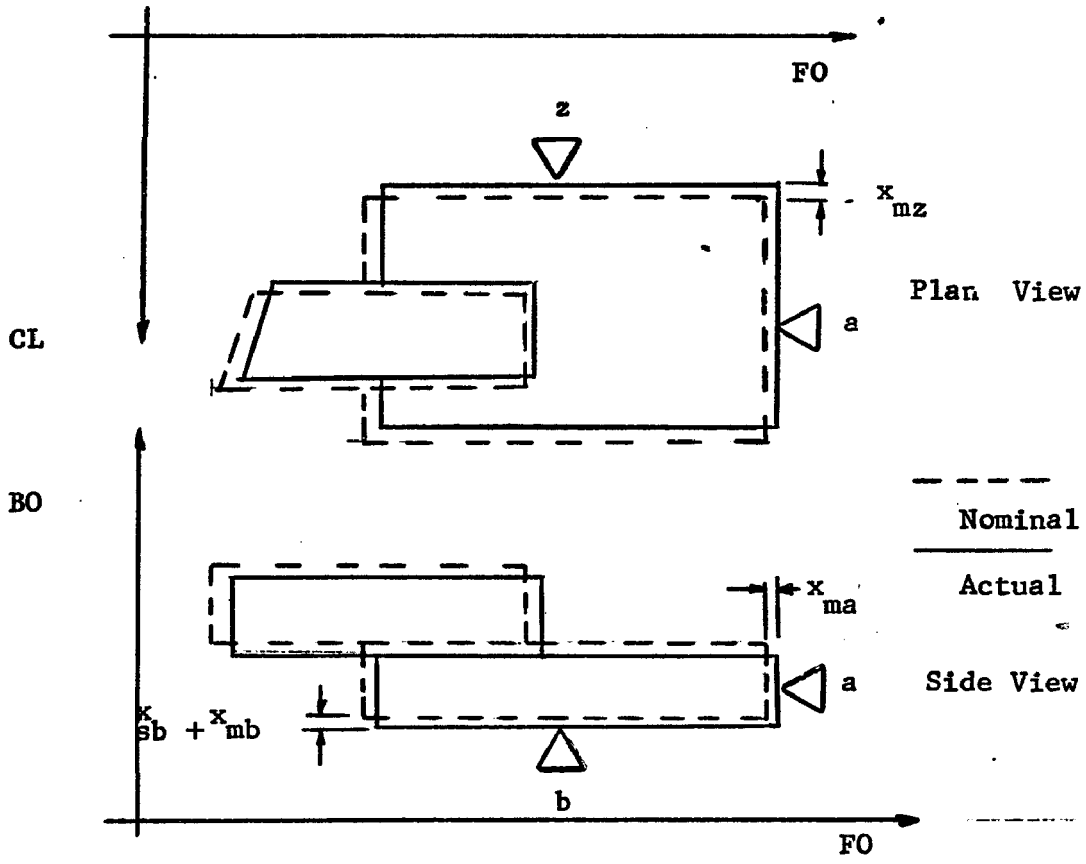


Figure 4.3 A Simple Subassembly in Assembly Tooling

We introduce the mastering errors to the locating blocks a and z by x_{ma} and x_{mz}, respectively. It is assumed that block b is another part which is located by a block in the tool. We denote these errors by x_{sb} and x_{mb} referring to the stacking deviation on the part and the mastering of the block that establishes the elevation for the part. The tooling band errors can be interpreted in our diagram as a translation of the coordinate axes.

The expression for the deviation from nominal (4.7) must have the terms representing these errors added to it.

The effect of mastering on x_s^i can be expressed as:

$$\vec{N}_i \cdot \vec{K}_a \, x_{ma} + \vec{N}_i \cdot \vec{L}_z \, x_{mz} + \vec{N}_i \cdot \vec{M} \, (x_{sb} + x_{mb}) \qquad (4.31)$$

The tooling band is expressed as:

$$\vec{N}_i \cdot \vec{E}_1 \, x_t^{FO} + \vec{N}_i \cdot \vec{E}_2 \, x_t^{CL} + \vec{N}_i \cdot \vec{E}_3 \, x_t^{BO} \qquad (4.32)$$

where $E_1 = (1,0,0)$ $E_2 = (0,1,0)$ $E_3 = (0,0,1)$

and $x_t^{FO}, x_t^{CL}, x_t^{BO}$ are the deviations from nominal of the tooling variability in the FO, CL and BO axes, respectively.

The expression for the surface can now be expressed by:

$$(x_h; a, b, z)^g = x_{h;\, a,\, b,\, z} + \vec{N}_h \cdot \vec{K}_a \, x_{ma} + \vec{N}_h \cdot \vec{L}_z \, x_{mz} + \vec{N}_h \cdot \vec{M} \, x_{sb}$$

$$+ \vec{N}_h \cdot \vec{M} \, x_{mb} + \vec{N}_h \cdot \vec{E}_1 \, x_t^{FO} + \vec{N}_h \cdot \vec{E}_2 \, x_t^{CL} + \vec{N}_h \cdot E_3 \, x_t^{BO} \qquad (4.32)$$

The superscript g, denotes the surface in body position.

The tolerance limits can be computed by:

$$(x_s^i)^g = E\left[(x_s^i)^g\right] \pm 3\sigma\left[(x_s^i)^g\right] \qquad (4.33)$$

Surfaces that are restrained by a tooling locator and clamp can be toleranced by considering the tooling band and the mastering of the block in the functional equation.

Careful attention must be given in calculating gaps and opening sizes to the variables included in the functional equation. If the difference between two surfaces that are held by different locating blocks in one gate side is desired, the tooling band should not be used. Also in computing a gap between two surfaces where one subassembly is located to the other subassembly, the mastering or the tooling variables should not be included.

The evaluation of the design is identical to the analysis of the subassembly. More emphasis must be placed on the effect of errors at restraining surfaces, on the structure dimensionally, and on the sealability of weld joints. The steps are listed below for completeness.

Step 8.1 Determine the class of fit at mating surfaces to be welded in the body.

Step 8.2 Compute the design clearance corresponding to the permissible interference, and the maximum gap expected at each weld joint.

Step 8.3 Evaluate the structural effects of closing clamps at restraining surfaces and closing gaps at weld joints.

Step 8.4 Evaluate the sealability of joints.

Step 8.5 If the design and process are acceptable, release detail and assembly prints with tolerances indicated. If unacceptable, review the holding concepts, die process and subassembly designs.

4.4 POST LAUNCH ANALYSIS

This section of the chapter describes the steps of the algorithm when the design and process have been implemented and the product is in production. The objective of this stage of the algorithm is to determine if the tolerance distributions for the tooling, parts, and subassemblies are being realized. This permits: first, a review for the design and process engineers who toleranced the design; secondly, the basis for reallocating tolerances where necessary; and finally, the process capability estimates that are needed for process control procedures. The steps of the procedure cover the detail parts, the subassembly process, and the final assembly of the body. Experiments will be described to provide parameter estimates of the variables that were used in the tolerancing procedure.

Step 9 Detail Part Dimensional Control

This step of the procedure estimates the actual capability of the die process to produce detail parts with the assumed distribution.

Step 9.1 Surface dimensions are recorded at die tryout for comparison with tolerances

The average dimensions for detail parts are set during the die tryout period. The dies are reworked at this time so that detail parts conform to their checking fixtures. The checking fixtures will have gauge surfaces defined and tolerances for the important surfaces identified as a result of the procedure.

Step 9.2 Record samples of surface deviations from initial production runs in order to estimate the overall process mean, the within run variance about the instanteous mean, and the variance between runs.

This analysis is consistent with the model for detail part characteristics that was described in the discussion following Step 5.4. A knowledge of the process mean and variance is necessary for the determination of process control limits.

Step 9.3 Determine process control limits for the sample mean and the range to be used by "in-process" inspectors.

The use of control charts is not required for every dimension. The use of limits for the important stacking surfaces and flanges is recommended so that an inspector checking samples from a new run may have objective acceptance criteria.

Step 10 Subassembly dimensional control

The purpose of this step is to determine if the locating system of the process is performing to process design and to

estimate the process effects by performing a capability study on a sample of premeasured parts.

Step 10.1 Layout a sample of premeasured inch lined subassemblies obtained from the first stage welding fixture to determine if the holding system is performing to design

This step determines the performance of the locating system with parts of known dimension. The inch lines are reference lines that have been placed relative to the reference and gauge surfaces. The deviation of these lines from nominal in the subassembly is a measure of the translation due to stacking and loading. It may be difficult to separate these two. However, it is sufficient to compare the deviations of these lines, which represent the coordinates, with those predicted by the tolerance procedure. An experiment is described following the discussion of the next step.

Step 10.2 Process the above sample through the remaining weld stations to determine the process effects of closing gaps.

The first stage of the process determines the location of the parts relative to each other. In addition, the surfaces may be measured in a subassembly checking fixture to determine the influence of this mismatch on the surface deviations from nominal. The remaining stages of the process submit the subassembly to clamping and welding pressures and localized heat. The errors in the detail parts interact with the process in an unpredictable manner. The experiment that is detailed below permits comparison between the actual and predicted surface measurements to measure these effects.

Step 10.3 Determine process control limits for the sample mean and range to be used by in-process inspection.

The previous step permits the determination that the process is performing to design. Additional samples from the same setup can be used to determine the process capability, and control limits for use by in-process inspection

An experiment to estimate the process effects is outlined below:

EXPERIMENT TO ESTIMATE STACKING, LOADING AND PROCESS EFFECTS—SUBASSEMBLIES

1. For each detail part in the subassembly identify the Master Gauge Surfaces (MGSU).

   The MGSU is:
   a) A mating surface which positions the detail before welding.
   b) A form surface which is used to position the detail in the fixture.

2. Identify the critical relationships of the detail parts which form the subassembly.

   The critical relationships are:
   a) The position of a mating surface to another part of the subassembly relative to the MGSU
   b) A surface on the detail which forms an opening relative to the MGSU

3. Choose one detail part as the primary detail part

   The primary detail part is usually the detail part that is largest in size and its gauge surfaces locate the subassembly in the body assembly tooling.

4. Place the primary detail part in its checking fixture. Net the detail at the MGSU. Measure the position of the mating surface of interest. Measure perpendicular to metal surface. Record deviation. Resolve into its FO, CL & BO components.

5. On the mating surface of interest scribe ordinate lines BO, FO, CL. Scribe lines on the outside of metal. Record position of lines.

6. Choose a secondary detail part which attaches to the primary detail part at the surface in Step 4.

7. Place the secondary part in its checking fixture. Net the part to the MGSU (this must include the surface measured in Step 4.)

   Measure the position of the mating surface to another detail part or subassembly or the position of a surface which forms an opening. Measure normal to the surface. Record deviations. Resolve this deviation into its BO, FO, and CL components.

8. On the mating surface to the primary detail part (Step 5) scribe ordinate lines at the same position as in Step 5. Scribe lines on the outside surface at the mating surface.

9. Compute the total deviation of the secondary mating or opening surface by geometrically adding the deviations recorded in Steps 4 and 7 above.

   This is the predicted value due purely to stacking the part deviations together.

10. Load the primary detail part into the subassembly welding fixture.

11. Load the secondary detail part into the subassembly welding fixture.

12. Actuate the fixture clamps.

13. Measure the position of the ordinate lines on the secondary part. Record deviations.

    This deviation is composed of the deviation in the mating surface due to the primary mating surface plus the loading error due to deviations in the weld fixture locators.

14. Subtract from the deviation the deviation recorded in Step 4. The result is the loading error.

15. To the deviation recorded in Step 9 add loading error from Step 14.

16. Weld the secondary detail to the primary detail to form a subassembly.

17. Place the subassembly into its checking fixture. Net subassembly to the MGSU.

    Measure the deviation of the surface of interest from Step 7. Record deviation and resolve into its BO, FO, CL component parts.

18. Compare Step 15 to Step 17.

    The difference is due to process effects, measurement error, and experimental error.

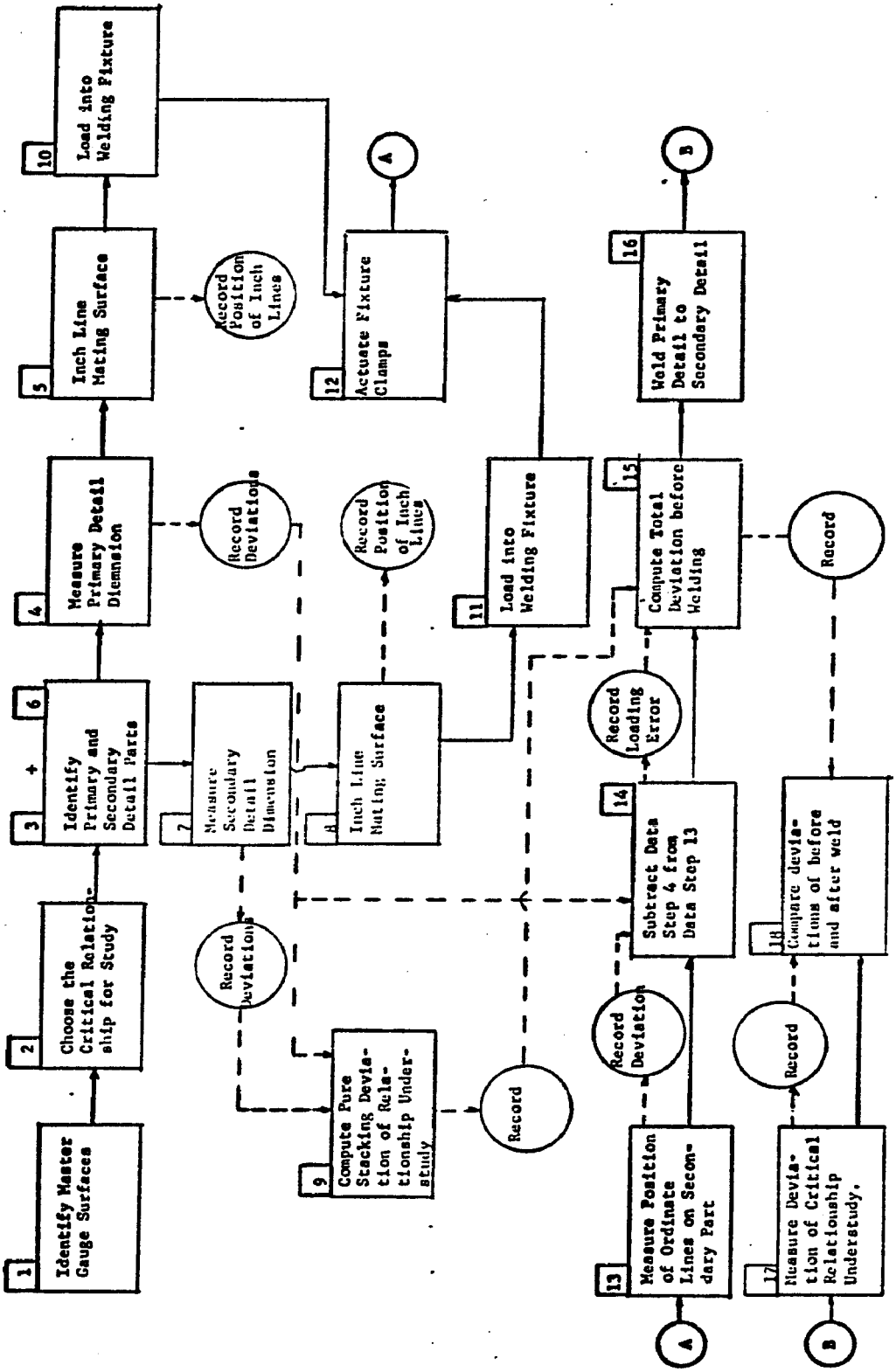


Figure 4.4 Flowchart of Procedure to Estimate Subassembly, Stacking, Loading and Process Effects

OBS #	4	7	9	13	14	15	17	18
	Primary MGSU To Mating Surface	Seconday MGSU To Mating Surface	Total Deviation From Pure Stacking	Position Of Secondary Part Ordinate Line	Loading Error	Predicted Total Deviation Before Welding	Actual Total Deviation After Welding	Difference Of Predicted To Actual Deviation

Figure 4.5 Observation Sheet for Subassembly Experiment

Step 11. Pilot Body Build Assembly Tooling Performance

This step of the procedure determines experimentally if the assembly locating concepts and subassembly tolerances are performing to design.

Step 11.1 Perform experiments to determine if the assembly tooling band is within the specified interval.

This step verifies that the tooling is performing as intended. An experiment is specified to measure the location of the tooling from its mastered position.

EXPERIMENT TO ESTIMATE ASSEMBLY TOOLING VARIATION

METHOD:

1. Load sidegate into build master fixture.
2. Select desired reference lines.
3. Using the fixture as the absolute reference base, scribe on the sidegate the desired reference inch lines.
4. Remove sidegate from fixture.
5. Select a framing truck that is within design tolerance.
6. Select desired reference lines.
7. Scribe the reference inch lines on the truck using the centerline of the front footlock for FO reference, centerline of the base for zero centerline.
8. Choose a set of tie bars which fit the master tie bar gauge.
9. Load sidegate to truck.
10. Lock tie bars in position.
11. Measure the reference inch lines on the sidegate with respect to the reference inch lines on the truck.

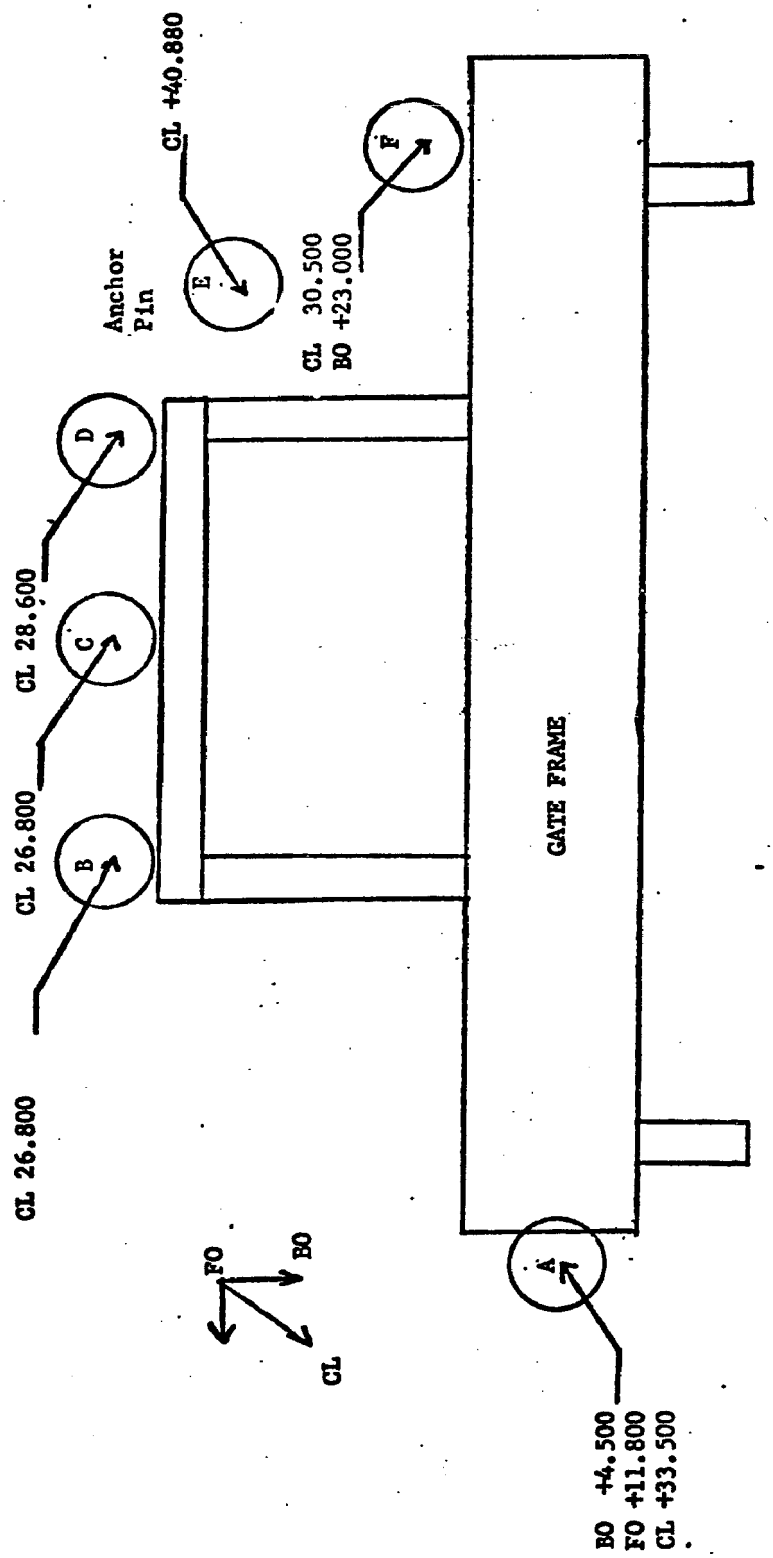


Figure 4.6 Reference Line Dimensions for Assembly Tooling Experiment

12. Record deviation.
13. Unload sidegate from truck. Repeat Steps 9-12 for N replications.

Step 11.2 Perform loading experiments with inch lined parts to determine mastering bias.

This step of the procedure is a verification that the checking fixture and gate mastering system is coordinated. The procedure to be outlined below permits the inch lines on subassemblies to be compared with equivalent reference lines on the assembly tooling. Any deviation between the two is the consequence of mastering errors in the gate or gate part interaction that changes the form of the subassembly from its checking fixture state.

EXPERIMENT TO ESTIMATE THE LOADING VARIATION OF A SUBASSEMBLY INTO A SIDEGATE WELDING FIXTURE

METHOD:

1. Load sidegate into build master fixture.
2. Using the fixture as the absolute reference base, scribe ordinate lines on the sidegate for BO, FO, and CL.
3. Unload sidegate from fixture.
4. Load metal subassembly into its checking fixture.
5. Net the subassembly to the fixture exactly as it nets to the sidegate fixture.
6. Using the checking fixture base as the absolute reference base, scribe ordinate lines on the subassembly for BO, FO, and CL.
7. Unload subassembly from checking fixture.
8. Load sidegate to major base.

9. Measure the absolute position of ordinate lines scribed on the sidegate fixture. Record.

10. Load subassembly into the sidegate.

11. Measure the absolute position of ordinate lines scribed on the subassembly. Record.

12. Repeat loading and unloading of subassembly for N replications.

The mean difference between the sidegate ordinate lines and the subassembly ordinate lines is due to the error in the lines plus the error in the sidegate plp's. The variance is an estimate of the loading variation due to gate part interaction plus experimental error.

Step 11.3 Determine if computed design clearances are adequate.

This is a visual verification that the subassemblies are stacking to their predominant surfaces as expected. This is necessary if the parts are to be assembled and welded with no or little interference. The gaps that are observed at surfaces to be welded are verified to be within the predicted maximum gap.

Step 11.4 Determine if subassemblies behave as expected when clamped at restraining surfaces.

This step verifies that there is no distortion of other mating surfaces when the restraining clamp is closed. Also the pressure to close the clamp when restraining the assembly should be verified as acceptable.

Step 11.5 Build Pilot Bodies and determine if openings are within tolerance.

This step verifies that the body can be assembled as expected. The state of the tooling has been verified with tooling band experiments and subassembly loading experiments. The openings should be within specifications. If they are not, the reasons should be detected at this the earliest possible stage for correction. Any changes that are made to the pilot tooling can be applied to all tooling units.

Step 12. Assembly Plant Process Capability and Control

The objective of this step is to determine the process effects of welding on body openings when all tooling and subassemblies are maintained within tolerance limits. The results of this analysis provide the plant with process control limits for the measurement system used to control openings.

Step 12.1 Perform a capability study on openings using premeasured parts.

This step of the procedure is similar to the procedure for determining the process capability of the subassembly process. An experiment that is described below provides an estimate of the coordinate difference between subassemblies due to the tooling, stacking and mastering. This permits verification that the tooling is performing within the tolerance interval. The sum of this translation to a surface and the measurement of the subassembly permits computation

of a predicted value of the surface in the body. Comparison with the actual value gives an estimate of the process effects.

The procedure for the experiment is given below:

EXPERIMENT TO ESTIMATE STACKING, LOADING AND PROCESS EFFECTS—BODY SURFACES

1. Identify the relationships on each subassembly that are critical to forming an opening.

   These relationships are the distances from the Principal Locating Surfaces used in the welding fixture (called Master Gauge Surfaces in the checking fixture) to the surface which mates with an adjoining subassembly.

2. Choose a primary subassembly.

3. Choose a secondary subassembly which mates to the primary subassembly.

4. Place the primary subassembly into its checking fixture. Net the subassembly at the Master Gauge Surfaces (these surfaces must be identical to the Principal Locating Surfaces in the welding fixture). Measure the critical relationship of interest. Measure normal to the metal surface. Record deviation.

5. Scribe ordinate lines on the mating surface to the secondary subassembly. Record position of lines.

6. Place the primary subassembly into the sidegate welding fixture. Net subassembly to the PLPSU. Measure the position of the ordinate lines. Record deviations. This is an estimate of mastering error and tool position error.

NOTE: The sidegate fixture is locked to the framing truck. The ordinate lines on the sheet metal are measured relative to the ordinate lines on the framing truck.

7. Place the secondary subassembly into its checking fixture. Net subassembly to its MGSU. These surfaces must include the mating surface to the primary subassembly. Measure the critical relationship. Measure normal to the metal surface. Record deviations.

8. Scribe ordinate lines on the mating surface to the primary subassembly mating surface. Record position of lines.

9. Load secondary subassembly into the sidegate welding fixture. Net the subassembly to the primary subassembly and the sidegate PLPSU. Measure the position of the ordinate lines on the secondary subassembly at the mating surface to the primary subassembly. Record deviations.

The position of these lines is determined by the stacking to the primary surface (step 4 and 6) plus the mastering error of the secondary subassembly locators on the sidegate fixture.

The final position of the opening surface of interest on the secondary subassembly is a function of the mastering error of the sidegate and the deviation of critical relationships of the primary and secondary subassembly plus process effects.

10. From the data collected above, compute the predicted position of the opening surface.

11. Weld the primary subassembly to the secondary subassembly.

12. Place the final assembly into its checking fixture. Net the primary subassembly at its MGSU. Measure the opening surface on the secondary subassembly. Record deviations. This is the actual value.

13. Compare the actual deviation from step (12) to the predicted deviation of step (10).

The difference is due to process effects, measurement error and experimental error.

step 12.2 Perform audits on the process to determine that all process factors are within specification.

The objective of this procedure is to determine the components of bias and variation in order that realistic tolerances may be placed on each process factor, i.e., parts, subassemblies, tools, fixtures, etc. Capability studies have been designed to estimate the opening sizes when all process factors are within specification. The measurement of bodies should therefore not be the primary point of process control. The primary point of control should be on the parts and the tooling which should be verified by direct methods. This step provides for procedures that are designed to audit the process. Bodies should be measured to determine the capability of the process and for identifying and solving problems. The use of premeasured bodies to determine the capability of downstream operations is also discussed.

Figure 4.7 illustrates an indirect procedure to determine the condition of the process by building a body on a gate and measuring the body openings. The body is control checked which means that the body is observed at all stages of its process to verify that each subassembly has been properly located and

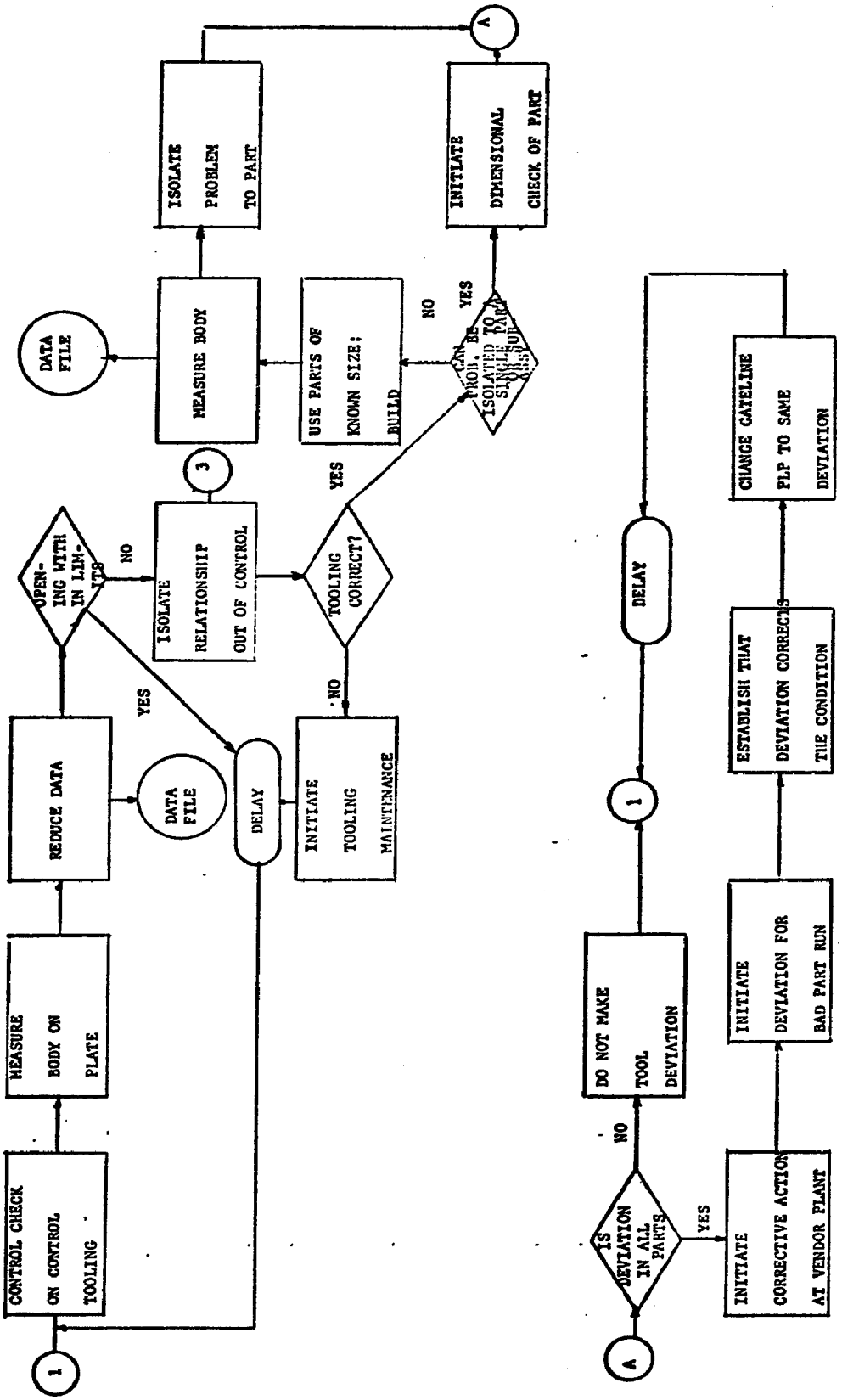


Figure 4.7 Procedure to Monitor Parts

clamped against its principal locating points. Any gaps that are found between the reference surfaces and the blocks are measured and recorded. The procedure also permits adjusting the locating blocks in order to compensate for opening surfaces not being to specification due to a run of bad parts. Figure 4.8 is a procedure to daily check the entire population of assembly tooling by checking openings with gauges, and then building bodies and measuring them after a control study.

The tolerancing of subassemblies permits the direct means of controlling the subassemblies and the tooling and should be used primarily. The parts and subassemblies are checked in fixtures to determine if they are in tolerance. In the event that some dimensions are not within specification and the subassemblies are in the system, then the procedure in figure 4.7 can be used to make temporary changes to the tooling to accommodate the bad run of subassemblies. The principle of control should be to leave the assembly tooling at nominal and to control the parts at their point of fabrication. Also, the desired method of control of the assembly tooling is by direct means rather than in finding the state of the tooling through the size of body openings. Knowledge that the parts are to specification permits the process to be examined when major subassemblies are being loaded into the tooling. The distance between restraining surfaces and the tooling can be observed. The gaps between joints of major subassemblies can

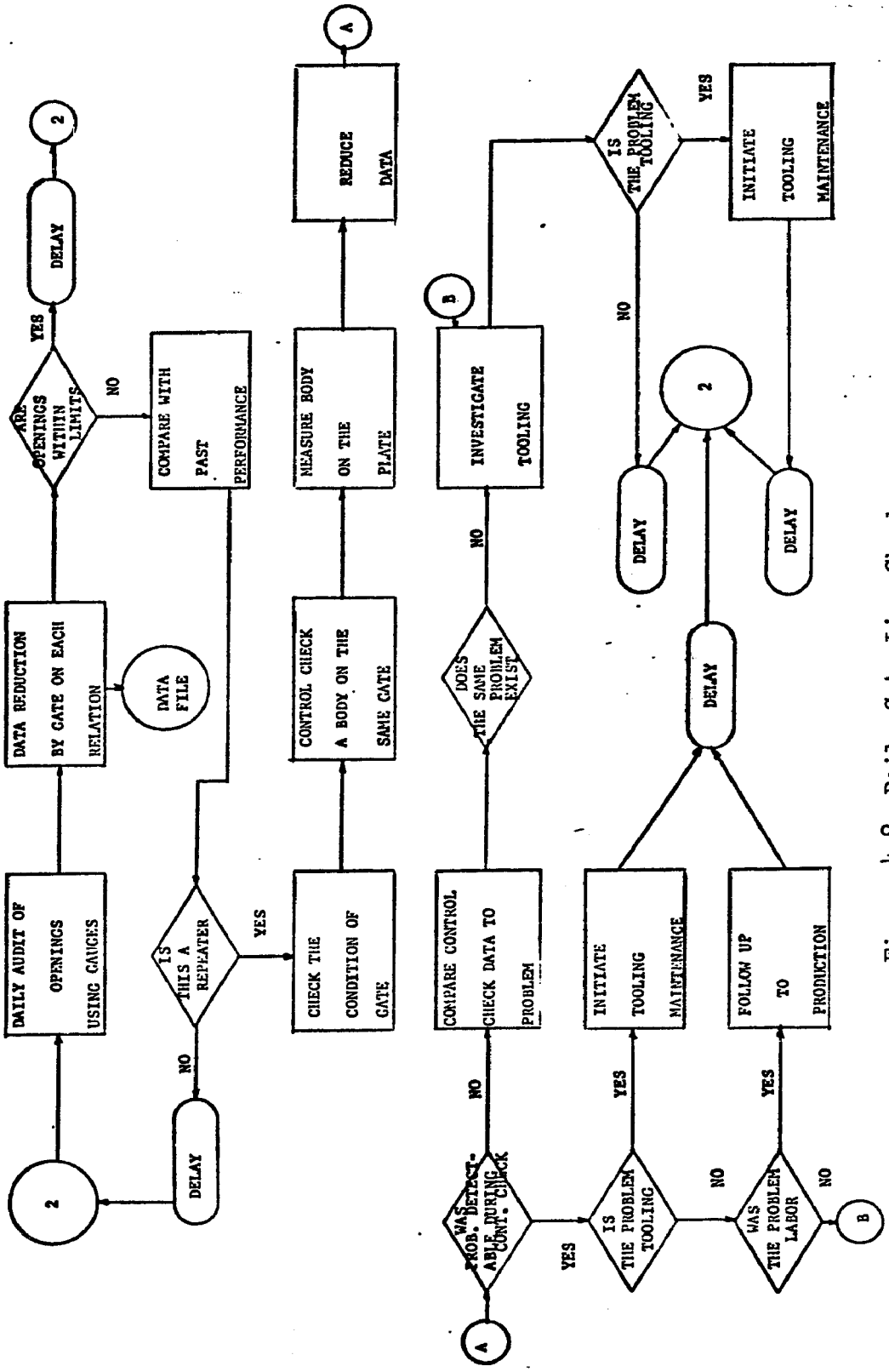


Figure 4.8 Daily Gate Line Check

also be examined and evaluated for acceptability. If these appear to be excessive and the locators and clamps are properly maintained, then the gate should be removed from the line and examined. Inch lined panels or tooling aids that permit the determination of whether or not the gate is properly mastered can be used. If this test is not satisfied, the tooling should be placed against the master gauge for re-mastering. This direct observation of the gateline tooling can be done quickly and easily to assure that the tooling is performing properly. This procedure is shown in figure 4.9.

The bodies that are built on control tooling under careful observation to determine the capability can be used to determine the capability of the processes down stream. These bodies have been measured and their opening sizes and surfaces recorded. Figure 4.10 shows the type of processes that would be checked using these bodies. Knowledge that the openings are within specification would permit the quality of subsequent operations to be evaluated.

Step 13.
Dimensional Review

The purpose of this step is to report to all body design, die process, subassembly process and body assembly technical personnel the performance of the parts, subassemblies, bodies and tooling they designed and processed. This permits a review of the tolerances for reallocation if necessary and to provide feedback for future designs.

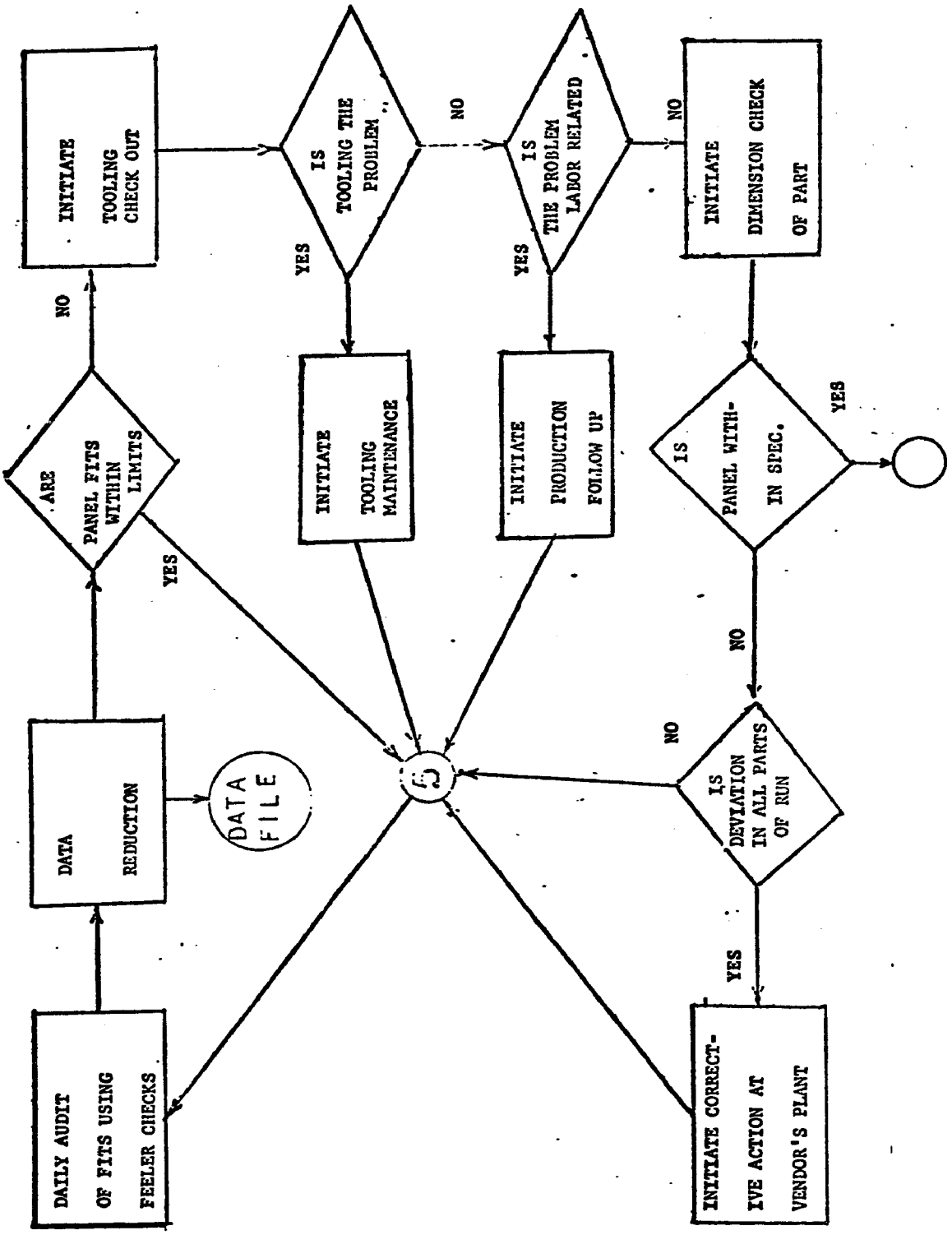


Figure 4.9 Daily Audit of Fits

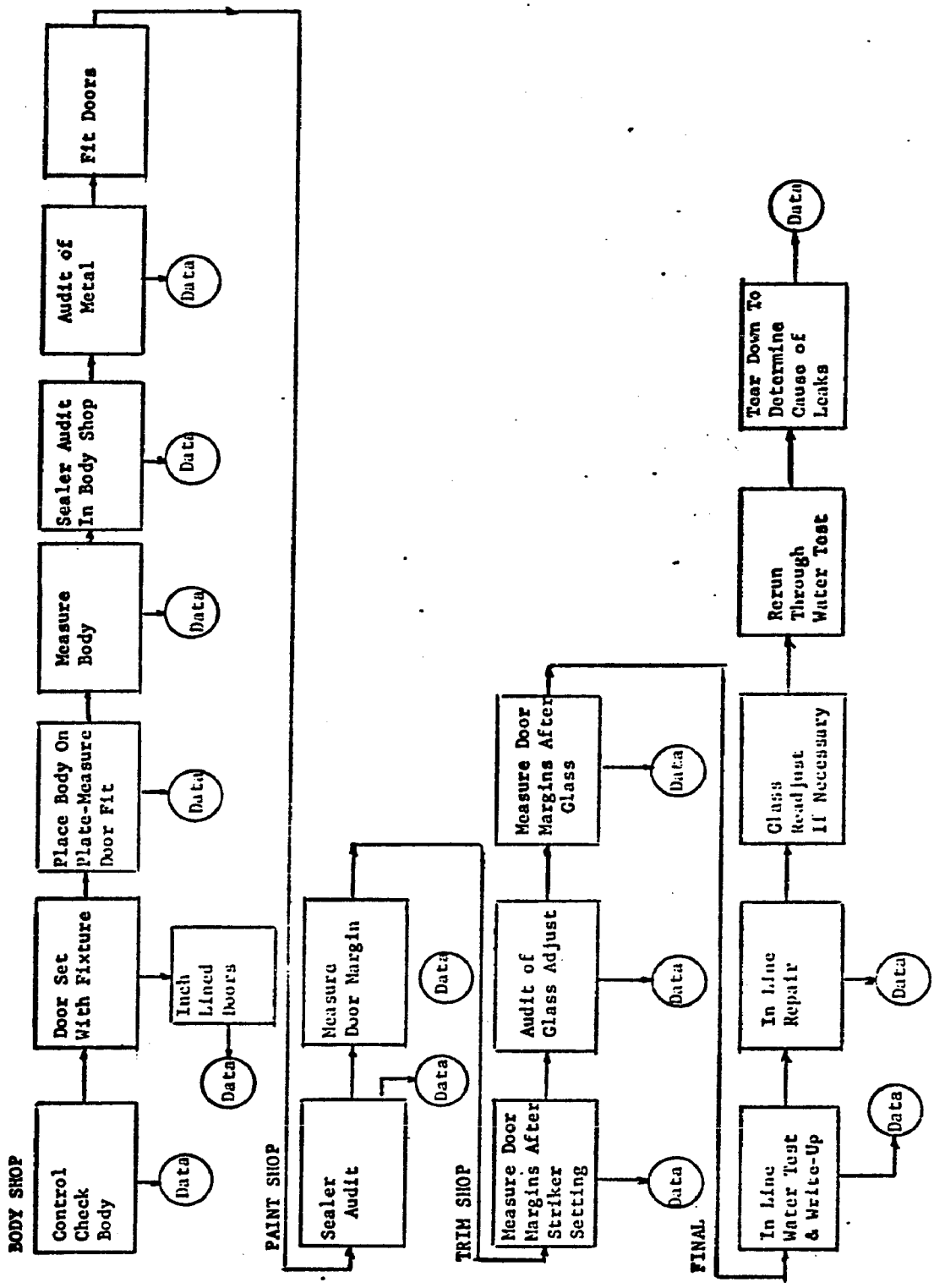


Figure 4.10 System to Generate Capability Information

Step 13.1 Compile actual versus design data for all part, subassembly and body surfaces.

Step 13.2 Report the results of tool band and loading experiments for all subassembly and assembly locating systems.

Step 13.3 Reallocate tolerances when justified.

Knowledge of the actual versus estimated capability of the process may necessitate the reallocation of tolerances. This is also true when the cost to achieve the desired tolerance is extremely high. The next chapter will discuss the reallocation of tolerances and the costs involved with the tolerancing problem.

4.5 AN EXAMPLE OF THE TOLERANCING PROCEDURE

This section of the chapter describes an application of the procedure to the design of an "A" pillar subassembly. The presentation will follow the steps of the algorithm.

Step 1.1 Define the assembly sequence.

The subassemblies of the body design that are pertinent to the "A" pillar and their assembly sequence are:

Gate Side 1. Sill subassembly

2. "A" pillar subassembly

Truck 3. Floorpan subassembly

Gate & Truck

4. Roof rail subassembly

5. Cowl top subassembly

These are shown in figure 4.11. The gate side and truck are loaded independently. The two gate sides are joined to the truck. The roof rail and cowl top subassemblies are then assembled to the two "A" pillars and the floorpan.

Step 1.2 Determine subassembly reference surfaces

The reference surfaces are also shown in figure 4.11 for the sill and the "A" pillar subassemblies. The sill is located to bottom 0 and centerline by blocks 1 and 2. Front 0 is established by the notch locator. The surfaces that touch these blocks become the reference surfaces. The sill then becomes the predominant stacking surface for the "A" pillar that establishes bottom 0. The centerline surface is shown in the figure as touching block 4. Front 0 is established by the surface that touches block 3.

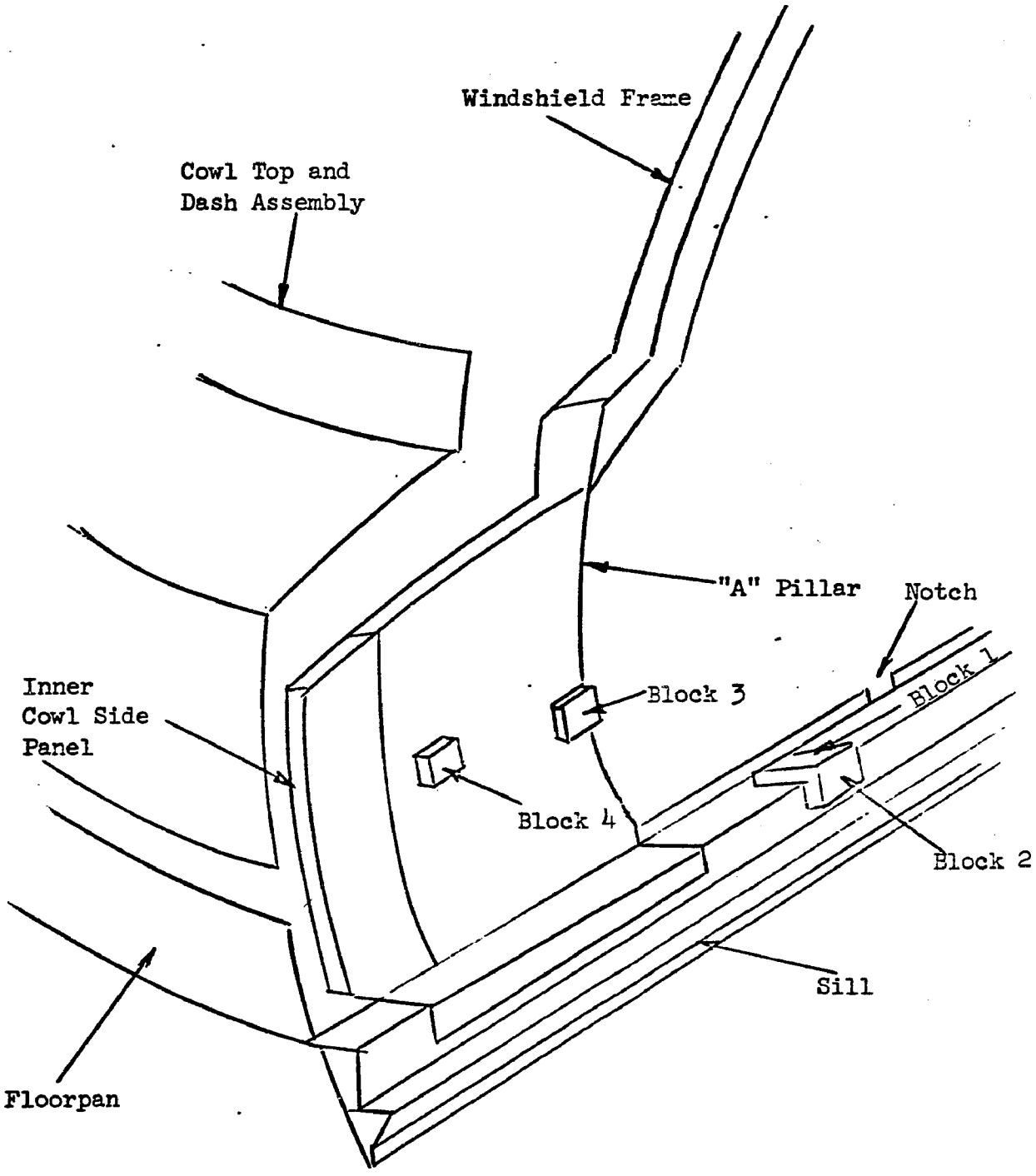


Figure 4.11 Body Front Components

Step 1.3 Determine the surfaces that will be clamped and restrained for mechanical support.

The surface d on the "A" pillar, shown in figure 4.13, is clamped to the roof rail frame to obtain a good weld.

Step 1.4 Identify the major stacking surfaces that locate other body components.

The "A" pillar stacks to the sill surface. The cowl top assembly stacks to surface 6 on the "A" pillar.

Step 2.1 Determine the assembly sequence and the predominant stacking surfaces for detail parts in the design.

Figure 4.12 shows the parts that are assembled into the "A" pillar. The sequence of the assembly is:

1. "A" pillar
2. Windshield frame
3. Inner cowl side panel

The surfaces d and I on the "A" pillar, shown in figure 4.13, are the stacking surfaces for the frame. Surface 6 on the "A" pillar is the stacking surface for the cowl side.

Step 2.2 Identify gauging surfaces for each part.

The "A" pillar gauge surfaces are the reference surfaces. The gauge surfaces for the frame are also shown in figure 4.14.

The inner cowl side gauge surfaces, shown in figure 4.15, are: the "A" pillar surface for centerline and surfaces 6 and 9 for front O and bottom O, respectively.

Step 2.3 Identify intermediate tool surfaces based on the preliminary process and holding concept.

There are no intermediate surfaces for this design.

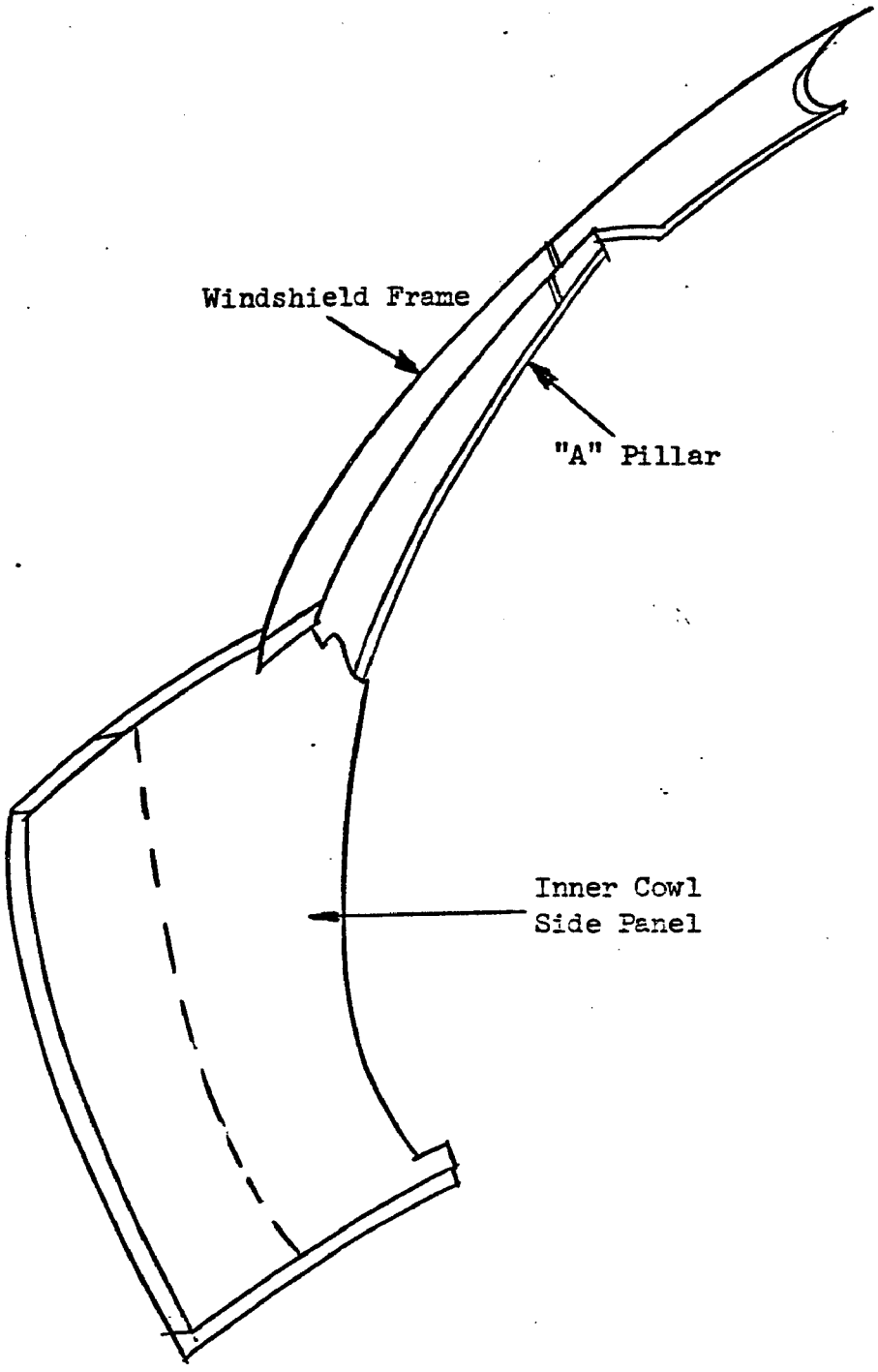


Figure 4.12 Component Parts of the "A" Pillar Assembly

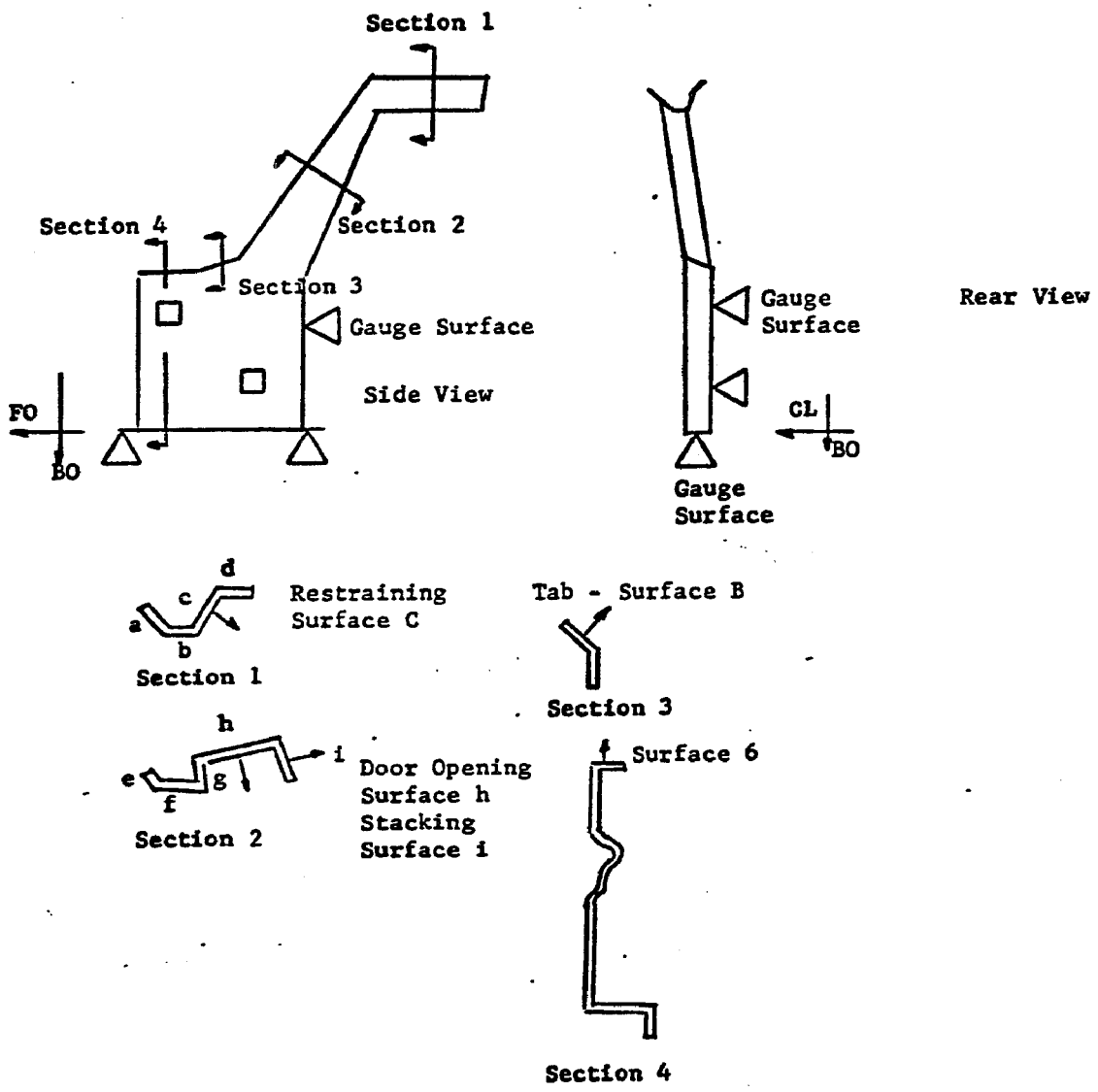


Figure 4.13 Sections of the "A" Pillar Tolerance and Gauge Surfaces

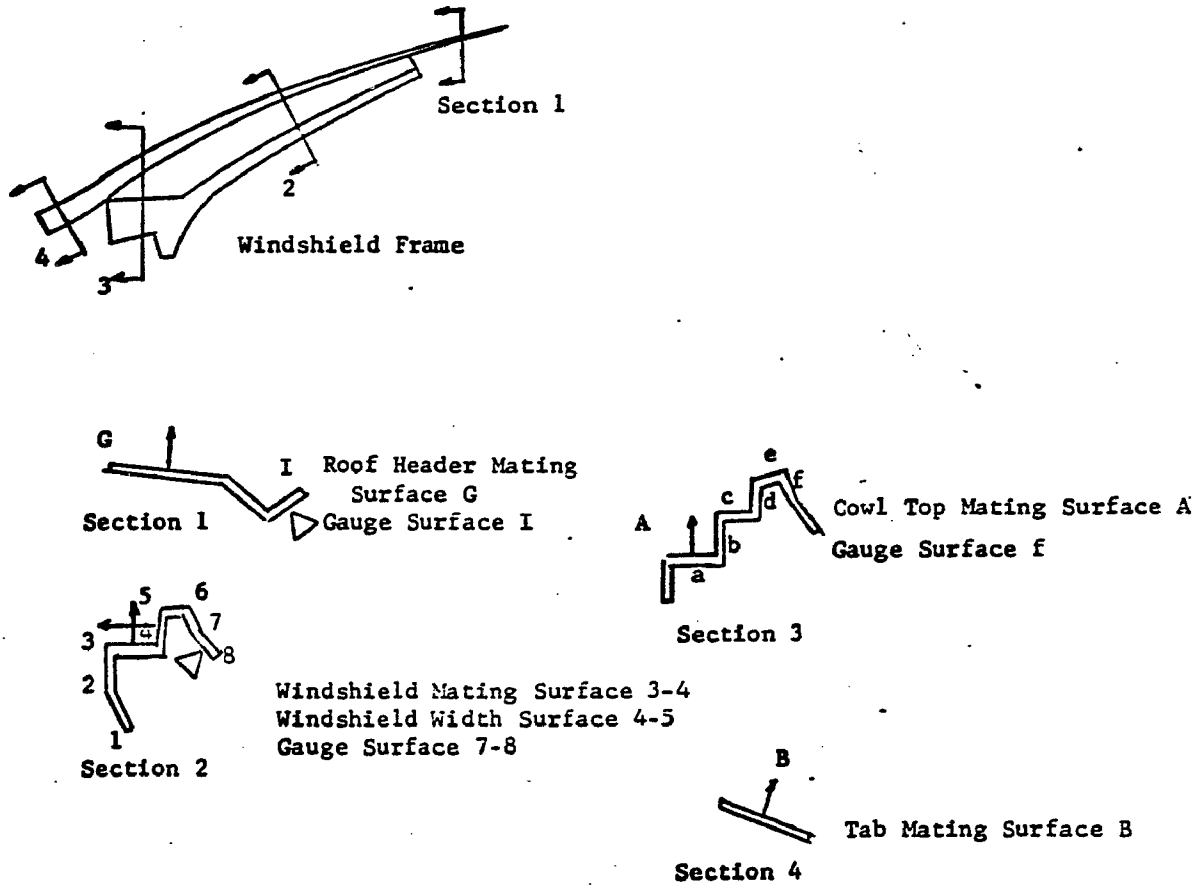
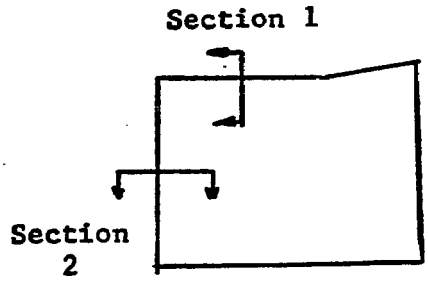
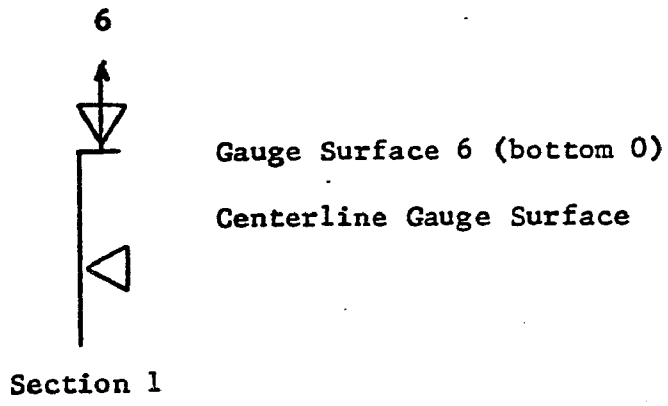


Figure 4.14 Sections of the Windshield Frame Showing Tolerance and Gauge Surfaces



Inner Cowl Side Panel
Side View



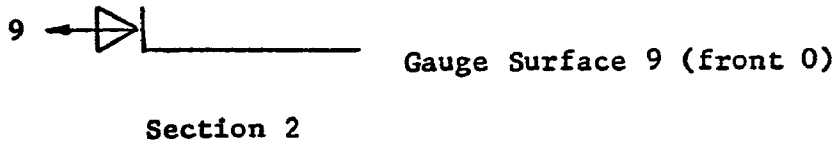


Figure 4.15 Sections of the Inner Cowl Side Panel Showing Tolerance and Gauge Surfaces.

Step 2.4 Determine the sequence of dimensional relationships for each surface that is to be controlled and toleranced.

The surfaces on the "A" pillar are determined with respect to the reference surfaces. In figure 4.13 they are indicated by the triangular locating points on the surface. The stacking surfaces are surface I and surface D. The surfaces on the frame, shown in figure 4.14, that are to be toleranced are G, I, 3-4, 4-5, A, and B. The path for these surfaces in the design are:

from reference surfaces to surfaces I and D on the "A" pillar,

from surfaces I and 7-8 on frame to the surface of interest.

The surfaces on the inner cowl panel, shown in figure 4.15, are located from surface 6 on the "A" pillar and from a nominal tool block on surface 9. The stacking surface is the vertical surface on the "A" pillar. The inner cowl panel bears against this surface. These are the gauge surfaces for the inner panel and the stacking translates the gauge surfaces.

Step 3.1 Obtain estimates for gate side tooling variability.

The experiment that was specified in Step 11.1 to measure the variability of the tooling from its mastered position was performed for one set of gates and one framing truck. The locations on the gate frame, where the reference lines were scribed, are shown in figure 4.6. The areas of interest for the "A" pillar are points A and B.

Table 4.1 shows the means and standard deviations for front O, bottom O, and centerline components of Point B. The bias for centerline deviations was estimated at .030" inboard. Assuming that point A remains fixed at nominal or zero deviation, the

centerline deviation of any point at an intermediate elevation is estimated by simple interpolation. The difference in elevation between points A and B is 34.50 in. Therefore, the deviation of a point k of an elevation that is D^k in. higher than point A is:

$$x_{tk} = \left(\frac{D^k}{34.5}\right) x_{tB} \tag{4.34}$$

The mean and standard deviation of the tooling is:

$$E\left[x_{tk}\right] = \frac{D^k}{34.5} \left[E(x_{tB})\right] \tag{4.35}$$

$$\sigma\left[(x_{tk})\right] = \frac{D^k}{34.5} \sigma\left[(x_{tB})\right] \tag{4.36}$$

TABLE 4.1

TOLERANCE INTERVALS, MEANS, AND STANDARD DEVIATIONS FOR COORDINATE OF REFERENCE POINT B ON ASSEMBLY TOOLING SIDES

COORDINATE	SYMBOL	TOLERANCE INTERVAL	MEAN	STD DEVIATION
Front O	x_{tFO}	.005, .025 Aft	.015 Aft	.0033
Centerline	x_{tCL}	-.023,-.037 Inboard	-.030 Inboard	.00236
Bottom O	x_{tBO}	0, .010 High	.005 High	.00167

Step 3.2 Obtain estimates for the mastering variability of the gate locating blocks for each subassembly.

The current specification for the mastering of blocks is a bandwidth from .002 in. to .015 in. measured normal to the nominal surface. Therefore, the blocks in the gate have a deviation from nominal, which is low for surfaces that are predominantly horizontal, outboard for vertical surfaces, and either forward

or aft depending on the position of the block to the nominal surface. These are summarized in Table 4.2.

TABLE 4.2

TOLERANCE INTERVALS, MEANS AND STANDARD DEVIATIONS FOR "A" PILLAR LOCATING BLOCK MASTERING ERRORS AND SILL STACKING SURFACE VARIABILITY

DESCRIPTION	SYMBOL	TOLERANCE INTERVAL	MEAN	STD DEVIATION
Mastering				
"A" Pillar Front O	x_{mFO}	.002, .015	.0085 Aft	.00217
"A" Pillar Centerline	x_{mCL}	.002, .015	.0085 Outbd	.00217
Sill Bottom O	x_{mBO}	.002, .015	.0085 High	.00217
Stacking				
Sill Bottom O	x_{sBO}	-.005, +.005	0	.00167

Step 3.3 Obtain estimates for the relative loading error and its direction between parts for each subassembly.

The loading error for the frame relative to the "A" pillar was from 0 to .040 in. in a direction perpendicular to the break line on surface 7-8 shown in figure 4.14.

The loading error for the inner cowl side to the "A" pillar is from 0 to .030 in. in a direction forward of the "A" pillar due to the type of location.

Step 4.1 Define the section points and break lines on all functional surfaces to be toleranced.

This definition is not necessary for the discussion of the example, but it must be known for the location of the checking fixture targets.

Step 4.2 Estimate part deviation interval.

The surfaces to be toleranced are shown in Figures 4.13, 4.14 and 4.15 for the "A" pillar, windshield frame, and inner cowl panel, respectively. Table 4.3 gives the part deviation intervals for each surface. These deviations are estimated by the die process engineers after a review of the preliminary die process. These deviations from nominal are with respect to the gauge surfaces for each part.

TABLE 4.3

TOLERANCE INTERVALS FOR "A" PILLAR DETAIL PART SURFACES

PART	SURFACE	INTERVAL (DEVIATION FROM NOMINAL)
"A" pillar	d	+.040, -.000
	I	+.040, -.000
	B	+.040, -.000
	6	+.040, -.000
	h	+.025, -.025
Windshield Frame	I	Net (Gauge surface)
	G	+.030, -.030
	4-5	+.005, -.005
	3-4	+.015, -.015
	A	+.030, -.030
	B	+.030, -.030
Inner Cowl Panel	6	Gauge
	9	Gauge

Step 5.1 Develop dimensional models for each surface as a function of the design path and process variables.

This section develops the model for the movement of the frame relative to the "A" pillar. The movements are assumed to be translations only. The deviation from nominal of a surface is assumed to apply to all points on the surface in a direction which is normal or perpendicular to the nominal surface. All surfaces are assumed to be planes. The coordinates

for the frame relative to the "A" pillar as a function of the stacking and loading errors are developed.

The results of these coordinate translations on the normals to the surfaces to be toleranced are determined next.

Finally, the deviation of the surface relative to the gauge surfaces are added to the above translation.

The motion of the frame is outlined below:

1. Stack the windshield frame to surface I on the "A" pillar. Denote the deviation from nominal to surface I by x_{s1}. Let $\vec{K} = (K^{FO}, K^{CL}, K^{BO})$ represent the coefficient of the normal vector to the surface. The coordinates due to stacking are:

$$\vec{x}_{s1} = \vec{K}\, x_{s1} \qquad (4.37)$$

2. Determine the influence of this stacking normal to surface d, the secondary stacking surface. Represent the coordinates of the normal to surface d by $\vec{L} = (L^{FO}, L^{CL}, L^{BO})$. The distance normal to surface d that the frame surface moves is:

$$y_d = \vec{L} \cdot \vec{K}\; x_{s1} = (L^{FO} K^{FO} + L^{CL} K^{CL} + L^{BO} K^{BO})\, x_{s1} \qquad (4.38)$$

This represents the distance that surface d moves from its nominal position in a direction that is perpendicular to the surface, as a result of stacking to surface I. It is equivalent to a gap or an interference at surface d.

3. Determine the motion of the frame due to stacking to surface d. In order to satisfy stacking at surface I and surface d, the frame must move or slip along the surface I. It is

assumed that this slip occurs along a line $(A\text{-}B)^1$ in the surface. This line is in the actual surface that is parallel to a line A-B in the nominal surface. A unit movement along this line has coordinates represented by the vector $\vec{P} = (P^{FO}, P^{CL}, P^{BO})$. The distance moved along line $(A\text{-}B)^1$ is a function of the difference between the deviation normal to the surface of d, x_{s2}, and the equivalent distance of d, $\vec{L} \cdot \vec{K}\ x_{s1}$, due to stacking at surface I. The relationship between a distance y_d and a distance x_{A-B} along line A-B can be expressed as:

$$y_d = \vec{L} \cdot \vec{P}\, x_{a-b} \tag{4.39}$$

Therefore

$$x_{a-b} = \frac{y_d}{\vec{L} \cdot \vec{P}} \tag{4.40}$$

In our example

$$y_d = x_{s2} - \vec{L} \cdot \vec{K}\ x_{s1} \tag{4.41}$$

Therefore,

$$x_{(a-b)^1} = \frac{x_{s2} - \vec{L} \cdot \vec{K}\, x_{s1}}{\vec{L} \cdot \vec{P}} \tag{4.42}$$

and the coordinates of this movement are:

$$\vec{P}\ x_{(a-b)^1} = \vec{P} \left[\frac{x_{s2} - \vec{L} \cdot \vec{K}\ x_{s1}}{\vec{L} \cdot \vec{P}} \right] \tag{4.43}$$

4. Determine the motion to the windshield frame due to loading errors, x_{L2}, in the plane of surface I in a direction $(C\text{-}D)^1$. $(C\text{-}D)^1$ represents a line parallel to a line C-D in the nominal surface I, and is perpendicular

to line A-B. The coordinates of a unit distance along line $(C\text{-}D)^1$ are expressed by the vector

$$\vec{Q} = (Q^{FO}, Q^{CL}, Q^{BO}).$$

Therefore, a loading error of $x_{(C-D)^1}$ has coordinates of $\vec{Q}\, x_{(C-D)^1}$. But this results in either a gap or an interference at surface d of magnitude $x_d = \vec{L} \cdot \vec{Q}\; x_{(C-D)^1}$. (4.44)

In order to satisfy the loading error and the mating of the surfaces at d, a motion along line $(A\text{-}B)^1$ is introduced by an amount opposite to the movement at surface d.

Therefore,

$$x_{A-B} = -\frac{x_d}{\vec{L} \cdot \vec{P}} \quad \text{where} \quad x_d = \vec{L} \cdot \vec{Q}\; x_{L2},$$

$$\text{or } x_{A-B} = -\frac{\vec{L} \cdot \vec{Q}\; x_{L2}}{\vec{L} \cdot \vec{P}} \tag{4.45}$$

The coordinates of this are:

$$\vec{P}\, x_{(a-b)^1} = -\frac{\vec{P}\; \vec{L} \cdot \vec{Q}\; x_{L2}}{\vec{L} \cdot \vec{P}}$$

Therefore, the total coordinate movement due to loading x_{L2} is:

$$\vec{Q}\; x_{L2} - \frac{\vec{P}\; \vec{L} \cdot \vec{Q}\; x_{L2}}{\vec{L} \cdot \vec{P}} \tag{4.46}$$

5. The loading error along line A-B, x_{L1}, can be expressed in coordinates by:

$$\vec{x}_{L1} = \vec{P}\; x_{L1} \tag{4.47}$$

The total coordinate translation is the sum of the individual coordinates determined from (4.37), (4.43), (4.46), (4.47) and is denoted by:

$$\vec{T} = (T^{FO}\ T^{CL}\ T^{BO}) = \vec{K}\, x_{s1} + \vec{P}\left[\frac{(x_{s2} - \vec{L}\cdot\vec{K}\, x_{s1})}{\vec{L}\cdot\vec{P}}\right]$$

$$+ \vec{Q}\, x_{L2} - \frac{\vec{P}\,\vec{L}\cdot\vec{Q}\, x_{L2}}{\vec{L}\cdot\vec{P}} + \vec{P}\, x_{L1} \qquad (4.48)$$

Step 5.2 Determine the equations and coefficients for the loading and stacking errors on the stacking surfaces.

The last step modeled the loading and stacking motion of the windshield frame relative to the "A" pillar, and derived the equations for the coordinates of this motion. This step determines the coefficients of the equation by determining the coordinates for normals to the surfaces and motion along lines in the plane. The coordinates for the normals and the motion are determined by geometric construction.

The construction for the normals to the surface is outlined below:

1. For each surface draw two sections which intersect at the point of interest.
2. Each section represents a line in the surface.
3. To each section fit a straight line tangent at the point of interest.
4. The two straight lines that intersect at the point and that are tangent to the surface define the tangent plane.
5. The tangent plane is shown in a view as a straight line.
6. A straight line is drawn perpendicular to the tangent plane in this view through the point of interest.

7. The normal line is then shown in two of the principal views.
8. The coordinates of the normal line are scaled in these principal views.

The construction for the motion is similar:

1. Construct the tangent plane by following the Steps 1 through 6 in the above procedure.
2. Show the plane in true size by taking a view perpendicular to the view which shows the plane as an edge.
3. Draw the lines of motion on the true size plane.
4. Trace a point on each line back to the principal views.
5. Scale the motion of the point with respect to the three coordinate axis.

The above construction resulted in the following vector coordinates:

$\vec{K}$ = (-.014, .800, .602) represents the coordinates of x_{s1} ,

$\vec{L}$ = (-.10, -.50, .88) represents the coordinates of x_{s2} ,

$\vec{P}$ = (.76, -.36, .56) represents the coordinates of motion along line $(A\text{-}B)^1$, x_{a-b} or x_{L1} , and

$\vec{Q}$ = (.69, .46, -.60) along line $(C\text{-}D)^1$, x_{C-D} or x_{L_2}.

Substituting these in the expression for $\vec{T}$, equation 4.48 we have

$$\vec{T} = (T^{FO}\ T^{CL}\ T^{BO}) = (-.014, .800, .602)\ x_{s1}$$

$$+(.76,-.36,\ .56)\left[\frac{x_{s2}-(-.10,-.50,.88)(-.014.,800,.602)x_{s1}}{(-.10,-.50,.88)(.76,-36,.56)}\right]$$

$$+(.69,.46,-.60)x_{L2}$$

$$(.76, -.36, .56) \quad (-.10,-.50, .88)\bullet(.69, .46, -.60\ )\ x_{L2}$$

$$-\ \frac{}{(-.10,-.50,.88)\bullet(.76,\ -.36,\ .56)} \qquad +(.76,-.36,\ .56)\ x_{L1}$$

$$= (-.014,\ .800,\ .602)\ x_{s1} + (1.273456,\ -.603216,\ .938336)\ x_{s2}$$

$$+ (-.167027,\ +.079118,\ -.123072)\ x_{s1} + (.69,\ .46,\ -.600)\ x_{L2}$$

$$+ (1.053150,\ -.498861,\ .776005)\ x_{L2} + (.76,\ -.36,\ .56)\ x_{L1}$$

$$= (-.1810,\ .8791,\ .4789)\ x_{s1} + (1.2735,\ -.6032,\ .9383)\ x_{s2}$$

$$+ (1.7432,\ -.0389,\ .1760)\ x_{L2} + (.76,\ -.36,\ .56)\ x_{L1} \qquad (4.49)$$

The next step applies the coordinates of $\vec{T}$ to the tolerancing of each surface.

Step 5.3 Determine the tolerance equations for all surfaces.

The tolerance equations for all surfaces on the "A" pillar can be expressed as x_p^i which represents the deviation from nominal of surface i on the primary part. The tolerance equation for surface i on the secondary part is expressed as

$$x_s^i = x_{s,p}^i + \vec{N}_i \bullet \vec{T} \qquad (4.50)$$

where

$x_{s,p}^i$ is the deviation from nominal on the secondary part with respect to the gauge surfaces that mate with the primary part.

$\vec{N}_i$ is the vector representing the coordinates of the normal to the surface i.

$\vec{T}$ is the vector representing the coordinates of translation of the secondary part due to loading and stacking.

The tolerance equations by surface on the primary and secondary parts are listed below:

$$x_s^d = x_p^d = x_{s2}$$

$$x_s^I = x_p^I = x_{s1}$$

$$x_s^{B(tab)} = x_p^{B\ (tab)}$$

$$x_s^6 = x_p^6$$

$$x_s^G = x_p^G + \vec{N}_G \cdot \vec{T}$$

$$x_s^{4-5} = x_p^{4-5} + \vec{N}_{4-5} \cdot \vec{T} \qquad (4.51)$$

$$x_s^{3-4} = x_p^{3-4} + \vec{N}_{3-4} \cdot \vec{T}$$

$$x_s^A = x_p^A + \vec{N}_A \cdot \vec{T}$$

$$x_s^B = x_p^B + \vec{N}_B \cdot \vec{T}$$

The values for normal components are:

$\vec{N}_G = (-.16,\ .36,\ .96)$, $\vec{N}_{4-5} = (-.58,\ -.080,\ .26)$, $\vec{N}_{3-4} = (-.35,\ .47,\ .83)$

$\vec{N}_A = (0,\ 0,\ 1)$, $\vec{N}_B = (-.14,\ .22,\ .98)$

Substituting the value of $\vec{N}_G$ above and the expression for $\vec{T}$ from (4.49) into the equation for the windshield frame surface G from 4.51 we obtain

$$x_s^G = x_p^G + (-.16,\ .36,\ .96)\ ((\ -.1810,\ .8791,\ .4789)\ x_{s1}$$
$$+ (1.2735,\ -.6032,\ .9383)\ x_{s2} + (1.7432,\ -.0389,\ .1760)\ x_{L2}$$
$$+ (.76,\ -.36,\ .56)\ x_{L1})$$

$$= x_p^G + .81\, x_{s1} + .48\, x_{s2} - .12\, x_{L2} + .29\, x_{L1} \qquad (4.52)$$

Similarly, we obtain for the remainder of the surfaces on the windshield frame:

$$\begin{aligned}
x_s^{4-5} &= x_p^{4-5} - .47\, x_{s1} - .01\, x_{s2} - .93\, x_{L2} - .01\, x_{L1} \\
x_s^{3-4} &= x_p^{3-4} + .87\, x_{s1} + .05\, x_{s2} - .48\, x_{L2} + .03\, x_{L1} \\
x_s^{A} &= x_p^{A} + .48\, x_{s1} + .94\, x_{s2} + .18\, x_{L2} + .56\, x_{L1} \\
x_s^{B} &= x_p^{B} + .69\, x_{s1} + .61\, x_{s2} - .08\, x_{L2} + .36\, x_{L1}
\end{aligned} \qquad (4.53)$$

An example of a mating surface that is to be welded joining the frame and the "A" pillar is surface B.

The equation for the gap at surface B is:

$$\begin{aligned}
x_{gap}^{B} &= x_s^{B} - x_p^{B(tab)} \\
&= x_p^{B} + .69\, x_{s1} + .61\, x_{s2} - .08\, x_{L2} + .36\, x_{L1} - x_p^{B(tab)}
\end{aligned} \qquad (4.54)$$

Step 5.4 Define the distributions and parameters for each variable in the functional equation.

The last step developed the functional equations which express the deviations for each surface as a function of the

deviations for the surface in the detail part and the deviations due to stacking and loading or mastering errors. Step 4.2 estimated an interval within which the die process could be expected to produce the surface deviations. It is assumed that all deviations from nominal are normally distributed with mean value being the middle of the interval. It is also assumed that the range of the interval is equal to six standard deviations about the mean.

The interval size, the mean and standard deviation for each surface, and loading errors are listed in Table 4.4.

TABLE 4.4

MEANS AND STANDARD DEVIATIONS FOR
"A" PILLAR DETAIL PART SURFACES AND LOADING ERRORS

PART	SURFACE	INTERVAL	E (x)	σ(x)
"A" Pillar	d	+.040, -.000	+,020	.0067
	I	+.040, -.000	+.020	.0067
	B	+.040, -.000	+.020	.0067
	6	+.040, -.000	+.020	.0067
Windshield Frame	I	Net Gauge Surface		--
	G	+.015, -.015	0	.005
	4-5	+.005, -.005	0	.0017
	3-4	+.015, -.015	0	.005
	A	+.030, -.030	0	.010
	B	+.030, -.030	0	.010
Loading	x_{L2}	+.040, -.000	.020	.0067
	x_{L1}	+.000, -.000	.000	.000

Step 5.5 Compute the parameters and the tolerance limits for each surface to be toleranced.

The parameters of the deviations from nominal are computed from the formulas for the mean and the standard deviation. These result in the following for surface G.

$$E(x_s^G) = E(x_p^G) + .81\,E(x_{s1}) + .48\,E(x_{s2}) - .12\,E(x_{L2}) + .29\,E(x_{L1})$$

$$= 0 + .81\,(.020) + .48\,(.020) - .12\,(.020) + .29\,(0)$$

$$= .0232$$

$$\sigma(x_s^G) = (\sigma^2(x_p^G) + .81^2\,\sigma^2(x_{s1}) + .48^2\,\sigma^2(x_{s2}) + (-.12)^2\,\sigma^2(x_{L2}) + (.29)^2\,\sigma^2(x_{L1}))^{1/2}$$

$$= ((.005)^2 + .81^2\,(.00667)^2 + .48^2\,(.00667)^2 + (-.12)^2\,(.00667)^2 + (.29)^2\,(0)^2)^{1/2}$$

$$= .008046$$

The tolerance specifications for the surface can be computed as follows:

$$E(x_s^G) \pm 3\,\sigma(x_s^G)$$

$$= .0232 \pm 3\,(.008046)$$

$$= .0232 \pm .0241$$

$$= +.047, -.001$$

Therefore, under the assumptions of normality, the distribution being centered in the middle of the interval and independence between parts and dimensions, approximately 99% of the subassemblies will have surface G fall between the tolerance specifications.

The maximum and minimum limits for surface G can be computed by substituting the limit of each variable that results in the "worst case". The maximum and minimum of x_G can be computed from:

$$x_G^{Max} = x_p^{Max} + .81\, x_{s1}^{Max} + .48\, x_{s2}^{Max} - .12\, x_{L2}^{Min} + .29\, x_{L1}^{Max}$$

$$= .015 + .81\ (.040) + .48\ (.040) - .12\ (0) + .29\ (0)$$

$$= .066$$

$$x_G^{Min} = x_p^{Min} + .81\, x_{s1}^{Min} + .48\, x_{s2}^{Min} - .12\, x_{L2}^{Max} + .29\, x_{L1}^{Min}$$

$$= -.015 + .81\ (0) + .48\ (0) - .12\ (.040) + 0$$

$$= -.020$$

The tolerance interval is .066 - (-.020) = .086 inches, whereas the interval using the sum of squares of the standard deviations was .048 inches. The smaller interval can be used only if the extreme limits are unlikely to occur due to the above assumptions.

Table 4.5 summarizes the parameters and the tolerance specifications for the surfaces to be toleranced.

TABLE 4.5

TOLERANCE SPECIFICATIONS FOR THE "A" PILLAR SUBASSEMBLY SURFACES

PART	SURFACE	$E(x_s^1)$	$\sigma(x_s^1)$	$3\sigma(x_s^1)$	$E(x)+3\sigma$	$E(x)-3\sigma(x)$
"A" Pillar	d	.020	.0067	.020	.040	.000
	I	.020	.0067	.020	.040	.000
	B(tab)	.020	.0067	.020	.040	.000
	6	.020	.0067	.020	.040	.000
Windshield Frame	I	.020	.0067	.020	.040	.000
	G	.0232	.0080	.0241	.047	-.001
	4-5	.0306	.0070	.0210	.052	.010
	3-4	.0088	.0067	.020	.029	-.011
	A	.0320	.0071	.021	.053	.011
	B	.0243	.0061	.018	.043	.006
Gap		-.0043	.009	.027	.023 Gap	-.031

Table 4.6 summarizes the extreme limits for each surface, in addition to the contribution of each variable to the limits.

TABLE 4.6

EXTREME LIMITS OF "A" PILLAR SUBASSEMBLY SURFACES

SURFACE	LOADING x_{L2} MIN	LOADING x_{L2} MAX	STACKING x_{s1} MIN	STACKING x_{s1} MAX	STACKING x_{s2} MIN	STACKING x_{s2} MAX	PART MIN	PART MAX	TOTAL MIN	TOTAL MAX
d	0	0	0	0	0	0	0	.040	0	.040
I	0	0	0	0	0	0	0	.040	0	.040
B tab	0	0	0	0	0	0	0	.040	0	.040
6	0	0	0	0	0	0	0	.040	0	.040
I	0	0	0	0	0	.040	0	0	0	.040
G	-.005	0	0	.032	0	.019	-.015	.015	-.020	.066
4-5	-.0374	0	-.019	0	0	0	-.005	.005	-.061	.005
3-4	-.019	0	0	.035	0	.002	-.015	.015	-.034	.052
A	0	.007	0	.019	0	.0375	-.030	.030	-.030	.094
B	-.003	0	0	.0275	0	.0243	-.030	+.030	-.033	.082

Step 6.1 Determine the class of fit at mating surfaces to be welded in the subassembly.

The windshield frame is assembled to the "A" pillar by an operator. The loose assembled subassemly is then placed in a machine welder for clamping and spot welding. The system of clamps and locators hold surface I of the frame to surface I of the pillar. This method is consistent with the assumption that stacking will occur on both surfaces. If the two parts are to be loose assembled, then no interference is permitted on surface B. Therefore, the class of fit requires no interference.

Step 6.2 Compute the design clearance and maximum gap expected at each weld joint.

Table 4.5 shows that at the tolerance specification .031 inches of interference is possible. Therefore, the tab is given .031 inches of design clearance, i.e., its nominal dimension is shifted by .031 inches. This results in a specification from the original nominal dimension of +.054, -.000. Therefore, no interference is expected, but the maximum gap is .054 inches between the tab and its mating surface B.

Step 6.3 Evaluate the effect on the structure of restraining surfaces to nominal and closing maximum gaps at welded joints.

The closing of a .054 inch gap between the tab and surface B is considered satisfactory. The force of the clamp will bend the tab to provide metal to metal contact for spot welding.

Step 7.1 Tolerance subassembly surfaces using the estimates of tool capability from Steps 3.1 and 3.2 and the subassembly tolerances from Step 5.5.

The tolerance specifications in Step 5.5 apply to the subassembly surfaces. This step adds the errors due to stacking, mastering and the tool band inherent in the side gate process.

Each locating block has a loading error, which is normally distributed with mean $E(x_m) = .0085$ and standard deviation $\sigma(x_m) = .00217$. The effect of mastering on surface G can be determined by:

$$x_m^G = \vec{N}_G \cdot \vec{E}_{FO}\, x_{mFO} + \vec{N}_G \cdot \vec{E}_{CL}\, x_{mCL} + \vec{N}_G \cdot \vec{E}_{BO}\, x_{mBO}$$

$$= (-.16, .36, .96) \cdot (1,0,0)\, x_{mFO} + (-.16, .36, .96) \cdot (0,1,0) x_{mCl}$$

$$+ (-.16, .36, .96) \cdot (0,0,1) x_{mBO}$$

$$= -.16\, x_{mFO} + .36\, x_{mCL} + .96\, x_{mBO} \qquad (4.55)$$

and $E(x_m^G) = -.16\, E(x_{mFO}) + .36\, E(x_{mCL}) + .96\, E(x_{mBO}) = .00986$

$$\sigma(x_m^G) = \left((-.16)^2\, \sigma^2(x_{mFO}) + (.36)^2\, \sigma^2(x_{mCL}) + .96^2\, \sigma^2(x_{mBO}) \right)^{1/2}$$

$$= \left((.16^2 + .36^2 + .96^2)\ (.00217)^2 \right)^{1/2} = (5.0705 \times 10^{-6})^{1/2}$$

$$= .00225$$

Also, the maximum and minimum extremes can be determined by:

$$(x_m^G)^{Max} = -.16\, x_{mFO}^{Min} + .36\, x_{mCL}^{Max} + .96\, x_{mBO}^{Max}$$

$$= -.16\ (.002) + .36\ (.015) + .96\ (.015)$$

$$= .01948$$

$$(x_m^G)\ Min = -.16\, x_{mFO}^{Max} + .36\, x_{mBO}^{Min} + .96\, x_{mBO}^{Min}$$

$$= -.16\ (.015) + .36\ (.002) + .96\ (.002)$$

$$= .00024$$

The "A" pillar is stacked against the sill and is therefore influenced by any variation in the mating surface on the sill. The mastering error considered above actually applies to the sill. The stacking error is with respect to the bottom O plane and is estimated to be normally distributed with

$$E(x_s^G) = 0, \sigma(x_s^G) = .00167$$

The extreme limits of the stacking on surface G are determined by

$$(x_s^G)^{Max} = .96\, x_s^{Max} = .96\ (.005) = .0048$$

$$(x_s^G)^{Min} = .96\, x_s^{Min} = .96\ (-.005) = -.0048$$

The effect of the tool band on surface G can also be determined from:

$$x_t^G = \vec{N}_G \cdot \vec{E}_{FO}\ x_{tFO} + \vec{N}_G \cdot \vec{E}_{CL}\ x_{mCL} + \vec{N}_G \cdot \vec{E}_{BO}\ x_{tBO}$$

$$= (-.16, .36, .96) \cdot (1,0,0)\ x_{tFO} + (-.16, .36, .96) \cdot (0,1,0)\ x_{tCL}$$

$$+ (-.16, .36, .96) \cdot (0,0,1)\ x_{tBO}$$

$$= -.16\, x_{tFO} + .36\, x_{tCL} + .96\, x_{tBO} \qquad (4.56)$$

Using the means and standard deviations from Table 4.1, we obtain:

$$E(x_t^G) = -.16\ (.015) + .36\ (-.030) + .96\ (.005) = -.0084$$

$$\sigma(x_t^G) = ((.16)^2\ (.0033)^2 + .36^2\ (.00233)^2 + .96^2\ (.00167)^2)^{1/2} = .00188$$

and $x_G^{Max} = -.16\ (.005) + .36\ (-.023) + .96\ (.010) = -.009$

$$x_G^{Min} = -.16\ (.025) + .36\ (-.037) + .96\ (0) = -.0173$$

Summing the mastering, stacking and tooling effects for surface G we have:

$$E(x^G_{m,s,t}) = E(x^G_m) + E(x^G_s) + E(x^G_t)$$

$$= .00986 + 0 + (-.0084) = .0015$$

$$\sigma(x^G_{m,s,t}) = (\sigma^2(x^G_m) + \sigma^2(x^G_s) + \sigma^2(x^G_t))^{1/2}$$

$$= ((.00225)^2 + (.00167)^2 + (.00188)^2)^{1/2} = .00337$$

Then, the tolerance specification = $.0015 \pm .010 = +.012, -.009$

The maximum and minimum limits for the sum are:

$$x^{G\ Max}_{m,s,t} = .01948 + .0048 - .009 = .0153$$

$$x^{G\ Min}_{m,s,t} = .00024 - .0048 - .0173 = -.0219$$

The tolerance specification for surface G in the body position i.e., in the tooling, is:

$$x^G = x_s + x_{m,s,t} \quad \text{and} \qquad (4.57)$$

$$E(x^G) = E(x_s) + E(x_{m,s,t}) = .0232 + .0015 = .0247 \qquad (4.58)$$

$$\sigma(x^G) = (\sigma^2(x) + \sigma^2(x_{m,s,t})^2)^{1/2} = (.0080^2 + .00337^2)^{1/2} = .00868 \qquad (4.59)$$

Tolerance specification = $.0247 \pm .0260 = .0507, -.001$

The maximum and minimum limits are:

$$x^{Max} = .066 + .0153 = .081$$

$$x^{Min} = -.020 - .0219 = -.042$$

It is very evident that probabilistic tolerance specifications are considerably smaller.

Table 4.7 shows the tolerance specifications and maximum, minimum limits for the surfaces in final body position.

TABLE 4.7

TOLERANCE SPECIFICATIONS & EXTREME LIMITS FOR THE "A" PILLAR SURFACES IN BODY POSITION

SURFACE	TOLERANCE SPECIFICATIONS		EXTREME LIMITS	
	$E(x)-3\sigma(x)$	$E(x)+3\sigma(x)$	MINIMUM	MAXIMUM
I	.017	.061	-.033	.069
G	-.001	.051	-.041	.091
4-5	.015	.061	-.079	.036
3-4	-.019	.025	-.067	.071
A	.022	.068	-.033	.124
B	.012	.054	-.045	.111
6	.009	.053	-.000	.069

Step 8.4 Evaluate the structural effects of closing clamps at restraining surfaces and closing gaps at weld joints.

Surface I in body position is restrained to its locating block. The tolerance specifications are +.017 and +.061 in. Therefore, the maximum deflection is .061 in. in the opposite direction. This deflection must be evaluated for its effect on other dimensions. Assuming that the surface can be brought to the locating block by clamping, the tolerance for the surface consists of the variation to the block, i.e., mastering and tooling variation. This amounts to a tolerance band of +.010, +.029.

Step 8.5 through 13.3

These steps are not discussed in this example.

The next chapter discusses the costs of dimensional control for detail part relationships and the least cost tolerancing problem.

CHAPTER V

ALLOCATION OF TOLERANCES AND COST CONSIDERATIONS

5.1 INTRODUCTION

The previous chapter presented a methodology to tolerance and evaluate a car body structure design. In addition, experiments were designed to estimate mastering errors, tool and loading variability, and process capability so process control procedures can be designed and implemented. This chapter discusses the allocation of tolerances when acceptable gaps at weld joints and surface deviations to be restrained are decided upon for the design. This permits the determination of the tolerances for surface deviations that must be obtained if these constraints are to be satisfied. The costs of inadequate control over body dimensions as reflected by defects in subsequent processes are discussed. This is followed by a discussion of process control costs on part deviations from nominal.

5.2 ASSEMBLY PROCESS FAILURE COSTS

This section discusses the costs associated with process control failures due to subassembly dimensional variability. These failures are the result of body openings not being controlled, joints not being welded properly, and subsequent processes not being adequately controlled. Virtually the quality of all assembly operations is dependent on the body surfaces, holes, attaching brackets and plates being produced within acceptable limits. This discussion applies to the more important assembly processes.

Figures 5.1 and 5.2 summarize the major processes that are typical of

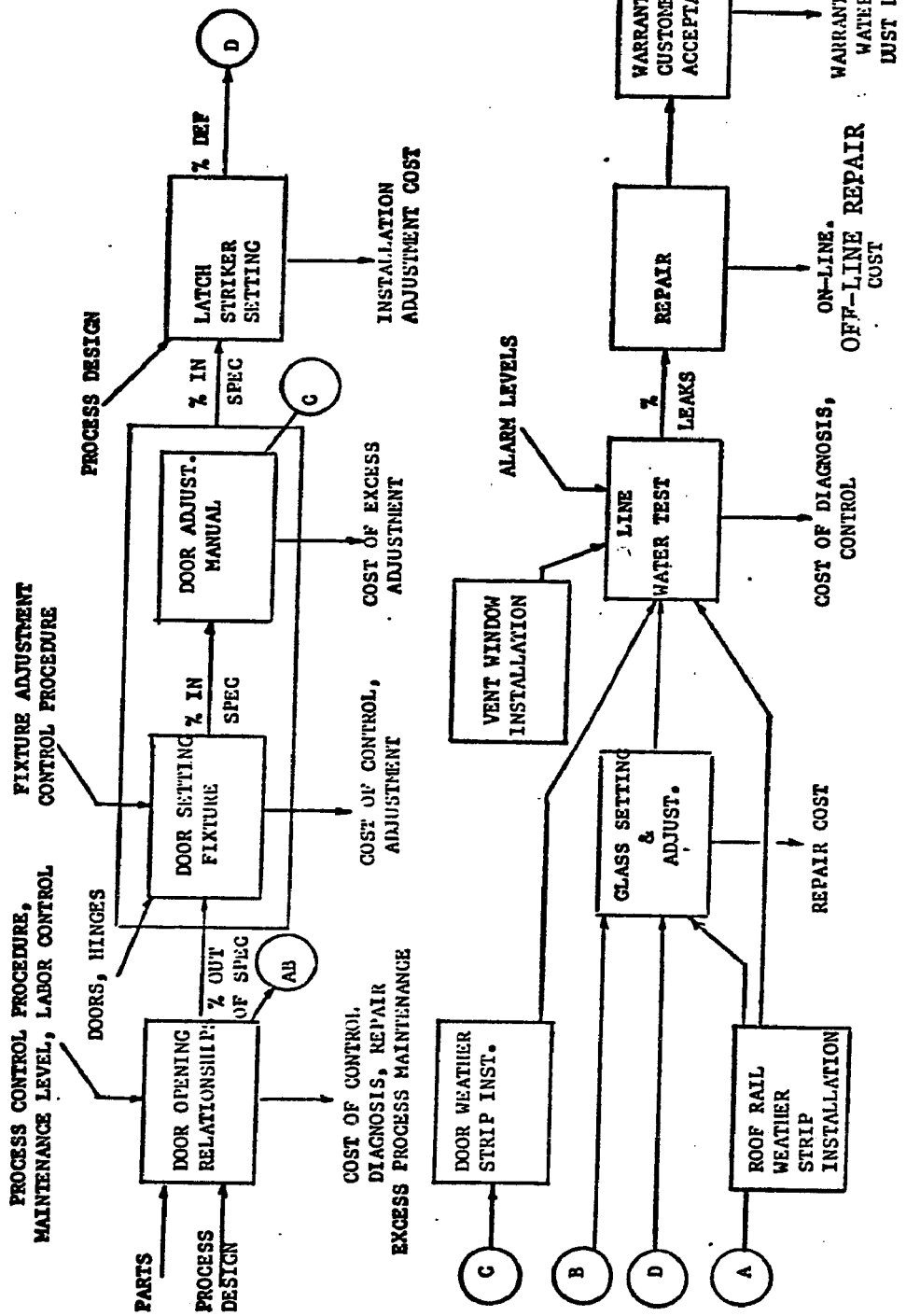


Figure 5.1 Multistage Process Control - Doors

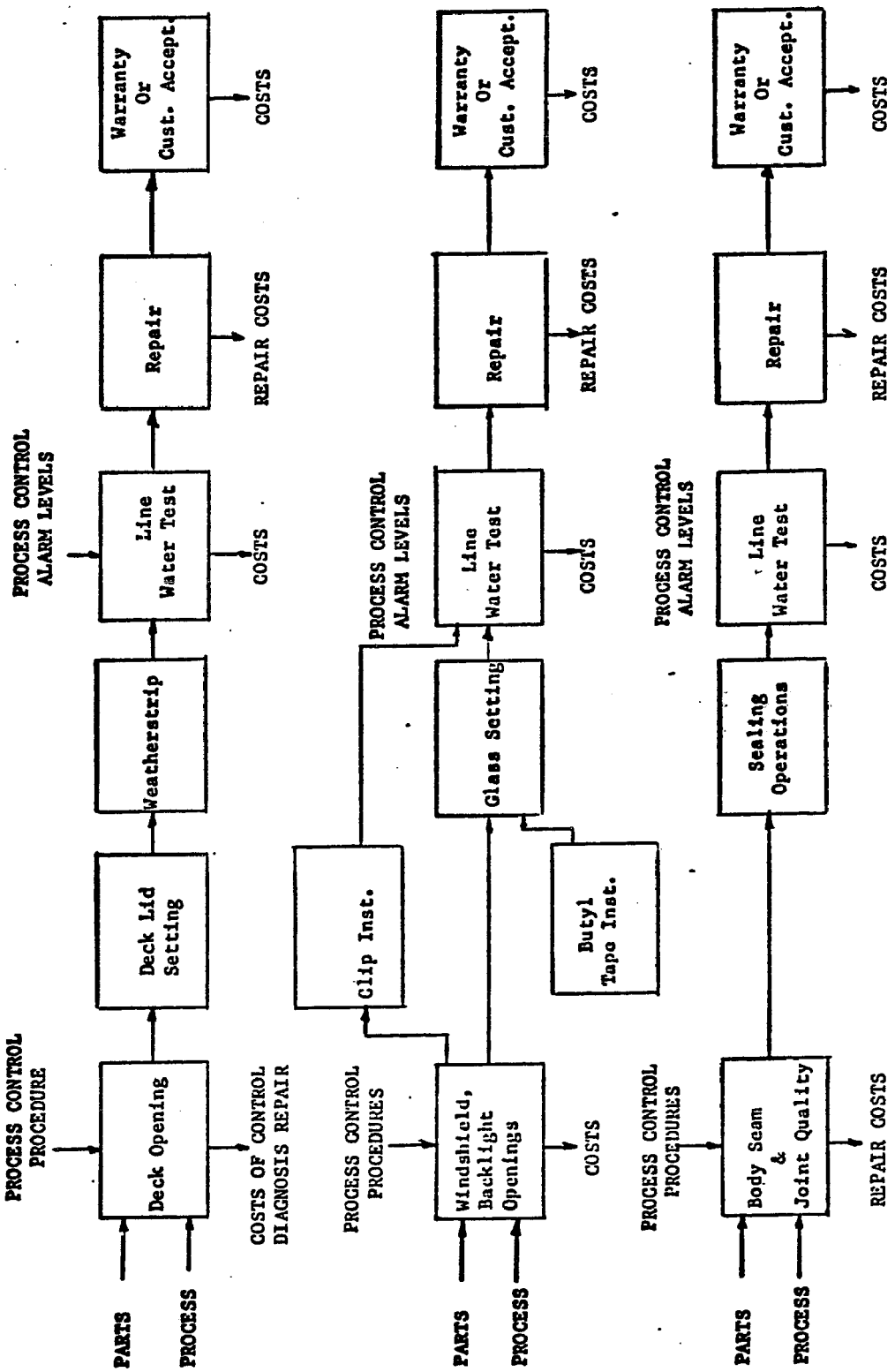


Figure 5.2 Multistage Process Control - Decks, Glass & Sealing

automobile assembly, and the type of costs associated with the process failures. This exhibit clearly shows the degree of dependence on the quality of preceding operations. In particular the seal of door glass for hardtop models depends on the opening size, the relationship of the door hanging pillar to the weatherstrip attaching surface, the installation of the weatherstrip, the fit of the door in the opening and the quality of the glass adjustment. Similar dependence exists for the seal and fit of hoods, deck lids, windshields and backlights.

In all cases, the failure of an operation results in a corrective repair operation. The costs of repair are very substantial, and the likelihood of the repair being acceptable in many cases is small. It is very difficult to control the quality of operations such as side glass adjustment when a high percentage of doors and weatherstrips are not correctly adjusted or installed. The repairs in the body shop for poor joints and for misaligned parts are also very expensive.

These process failures result in poor fits and water and dust leaks that may or may not be detected during the line water test. The pressures to maintain production and the difficulty to detect and repair a leak result in cars being delivered to dealers that are not acceptable. The repairs that are made to stop leaks due to poor weld joint quality are also difficult and in most cases are temporary. Difficulties in sealing the bodies and the failure to contain these defects result in customer warranty complaints and claims. Estimates of the warranty expense that could be saved by improvements in quality with better process control are in the order of millions of dollars. Approximately two-thirds of these process failures can be attributed

to body openings and the fitting and sealing of panels to these openings. When the cost of repair manpower is added to the warranty expense, it is obvious that investments in process control become very attractive. For a given engineering design, the appropriate point to control the process has been shown in Chapter III to be the detail parts. The next section discusses the costs associated with detail part control.

5.3 DETAIL PART CONTROL

This section discusses the costs associated with controlling the major process variables that were included in the model for subassembly surfaces. These variables are x_{s1}, x_{s2}, x_p, and x_L which represent the deviations from nominal due to stacking surfaces, the tolerance surface, and loading, respectively. The first three variables representing the part characteristics contribute the most to the variability of the subassembly surfaces.

In order to estimate the degree of error in the surfaces from nominal, the data from Chapter III which represents the detail parts of an "A" pillar design were analyzed. Figure 5.3 shows histograms of the mean and range of samples of size five. The large majority of the cases 73% show the sample ranges to be less than or equal to .015 in. and 90% less than or equal to .030 in. The sample averages are larger and more distributed, i.e., 55% are within $\pm$ .030 in. These histograms indicate that the variability of the stamping process is small. The distribution of the sample mean indicates larger variability.

The range of a surface deviation is due primarily to the design of the part which dictates the number of stages of the process. The surfaces and their relationship to one another determine the amount of forming that can be done within a given die. The variability due to loading

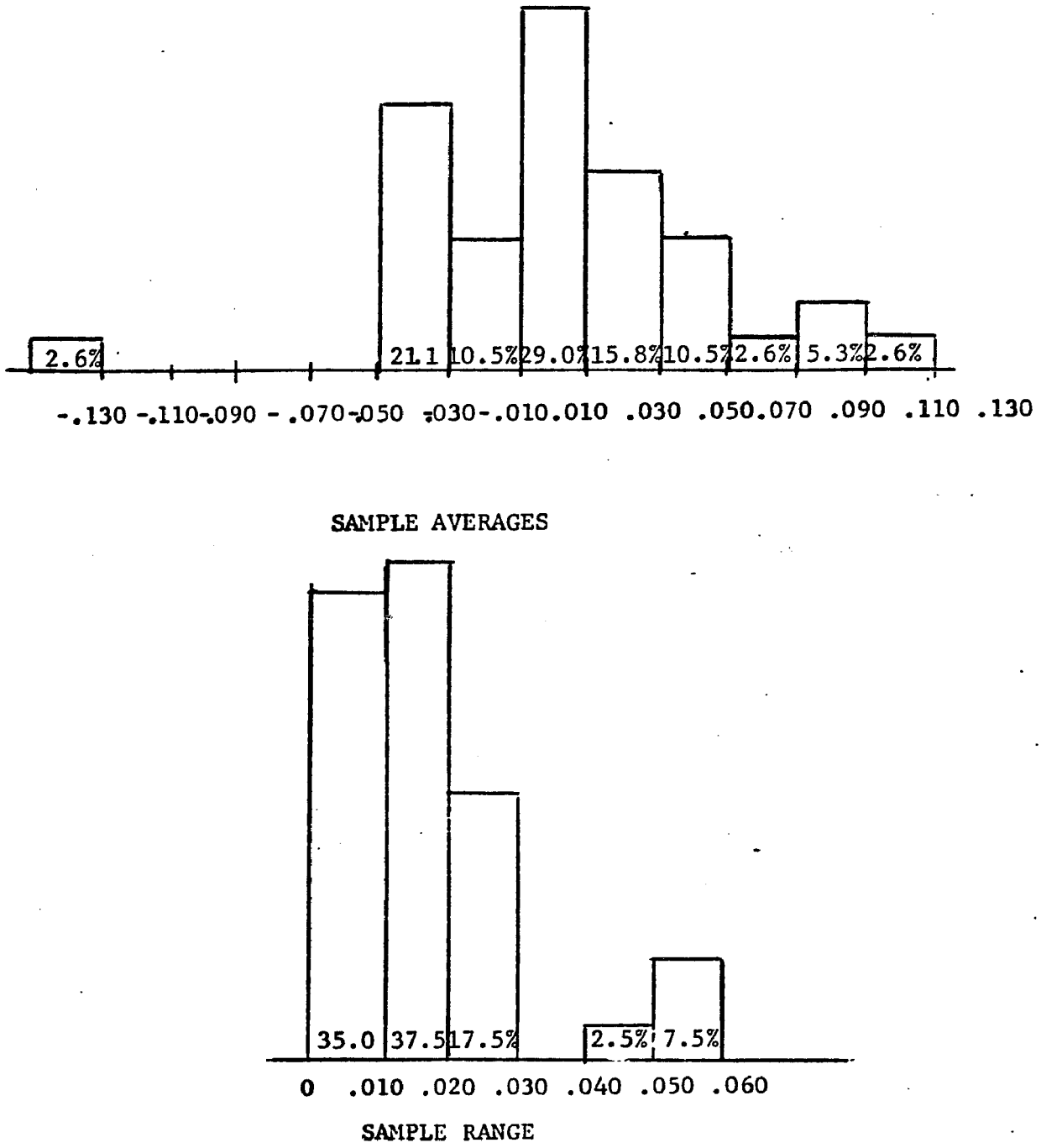


Figure 5.3 Histograms of Sample Means and Ranges "A" Pillar Detail Parts

and gauging deviations increases as the number of stages or dies increase. In order to extract the piece from the die, clearances must be provided between the piece and the location device or features. The greater the clearance the easier the pieces can be located and extracted,and the greater the rate of production. The range of the dimension is determined by the gauging and the number of stages. It is predictable provided good tool maintenance is practiced.

The mean is largely determined by the construction of the die. The mean of the process is established during the die tryout period of a new product launch or start up, and it represents the effort of building the part to the checking fixture. The mean deviation of a surface from nominal is also influenced by different steel compositions and thicknesses and by the amount of spring back from the die position. In addition, the mean dimension is also influenced by the die setter who adjusts the presses for each run of the part. The mean can therefore be expected to change for these reasons from one run to another. The mean will also change as a result of wear to the die, and this is determined by the maintenance effort expended. The mean is then determined by a die tryout effort during preproduction and also by die maintenance throughout the life of the part. The amount of effort expended on these activities is determined by the amount of staffing that is provided by the plant for these functions. The out-of-pocket expense to maintain the mean within reasonable limits should be small. In the event the staffing is not adequate, then the out-of-pocket expense required would be greater.

Burr [6] and Mansoor [24] have developed models for the dimensional characteristics of a part. The model that is proposed here is similar to the one described by Mansoor because it assumes that the mean deviation from the dimension mean is equally likely to occur anywhere in a prescribed interval. This is illustrated in the figure 5.4.

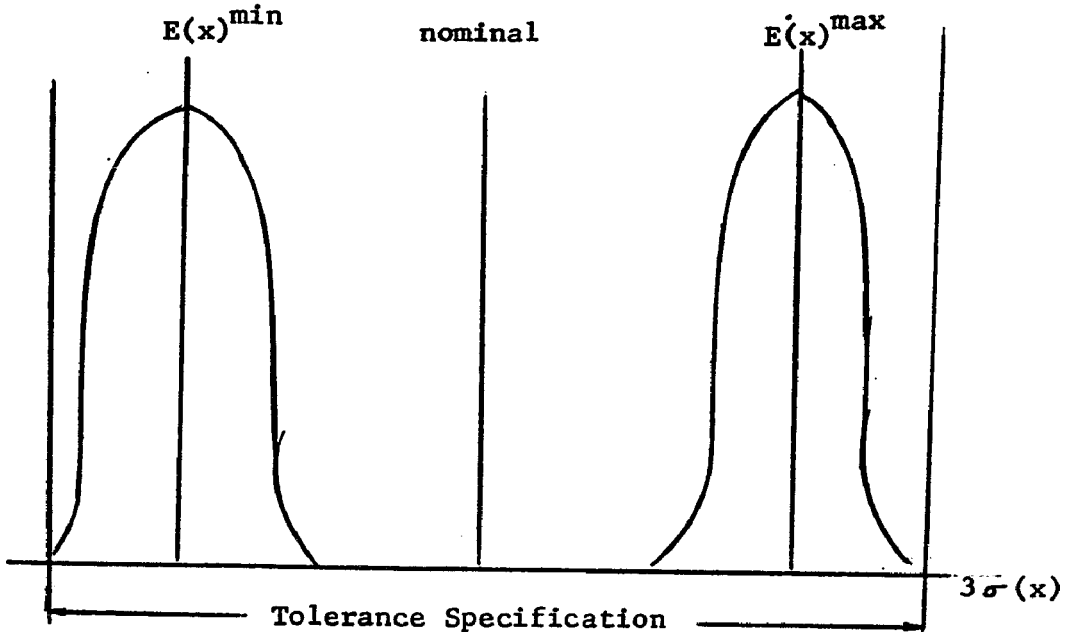


Figure 5.4 Tolerance Interval for Detail Part Dimensions

The notation used for the model is:

$E(x)^{max}$ represents the maximum mean deviation from nominal or the mean deviation in the positive direction

$E(x)^{min}$ represents the minimum mean deviation from nominal or the mean deviation in the negative direction

The positive direction is defined by a normal vector to the nominal surface that directed away from the origin of the coordinate system, i.e., coming out of the surface of the metal.

$\sigma(x)$ represents the standard deviation of the within run variability about the mean. $6\sigma(x)$ then represents the range for the process.

Sp^{max} represents the upper specification limit and equals

$E(x)^{max} + 3\sigma(x)$

Sp^{min} represents the lower specification limit and equals

$E(x)^{min} - 3\sigma(x)$

Sp represents the specification interval and is defined by

$$Sp = Sp^{max} - Sp^{min} = E(x)^{max} + 3\sigma(x) - (E(x)^{min} - 3\sigma(x))$$

$$= E(x)^{max} - E(x)^{max} + 6\sigma(x)$$

As discussed earlier, the value of $\sigma(x)$ is fixed by the process, and $E(x)^{max}$, $E(x)^{min}$ are limits that are controlled by the initial construction and tryout of the die and by maintenance efforts. The interval between $E(x)^{max}$ and $E(x)^{min}$ provides for between run shifts of the mean and process drift due to die wear. Process averages outside this interval require maintenance attention.

The most appropriate point of process control for the body assembly process is at the detail part level. The characteristics of the detail parts should therefore fall within the tolerance specification for which the design was evaluated and accepted.

5.4 THE LEAST COST TOLERANCING PROBLEM

The methodology in Chapter IV permits the tolerancing of the assembly when the tolerances of the detail part surfaces are known. This procedure also predicted gaps at weld joints for different classes of fit and design clearances. The problem considered here is the allocation of tolerances to surfaces and tooling features in order to satisfy dimensional constraints on surface deviations from nominal and for gaps and interferences at weld joints according to some economic criteria. Section 5.2 discussed the repair and warranty costs of quality and process failures. These costs are of sufficient magnitude that practical dimensional specifications must

be developed for the openings and weld joints. The appropriate point of control for a given design then is the detail part dimensions in order to satisfy these assembly process specifications.

These specifications include:

1. Opening and seal surface tolerances based on sealing system parameters
2. Maximum deviations from nominal for surfaces to be restrained by mastered tooling
3. Maximum permissible gaps at surfaces to be welded and sealed.

These specifications would be developed during the review of the design as detailed in the last chapter. It is expected that seal design, welding process, and body structural analysis engineers would participate in the review of these specifications.

The model used for detail part deviations from nominal is based on the extreme mean deviations from nominal. The tolerance specifications for the component parts will be smaller due to the arithmetic summation of the extreme mean values. This method has the advantage that it is easier to understand and to demonstrate the part bias. Section 5.3 shows clearly that the variation within a run of part is very small. The extreme limits then become decision points for small samples to correct the dies. As experience with the dimensions of detail parts is obtained, a process mean can be used and a total variance about the mean can be estimated using the approach suggested by Burr (6).

The evaluation of the body structure design as described in the previous chapter results in the design path and functional relationships for each surface and for each joint to be welded.

These relationships can be used to define the constraints for the allocation problem. The problem becomes the selection of those extreme means for each surface in order to minimize the total cost of die tryout and die maintenance. These extreme means must satisfy the opening tolerances, restraining tolerances and maximum permissible gaps at weld joints. Appendix D contains the formulation of the problem where the objective function and constraint equations are linear.

CHAPTER VI

SUMMARY AND RECOMMENDATIONS FOR FURTHER RESEARCH

This chapter summarizes the research that was done to define the problem and help solve the problem. The tolerancing of sheet metal subassemblies is accomplished under stated assumptions. Also, this chapter recommends further research to relax the assumptions and to gain further knowledge concerning the design of the product and the process.

6.1 SUMMARY

This research studied the assembly operations of the automobile assembly process from the view point of process capability and control of many serial work systems. The primary objective of the study was to improve the quality of vehicles shipped to the dealer, in order to reduce warranty claims due to assembly defects. Process control experiments, which used in-process indicators as signal detectors of process failures, showed that profitable investments could be made by reducing the defect rate of a large number of operations. Reduction of these process failures resulted in a decrease of quality containment and repair costs.

The plant inspection and repair system was also able to cope with the more random failures, further reducing the likelihood of assembly defects that require servicing by the dealers. These experiments concluded that approximately two thirds of the operations that had high defect rates were the result of processes and procedures under the control of the corporation. Study of these operations showed that fits and leaks, due to body sealing, were the major problems all related to the assembly of the body.

Study of the body assembly process and controls clearly showed that the process was not building openings within the prescribed opening tolerances. Chapter II describes the process and the major process indicators that were used in reaching this conclusion. The control procedures used by the plant resulted in adjustments to the assembly tooling, which appeared to do very little to improve the conformance of openings to specifications. Tolerances were not available for the subassembly checking fixtures. Very little emphasis was placed on subassembly control by the plant being studied.

Chapter III describes a capability study that was performed using mastered tooling and current production parts. This study showed that tooling that contained no deviations or adjustments produced some openings within tolerance, while other openings had dimensional characteristics that were similar to the production tooling. This study also concluded that the attempts to shift the process by tooling adjustments resulted in larger opening variances. A component of variance analysis was also performed to determine if the differences between tooling units constituted a significant contribution to the variance. This study concluded that the largest component of variance was due to the within gate variance. Dimensional models are developed in chapter II that describe the deviations from nominal of body surfaces due to the tooling and subassembly relationships. Chapter III estimates their contribution to the total variability in the body.

An analysis of the holding concepts used by the assembly tooling and the relationships between mating parts and opening dimensions was performed. An experiment to predict the dimensions of openings using

premeasured subassemblies resulted in very low correlation between relationships in the body and in checking fixtures. Investigation into reasons for poor correlation lead to the conclusion that checking fixture holding concepts did not agree with the assembly tooling and in some cases, the relationships between parts and the tooling precluded the correct mating of surfaces. The conclusion was made that the subassemblies should be toleranced and gauged so that the tooling can locate surfaces with little or no interference.

The capability of the subassembly process was also studied. The tolerances on detail parts were found to be very difficult to interpret based on functional gauging procedures. Samples of details that formed a subassembly were measured. The within run variance was found to be small for the great majority of dimensions. The mean or average errors were found to be larger. The major variables are the detail parts and the loading or mastering errors that locate parts relative to each other in the weld fixtures. Relationships were studied where these variables combined in such a manner that the design dimension was difficult to obtain. It was concluded that the design of subassemblies must be evaluated considering the variation that is likely to occur when good manufacturing procedures and controls are practiced.

Chapter IV describes the steps of a procedure to tolerance and evaluate engineering designs of sheet metal subassemblies. Traditionally, the design engineer tolerances his designs for function. The process engineer interacts with the design engineer when the tolerances require very expensive tooling. The tolerancing of sheet metal subassembly designs has not been practiced due to the complexity of the geometry of the design and the specialized knowledge of the die process engineer.

The subassembly process engineer designs a locating and clamping system to obtain good welds and to overcome any discrepancies in the parts. The body assembly process engineer is concerned with obtaining openings within tolerance and sealing the body. In order to obtain the surfaces in the body in a specified tolerance band, a great deal of coordination is required between these engineers.

In addition, the design should be based on the capability of the stamping process. The geometry of the design determines the die process. The degrees of freedom that manufacturing has include the complexity of the dies, the method of gauging surfaces between die stages, and the effort devoted to obtain the desired surface dimensions during the die tryout phase of the process.

The methodology described in Chapter IV defines the coordination problem as the specification of the assembly sequence and the design path for the surfaces in the body. This enables the definition of the gauging surfaces for each part and the mating or stacking surfaces that locate each surface in assembled body position relative to the tooling locating blocks. The advantages of coordinating the design with manufacturing at the initial stages are:

1. Selection of stacking surfaces can be based on structural properties of the design.
2. Definition of the stacking surface permits the determination of the forgiveness of the design and where the assembly process can make adjustments.
3. The die designer is informed of the important surfaces and relationships to be held.

4. The die designer can inform process engineers of the degree of dimensional control over detail part surfaces to expect.
5. The design engineer can geometrically evaluate his design, based on manufacturing variables, for the type of weld joints and clearances between surfaces.
6. The welding and sealing engineers can evaluate the design from their disciplines.

The methodology provides for the determination of the functional equations as a function of the manufacturing variables. The setting of realistic limits for the surface deviations of parts permit the surfaces in the subassembly to be toleranced. Chapter IV also contains a description of the basic tolerancing model used to tolerance one part relative to another.

The tolerancing procedure assumes no distortion or bending of the design due to clamping or weld forces. The procedure permits the calculation of clearances so the parts can be assembled according to design. Tolerances for surfaces are based on normal manufacturing tooling and loading variation.The actual variation of the subassembly surfaces must be determined empirically. The variation should be very close to the predicted due to the engineering and the coordination of the process. The procedure describes experiments to estimate the variability of surfaces in subassemblies and body openings. These experiments determine if the assumptions on loading and stacking errors are realized. The process effects due to clamping and welding are estimated.

The determination of the process capability in the methodology is included so that resources may be allocated early in the program if the process design is not acceptable. Also, feedback is provided on the dimensional performance of the body openings to all design engineers so future designs may show improvements. The availability of capability information permits the state of the process to be monitored easily. This information can be used for control at each stage of the process to prevent the system from being filled with assemblies that are not to specification. Therefore, realistic tolerances on parts and subassemblies permit controls to be placed where they are most effective.

Chapter V describes the variability of part data and provides a model for part dimensions based on extreme mean values that can be realistically achieved. A method of considering the costs of maintaining dimensions within these limits is discussed.

Finally, the least cost tolerancing problem for a subassembly design is formulated. The constraints to be satisfied for this design are the extreme limits for the subassembly surfaces and the limits on gaps between mating surfaces to be joined in the design. The formulation permits a definition of the subassembly design problem in terms of the geometry of the problem, the part dimensions, loading and mastering variables,and the manufacturing constraints above. The costs include the die tryout costs, loading costs and die maintenance costs associated with maintaining surfaces within a specified interval from nominal.

Application of the tolerancing procedure to future designs will provide for greater communication and coordination between product design and process design engineers. This communication should result in designs that are more forgiving and that have small variability with no increase in cost. Smaller variation in body surfaces permit better processes for fitting and sealing body panels with a resultant decrease in repair and warranty costs.

The contribution of this research to the state of technical knowledge in the field of management engineering control of manufacturing is twofold. A methodology has been developed to tolerance sheetmetal subassembly designs. In the past tolerances have not been available. The conformance of detail part surfaces to nominal has been left to the part fabricator. Secondly, a methodology for the design of a process control system has been developed and applied to the automobile industry. The major processes have been modeled as a process. The process factors have been identified and their contribution to dimensional variation estimated.

6.2 RECOMMENDATIONS FOR FURTHER RESEARCH

This section discusses the aspects of the problem that require further research in order to make the methodology more general.

The model that was developed in Chapter IV was based on the following assumptions:

1. All surfaces are approximated by planes
2. All movements on tooling surfaces are assumed to be translations with no rotation.

This model can be generalized to tolerance curved surfaces and to describe slip along curved surfaces. This would include the rotation of the secondary subassembly part about some axis. A tolerancing module could be developed and used as part of a computer aided design program to be used in subassembly and process design to provide insights into the performance of different weld joint designs and holding concepts.

The least cost tolerancing model in Chapter V can be used with detail part capability data and associated costs to develop tolerance intervals for designs. This formulation can be expanded to determine the impact on operating budgets for die tryout and die maintenance.

APPENDIX A

ANALYSIS OF BODY MEASUREMENT DATA

Table A-1 contains the calculations for a goodness of fit test for normality for a selected principal locating point (plp) 150 CL. This plp represents a point on the lower body structure, the sill, in the centerline plane. The test at the 5% levels fails to reject the hypothesis of normality. Table A-2 at the 5% level contains the results of a significance test for nomality based on sample values of skewness and kurtosis. The centerline plp's have most values of skewness within the interval from -.050 to .50 and kurtosis values close to 3.00. These plp's have little part distortion and the deviations are primarily the results of errors. The bottom 0 readings of deviations for plp 101 L and 150 L are clearly not normal. Plp 101 L represents the centerline of a notch, while plp 150 represents points on a sill. The non-normality of these points can be explained by the notch and by distortion of the sill. The remaining plp deviations are considered to be normally distributed.

TABLE A-1

CHI-SQUARE TEST FOR A PRINCIPAL LOCATING POINT

UPPER LIMIT OF GLASS INTERVAL X	LIMITS IN STANDARD UNITS $Z=(x-\bar{x})/s$	REL. FREQ. FROM $-\infty$ TO Z	REL. FREQ. OF CELL	ABS. THEOR. FREQ. f	ACTUAL FREQUENCY F	F - f	$(F-f)^2$	$\frac{(F-f)^2}{f}$
-.128	-1.523	.0643	.0643	4.4	8	+3.6	12.96	2.95
-.096	- .9008	.1841	.1198	8.3	5	-3.3	10.89	1.31
-.080	- .5895	.2776	.0935	6.5	10	+3.5	12.25	1.88
-.064	- .2782	.3897	.1121	7.7	5	-2.7	7.29	.95
-.048	+ .0329	.5120	.1223	8.4	12	+3.6	12.96	1.54
-.032	+ .3444	.6331	.1211	8.4	4	-4.4	19.36	2.30
-.016	+ .6556	.7442	.1111	7.8	6	-1.8	3.24	.41
.00	+ .9669	.8315	.0873	6.0	7	+1	1.0	.17
+.016	+1.278	.8980	.0665	4.5	6	+1.5	2.25	.50
+.128	+3.45	1.000	.1020	7.0	6	-1	1	.14
				69	69			10.15

1. Sample size = 69
2. Sample mean = -.0497 in.
3. Sample standard deviation = .0514 in.
4. Rejection point $X^2_{.05,7} = 14.1$

TABLE A-2

TESTS FOR NORMALITY BASED ON SKEWNESS AND KURTOSIS OF BODY MEASUREMENTS

PLP	NO. OBS.	ACTUAL		THEORETICAL		HYPOTHESIS: SAMPLE IS NORMAL	
		SKEWNESS	KURTOSIS -3.00	SKEWNESS	KURTOSIS -3.00	SKEWNESS	KURTOSIS
101 BO LEFT	60	1.35	2.47	0.492	0.57	REJ.	REJ.
150 BO LEFT	66	-0.47	1.36	0.472	0.57	ACC.	REJ.
172 BO LEFT	63	-0.19	-.043	0.482	-0.49	ACC.	REJ.
150 CL LEFT	69	0.54	0.36	0.462	0.57	REJ.	ACC.
102 CL LEFT	67	-0.35	-.086	0.469	-.049	ACC.	REJ.
210 CL LEFT	67	-0.10	-0.26	0.469	-0.49	ACC.	ACC.
202 CL LEFT	67	-0.23	-0.23	0.469	-0.49	ACC.	ACC.
150 CL RIGHT	61	0.14	-0.10	0.489	-0.49	ACC.	ACC.
202 CL RIGHT	54	0.04	-0.76	0.517	-0.49	ACC.	REJ.
210 CL RIGHT	63	0.43	-0.53	0.482	-0.49	ACC.	REJ.

Significance level = .05

APPENDIX B

TESTS OF HYPOTHESIS FOR THE MEANS AND VARIANCES OF OPENINGS BETWEEN PRODUCTION AND EXPERIMENTAL BODIES

The opening sizes and body relationships were computed by taking the differences between principal locating point measurements. The sample means and standard deviations of these relationships were computed for samples of the experimental bodies, the production bodies, and the bodies from a second assembly plant. The openings for the experimental bodies were compared with each of the production samples. Tests of hypothesis for the sample means and sample standard deviations were performed for both comparisons at the 5% level. Table B-1 shows the relationships where a significant difference existed either in the mean or standard deviation for the experimental and production bodies at the first plant. This table also shows the adjustments that were performed on production tooling to eliminate any bias in the openings.

Table B-2 shows a similar comparison between the experimental and production bodies from the second assembly plant. The practice at this plant was to adjust each gate for bias rather than the entire gate line. The fewer number of relationships with larger variance, 4 versus 8, at this plant indicate that the adjustments were made with greater care and the maintenance of the tooling was also more effective.

TABLE B-1

TESTS OF HYPOTHESIS FOR MEANS AND VARIANCES
PRODUCTION VERSUS EXPERIMENTAL BODIES

RELATIONSHIP	$H_0: \bar{x}_{prod} = \bar{x}_{Exp}$	$\bar{x}_{prod}$ Smaller	$\bar{x}_{prod}$ Larger	$H_0: S^2_{Prod} = S^2_{Exp}$	S^2_{Prod} Larger	Tool Deviations in Production Gates
Door Width Upper Left	No		X	Yes		A Post Forward .120" both sides
Backlight Depth Right	No	X		Yes		
Windshield Depth Left	No		X	Yes		A Post Forward .120" both sides
Right	No		X	Yes		
Door Height Rear Left	No	X		No	X	Sill Upwards .120"
Right	Yes			No	X	Sill Upwards .060"
Door Height Front Left	No	X		No	X	Sill Upwards .120"
Right	Yes			No	X	Sill Upwards .060"
Windshield Height Left	No	X		No	X	Cowl top..060" down. A Pillar Forward .120"
Right	No		X	No	X	Cowl top .060" down A Pillar Forward .120"
Backlight Width	No	X		Yes		
Windshield Width	No	X		No	X	A pillar .060" outboard
Roof Rail Width Front	-			No	X	A pillar .060" outboard

TABLE B-2

TESTS OF HYPOTHESIS FOR MEANS AND VARIANCES OF BODY RELATIONSHIPS
PLANT NO. 2 VERSUS EXPERIMENTAL BODIES

RELATIONSHIP	$\bar{x}_2 = \bar{x}_{2\,Exp}$	$\bar{x}_2$		$S_2^2 = S_{2\,Exp}^2$	S_2^2	
		Smaller	Larger		Smaller	Larger
Backlight Depth Left	No	*		Yes		
Windshield Depth Left	Yes			No		X
Door Height Rear Left	No	X		Yes		
Right	No	X		No		X
Door Height Front Left	No	X		No		X
Right	No	X		Yes		
Windshield Height Left	No	X		No		X
Right	No		X	Yes		
Deck Opening Width	No	X		Yes		
Backlight Width	No		X	No	X	
Roof Rail Width Rear				No	X	

* Absolute deviations are equal .139 inches versus -.140 inches

APPENDIX C

RESOLUTION OF DEVIATIONS NORMAL TO THE METAL SURFACE INTO REFERENCE PLANE COORDINATES

Resolution of deviations normal to the metal surface into reference plane coordinates.

Objective: The deviations that are obtained from checking fixtures are recorded in a plane that is normal to the surface of the metal. In order to compare these deviations with deviations from nominal obtained from surface plate measurements the deviations must be resolved into components in each of the three reference planes.

Procedure:

The principal locating point is defined by passing a reference plane through the body. The point is then located at the intersection of the plane with a physical line on the metal surface. The angle that this reference plane makes with the normal vector to the surface must be obtained. The angle that the component of this normal vector in the reference plane makes with one of the two remaining planes must be obtained. The component deviations can be resolved from the normal deviation D by the following equations:

$$D_x = D \sin \alpha \cos \theta$$

$$D_y = D \cos \alpha \cos \theta$$

Example:

An example of this resolution is applied to a deviation measured on the "A" pillar in its checking fixture. The deviation is found on the surface of the "A" pillar roof mating surface at the 23" line with respect to the centerline plane. The deviation D is measured in the checking fixture with a feeler gauge to a target value which is normal to the surface of the metal at this point.

The deviation from nominal with respect to the front 0 and bottom 0 plane is required.

Figure C-1 shows how the angle $\theta = 4^{\circ}$ is estimated.

Figure C-2 gives $\alpha = 31^{\circ}$

The component of the deviation D with respect to the bottom 0 plane is:

$$= D \cos \alpha \cos \theta$$

$$= D \cos 31^{\circ} \cos 4^{\circ}$$

$$= 0.85\ D$$

The component of D with respect to the front 0 plane is:

$$= D \sin \alpha \cos \theta$$

$$= D \sin 31^{\circ} \cos 4^{\circ}$$

$$= 0.51D$$

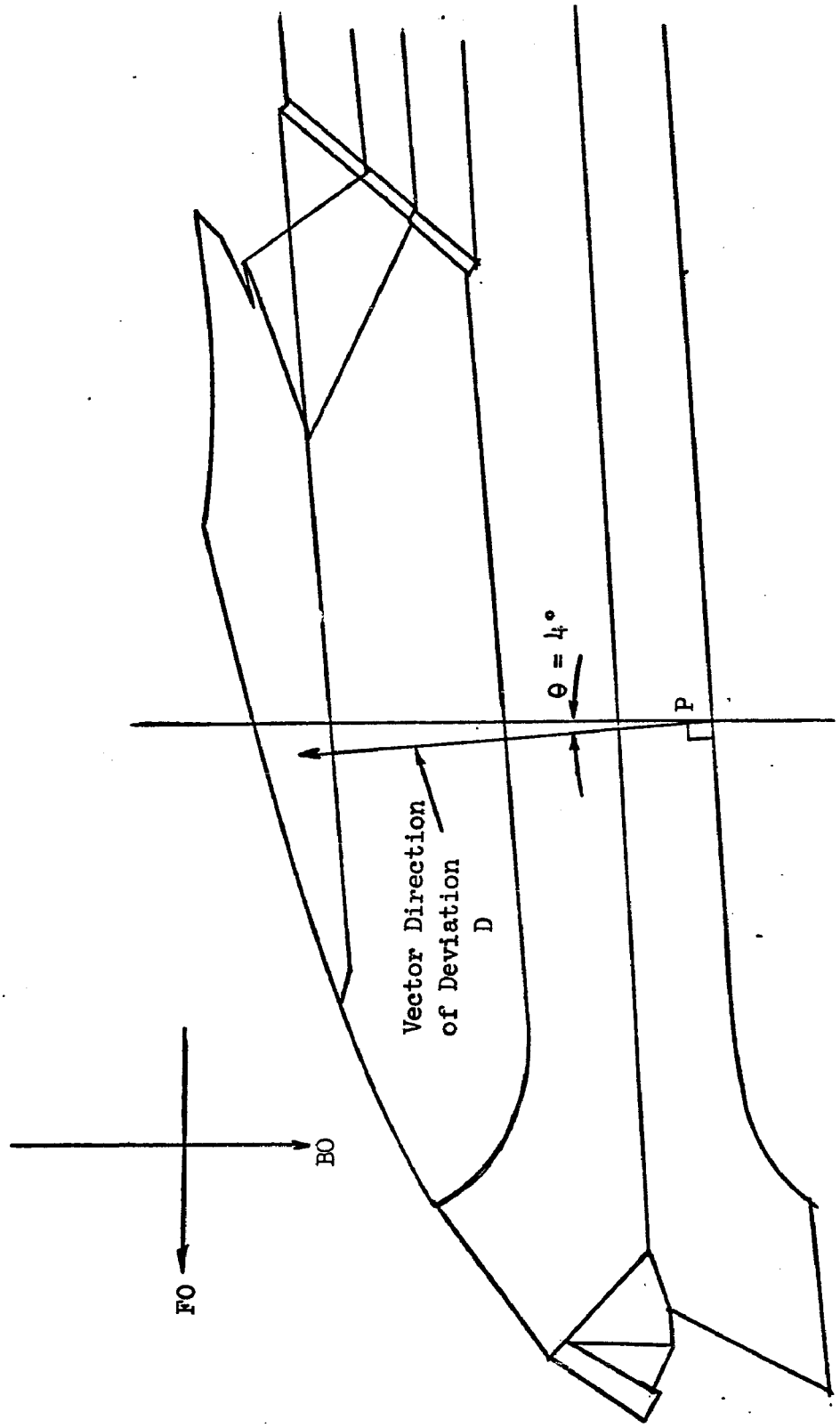


Figure C-1 Front View of Nominal Subassembly Surface

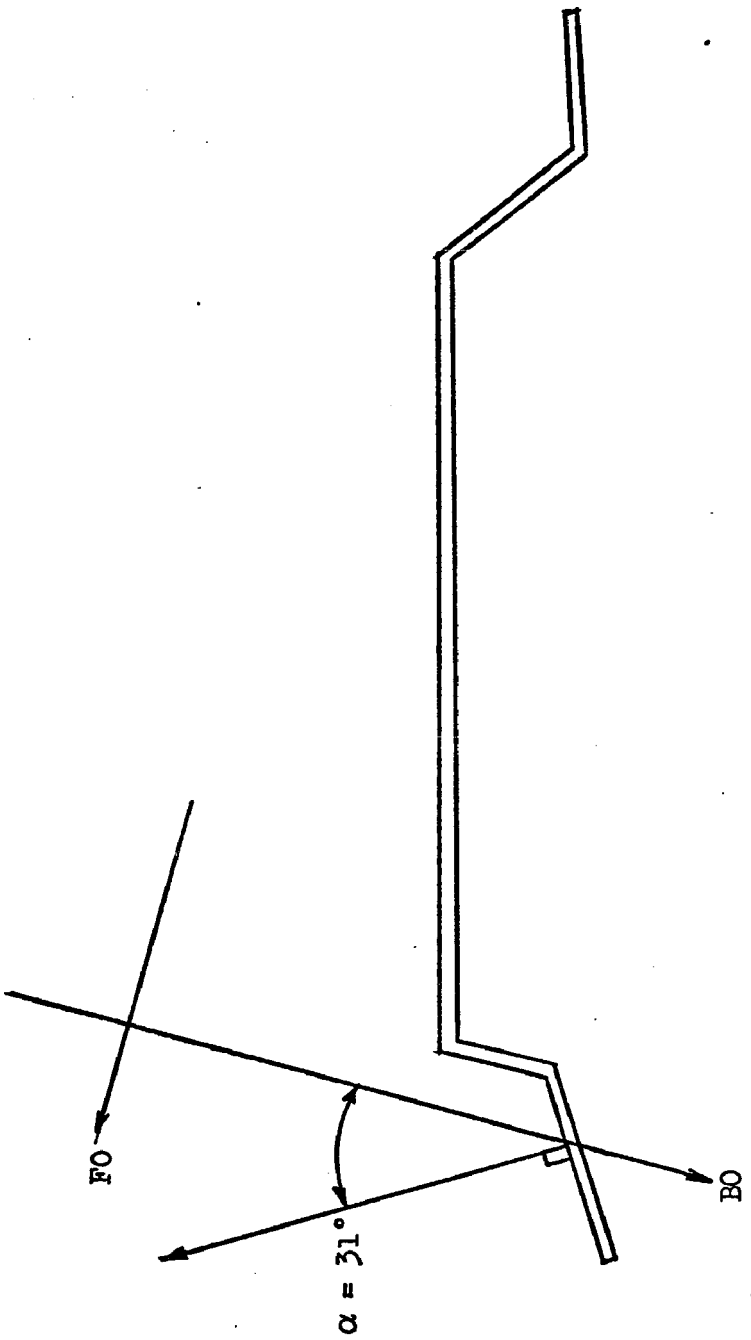


Figure C-2 Section Showing Nominal Subassembly Surface

APPENDIX D

FORMULATION OF THE LEAST COST TOLERANCING PROBLEM

The functional equations for surfaces and gaps that were developed for the examples in the text were of the following linear form:

$$x_{si} = a_{ii}\, x_{pi} + a_{i,u+v+1}\, x_{s1} + a_{i,u+v+2}\, x_{s2} + a_{i,u+v+3}\, x_{L1} \quad \text{for surface } i, \quad i = 1 \text{ to } u$$

and

$$x_{gj} = a_{u+j,u+j}\, x_{pj1} + a_{u+j,u+v+1}\, x_{s1} + a_{u+j,u+v+2}\, x_{s2} + a_{u+j,u+v+3}\, x_{L1} + a_{u+j,u+v+3+j}\, x_{pj2}$$

for gap j $\quad j = 1, \ldots v$

The independent variables x_{Pi}, x_{s1} and x_{s2}, x_{L1} represent deviations from nominal of the tolerance surface, stacking surfaces, and tooling surface, respectively. The coefficients $a_{p,q}$ are functions of the vectors $\vec{K}$, $\vec{L}$, $\vec{M}$, $\vec{P}$, $\vec{N}_i$, $\vec{N}_{j1}$, and $\vec{N}_{j2}$ which represent the geometry of the stacking surfaces, locating blocks and the toleranced surface.

The random variables are the deviations from nominal , and the tolerance specifications for these variables can be written as:

$$S_{pi}^{min} \leq x_{pi} \leq S_{pi}^{max}$$

where S_{pi}^{max} is the upper extreme limit and is equal to

$$E[x_{pi}]^{max} + 3\sigma[x_{pi}]$$

S_{pi}^{min} is the lower extreme limit and is equal to

$$E[x_{pi}]^{min} - 3\sigma[x_{pi}]$$

The standard deviation, for the deviations from nominal of the surface, $\sigma[x_{pi}]$ is estimated for the die process and gauging as discussed in section 5.3. The remaining random variables x_{s1}, x_{s2} and x_L have tolerance specifications defined similarly.

The tolerance specifications for the subassembly surfaces can be expressed in terms of the part and loading extreme mean values as follows:

$$S_{si}^{max} = E[x_{si}]^{max} + 3\sigma[x_{si}]$$

$$S_{si}^{min} = E[x_{si}]^{min} - 3\sigma[x_{si}]$$

where

$$E[x_{si}]^{max} = a_{i,i}E[x_{pi}]^{r} + a_{i,u+v+1}E[x_{si}]^{r} + a_{i,u+v+2}E[x_{s2}]^{r} + a_{i,u+v+3}E[x_{L}]^{r}$$

$$E[x_{si}]^{min} = a_{i,i}E[x_{pi}]^{s} + a_{i,u+v+1}E[x_{sl}]^{s} + a_{i,u+v+2}E[x_{s2}]^{s} + a_{i,u+v+3}E[x_{L}]^{s}$$

$$r = \begin{cases} \text{max, when } a_{i,i};\ a_{i,u+v+1};\ a_{i,u+v+2};\ a_{i,u+v+3} \geq 0 \\ \text{min, otherwise} \end{cases} \qquad i = 1,..,u$$

$$s = \begin{cases} \text{min, when } a_{i,i};\ a_{i,u+v+1};\ a_{i,u+v+2};\ a_{i,u+v+3} \geq 0 \\ \text{max, otherwise} \end{cases}$$

and

$$\sigma[x_{si}] = [a_{i,i}^2\,\sigma^2[x_{pi}] + a_{i,u+v+1}^2\,\sigma^2[x_{si}] + a_{i,u+v+2}^2\,\sigma^2[x_{s2}] + a_{i,u+v+3}^2\,\sigma^2[x_{L}]\,]^{1/2}$$

The constraints or specification limits on the subassembly surface are expressed by:

$$E[x_{si}]^{max} + 3\sigma[x_{si}] \leq e_i \quad \text{or} \quad E[x_{si}]^{max} \leq e_i - 3\sigma[x_{si}]$$

$$E[x_{si}]^{min} - 3\sigma[x_{si}] \geq f_i \quad \text{or} \quad E[x_{si}]^{min} \geq f_i + 3\sigma[x_{si}]$$

The specifications for gaps can also be expressed in terms of the extreme limits for the surface deviations from nominal similarly. The expression for the gap j,

$$x_{gj} = a_{u+j,u+j}x_{pj1} + a_{u+j,u+v+1}x_{s1} + a_{u+j,u+v+2}x_{s2} + a_{u+j,u+v+3}x_{L} + a_{u+j,u+v+3+j}x_{pj2}$$

can be interpreted as a gap if $x_{gj} \geq 0$ and as an interference if $x_{gj} < 0$. The specifications for weld joints can then be expressed as d_j which represents the maximum gap and F_j which represents the class of fit by the maximum possible interference permitted by the surfaces. Therefore

$$E[x_{gj}]^{max} + 3\sigma[x_{gj}] + DC_j \leq d_j$$

where DC_j represents the design clearance as a deviation from nominal that

is designed into the joint. This expression states that the maximum gap cannot exceed a value d_j.

The constraint on the amount of interference is expressed by $E[x_{gj}]^{min} - 3\sigma[x_{gj}] + F_j + DC_j \geq 0$ This implies that with the selected value of design clearance the permissible interference cannot exceed a value F.

The values of $E[x_{gj}]^{max}$, $E[x_{gj}]^{min}$ and $\sigma[x_{gj}]$ are determined from

$$E[x_{gj}]^{max} = a_{u+j,\,u+j}E[x_{pj1}]^{r} + a_{u+j,u+v+1}E[x_{s1}]^{r} + a_{u+j,u+v+2}E[x_{s2}]^{r} + a_{u+j,u+v+3}E[x_{L}]^{r} + a_{u+j,u+v+3+j}E[x_{pj2}]^{r}$$

$$E[x_{gj}]^{min} = a_{u+j,u+j}E[x_{pj1}]^{s} + a_{u+j,u+v+1}E[x_{s1}]^{s} + a_{u+j,u+v+2}E[x_{s2}]^{s} + a_{u+j,u+v+3}E[x_{L}]^{s} + a_{u+j,u+v+3+j}E[x_{pj2}]^{s}$$

$$r = \begin{cases} \max \text{ when } a_{u+j,u+j};\ a_{u+j,u+v+1};\ a_{u+j,u+v+2};\ a_{u+j,u+v+3};\ a_{u+j,u+v+3+j} \geq 0 \\ \min \text{ otherwise} \end{cases}$$

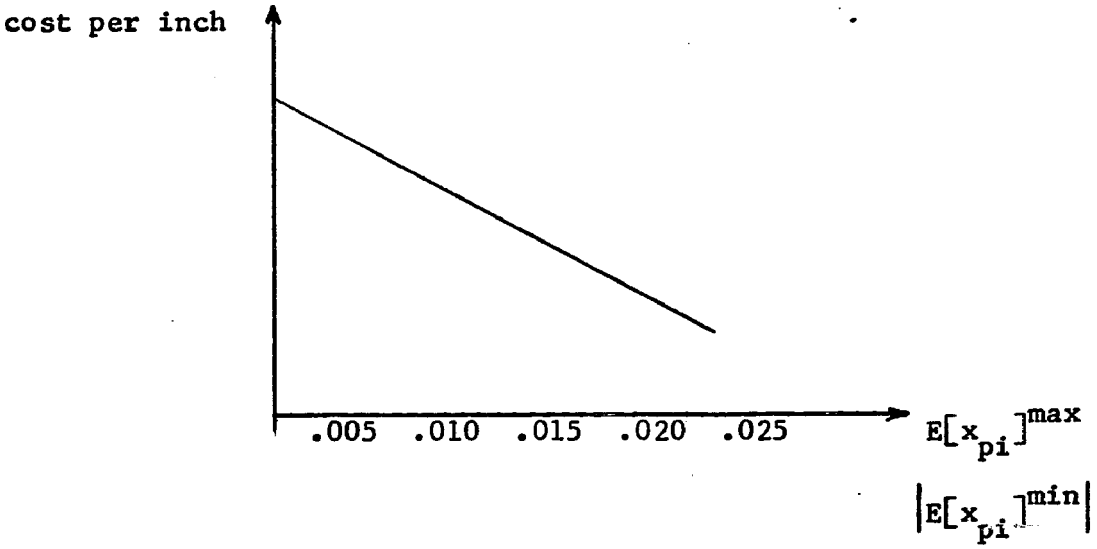
$$s = \begin{cases} \min \text{ when } a_{u+j,u+j};\ a_{u+j,u+v+1};\ a_{u+j,u+v+2};\ a_{u+j,u+v+3};\ a_{u+j,u+v+3+j} \geq 0 \\ \max \text{ otherwise} \end{cases}$$

and $$\sigma[x_{gj}] = [a^2_{u+j,u+j}\,\sigma^2[x_{pj1}] + a^2_{u+j,u+v+1}\,\sigma^2[x_{s1}] + a^2_{u+j,u+v+2}\,\sigma^2[x_{s2}] + a^2_{u+j,u+v+3}\,\sigma^2[x_{L}] + a^2_{u+j,u+v+3+j}\,\sigma^2[x_{pj2}]\,]^{1/2}$$

The problem is to select those values of $E[x_{pi}]^{max}$, $E[x_{s1}]^{max}$, $E[x_{s2}]^{max}$, $E[x_{L}]^{max}$, $E[x_{gj}]^{max}$; $E[x_{pi}]^{min}$, $E[x_{s1}]^{min}$, $E[x_{s2}]^{min}$, $E[x_{L}]^{min}$, $E[x_{gj}]^{min}$ for i = 1,2,..u surfaces, j = 1,2,..v gaps that minimize cost..

The cost of the tolerancing problem can be the piece cost associated with the different maximum and minimum values of the mean deviation from

nominal. As discussed in section 5.3 the cost associated with these extremes represents the effort of die construction, die tryout and die maintenance, and dimensional control. The cost function can be approximated by a straight line for the values of $E[x_{pi}]^{max}$ and $E[x_{pi}]^{min}$ as shown below:



The cost can be expressed as

$$\text{Cost} = \sum_{i=1}^{u} C_i [E[x_{pi}]^{max} - E[x_{pi}]^{min}] + \sum_{j=u+1}^{u+v} C_j [E[x_{pj1}]^{max} + E[x_{pj2}]^{max} - E[x_{pj1}]^{min} - E[x_{pj2}]^{min}] + C_{u+v+1}[E[x_{s1}]^{max} - E[x_{s1}]^{min}] + C_{u+v+2}[E[x_{s2}]^{max} - E[x_{s2}]^{min}] + C_{u+v+3}[E[x_{L1}]^{max} - E[x_{L1}]^{min}]$$

It is assumed that the values for the standard deviations are fixed for the die process. In the event there are alternative processes with corresponding values of $\sigma[x_p]$ and $\sigma[x_L]$, they may also be included. Their cost function would reflect the differences in production rates and expenditures.

Summarizing the problem we have

Minimize Cost

$$= \sum_{i=1}^{u} C_i [E[x_{pi}]^{max} - E[x_{pi}]^{min}] + \sum_{j=u+1}^{u+v} C_j [E[x_{pj1}]^{max} + E[x_{pj2}]^{max} - E[x_{pj1}]^{min}$$

$$- E[x_{pj2}]^{min}] + C_{u+v+1}[E[x_{s1}]^{max} - E[x_{s1}]^{min}] + C_{u+v+2}[E[x_{s2}]^{max} - E[x_{s2}]^{min}]$$

$$+ C_{u+v+3}[E[x_{L1}]^{max} - E[x_{L1}]^{min}]$$

subject to

$$a_{i,i} E[x_{pi}]^r + a_{i,u+v+1} E[x_{s1}]^r + a_{i,u+v+2} E[x_{s2}]^r + a_{i,u+v+3} E[x_L]^r \leq e_i$$

$$- 3[a_{i,i}^2 \sigma^2[x_{pi}] + a_{i,u+v+1}^2 \sigma^2[x_{s1}] + a_{i,u+v+2}^2 \sigma^2[x_{s2}] + a_{i,u+v+3}^2 \sigma^2[x_L]]^{1/2}$$

$$a_{i,i} E[x_{pi}]^s + a_{i,u+v+1} E[x_{s1}]^s + a_{i,u+v+2} E[x_{s2}]^s + a_{i,u+v+3} E[x_L]^s \geq$$

$$f_i + 3[a_{i,i}^2 \sigma^2[x_{pi}] + a_{i,u+v+1}^2 \sigma^2[x_{s1}] + a_{i,u+v+2}^2 \sigma^2[x_{s2}]$$

$$+ a_{i,u+v+3}^2 \sigma^2[x_L]]^{1/2}$$

for $i = 1,2,\ldots,u$

$$a_{u+j,u+j} E[x_{pj1}]^r + a_{u+j,u+v+1} E[x_{s1}]^r + a_{u+j,u+v+2} E[x_{s2}]^r + a_{u+j,u+v+3} E[x_L]^r +$$

$$a_{u+v+3+j} E[x_{pj2}]^r + DC_j \leq g - 3[a_{u+j,u+j}^2 \sigma^2[x_{pj1}] + a_{u+j,u+v+1}^2 \sigma^2[x_{s1}]$$

$$+ a_{u+j,u+v+2}^2 \sigma^2[x_{s2}] + a_{u+j,u+v+3}^2 \sigma^2[x_L] + a_{u+j,u+v+3+j}^2 \sigma^2[x_{pj2}]]^{1/2}$$

$$a_{u+j,u+j} E[x_{pj1}]^s + a_{u+j,u+v+1} E[x_{s1}]^s + a_{u+j,u+v+2} E[x_{s2}]^s + a_{u+j,u+v+3} E[x_L]^s$$

$$+ a_{u+j,u+v+3+j} E[x_{pj2}]^s - 3[a_{u+j,u+j}^2 \sigma^2[x_{pj1}] + a_{u+j,u+v+1}^2 \sigma^2[x_{s1}]$$

$$+ a_{u+j,u+v+2}^2 \sigma^2[x_{s2}] + a_{u+j,u+v+3}^2 \sigma^2[x_L] + a_{u+j,u+v+3+j}^2 \sigma^2[x_{pj2}]]^{1/2}$$

$$+ F_j + DC_j \geq 0$$

for gap j, $j = 1,2,..,v$

$$\text{where } r = \begin{cases} \max & \text{when } a_{i,i};\ a_{i,u+v+1};\ a_{i,u+v+2};\ a_{i,u+v+3} \\ & \quad a_{u+j,u+j};\ a_{u+j,u+v+1};\ a_{u+j,u+v+2};\ a_{u+j,u+v+2}; \\ & \quad a_{u+j},\ a_{u+v+3},\ a_{u+j};\ a_{u+v+3+j} \\ & \quad \geq 0 \quad \text{for } i = 1,2,\ldots u, \quad j = 1,2,\ldots,v \\ \min & \text{otherwise} \end{cases}$$

$$\text{where } s = \begin{cases} \min & \text{when } a_{i,i};\ a_{i,u+v+1};\ a_{i,u+v+2};\ a_{i,u+v+3}; \\ & \quad a_{u+j,u+j};\ a_{u+j,u+v+1};\ a_{u+j,u+v+2};\ a_{u+j,u+v+3} \\ & \quad a_{u+j,u+v+3+j} \geq 0 \\ & \quad \text{for } i = 1,2,..u, \quad j = 1,2,\ldots v \\ \max & \text{otherwise} \end{cases}$$

$$0 \leq E[x_{pi}]^{max} \leq e_{pi}$$

$$f_{pi} \leq E[x_{pi}]^{min} \leq 0$$

$$i = 1,2,\ldots u$$

$$0 \leq E[x_{pj1}]^{max} \leq e_{pj1}$$

$$f_{pj1} \leq E[x_{pj1}]^{min} \leq 0$$

$$0 \leq E[x_{pj2}]^{max} \leq e_{pj2}$$

$$f_{pj2} \leq E[x_{pj2}]^{min} \leq 0$$

$$j = 1,2,..v$$

$$0 \leq E[x_{s1}]^{max} \leq e_{s1}$$

$$f_{s1} \leq E[x_{s1}]^{min} \leq 0$$

$$0 \leq E[x_{s2}]^{max} \leq e_{s2}$$

$$f_{s2} \leq E[x_{s2}]^{min} \leq 0$$

$$0 \leq E[x_L] \overset{\max}{\leq} e_L$$

$$f_{Ll} \overset{\min}{\leq} E[x_L] \leq 0$$

$$DC_j \geq 0 \quad j = 1,2,\ldots v$$

This formulation permits the determination of the values of the tolerance specifications that satisfy the constraints on surfaces and gaps. In addition the values of design clearance are also determined. It is assumed that there is no cost differentials between different clearances. Changes to the design path and stacking surfaces are accomplished by changing the coefficients a_j's through changing the surface vectors $\vec{K}$, $\vec{L}$, $\vec{M}$, $\vec{P}$, $\vec{N}_i$. Thus several designs can be evaluated by solving a problem for each alternative.

If the cost functions are linear and the standard deviations are fixed values determined by the process, then the minimization problem can be solved by linear programming algorithms. This has the advantage of providing a sensitivity analysis for the different parameters. The sensitivity of the tolerance allocation to changes in the specified surface tolerances and gap specifications can be determined. This method can also be used for tolerance reallocation when more knowledge is available on the capability of the process. The values of the extremes for some surfaces can be fixed and the other tolerances can be reallocated. The linear programming algorithm will also determine if a feasible solution for the problem exists in terms of the specifications.

If the cost functions are nonlinear, or if the standard deviations become variables, then linear programming cannot be used and some other optimization procedure must be employed.

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