

Event-Based Functional Build:
An Integrated Approach to Body Development

July 1999

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Final Report – July 1999

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Preface

This report is one of a series of several reports published by the Auto/Steel Partnership Body Systems Analysis Project Team on stamping and assembly variation, body measurement systems and process validation. These reports provide a summary of the project research and are not intended to be all inclusive of the research effort. Numerous seminars and workshops have been given to individual automotive manufacturers throughout the project to aid in implementation and provide direct intervention support. Proprietary observations and implementation details are omitted from the reports.

This automotive body development report “*Event-Based Functional Build: An Integrated Approach to Body Development*,” updates ongoing research activities by the Body Systems Analysis Team and the Manufacturing Systems staff at The University of Michigan's Office for the Study of Automotive Transportation. This report has two versions. First, an executive version provides a basic overview of functional build and its benefits. A main report then examines functional build in greater detail and addresses many implementation issues. We do note that each version is a stand-alone report, thus, the information in the executive version is a subset of the main report.

An over-riding goal of this research is to develop new paradigms that will drive automotive body-in-white development and production towards a total optimized processing system. Previous reports described fundamental research investigating simultaneous development systems for designing, tooling and assembling bodies, and also flexible body assembly. Since the inception of this research program, considerable emphasis has been focused on benchmarking key world class body development and production processes. These benchmarks created foundation elements upon which further advances could be researched and developed.

This report summarizes recommendations for moving toward a new “functional build” paradigm by tightly integrating the many individual activities ranging from body design and engineering, on through process and tooling engineering. Revised stamping die tryout and buyoff processes receive special emphasis in addition to the launch of stamping and assembly tools.

The researchers are indebted to several global automotive manufacturers for their on-going dedication and participation in this research. They include Daimler-Chrysler Corporation, Ford Motor Company, and General Motors Corporation. Each conducted experiments under production conditions, involving hundreds of hours of effort, often requiring the commitment of many production workers and engineering personnel. Although it may be impractical to mention each one of these people individually, we do offer our sincere appreciation.

These reports represent a culmination of several years of effort by the Body Systems Analysis Project Team. Team membership has evolved over the course of this project. They include:

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Executive Summary

North Automotive manufacturers traditionally have utilized a sequential process validation approach for the automotive body. This approach begins by validating individual components, then small sub-assemblies, ultimately leading up to the finished body. This approach assumes that the quality of each higher level assembly is predicated on the quality of incoming, lower-level components. Validation at each step usually is measured by quality indices such as C_p and C_{pk} . Unfortunately, this sequential approach has proven non-competitive for car bodies, often resulting in missed development schedules and unnecessarily high costs for process rework. Two attributes of sheet metal stamping and assembly processes inhibiting the sequential approach are the inability to produce all component dimensions precisely at their nominal specification, and the weak correlation in dimensions between non-rigid, lower-level components and their assembled counterparts. Manufacturers attribute the deviations from nominal specification to difficulties predicting metal flow during forming operations, as well as the measurement process itself. In addition, no stamping die-maker has shown an ability to significantly shift all part dimensions on a complex part close to nominal on a consistent basis, even after several die-rework iterations. Manufacturers using C_{pk} buyoff indices, ultimately modify tolerances to meet the required threshold to accommodate these mean deviations. Furthermore, the lack of correlation between component dimensions and first-level sub-assemblies suggests that some of this die rework is non-value added. These industry-wide problems have led several manufacturers to adopt a more integrated process validation approach called functional build.

The functional build approach to process development focuses on the customer perceived quality of the final car body when evaluating the need for process changes. This approach shifts the development focus from optimizing individual components to the whole car body, and integrates product, process and manufacturing. Necessary changes are identified based on lowest-cost solutions. These solutions might involve modifications to a product design, a stamping die or an assembly process.

Manufacturers implement functional build using a process called a “screw-body” to attach mating component parts. These parts are screwed (or riveted) in order to isolate the influence of the assembly process. One concern with functional build is the subjective nature in

which decisions are made; research is needed to help quantify decision-making. Since the original specifications become targets under the functional build paradigm, deviations from specification may be partitioned into three regions: obvious die rework changes (large deviations), obvious assembly tooling changes (small deviations) and uncertain rework changes (between small and large deviations) requiring an integrated investigation. This research helps in identifying these regions which should reduce the amount of subjective decision making. By using an integrated validation approach like functional build, manufacturers may accelerate the product development life cycle while saving costs in process development.

This report has two stand-alone versions: an executive version and a main report. Thus, readers may choose the report that is appropriate for their needs. This version is the main report.

1.0 Introduction

The development of the automotive body represents a major challenge for all manufacturers as they continuously strive to reduce the time and cost of bringing a new vehicle to market. Using practices such as concurrent engineering, rapid prototyping and computer simulation, manufacturers have reduced their development costs and lead-time by integrating process engineering and manufacturing into the design phase or front end of body development. Unfortunately, this integration has been far less common from the product and process design phases forward into the manufacturing validation phases.

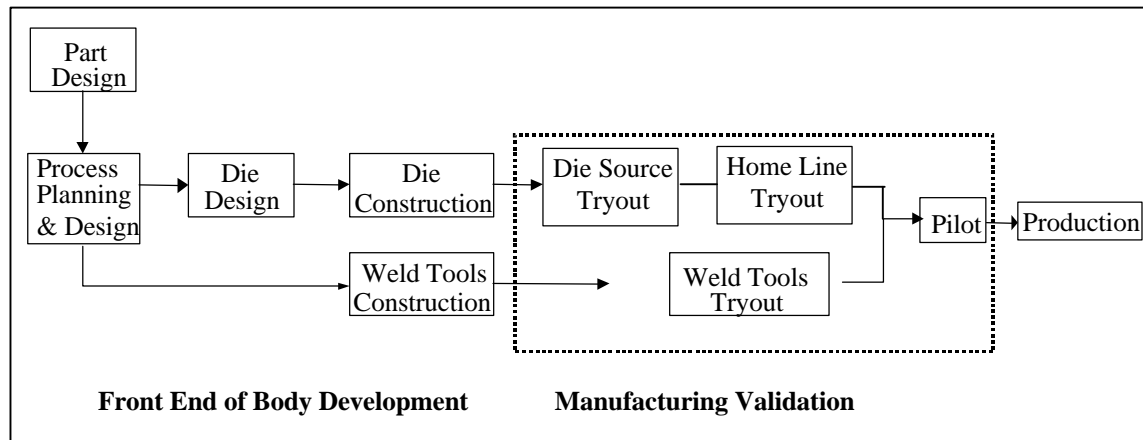


Figure 1. Major Body Development Activities

Figure 1 shows the major stages of body development from part design to final tryout of the assembly process using stamped parts off the home line (production presses). Once designs are released and manufacturing processes are constructed, manufacturers traditionally evaluate their parts using a sequential validation approach (see Figure 2). First, they validate that the processes for stamped components are capable of meeting all design requirements. After each component is approved, manufacturers validate their sub-assembly processes, and finally the complete body-in-white. This sequential approach subscribes to the basic paradigm that final product quality will be maximized if each individual component meets all its performance requirements.

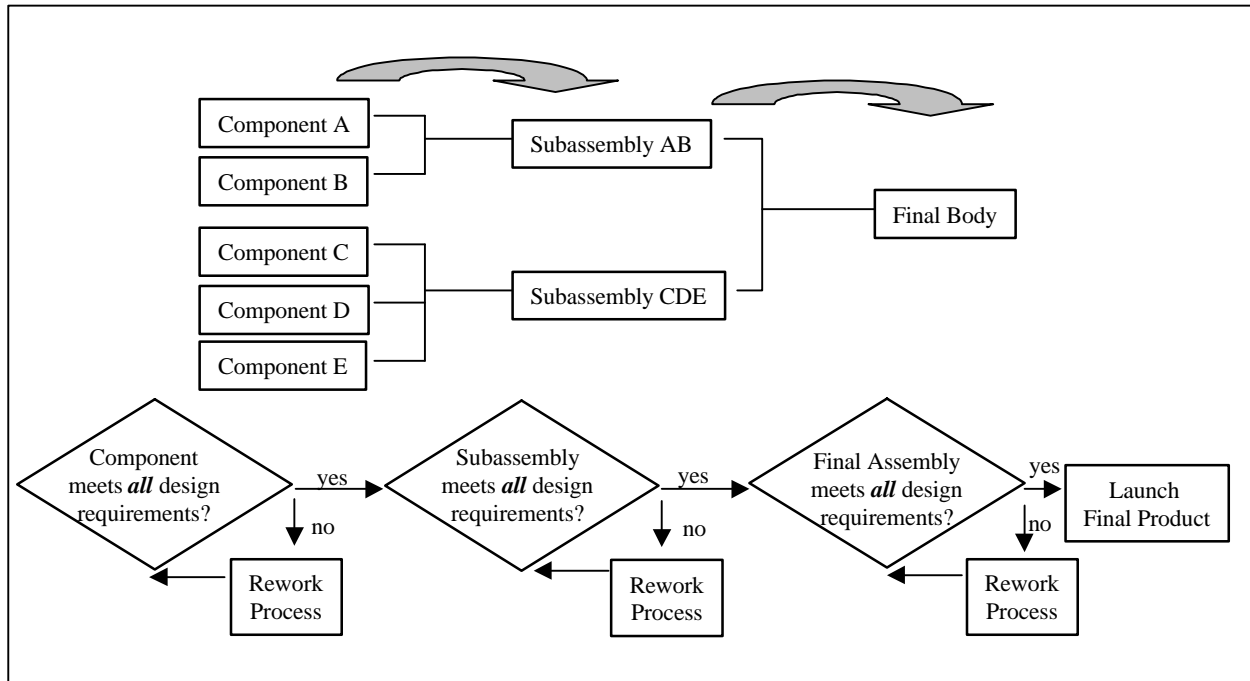


Figure 2. Sequential Manufacturing Validation

Although sequential process validation is logistically simple and has proven effective for many automotive components, few manufacturers have effectively executed this approach for automotive body validation. The principal cause has been difficulties approving all component characteristics to generic requirements such as $C_{pk} > 1.67$. This inability to meet all component requirements subsequently reduces the allotted time to resolve assembly-related concerns because of fixed production start dates for a new model. Even manufacturers relying on C_{pk} evaluation criteria ultimately will abandon the sequential approach because of an inability to meet all their original specifications. In contrast to the traditional sequential approach, several manufacturers have adopted a more integrated validation approach known as *Functional Build*.

1.1 Functional Build: An Integrated Validation Approach

Under functional build, rather than validating components solely to their part print specifications, manufacturers also evaluate components relative to their mating parts and subsequent assembly processes. They strive to produce part dimensions to their original specifications, but they treat these specifications as targets rather than absolute requirements. Thus, if manufacturer experience difficulty meeting a particular component requirement, they

may resolve the problem in a downstream assembly process or change another related, mating component more expediently. By analyzing components in their subsequent assemblies, manufacturers also may find that certain original requirements are not critical to the final product build. Here, a modification to the design print is less expensive than physically changing already-constructed stamping dies.

When functional build is used, manufacturers may realize substantial cost savings over a traditional process and product development life cycle. These savings result from eliminating unnecessary process rework during the validation phase. Under functional build, rework decisions focus on meeting final vehicle objectives and not necessarily on conformance to all original component specifications.

Figure 3 illustrates the basic difference between sequential validation and the functional build approach to dimensional validation decision-making. All manufacturers evaluate the conformance of stamping dimensions to their design specifications. Typically, most dimensions are within their specification limits; but some are not. At this point, manufacturers face a decision. They can either rework the stamping process until all dimensions satisfy the print requirements (traditional sequential approach) or adopt a functional build approach. Under functional build, they may accept certain out-of-specification dimensions that can be corrected in assembly and rework the others. In another scenario, a manufacturer may even allow a deviation from the original design if it is unnoticeable to the customer.

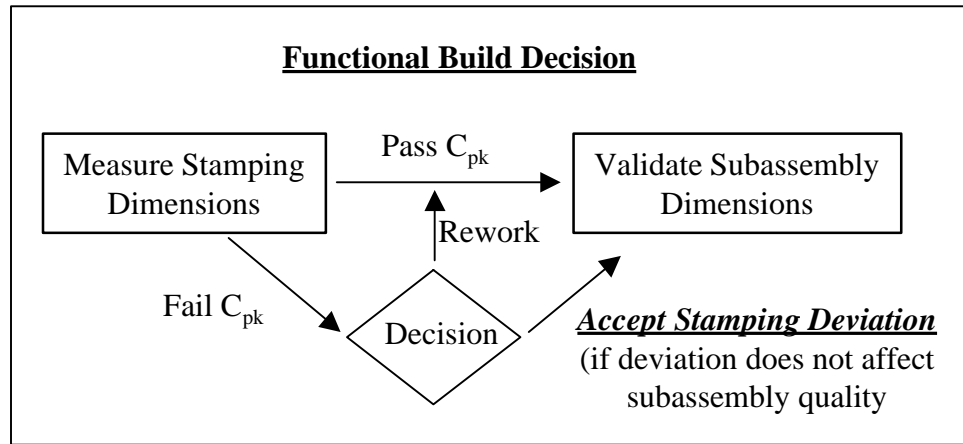


Figure 3. Validating Stamping Processes

The functional build evaluation process typically involves the construction of screw-bodies. Most manufacturers construct screw-bodies off-line using fixtures or bucks. Rather than build special fixtures for each subassembly, some manufacturers add extra locators to sub-assembly check fixtures to allow them to “slow build” the stamped components.

One of the most common misconceptions of functional build is that it evaluates assembly robustness to stamping variation. Functional build manufacturers only build one or two screw-bodies for each sub-subassembly. Thus, the principal effect of constructing screw-bodies is an evaluation of mean deviations and not variation. This requires manufacturers to first establish short-term process stability prior to functional build evaluations.

In the functional build process, manufacturers usually assemble both the sub-assemblies and the full screw-body with screws or rivets instead of the normal welding operations. They use screws or rivets to minimize the distortion of components caused by welding. Thus, screw-body assemblies help to determine whether individual components may feasibly produce an acceptable sub-assembly or final assembly. Manufacturers assume that if the screw-bodies are acceptable, they may eventually set-up weld tools to match them. In certain cases, a manufacturer may produce a screw-body subassembly whose dimensions are unacceptable. This result, however, does not necessarily trigger die rework. Manufacturers may decide to make a simple tool change in assembly to bring the sub-assembly into specification rather than rework the stamping die. Thus, the screw-body process also aids in setting-up and tuning-in welders.

Functional build typically occurs in two phases. In the first phase, manufacturers construct “screw-body” assemblies using parts off regular production dies but at the construction or tooling tryout source. The evaluation process provides a mechanism to conditionally approve parts and subsequently trigger the shipment of dies (“die buy-off”) to the production facility. In this process, manufacturers consider both the actual dimensional measurements of the components and their relationship to mating components. A manufacturer might even choose to rework certain in-specification dimensions if the changes will improve the overall manufacturability or appearance of the final body. The primary objective of this first phase is to correct those problems known to affect subsequent assembly operations, while delaying rework decisions for those dimensions with unknown impacts. The second functional build phase occurs after the dies are shipped to the production facility. The primary objective for this evaluation is to produce a dimensionally acceptable finished body.

Most companies construct the first screw-body sub-assemblies between twelve and fifteen months prior to the start of production. Additional screw-body prototypes are assembled based on need and strategy. For example, manufacturers may construct additional screw-bodies if a part significantly changes during tryout due to a design change or a manufacturing process change. Section 5.0 includes a discussion of the timing of screw-body construction phases in greater detail.

The screw-body process may result in significant changes to the original design without impacting customer expectations. For example, although engineers may symmetrically design the right and left side of a car body, a functionally built body may not have this characteristic. The right side may build a couple of millimeters outward, while the left side may be inward from design intent. As long as this lack of symmetry does not result in structural or appearance problems such as inconsistent body gaps, the customer is unaware of the lack of conformance to the original design. The argument for this approach is that manufacturers should not commit resources to correct deviations from the original design unless the deviations affect customer requirements.

When making an engineering change under the functional build approach, manufacturers search for the least costly alternative without sacrificing product quality. For example, suppose two mating dimensions that are significantly deviating from nominal result in a non-conforming sub-assembly. Here, a functional build manufacturer would rework only one of the parts (the

least expensive) if this change could bring the sub-assembly closer to nominal. In an extreme case, a manufacturer might choose to rework a dimension near its nominal if it is less expensive than reworking a mating out-of-specification dimension. (Note that in observing functional build practices, manufacturers rarely rework dimensions near nominal.)

This functional build rework approach differs from the traditional, sequential validation approach. Under sequential validation, each part is evaluated independently against its design specifications. Thus, a more expensive die or possibly several dies might require modification.

1.2 Research Methodology and Report Outline

The purpose of this report is to show why several manufacturers have adopted a functional build approach and then explore various implementation strategies. Simply put, functional build provides manufacturers with an integrated system to evaluate the effects of stamping and sub-assembly mean deviations (not variation) on the final assembly build. The principal appeal of this approach is to better integrate upstream manufacturing needs into component requirements by shifting the body development focus from individual components to the final body. The overall goal, as with any body dimensional validation strategy, is to minimize overall development costs and timing while still meeting customer requirements.

The supporting data for this report are based on studies of seven manufacturers (General Motors, Ford, Daimler-Chrysler, NUMMI (Toyota), Nissan, Opel and Renault). These manufacturers have provided information on their validation processes. Several manufacturers have augmented descriptions of their validation procedures with dimensional conformance data from die source and production source tryout. In addition, a production case study was conducted at each manufacturer on their body side assembly and the key components comprising it. Manufacturers assembled 36 body sides using individual components with known dimensional characteristics. They obtained the 36 samples for each component across six different production runs (sample of 6 per run). These case studies provide the basis for examining the relationships between stamping dimensional conformance and assembly conformance, in order to identify more effective criteria and procedures to evaluate stamped parts prior to production.

In this report, the evolution of the functional build approach is examined. This approach has arisen in response to three recurring challenges that all manufacturers must overcome to

reduce costs and lead-time for automotive body development. These challenges relate to limitations predicting metal flow in stamping operations, measuring non-rigid stamped components, and assessing the impact of stamping on assembly dimensional conformance. A discussion follows of how certain manufacturers have managed these challenges through the functional build process.

Section 3 presents case studies that highlight why the functional build approach works. Section 4 addresses several functional build implementation issues. Among these issues are potential conflicts between achieving dimensional and timing requirements, the use of the screw-body as a decision tool, the development of evaluation criteria to evaluate stamped parts at the die source, and the organizational requirements necessary to implement a functional build approach. This section also examines several concerns from manufacturers currently using a functional build approach.

Section 5 synthesizes various dimensional validation strategies used across manufacturers into a common functional build process. This common process provides a roadmap for companies trying to implement and/or improve their functional build activities. The last section, Section 6, considers the future of functional build; whether it is a short or long-term strategy for automotive body validation.

2.0 Evolution of the Functional Build Approach

This section examines why several manufacturers have adopted or are experimenting with functional build. Understanding the evolution of functional build requires a fundamental understanding of the recurring challenges with producing and assembling stamped body components. This section examines these recurring challenges and then discusses how functional build has evolved to meet them.

2.1 Recurring Body Development Challenges

Manufacturers have adopted functional build approaches to automotive body development primarily in response to three recurring production validation challenges:

1. An inability to produce component mean dimensions at their nominal specification,
2. Limitations measuring non-rigid components and
3. Weak correlation between component dimensions and their resultant assemblies.

2.1.1 Mean Deviations from Nominal

Ideally, a manufacturer would like to produce each stamped component such that the mean value at each measurement location is at its nominal specification with minimal variation. Unfortunately, all manufacturers produce some component dimensions whose mean values are off nominal. Figure 4 illustrates several potential mean-related issues for a stamping dimension. First, a dimension may deviate from nominal at the die source. Second, a dimension may shift from the die source to the home line. Although this particular dimension shifts away from nominal, some dimensions improve. The main point is that manufacturers cannot assure that rework at the die source will eliminate all mean deviations from the production source (press shop). They must therefore evaluate mean deviations at both the die and production source.

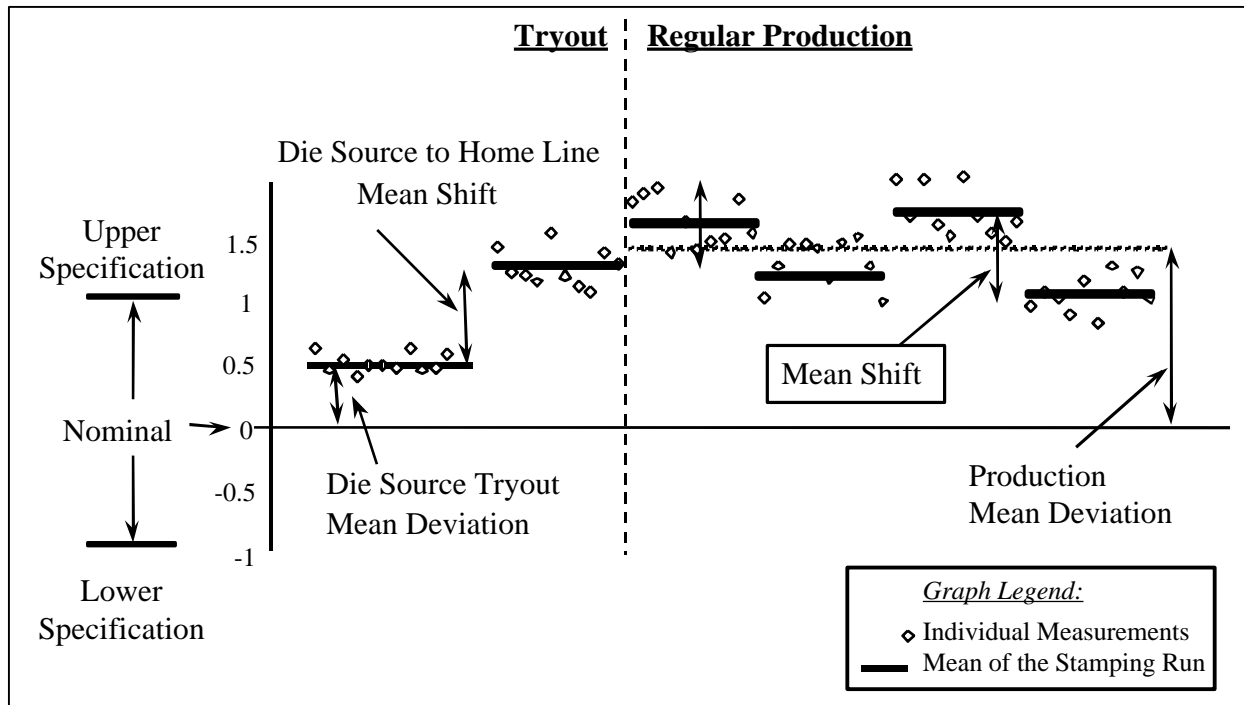


Figure 4. Sources of Variation

Mean conformance is a concern with many stamping dimensions. Figure 5 illustrates five body side assembly components from one of the case studies. These components include two non-complex, rigid parts (Front and Center Pillar Reinforcements), and three complex and/or non-rigid parts (Body Side, Roof Rail Outer, and Windshield Frame).

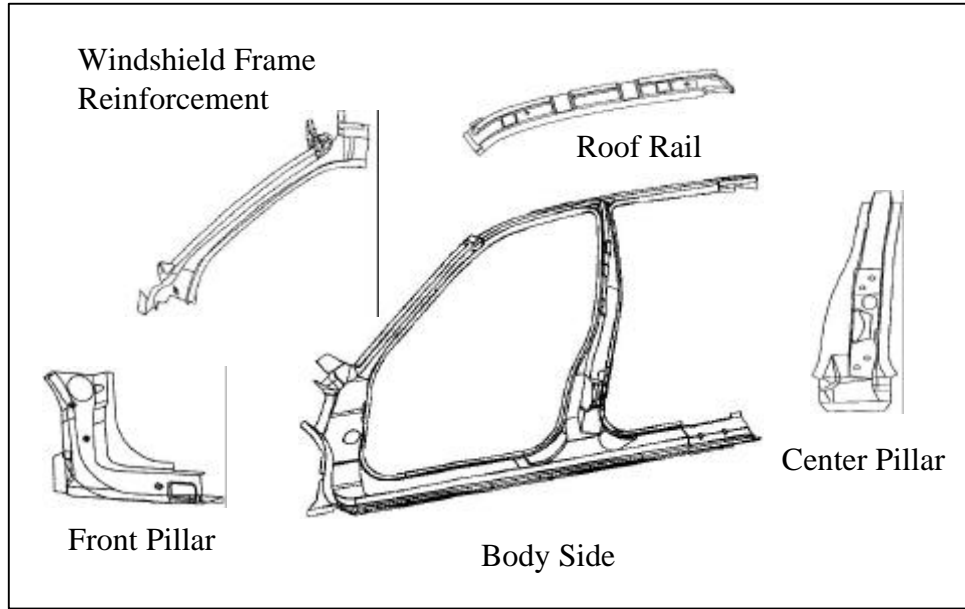


Figure 5. Stamped Components in Body Side Assembly

Figure 6 provides a histogram of the 143 mean dimensions (mean deviations) across these five components. This figure indicates that the die construction and stamping process typically generate parts whose mean deviations are normally distributed.

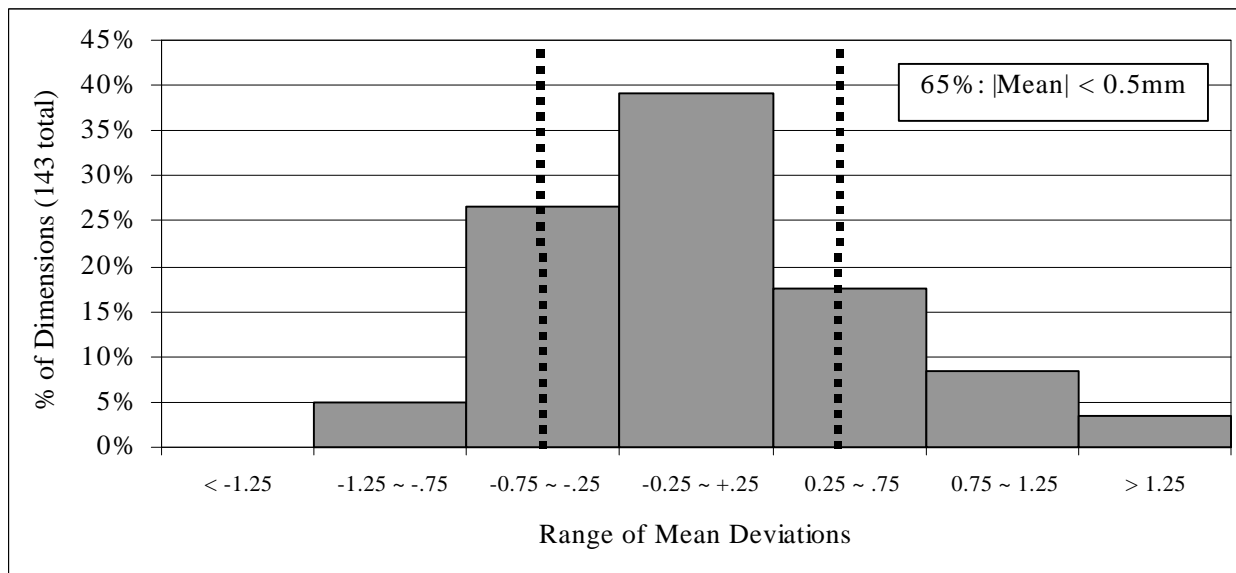


Figure 6. Distribution of Mean Values

This normality of mean deviations typically occurs regardless of whether parts are relatively simple, such as the front and center pillar reinforcements, or complex, such as the body side or quarter panels. Although the mean distribution is approximately normal, some differences exist in the variance of the mean deviation distribution. For example, simple rigid parts typically have a tighter spread of mean deviations. Figure 7 compares the mean deviation distributions for non-rigid panels versus rigid panels at Company A.

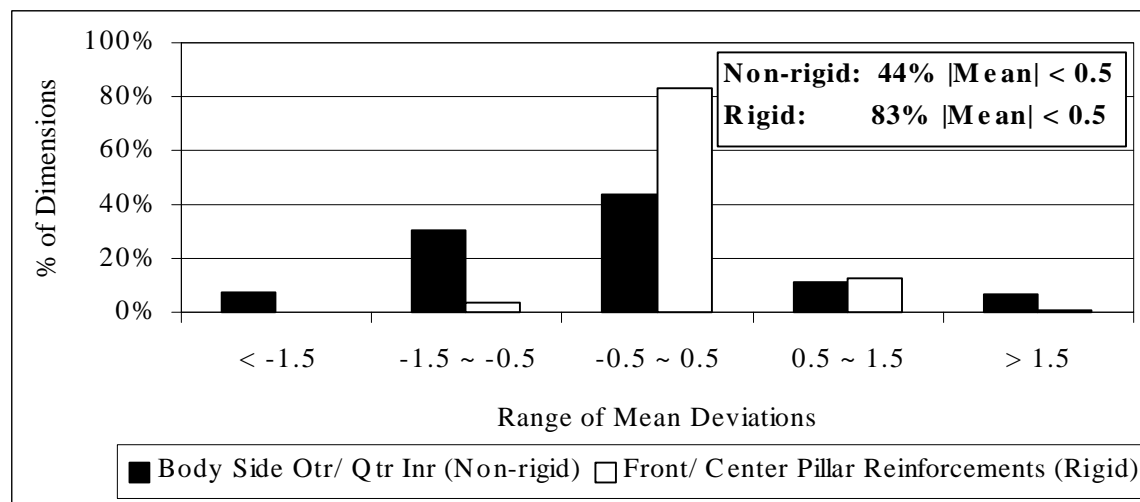


Figure 7. Distribution of Mean Deviations by Type of Part at Company A

The difficulty with producing all mean dimensions to nominal is not unique to these manufacturers. Table 1 provides a comparative look at mean deviations for all the manufacturers studied. This table confirms that all of these manufacturers have mean deviation concerns, although some manufacturers have fewer large deviations. Some of these differences do not appear related to the die design process but rather to other factors such as panel complexity, degree of constraint in the measurement system, assigned tolerances and rework strategies. For example, Company A and B had the largest, most complex body sides. In terms of measurement system constraint, Companies' E-G use significantly more clamps to locate their body sides in their checking fixtures. Another factor that explains the greater mean conformance at Company F is the more stringent requirements at the die source. Company F places a greater emphasis on reworking stamped panels that do not meet tight tolerances (say, +/- 0.3mm).

Company	Body Side Type	Typical tolerance	# cross/car clamps in fixture	Average Mean	% Dimensions Mean > 1	% Dimensions Mean > tol (t)
A	Integrated Quarter	+/- 0.7	11	1.10	56%	66%
B	Integrated Quarter	+/- 0.7	5	0.90	33%	50%
C	Two-piece	+/- 1.0	7	0.51	15%	5%
D	Two-piece	+/- 1.0	8	0.88	39%	39%
E	Two-piece	+/- 0.5	22	0.36	3%	14%
F	Two-piece	+/- 0.3	16	0.31	3%	39%
G	Integrated Quarter	+/- 0.5	17	0.37	2%	28%

Table 1. Mean Deviations for Several Manufacturers

One source of large mean deviations relates to difficulties predicting metal flow throughout the forming process. These difficulties are exacerbated by the lack of adjustment factors to shift dimensional measurements. Many processes have built-in mechanisms, or setup parameters, which allow manufacturers to shift critical part dimensions to a nominal value at relatively low cost. For example, manufacturer may typically change the mean diameter in a machining operation by adjusting a tool. In the case of sheet metal stampings, these simple adjustments are not available.

Changing a part dimension typically requires physical rework to the dies. This rework may involve several iterations making it an expensive and time-consuming process. Moreover, the effects of excessive die rework are not limited to additional construction and tryout costs. Several manufacturers maintain that numerous rework iterations for a set of component dies also impacts the reliability of the tooling. Constant grinding and welding of dies increases the likelihood of subsequent tooling failure. Even with several rework iterations, manufacturers cannot always correct every mean dimensional deviation. The functional build approach provides manufacturers with a process to manage these mean deviations. In some cases, they may choose

to rework the tools, but in others they may allow certain component dimensions to deviate from the design intent provided the assembly meets its specifications and functions properly.

Another challenge for manufacturers is maintaining a consistent mean between die source tryout and the production source or home line tryout. Table 2 suggests that approximately 25 to 30% of dimensions may shift more than 0.5mm from the die source to the final part approval run on the home line. Of those manufacturers in this study providing die source-to-production source data, only Company F showed an overall improvement in mean conformance by the end of tryout. Although they eliminated most of their significant mean deviations, they still entered production with 15% of their dimensions having mean deviations in excess of 0.5mm. (Note: these dimensions would not meet a C_{pk} requirement).

Company	% of Dimensions		
	Shift in Mean > 0.5mm Die Source to Home Line	Die Source Tryout Mean > 0.5mm	Home Line Tryout Mean > 0.5mm
B	34%	33%	45%
C	23%	30%	31%
F	25%	25%	15%

Table 2. Change in Mean from Die Source to Production Source

Mean shifts from the die source to the production source affect whether manufacturers should perform functional build evaluations at the die source, production source, or both. Based on the historical problems of mean shifts, most manufacturers recognize the need to perform functional build evaluations using home line tryout parts regardless of the die source results. Given these mean shifts, some manufacturers question the usefulness of functional build at the die source. The principal argument in support of functional build at the die source is that while some dimensions may change, many do not. In addition, empirical studies suggest that the majority of dimensions accepted out-of-specification at the die source are not reworked later at the die source. Press shop rework typically involves new conditions rather than correcting known conditions from die source evaluations. Thus, functional build evaluations at the die source allow manufacturers to identify many potential build issues prior to shipping dies to the home line.

The lack of correlation in the mean from die source to press shop tryout does, however,

question the usefulness of adjusting tolerances at the die source solely to pass a C_{pk} criteria. Parts requiring tolerance changes at the die source may require additional tolerance changes in the press shop. Thus, manufacturers should delay formal print tolerance revisions until the completion of home line tryout.

2.1.2 Measurement System Challenges

Mean dimensional deviations often result from difficulties predicting metal flow during forming operations. Another less recognized problem is the difficulty associated with measuring large, complex-shaped components. Automotive manufacturers measure body components in absolute, three-dimensional space (X, Y and Z body coordinate). For rigid structures, they typically use a 3-2-1 part-locating scheme in the holding fixture. This scheme utilizes the six degrees of freedom necessary to locate a part in absolute space prior to measurement. For large, non-rigid parts, however, body manufacturers often must use additional clamps or locators to stabilize the part for measurement. One concern with these additional locators is that they actively influence the location of the surfaces being measured. In other words, the positioning of the locators, not the stamping dies, may affect mean deviations.

This effect is highlighted using a case study comparing constrained versus over-constrained clamping strategies. Figure 8 illustrates ten dimensions on a body side and the location of two sets of clamps (one constrained and one over-constrained). In this experiment, ten body sides were measured in the same locations using the two different sets of clamps.

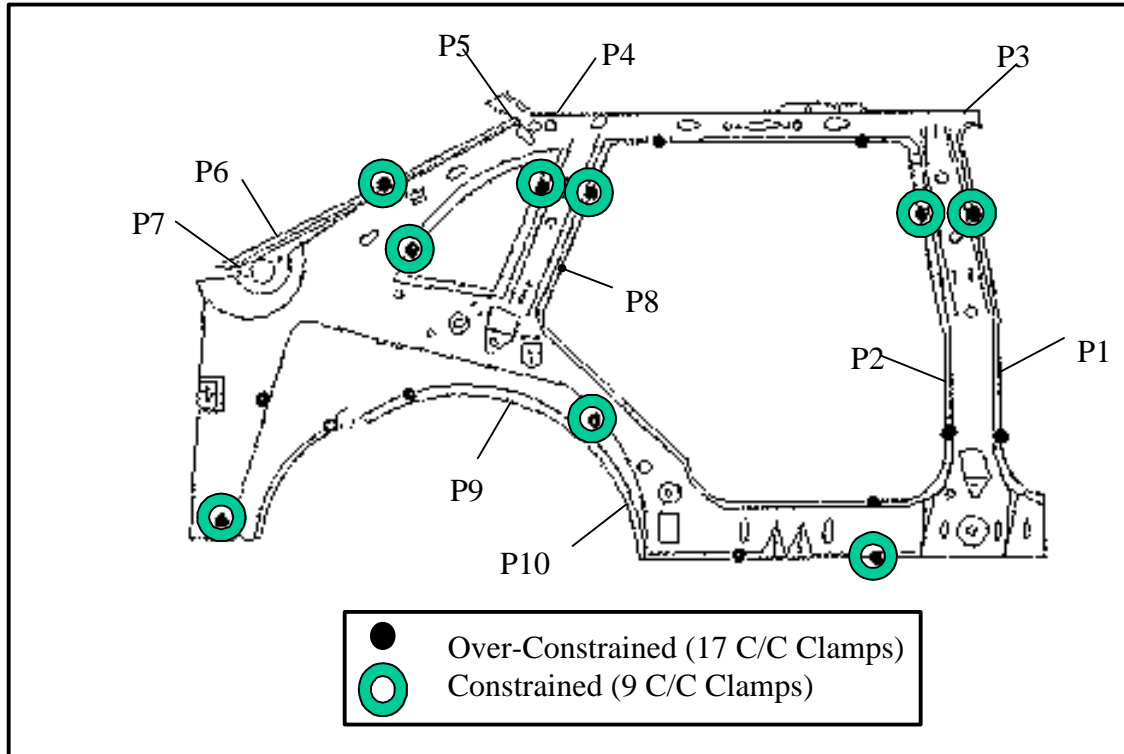


Figure 8. Body Side Conformance and Clamping Strategies

Table 3 indicates that the use of *additional* clamps may significantly shift mean dimensions and/or reduce variation. In this study, three of the ten dimensions shifted more than 0.5mm. Interestingly, these mean shifts were not always toward nominal. For example, one dimension (P10) shifted away from nominal using the more-constrained clamping system. The point of this case study is not simply to show dimensional changes due to clamping, but to question the ability to accurately assess mean deviations.

	Average Deviation from Nominal (mm) by Panel Dimension										
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Median Difference
Constrain (9 clamps)	-0.54	-0.96	-0.46	0.09	0.10	-0.29	0.70	-0.06	-0.74	0.56	
Over-Constrain (17 clamps)	-0.20	-0.45	0.15	0.38	0.43	-0.23	0.67	-0.09	-0.55	1.60	
Mean Difference	0.34	0.51	0.61	0.29	0.33	0.06	0.03	0.03	0.19	1.04	0.31

	Standard Deviation (mm) by Panel Dimension										
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Average Sigma
Constrain (9 clamps)	0.23	0.21	0.19	0.18	0.21	0.16	0.31	0.09	0.15	0.22	0.20
Over-Constrain (17 clamps)	0.08	0.03	0.14	0.14	0.25	0.07	0.20	0.17	0.06	0.16	0.13
Statistical Difference? (based F-test, $\alpha=.05$)	Dec	Dec	--	--	--	Dec	--	--	Dec	--	

Table 3. Mean and Variation Conformance by Clamping Approach

Observed stamping mean deviations (especially non-rigid part dimensions) are not independent of the measuring fixtures. This finding suggests that reworking stamped parts to their nominal position based on check fixture measurements does not guarantee a dimension at nominal during assembly. Since manufacturers cannot possibly use *every* stamping check fixture locator in the assembly processing, some inherent mean differences are inevitable. Rather than attempting to rework all stamping dimensions to some check fixture nominal, functional build seeks to identify those mean deviations that truly affect the build. The functional build approach is predicated on the belief that not all *observed* stamping mean deviations are accurate or related to the stamping process.

2.1.3 Correlation of Stamping and Assembly Dimensions

Another recurring automotive body manufacturing problem is a lack of correlation between stamping components and their welded assemblies. For rigid structures such as engines, manufacturers assume that dimensions will stack-up in the mating of two components. In other words, the assembly mean and variance are based on a linear addition of the two component means and variances. For example, the additive theorem of variance suggests that the assembly variance will be greater than the component variances. Based on this additive assumption,

manufacturers try to produce individual component mean dimensions at their nominal specification with minimal variance. These manufacturers further assume that they may predict their assembly outputs based on the measurements of the input components (i.e., input component dimensions are correlated with their assembly outputs).

These assumptions, however, do not always hold with non-rigid components. These components may continue to deform during weld processes. Some components will more closely resemble the geometry of the fixtures used to orient them at time of assembly than their initial measurements. Non-rigid component dimensions also may conform to more rigid dimensions during assembly. The net effect is that non-rigid component measurements often poorly predict final assembly measurements.

Table 4 provides a summary of the dimensional relationships between stamped body side components and their respective assemblies. These data suggest two critical findings. First, coordinated measurements (measurements taken in the same physical location before and after assembly) often shift during the weld assembly process. Nearly half of the dimensions exhibit mean shifts of four and five sigma from stamping-to-assembly (typical sigma values = 0.1 ~ 0.2mm). Second, almost none of the coordinated dimensions have a strong correlation between their stamping and assembly measurement values.

Company	# of Coordinated Dimensions	% of Dimensions			
		Stamping $6\sigma > 1.5$	Assembly $6\sigma > 1.5$	Correlation (R) > .6	Stamp Mean - Asm Mean Difference > 0.5
A	32	3%	39%	3%	66%
B	104	78%	36%	8%	65%
C	32	50%	68%	6%	66%
D	31	16%	23%	0%	48%
E	32	0%	3%	0%	34%
F	8	0%	33%	0%	50%
G	77	8%	13%	1%	61%

Table 4. Correlation of Part Dimensions Before and After Assembly

(Note: R in the above table is the correlation coefficient)

These case studies suggest that manufacturers may not expect to reduce their assembly variation simply by reducing their stamping variation. This issue is explored using Company C

as an example because their variation significantly increased in assembly. To examine assembly robustness, two groups were created: a set of panels with low stamping variation and a set with high variation. Table 5 summarizes the results. In the windshield area, the second set of panels exhibited large stamping mean shifts resulting in significantly higher assembly variation. In the center pillar area, the high stamping variation group exhibits similar behavior as the low variation group. The main difference in the center pillar area is that the high variation group was not the result of large between run mean shifts. Thus, low levels of assembly variation appear related to control of stamping mean shifts and the assembly process itself. Moreover, in the absence of large mean shifts, these data suggest that assembly processes essentially are robust up to six sigma levels of at least 1~1.5mm ($6 \times 0.25=1.5$). Therefore, reducing stamping variation below these levels is unlikely to automatically reduce assembly variation.

Body Side Area	Panel Set	Stamping Average σ	Assembly Average σ
Windshield	#1	0.11	0.19
	#2	0.37	0.42
Center Pillar	#1	0.12	0.34
	#2	0.28	0.36

Table 5. Assembly Robustness to Stamping

Table 6 examines mean conformance from stamping-to-assembly by type of stamped component. One interesting finding is that even though Company D has significant mean deviations on their body side outer stamping, they effectively compensate for these deviations and produce assemblies closer to nominal. One hypothesis supported by the above data is that this manufacturer has better mean conformance in their reinforcements and also is effectively managing their assembly process to minimize dimensional changes. In contrast, Company G has excellent mean conformance on their body side outer and its reinforcements, but relatively poor mean conformance in assembly. This finding suggests that mean conformance in assembly is clearly impacted by assembly process setup and not simply a function of stamping mean conformance. Company E, which utilizes an over-constrained measurement approach, has the highest mean conformance in both stamping and assembly. Still, one-third of their stamping dimensions shift in excess of 0.5mm during assembly, although few dimensions shift from in-

specification to more than 1mm away from nominal. These results demonstrate the importance of effectively compensating for stamping deviations throughout assembly processing.

Company	% of Dimensions with Mean Bias > 1.0 mm			
	Body Side/ Quarter Outer	Reinforcements	Non-Rigid Inner Panel	Body Side Assembly
A	56%	1%	30%	40%
B	33%	--	16%	35%
C	15%	3%	0%	39%
D	39%	0%	0%	6%
E	3%	--	--	6%
F	3%	17%	17%	8%
G	2%	6%	8%	33%

Table 6. Mean Deviations: Stamping-to-assembly

(Note: excludes cases where fewer than 10 dimensions are measured)

Several explanations exist for the lack of correlation between individual components and their respective assemblies. Among them are:

- Deformation of metal during the weld process,
- Changes in the part locating schemes between stamping and assembly,
- Conformance of non-rigid component dimensions to other rigid areas of the assembly and
- Measurement system errors.

This lack of correlation presents serious ramifications for those manufacturers utilizing build to nominal criteria such as C_{pk} . Here, manufacturers rework dies at both the die source and the production facility trying to meet C_{pk} for all component dimensions. Estimates of the rework costs at these manufacturers suggest that rework may account for 20 to 30% of the die costs. The above correlation analysis suggests that this rework may have minimal impact on the final body dimensional accuracy. In one study of a vehicle launch, a manufacturer reported that over 70% of root causes for major body dimensional variation problems were related to assembly fixture

issues. Therefore, if launch dates are fixed, delaying assembly tryout to rework individual components may not allow sufficient time to resolve the primary causes of final body dimensional problems.

Through experience, most manufacturers recognize that they may produce an acceptable body without meeting C_{pk} requirements for *all* single component dimensions. They ultimately make tolerance revisions to approve parts that fail C_{pk} requirements. In some extreme cases, a manufacturer may even stop rework, waiting for timing pressures to force tolerance revisions in order to start production. The next section discusses how the recurring difficulties of producing and measuring mean stamping dimensions to nominal inhibits the effective use of C_{pk} as the primary decision criteria for stamped components.

2.2 The C_{pk} “Game”

Most manufacturers using sequential validation rely on C_p and C_{pk} indices to approve parts for the next validation phase. This approach follows the basic quality paradigm, which suggests that in order to produce final body dimensions at their desired nominal (target) value with minimum variation, manufacturers must produce the input dimensions at their nominal values, and with even less variation. In stamping, many manufacturers subscribe to this approach by requiring that all dimensions on each individual stamped part achieve a C_p and $C_{pk} > 1.33$ (or, C_p and $C_{pk} > 1.67$). Both the C_p and C_{pk} index assess the ability of a process to produce outputs within their specification limits. For example, C_p is determined by dividing the total tolerance by six times the standard deviation. The C_{pk} index differs from C_p because it includes the deviation of the mean from its nominal in assessing process capability. These indices have become widely accepted in the automotive industry because they provide objective criteria to validate the conformance of components to their design requirements. By using this criteria, manufacturers hope that conformance to specification of individual stamped components will result in more consistent final body measurements.

Empirical studies of stamping tryout suggest that even if manufacturers achieve C_p requirements, they often fail to achieve C_{pk} requirements due to mean deviations from nominal. In other words, their processes have sufficiently low variation but are off target. For the body side case study dimensions presented in Table 7, dimensions with mean bias greater than 0.3mm

typically would not pass C_{pk} requirements for tolerances of $\pm 0.7\text{mm}$ even though many would pass a C_p criteria. Even Company F, which has greater mean and variation conformance than the others, would not meet C_{pk} criteria for nearly half their dimensions.

Company	% Dimensions $C_p > 1.33$ (Pass)	% Dimensions $C_{pk} > 1.33$ (Pass)	% Dimensions Mean Bias $> .3$	% Dimensions Bias $> .3$ and $C_{pk} > 1.33$ (ok)	% Dimensions Bias $> .3$ and $C_p > 1.33$ (ok)
B	73%	19%	69%	11%	72%
C	63%	33%	57%	10%	59%
D	71%	26%	56%	0%	69%
F	92%	58%	47%	20%	88%

Table 7. C_p versus C_{pk} Conformance at Tryout

(Note: above C_p and C_{pk} calculations are based on generic tolerances of ± 0.7)

In general, the use of a C_{pk} index is most effective under the following conditions: adjustment factors exist to shift mean dimensions, tolerance stack-ups are predictable and a reliable system exists to measure stamped parts. Unfortunately, none of these conditions currently exist in stamping. Consider the following issues facing automotive manufacturers relying on C_{pk} :

1. Many part dimensions (primarily non-rigid) that do not meet C_{pk} acceptance criteria are found to have little impact on the resultant assembly due to poor correlation between stamping measurements and their resultant assemblies.
2. Many part dimensions that meet C_p requirements fail C_{pk} . Thus, many stable processes are reworked. In some cases, this rework may even add to the inherent process variation.
3. Efforts to rework dies to pass C_{pk} criteria often drive-up die costs and lead-time.
4. Even with extensive die rework, manufacturers ultimately make tolerance adjustments to pass the C_{pk} acceptance criteria for many part dimensions questioning the value of the original rework attempts.
5. Many parts which eventually pass C_{pk} at the die source still require additional rework once the dies are shipped to the production facility because of inherent differences in the stamping presses between facilities.

In addition to these issues, the use of C_{pk} also may have an adverse effect on the assignment of part tolerances. Consider the common result of a capability study shown in Figure 9. This dimension has extremely good capability in terms of variation, but the mean is off nominal. Since this manufacturer must pass a C_{pk} criteria, they may choose to either rework this die or modify the manufacturing tolerance. If they modify the tolerance, the adjustment might consist of a bilateral expansion of the tolerance from $\pm 0.75\text{mm}$ to $\pm 1.1\text{mm}$ just to pass C_{pk} . This bilateral expansion often occurs without evidence that tolerance relief is needed or allowable on *both* sides of nominal. Therefore, even though this process is really capable of producing panels within a range of 1mm (i.e. $6\sigma < 1$), a manufacturer might allow less control of stamping variation simply to compensate for the mean deviation. In this instance, the press shop could have a mean shift over 1mm and still fall within the -1.1mm lower specification if they bilaterally expand the tolerance. As an alternative to widening tolerances, this manufacturer may even try to rework this acceptable part to avoid the logistical inconveniences of tolerance expansions.

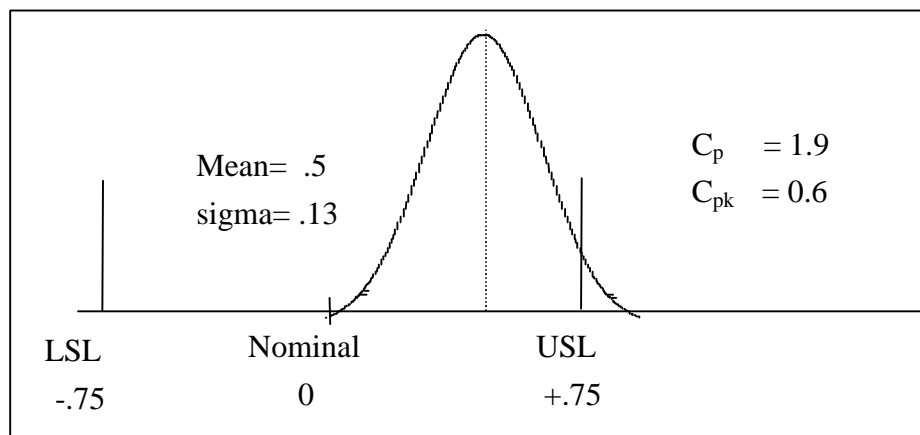


Figure 9. Common Dimensional Problem: Pass C_p – Fail C_{pk}

To avoid the potential effects of bilateral expansions, the use of lateral tolerance adjustments through functional build is recommended. In this approach, manufacturers re-assign target values based on the functional build means and then laterally shift tolerances accordingly.

The preceding example suggests setting the target to 0.5mm and laterally shifting the tolerances to -0.25/+1.25. Thus, the overall tolerance width would remain the same.

Another potential effect of using C_{pk} relates to the assignment of original tolerances. Manufacturers with C_{pk} requirements push for wider tolerances to allow greater mean deviations. They also expand tolerances based on the actual C_{pk} requirement. For instance, manufacturers with a requirement of $C_{pk} > 1.0$ typically have tighter tolerances than those requiring $C_{pk} > 1.67$. For $C_{pk} > 1.0$, manufacturers assign tolerances based on $\pm 3\sigma$. If the requirement is 1.67, manufacturers need tolerances of $\pm 5\sigma$. Therefore, even if the inherent variation of both manufacturers is the same, the manufacturer with the 1.67 requirement will need significantly larger tolerances. One interesting phenomenon is that those manufacturers with higher C_{pk} standards (e.g., $C_{pk} > 1.67$) and subsequently larger tolerances tend to have more stamping variation than those companies not using C_{pk} . In other words, widening tolerances to address mean deviation concerns may inadvertently lessen control of variation.

These problems with tolerances and the use of C_{pk} lead to what may be referred to as the “ C_{pk} game”. The C_{pk} game is as follows:

At Die Source Tryout:

- Parts fail C_{pk} because of mean bias.
- Manufacturers rework dies in efforts to pass C_{pk} .
- After unsuccessful rework attempts, specifications are changed for many dimensions to pass C_{pk} .
- Manufacturers ship the dies.

Home Line Tryout:

- Part dimensions change from die source to home line.
- Manufacturers rework dies in efforts to pass C_{pk} .
- After unsuccessful rework attempts, specifications are changed for many dimensions and parts are approved for production.

The word “game” is used because most manufacturers really do not use the C_{pk} index to determine a good part from a bad one. Rather, they figure out ways to manipulate the index so

that parts they believe are acceptable may be labeled accordingly. Thus, the use of C_{pk} becomes more of a game of numbers rather than a validation tool.

The effect of this “game” is low confidence in the C_{pk} results from dimensional studies at both the die source and press shop. Since manufacturers rarely demonstrate an ability to meet C_{pk} acceptance criteria or the necessity to do so to produce acceptable bodies, many manufacturers are examining alternative methods and evaluation criteria. The following section discusses the rise of functional build as an alternative approach to the traditional sequential validation and the use of C_{pk} .

2.3 Rise of Functional Build

Functional-build type practices have existed for many years. The principal evaluation tool, or screw-body process, may be traced to at least the early 1970s to a process known as “screw and scribe” or matching. Manufacturers would screw mating components together to check for assembly interference. One Japanese manufacturer iterated on this process and began using it as an evaluation tool for die rework decisions. By performing functional build evaluations, this manufacturer has been able to eliminate unnecessary rework and reduce overall validation time for new vehicle launches.

Figure 10 illustrates the spectrum of the various approaches for body dimensional validation. On one end is pure net build or sequential validation. This approach consists of insuring that component dimensions achieve all of their requirements prior to evaluating assemblies. If any dimension does not conform, it is reworked until it does. On the other end of the spectrum is pure functional build. In this approach, manufacturers evaluate the vehicle from the top-down. They first construct a full screw-body once stable metal is achieved (i.e., the process is repeatable with no unacceptable splits, wrinkles). The evaluation of this screw-body vehicle then drives changes to those sub-assemblies affecting final body-in-white conformance. Then, only if they cannot resolve the problem in the sub-assembly tooling level would they go back and rework dies.

The principal concern with pure functional build is timing requirements for modifications. If manufacturers wait until the full screw-body evaluation, they reduce some of the time available to make die or process modifications. To balance the risks of unnecessary

rework and timing constraints, most manufacturers utilize some dimensional criteria for individual components. Ideally, these dimensional criteria attempt to minimize unnecessary rework while maximizing the ability to utilize time effectively. What appears to separate companies is their emphasis on meeting dimensional criteria in determining when to begin the first functional build event or evaluation. For example, Company E in Figure 10 measures components but relies primarily on schedule, experience and subjective evaluations of dimensional data to determine which areas to rework and which to delay until a functional build evaluation.

Figure 10 also indicates that Companies G, A, C, and D (all manufacturers actively pursuing functional build processes) rely more on objective dimensional criteria to aid them in determining what to fix prior to the first functional build evaluation. These manufacturers are trying to minimize the number of out-specification component conditions that are rejected in functional build evaluations.

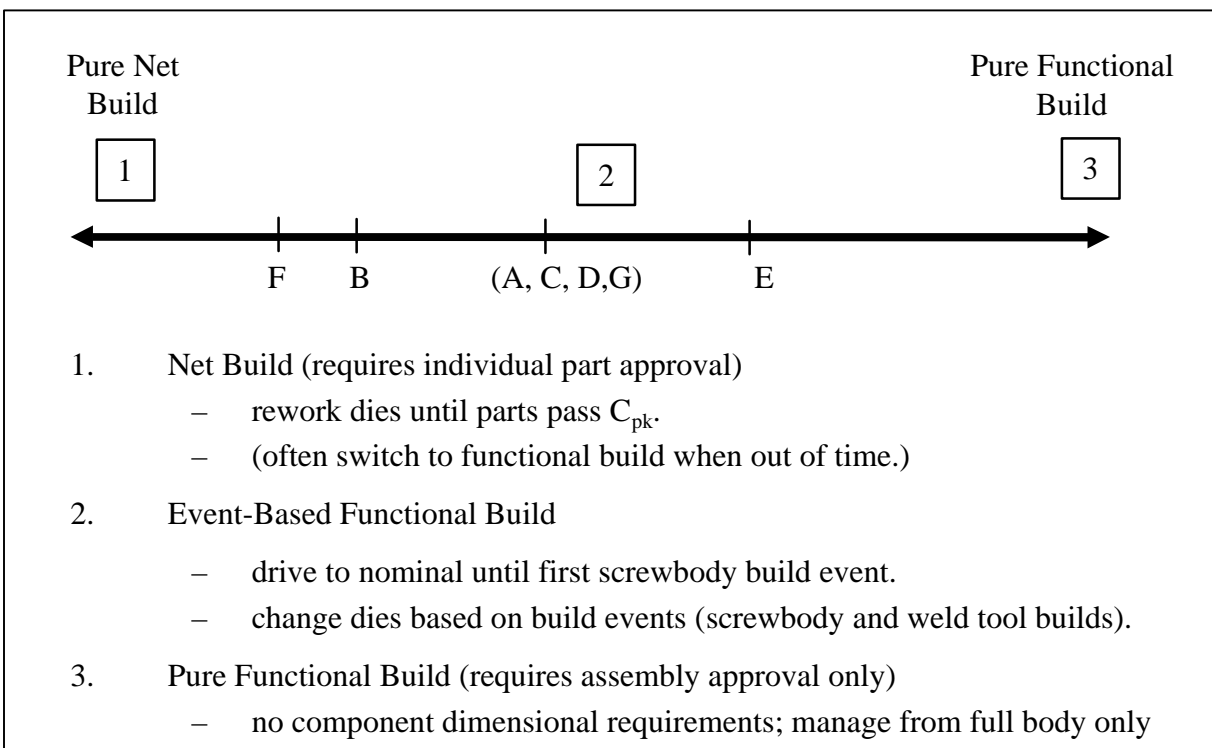


Figure 10. Various Functional Build Implementation Strategies

One interesting comparison across the manufacturers in this study is experience using functional build. Company E has utilized functional-build the longest and appears the most comfortable relying on subjective decision-making. They also have greater confidence in their ability to control variation even if they cannot produce every mean dimension at nominal. Given their lower experience levels, the other manufacturers making a transition toward functional build may benefit from the use of objective criteria to determine when to start the functional build process. This middle ground between pure net build and pure functional build is referred to as event-based functional build for the purposes of this report. The term event-based implies that timing considerations also play a key role in the establishment of criteria.

Furthermore, event-based functional build is characterized as a process utilizing objective criteria that are relatively loose in dimensional conformance and stringent in terms of timing. Some component criteria are necessary to insure part dimensions are relatively stable without excessive mean deviations. In other words, it is recommended that manufacturers get all component dimensions within an acceptable window prior to performing a functional build evaluation. (Note: criteria that define this dimensional window are established in Section 5).

3.0 Functional Build Case Examples

The use of the functional build process appears most applicable in the assembly of either two non-rigid components or a non-rigid to a rigid component. In general, a component may be considered non-rigid if it has a blank thickness $< 1.5\text{mm}$. These components typically do not become rigid until after they are assembled. Of course, even a flimsy body side outer panel has certain areas that are quite rigid such as the rear door opening near the wheelhouse. Moreover, a small, simple part with a blank thickness less than 1.5 could also be rigid. Still, a 1.5mm guideline is used for part classification.

To demonstrate why functional build works, consider the mating of the center pillar reinforcement and the body side panel in Figure 11. The center pillar reinforcement is a structural component and thus will have greater influence on the final assembly. If the body side panel is 1mm outboard from the centerline of the car, but the center pillar is at nominal, the overall assembly will likely shift toward nominal. This shift occurs because the mating surfaces are in parallel. Thus, the less rigid body side panel will conform to the rigid inner structure. Under the traditional approach, a manufacturer would likely rework the body side panel because the outboard stamping condition would cause this part dimension to fail its C_{pk} requirement. In contrast, a functional build manufacturer would assemble these two components and only make rework decisions based on the resultant assembly and not necessarily on C_{pk} compliance. In some cases, the resultant assembly might still deviate from nominal, but this manufacturer may find it easier to adjust an assembly process locator than physically alter a stamping die.

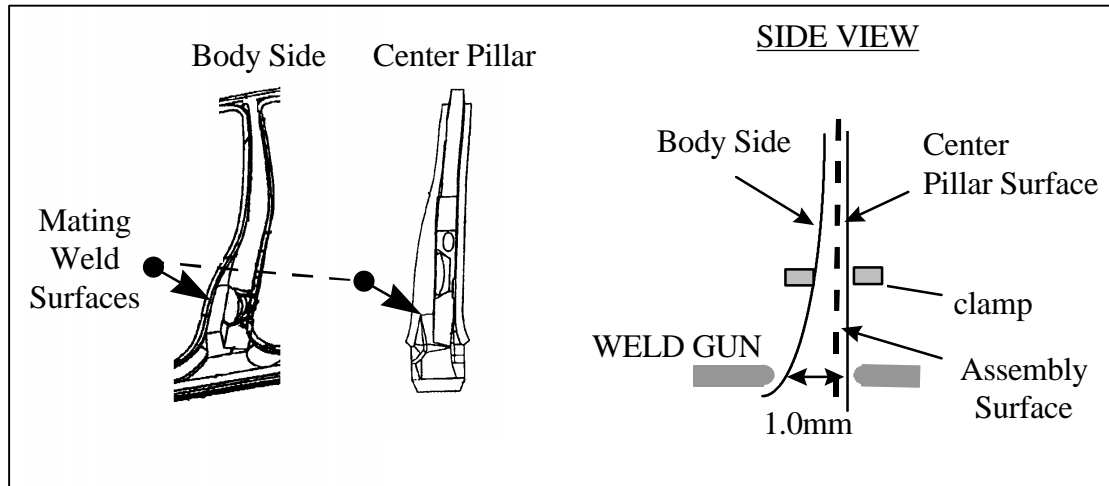


Figure 11. Parallel assembly of a non-rigid surface to a rigid reinforcement

Next, several empirical examples are explored, comparing the two most common mating conditions: non-rigid to non-rigid and non-rigid to rigid. The rigid-rigid example is not explored for two reasons. First, due to weight considerations, few major sub-assemblies consist of the mating of rigid components. Second, a principal argument for the use of functional build is lack of stamping-assembly predictive relationships. In the case of rigid components, stronger relationships are expected. For instance, the assembly of rigid parts is expected to follow the additive theorem, which states that the means and variations for two mating dimensions will add linearly.

3.1 Case Example 1: Non-rigid to rigid (Windshield to Body Side)

Figure 12 shows the mating of the non-rigid body side outer to the rigid windshield frame reinforcement. For simplicity, attention is focused on the tab (area #1) of the body side outer. This surface is clearly a non-rigid area. Table 8 summarizes the mean deviations in this area for the body side outer panel, the windshield reinforcement and the body side assembly (measurements are high/ low). These data suggest that the assembled parts more closely resemble the dimensional conformance in the rigid windshield as opposed to the non-rigid tab on the body side. This simple example shows how a non-rigid surface may conform to a more rigid mating part.

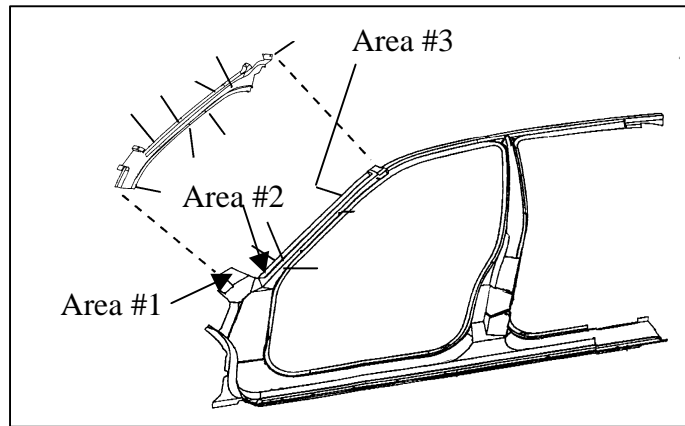


Figure 12. Body Side Outer and Windshield Reinforcement

Area	Body Side Mean	Windshield Frame Mean	Assembly Mean
#1	-0.7	0.5	0.6
#2	0.9	-0.2	-0.4

Table 8. Summary of Mean Dimensions

One concern with using functional build (or even net build) is significant shifts in the stamping mean between runs. For instance, if a manufacturer accepts a mean deviation through a functional build evaluation by making an adjustment to assembly tooling, then significant changes to the stamping mean may cause severe problems in assembly. Figure 13 shows a run chart for dimension #3 on the body side outer before and after assembly. This figure shows that even though the mean is off nominal for four stamping runs, the assembly process is stable. However, when the mean shifted significantly closer to nominal at the start of the fifth run, the assembly variation increased. In this instance, maintaining a consistent stamping mean appears more important than the relative location of this dimension to nominal.

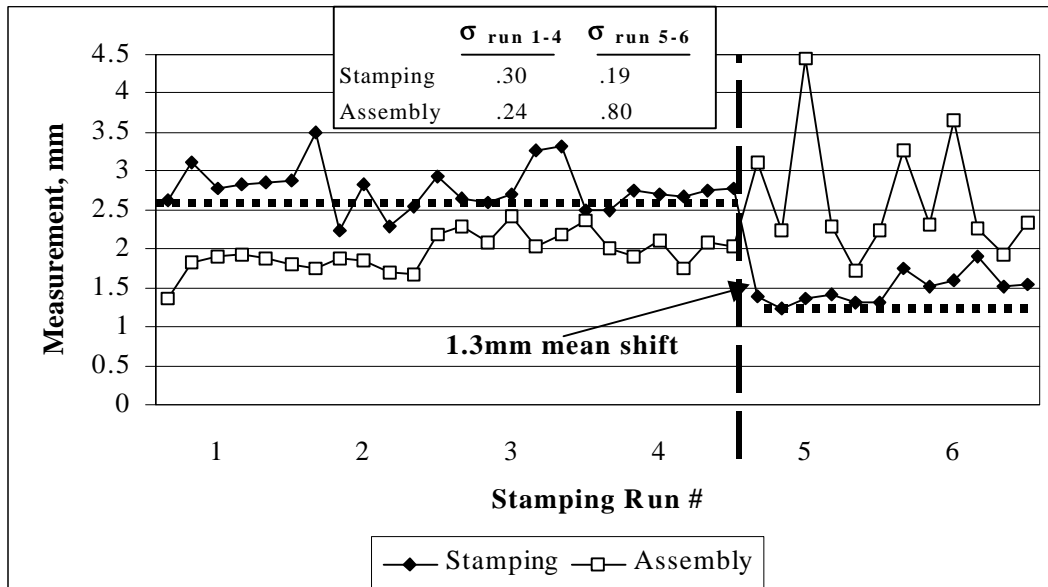


Figure 13. Example of Possible Effect of Stamping Mean Shift on Assembly

3.2 Case Example #2: Non-rigid to Non-rigid: Body Side Outer to Inner

Next, a case example is presented to examine the mating relationship of two non-rigid parts: a body side outer and a body side inner (Figure 14). These components have similar blank thickness. A finite element analysis of this joining process indicates that the weld process has a greater influence on these parts than the dimensional conformance of the individual components. For example, the stiffness coefficient of these two surfaces is substantially higher in assembly than for either individual mating flange. Table 9 presents data supporting this weld process effect, as the assembled part is closer to nominal and has less variation than would be predicted using traditional component stack-up models.

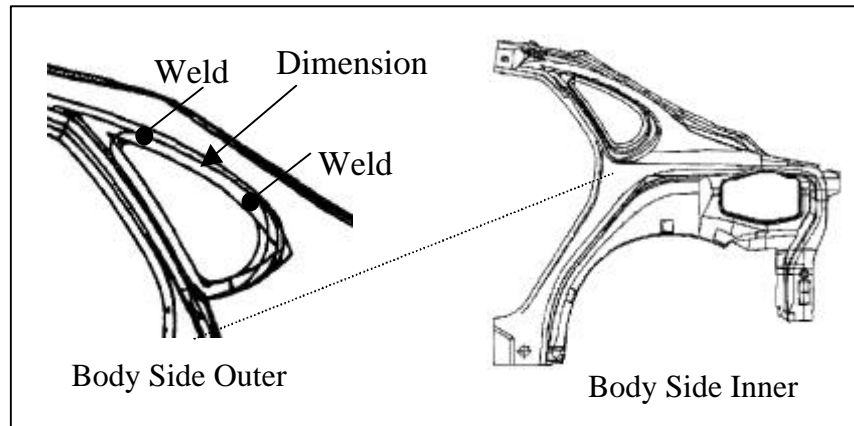


Figure 14. Body Side Outer to Body Side Inner Case Example

Part	Blank Gauge	Mean	Sigma
Body Side Outer	0.9 mm	0.11	0.43
Body Side Inner	0.8 mm	-0.41	0.18
Body Side Assembly		0.05	0.2

Table 9. Dimensional Summary of Components in Case Study

4.0 Functional Build Implementation Issues

This section examines several functional build implementation issues. These include:

1. Type of part,
2. Part submittal and approval criteria,
3. Subassembly evaluation criteria, and
4. Organizational requirements.

4.1 Categorization of Stamped Parts – “One Size Does Not Fit All”

Although organizational advantages exist with one process for all components, the reality is that the ability of manufacturers to meet dimensional criteria is largely related to the type of part. For example, part buy-off for small, relatively non-complex reinforcements is less cumbersome than for large or complex-shaped panels. Moreover, major outer panels typically have more problems than non-rigid inner panels because they have additional criteria such as parallelism of body gap lines. Differences in the type of part also impact the functional build process. Non-rigid panels tend to have larger mean deviations, but also are more likely to have these deviations compensated in assembly. In other words, non-rigid dimensions are more likely to shift during assembly, especially if they join to a rigid part.

As a general rule, manufacturers typically produce parts whose blank thickness is greater than 1.5mm closer to nominal and with less variation. Note, however, that certain heavy gauge panels do not follow this rule. For example, some stamped components such as the windshield frame inner reinforcement or front body hinge pillar reinforcement historically have twists or other large deviations resulting from complex forming operations. In addition, some small, light-gauge panels may exhibit similar properties as thick reinforcements.

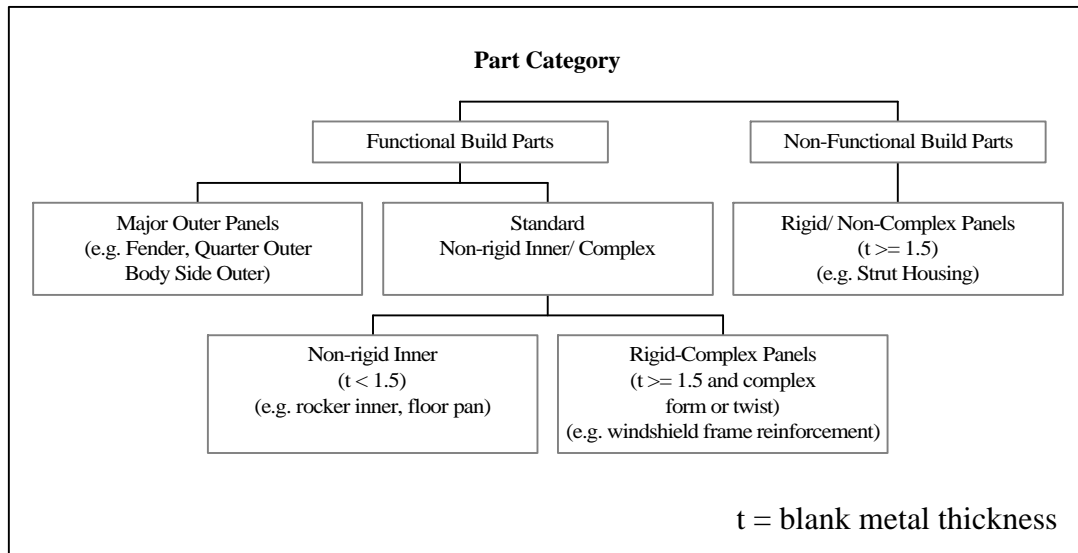


Figure 15. Part Categorization for Dimensional Evaluation

Due to differences in panel rigidity, complexity and body requirements, the recommendation is to establish three part categories: simple/rigid, standard and major outer. Figure 15 provides examples for each of these categories. The intent of these categories is to allow the development of multiple criteria to better utilize tryout resources. For instance, manufacturers should be able to meet more stringent criteria for simple/rigid parts and therefore focus functional build resources on evaluating standard and major outer panels. Although blank material thickness should be considered in part categorization, die engineering, stamping, and the functional build team should jointly agree on the final classification.

A functional build approach is not recommended for simple/rigid parts. First, since manufacturers usually are capable of meeting stricter dimensional requirements for these parts in die construction and tryout, they may shift functional build resources to concentrate on the more challenging non-rigid panels. In addition, by requiring stricter dimensional conformance for rigid panels, evaluations of non-rigid panels should be more effective because of greater confidence in the location of mating flanges and other part dimensions. Finally, the greater the panel rigidity, the less likely manufacturers may compensate for large mean deviations in assembly. Benchmark studies further confirm that producing rigid reinforcements closer to their original specifications improves the likelihood of producing dimensionally correct assemblies. Note, however, that the functional build process would still use rigid panels to construct screw-bodies in order to

evaluate other mating parts within a sub-assembly. As a result of the build, manufacturers might even modify a rigid component that is within specification to compensate for a problem in a non-rigid part.

4.2 Part Submittal and Approval Criteria

Prior to establishing functional build criteria, it is important to first recognize the difference between submittal and approval criteria. The purpose of submittal criteria is to identify when to construct and evaluate screw-body assemblies. For example, manufacturers using an event-based functional build strategy seek submittal criteria that if met, reduce the number of component dimensions rejected in the first screw-body build event without prohibiting the ability to meet timing schedules. Contrast this objective with those for approval criteria where the principal objective is to insure a dimensionally correct final body. Under functional build, component approval ultimately is determined by the conformance of the sub-assembly and the full body assembly. Of course, since functional build only evaluates mean deviations, variation requirements for individual components should be consistent between submittal and approval criteria.

To demonstrate the role of submittal criteria, suppose a mating flange on a surface is 4mm from nominal and the other surface is 1mm from nominal. The ability to evaluate the mean deviation on the second flange is limited by the fact that its mating component is not even close to nominal (4mm). Empirical studies of functional build programs suggest that component parts need to be within some dimensional window (e.g., less than 0.5-1.0 mm greater than specification limits) to effectively perform an evaluation. Organizational pressure to reduce vehicle development time also decreases the available time after functional build evaluations to perform modifications. If time is available to rework a significant mean deviation prior to the first functional build, manufacturers may prefer to minimize their risk of rejection and perform the rework. The rationale is that for certain large mean deviations (e.g., greater than 1mm out-of-tolerance), the risk for subsequent rework following a functional build exceeds the risk of unnecessarily modifying a die prior to the build.

The purpose of this section is to examine the central issues regarding the establishment of effective submittal criteria. Subassembly approval criteria are examined in the following section.

4.2.1 Timing-Dimensional Conformance Tradeoff

A fundamental issue in developing a functional build strategy is how manufacturers address timing-dimensional conformance conflicts. These conflicts occur when a component does not meet its dimensional requirements at the time of a validation event such as the first functional build screw-body. Essentially, manufacturers must decide whether to proceed with an event using components with known problems or delay the build until the parts meet all requirements. Reasonable arguments may be made for either decision. First, by delaying the build, the effectiveness of the build evaluation increases because components more closely reflect their production conditions. On the other hand, meeting all timing deadlines is critical to managing the overall development process because of the inter-dependencies of other concurrent and subsequent activities. For example, delaying the evaluation of a body side assembly to wait for the body side stamped component could subsequently delay the evaluation of the center pillar. Obviously, certain extreme cases may arise where a particular component does not even remotely resemble the intended part and a special recovery plan may be needed. However, if the majority of dimensions are within specification, manufacturers typically will benefit more from performing the evaluation at this point than delaying the overall process. Empirical evidence further suggests that meeting timing deadlines is critical to realizing the potential savings associated with a functional build approach. Thus, under the event-based functional build approach, timing is sacred.

Under this timing-sacred philosophy, manufacturers should view dimensional criteria as goals rather than absolute requirements. In other words, manufacturers should make every effort to meet all submittal goals, but ultimately should submit components based on timing. Given this timing priority, manufacturers may question the usefulness of even having dimensional goals. The argument in support of goals is that meeting them lowers the likelihood of rework following a functional build evaluation.

One implementation issue with an event-based approach is allotting resources to make die modifications between build evaluations. Under event-based functional build, manufacturers may delay certain die rework or engineering changes at the die source in order to meet timing deadlines. In this scenario, manufacturers should not expect to ship dies immediately following

the functional build evaluation. One benefit of a modification period following functional build is that manufacturers may batch change screw-body rework requests with late engineering revisions.

4.2.2 Dimensional Validation Metrics

Most manufacturers using the traditional validation approach rely on C_{pk} as the main criteria for determining dimensional acceptance. One alternative to using C_{pk} for part approval is to separate mean and variation conformance (note: C_{pk} combines them). The principle behind this approach is that for non-rigid sheet metal components, controlling variation about the mean is more critical than the relative location of the mean to a design nominal.

To evaluate variation, this study supports the use of C_p or CR (Capability Ratio = $1 / C_p$). These indices effectively measure short-term process capability and identify if the expected range of stamping variation is less than the specified tolerance (this assumes that the design tolerance represents the robustness of the assembly process to the variation of incoming stamped parts). Requiring that the variation is stable also improves the estimate of the mean deviation. Large shifts in stamping means between or within any phase of development hinder the estimate of the process mean and subsequently the effectiveness of screw-body evaluations.

From a total systems perspective, a dimensionally acceptable stamped part might be defined as one that is capable of producing an acceptable assembly. It might also be agreed that low stamping standard deviations are universally desired over larger ones. Disagreements over panel acceptability, thus, often relate to quantifying allowable mean deviations.

Numerous cases exist where assembly processes may compensate for mean deviations. In some instances, these mean deviations may even exceed the original specifications. Although failure to produce mean dimensions at nominal may not always affect the build, it is important to recognize the need for eliminating excessively large mean deviations. Moreover, parts with a large percentage of dimensions exceeding their tolerance requirements typically are rejected in functional build evaluations. The next section establishes dimensional windows for conformance.

4.2.3 Defining the Mean Conformance “Gray Area”

Several reasons support the use of mean deviation criteria. First, manufacturers often may compensate for mean deviations at less cost in the assembly process than in reworking the

stamping dies. The lack of correlation from stamping-to-assembly also mitigates the need to precisely hit nominal. For example, if non-rigid stamping mean dimensions routinely shift during assembly, then improving a stamping mean from 0.5mm to 0.25mm does not necessarily constitute a better or worse part. The inherent noise in measuring large, complex-shaped non-rigid stamped parts further limits the ability to assess mean conformance. Consider, for example, a part with one dimension 0.75mm from nominal and another 0.1mm from nominal. An adjustment to the measuring system such as adding a clamp or changing the clamping sequence could yield the opposite result (#1 at 0.1mm and #2 at 0.75mm). Thus, the true process mean bias is not simply a function of the dies; it also is relative to the measurement system.

Figure 16 presents the basic tool-buyoff decision model. If a stamping mean dimension deviates from nominal, manufacturers must decide whether to rework the dies, or attempt an adjustment to the assembly process. This figure examines this decision for various levels of mean deviation for a non-rigid stamping dimension. In the case of assembly adjustments, this figure presents two cost curves to represent the greater compensation uncertainty. For instance, large stamping deviations may require only minor tooling adjustments especially if slip planes are available. Other large deviations, however, may require significant changes to the tooling to prevent undue stress in the assembly. Manufacturers may even find that compensating certain deviations in assembly is infeasible, in which case they ultimately would need to rework the dies.

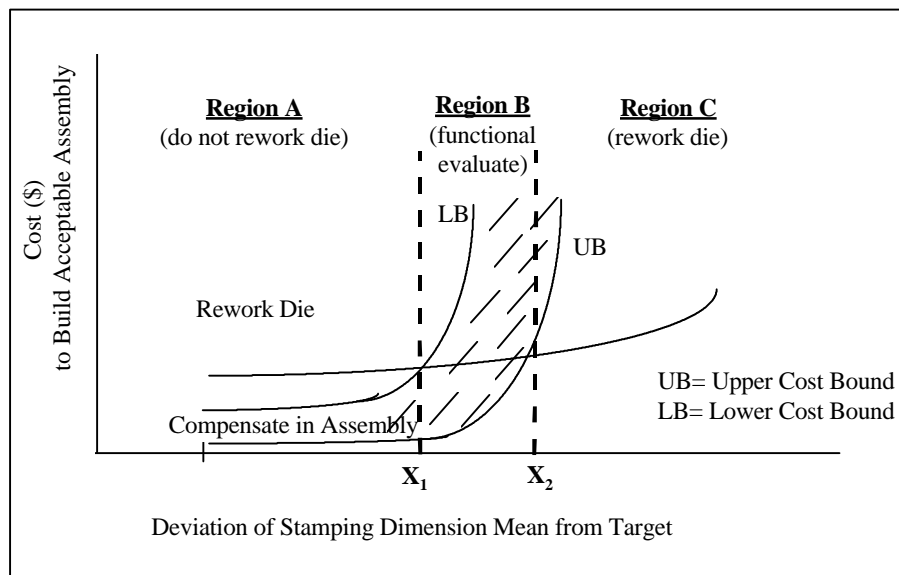


Figure 16. Decision model for tooling rework

The tooling rework decision model presented in Figure 16 suggests manufacturers are unlikely to benefit from reworking dies for small mean deviations (less than X_1). They should be able to either ignore these deviations or make a simple adjustment in the assembly tooling. In this region, manufacturers should not rework the tools regardless of C_{pk} compliance.

At some level of mean deviation (greater than X_2), however, manufacturers may be unable to make a correction to the assembly process. In this region, manufacturers should rework the die before constructing screw-body prototypes because they likely will have to ultimately rework the die. The region between X_1 and X_2 represents the unknown or functional build region. In this situation, reworking the die may or may not be less expensive than making a compensation in assembly.

Values for X_1 and X_2 appear to depend on complexity and rigidity of the stamped part. The more complex/ less rigid a part, the larger the values for X_1 and X_2 . Table 10 provides recommended values for dimensions by part category based on historical data available. This table may be further refined to include tolerances. For instance, manufacturers may choose to define the gray area from 50% to 150% of the original tolerance. Therefore, for tolerances of ± 1 mm, the gray area would still range from 0.5 to 1.5. However, for tolerances of ± 0.7 mm, the gray area would range from 0.35mm to 1.05mm. The inclusion of tolerances allows more stringent criteria for critical dimensions.

Part Type	Region A (no die rework)	Region B (Gray Area)	Region C (usually rework)
Non-Rigid Surface	< 0.5	0.5 ~ 1.5	> 1.5
Rigid Surface	< 0.3	0.3 ~ 1.25	> 1.25

Table 10. Assigning Values for the “Dimensional Gray Area” by Part Type

Although these criteria relate to the likely acceptance of a particular dimension, manufacturers should also consider the percentage of dimensions for a given part in the gray area. For example, the more dimensions across an entire panel in the dimensional gray area, the lower the likelihood of acceptance. If a panel has ten dimensions and the mean deviation of each is in the gray area, this panel is likely to be rejected. However, if only one dimension is in the

gray area and the rest have mean deviations less than 0.3, this part will likely be accepted. Figure 17 suggests that if manufacturers can produce 80% of the mean dimensions within specification and a maximum mean deviation within the gray area, a part will have a high likelihood of acceptance.

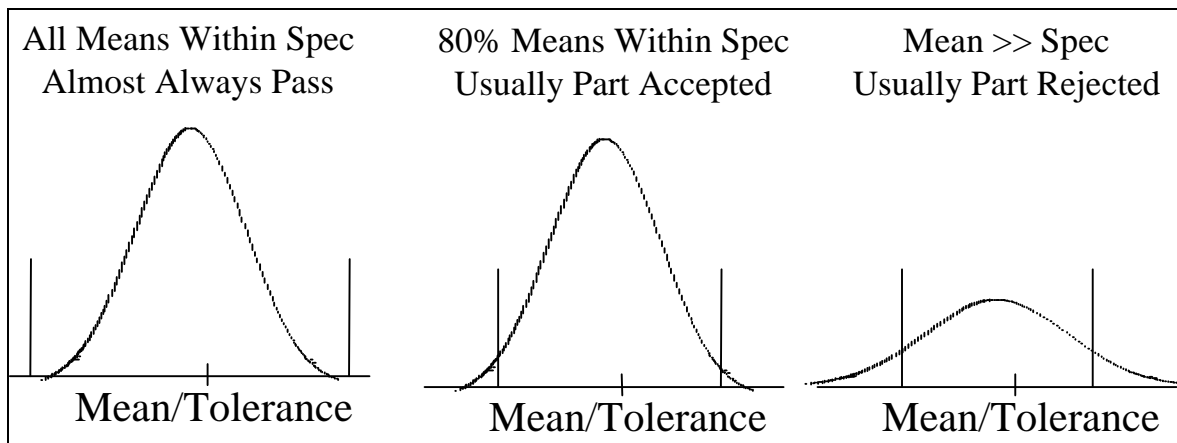


Figure 17. Mean Distribution and Part Acceptance

4.2.4 Sample Size Planning

Another functional build implementation issue is the number of runs and the sample size of each dimensional study. Manufacturers typically conduct at least four to five dimensional studies for each body component. Certain problem parts such as the body side outer may have more tryout runs. Manufacturers also might perform additional runs for other reasons such as evaluating material handling devices.

Table 11 shows the planned number of dimensional studies and measurement samples for several manufacturers. (Note: measurement sample size is different from the length of run. Manufacturers typically measure only of a subset of panels from a run). One obvious difference among manufacturers is the measurement sample size for a run. For example, only one company strictly adheres to the Production Part Approval Process¹ (PPAP) which requires samples of 100

¹ Production Part Approval Process, published by Automotive Industry Action Group (AIAG), Second Edition, July, 1995.

panels from a run of at least 300. The other OEMs measure, at most, 30 panels for their final part approval runs.

Company	Typical # of Tryout Runs	# Measured Samples for Each Run	Total # of Planned Measurement Samples
A	4 ~ 5	25, 5, 5, 25	60
B	4 ~ 5	10, 30, 30, 30	100
C	4 ~ 5	10, 10, 25, 100	145
D (J)	5	5-10 per run	50
E (J)	5	3 per run	15
F	7	3 per run	21

Table 11. # Panels Measured by Tryout Run

(Note: Companies D and E are Japanese Manufacturers)

The basic factor in determining appropriate sample sizes relates to the purpose of the study. If manufacturers want to assess short-term process capability, then larger sample sizes of at least 30 are needed. If the principal objective is to estimate the process mean for a given run, then smaller samples of 5 or 10 usually are sufficient, assuming inherent stamping variation (sigma) of approximately 0.1 to 0.15mm. Company E, a Japanese manufacturer, measures only three panels per run regardless of the tryout phase. This sampling plan suggests an inherent confidence that short-term variation is not a principle concern.

For manufacturers with some concerns related to short-term variation, it is recommended that they conduct one larger sample of 30 to validate that the process is meeting C_p objectives for variation conformance. This variation conformance validation should occur on the home line with automation to insure a reasonable evaluation of typical short-term production conditions.

4.3 Sub-assembly Build Issues

Under the functional build process, manufacturers evaluate components based on the ability to produce an acceptable assembly rather than solely on dimensional conformance to specifications. But, what is an acceptable build? Does it mean that all sub-assembly dimensions

are at nominal? Or, that all sub-assembly dimensions are within specification? Or, that the components have the “potential” to produce all subassembly dimensions within specification?

In defining an acceptable assembly, it is necessary to re-examine the reasons for implementing a functional build approach. First, consider the issue of part rigidity. Previously, it was argued that traditional mean stack-up models might be ineffective if the mating parts lack rigidity. Although mating components may be non-rigid, resultant assemblies typically are not. This suggests that manufacturers are less likely to compensate for out-specification sub-assembly dimensions and therefore should strive to produce sub-assemblies closer to nominal. Similar to stamping processes, assemblers also have difficulties simultaneously producing every assembly dimension at nominal. In addition, manufacturers may improve the dimensional conformance of a sub-assembly by making adjustments to weld tools. Following this logic the decision to rework a stamped part dimension off nominal relates to its *potential* to produce a dimensionally correct sub-assembly and not solely based on the results of a screw-body build constructed prior to assembly tooling adjustments.

Defining an acceptable assembly based on potential to produce subassembly dimensions to nominal involves risk. Some dimensional decisions that are delayed until the evaluation of weld tools eventually may require die rework. Clearly, manufacturers must be cautious of delaying too many decisions based on potential to compensate in assembly because of resource limitations to make changes. This leads to a similar argument for defining acceptable assemblies as used for stamped components.

Mean dimensions across an assembly often are normally distributed. This normality affects the ability to meet C_{pk} criteria for *all* sub-assembly dimensions. Again, separating mean and variation conformance is proposed. In the area of variation conformance, the use of process capability indices such as C_p or CR is recommended to demonstrate the inherent ability to produce assembly dimensions within the tolerance width. On the issue of mean conformance, tighter requirements than in stamping are proposed because of the lower likelihood to compensate for out-specification dimensions due to higher rigidity.

One challenge facing manufacturers is that they cannot always determine which component dimensions require rework to correct an assembly condition. Moreover, they cannot afford to rework every stamping deviation as this approach precludes them from meeting cost and timing goals. Thus, the development of sub-assembly criteria must tradeoff potential for die

rework during assembly validation versus delaying the start of validation to correct all stamping deviations.

Empirically, it may be shown that sub-assembly mean deviations within 50% of their assigned tolerances rarely prevent manufacturers from meeting final vehicle requirements. Figure 18 and Table 12 examines sub-assembly conformance for two benchmark vehicles with excellent body gap quality. While neither manufacturer meets C_{pk} requirements for all subassembly dimensions, both produce the majority of mean subassembly dimensions within 50% of the tolerance limits with relatively few mean sub-assembly dimensions outside their specifications (~ 6%). (This is based on assembly tolerances of +/- 1mm. Note: Company E uses more clamps in their assembly check fixture.)

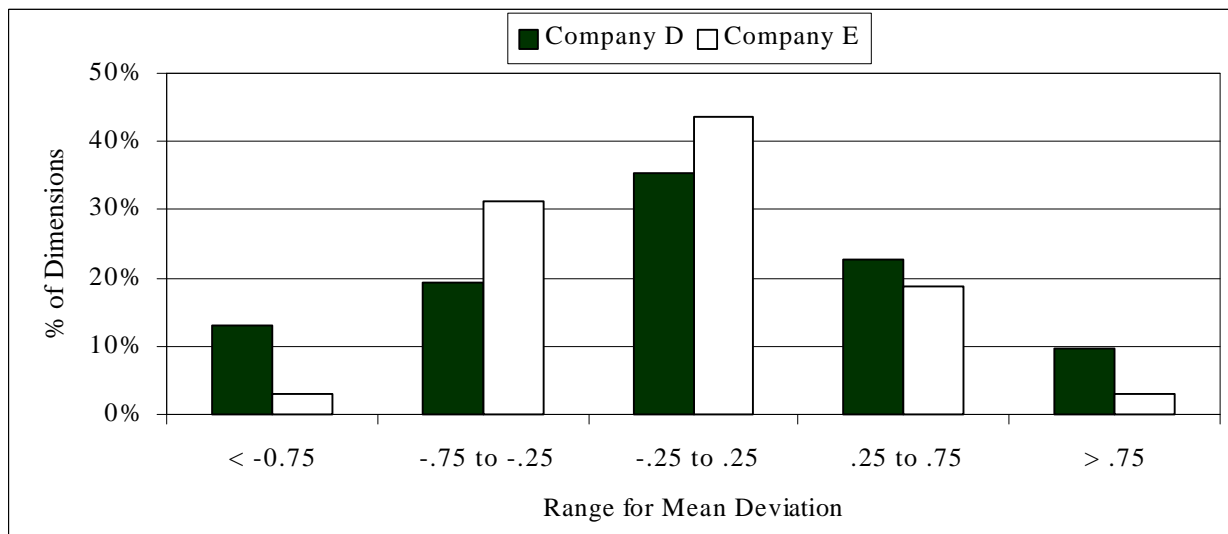


Figure 18. Body Side Assembly Mean Conformance

Company	% Dimensions $C_{pk} < 1.33$	% Dimensions $ \text{Mean} < \text{Tolerance}/2$	% Dimensions $ \text{Mean} > \text{Tolerance}$
D	84%	52%	6%
E	38%	75%	6%

Table 12. Body Side Assembly Mean Conformance Relative to Tolerance

Using mean conformance at these companies as benchmarks, Table 13 recommends criteria based on the distribution of mean dimensions across an entire assembly. This table links mean conformance with risk. The recommendation is to limit the % of dimensions at risk to less than 30%. A further recommendation is to limit the % of out-of-specification sub-assembly dimensions to less than 10% to reduce the potential for major rework during assembly validation.

Build Event	% Dimensions Mean < Tolerance/2	% Dimensions Mean < Tolerance
Screwbody #1	60%	85%
Screwbody #2	70%	95%

Table 13. Sub-assembly Build Goals for Screw-body Evaluations

As with stamping criteria, some inevitable subjectivity is inherent in the decision-making process. For example, vehicle build teams must make some decisions regarding sub-assembly acceptance based on experience. In other words, teams must identify those cases where they believe an adjustment to the assembly tooling may likely improve a dimensional problem as opposed to expensive die rework. On the other hand, if they know that a particular sub-assembly dimension or set of dimensions is likely to create problems in the final build, they should correct the problem before final weld validation.

One particular requirement that is difficult to compensate for in assembly relates to parallelism of feature lines for major closure panels. Figure 19 shows an example of the rate of change or parallelism along the fender-hood line. Regardless of whether this manufacturer moves the fender sub-assembly in the in/out or up/down direction, lack of parallelism along a sub-assembly feature line (especially in terms of waviness) will likely result in failure to meet final vehicle objectives for gap and flush parallelism. The only conceivable scenario in which it might not cause a problem is if the hood feature line exhibited a similar rate of change pattern. Since the likelihood of this occurring is extremely low, manufacturers should resolve all parallelism concerns in the stamped components or after sub-assembly hem operations. Many functional build evaluators maintain that meeting parallelism requirements in the detail components and after hemming operations is the most critical requirement to meet. This

particular example demonstrates the case where failure to meet specification should be addressed prior to any screw-body evaluations.

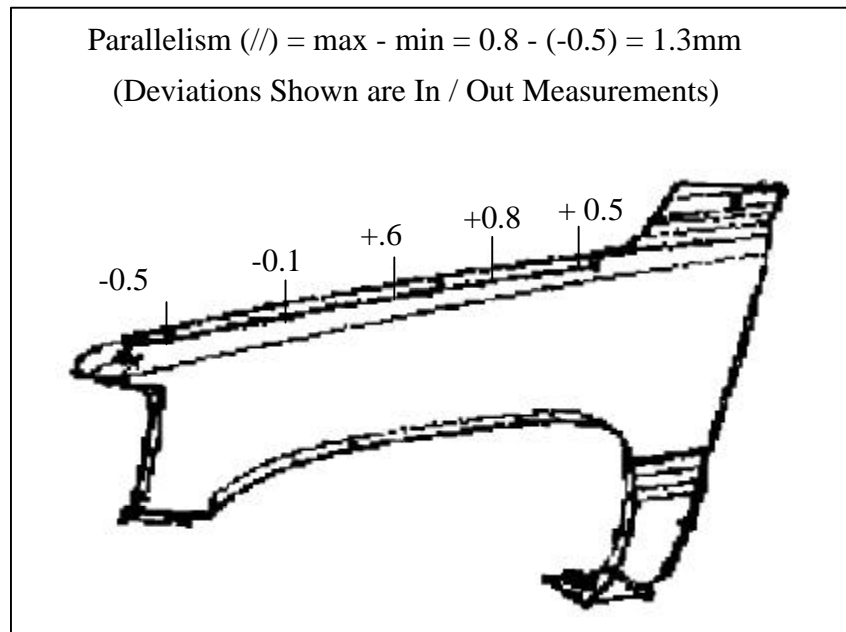


Figure 19. Out of Parallel Condition on Fender-to-Hood Line

(Note: assumes parallelism requirement of < .0.7mm)

4.4 Roadblocks to Functional Build Implementation

Specialization in stamping and welding often results in a narrow focus by engineers and manufacturers toward their individual tasks. Functional build, however, shifts the development focus from optimizing individual components to the entire body. This approach represents a major paradigm shift for product designers, process engineers and manufacturers. Final specifications for the components within an assembly are determined almost concurrently with the approval of the assembly. Whereas concurrent engineering requires more integration of downstream functions into the design process, functional build involves a more active role of design engineers into the validation process.

One concern among design engineers is that functional build simply shifts development problems from die construction and metal stamping to final assembly validation. Assembly

manufacturers and process engineers argue that if stamping plants would produce parts at nominal, then they could more efficiently validate their tooling. Even proponents of functional build certainly agree that greater conformance of stamping dimensions to specification is desirable. Proponents, however, recognize that once manufacturing processes are constructed, drawing changes to design prints or minor modifications to assembly tooling locators may be less expensive than physically reworking tools. Functional build does not imply that the original design would not produce a high quality body, rather that components with small mean deviations also may lead to the desired result. Thus, a basic tenet for functional build success is a commitment from product engineering, stamping and assembly to work toward improving the overall vehicle development process and not necessarily optimizing an individual activity.

Another area of contention with the functional build (FB) process is the usefulness of constructing the first screw-body using die source tryout parts. Table 14 lists several benefits and concerns with constructing the first screw-body. These findings suggest that although the functional build process has many benefits including lower die rework costs, some concerns remain regarding functional build's ability to reduce time.

Benefits	Main Concerns
Provides system to approve out-specification component dimensions, saving die rework.	Certain problem parts (e.g., body sides, quarter outers, fenders) may require many evaluations.
Dimensions approved out-of-specification are rarely rejected at home line.	If parts are not in dimensional window, high likelihood of failure.
Enables manufacturers to identifying problems not captured in the measured dimensional data.	Parts change from die source to home line.
Enables manufacturers to eliminate and/or re-classify dimensions as less important.	Cost and time to conduct FB. Evaluations require tryout resources.
Identify potential build issues for in-specification dimensions (design errors).	Lack of support for the FB process from those resisting organizational change.
Identify datum and fixture problems	

Table 14. Benefits and Concerns of FB#1

Some manufacturers also are unsure whether to use functional build as a “formal” buyoff process or merely as an input to the die shipment decision process. Under a formal “buyoff” process, components not approved at the first functional build would require re-submittal for approval. The benefit of this approach is that it requires die shops and release engineers to make

the changes requested by the functional build team. The tradeoff with this approach is the extra time necessary to perform multiple evaluations prior to shipping dies. For this reason, several manufacturers view the first functional build as a “one-shot” system.

Another approach to functional build that subscribes to the “one-shot” system is to view the overall functional build approach as a narrowing process. Manufacturers set goals not based on the percentage of components accepted at a functional build event, but rather the percentage of dimensions either in-specification or approved out-specification. Under the latter, manufacturers set goals for various stages. For example, they may want 80% of their stamping dimensions in-specification prior to the first functional build event. They would then expect to conditionally approve another 10% through the first functional build event. By the end of the second functional build (components in the home line), they might expect to have 95-98% of the dimensions accepted either in-specification or through tolerance revisions. The remaining dimensions then are resolved during the weld validation process by either reworking dies or assembly tooling. The strategy here is to view functional build as a system for the continuous resolution of problems.

5.0 Event Based Functional Build

This section recommends a dimensional evaluation process for event-based functional build. Figure 20 lists several key dimensional evaluation events and approximate timing guidelines. This hypothetical program is based on meeting a 24-month or 104 week timing objective. This further assumes a 52-week time frame from die source tryout to start of production (note: the other 52-week time frame is for design and construction). Of course, actual timing would certainly vary by manufacturer and a particular car program.

Figure 20 separates the overall process into three validation phases: die-source tryout, press shop tryout (home line) and body shop tryout. Note that many events overlap due to the status of individual components. For example, if a manufacturer accepts the front pillar reinforcement in the first screw-body build but rejects the body side, then the front pillar dies may be shipped to the press shop while modifications on the body side occur at the die source.

Under event-based functional build, the screw-body build events must occur on time. Therefore, at the time of a scheduled build, if a particular component is not meeting its dimensional objectives or not updated to its most recent engineering change level, then the event must occur with non-conforming products. Under this approach, manufacturers delay changes until the modification period after the event rather than miss a timing deadline. For some problem parts, they may need to execute special recovery plans to insure that components meet the next event objectives. Obviously, using non-conforming product diminishes the value of the screw-body build, but meeting timing objectives is sacred under event-based functional build.

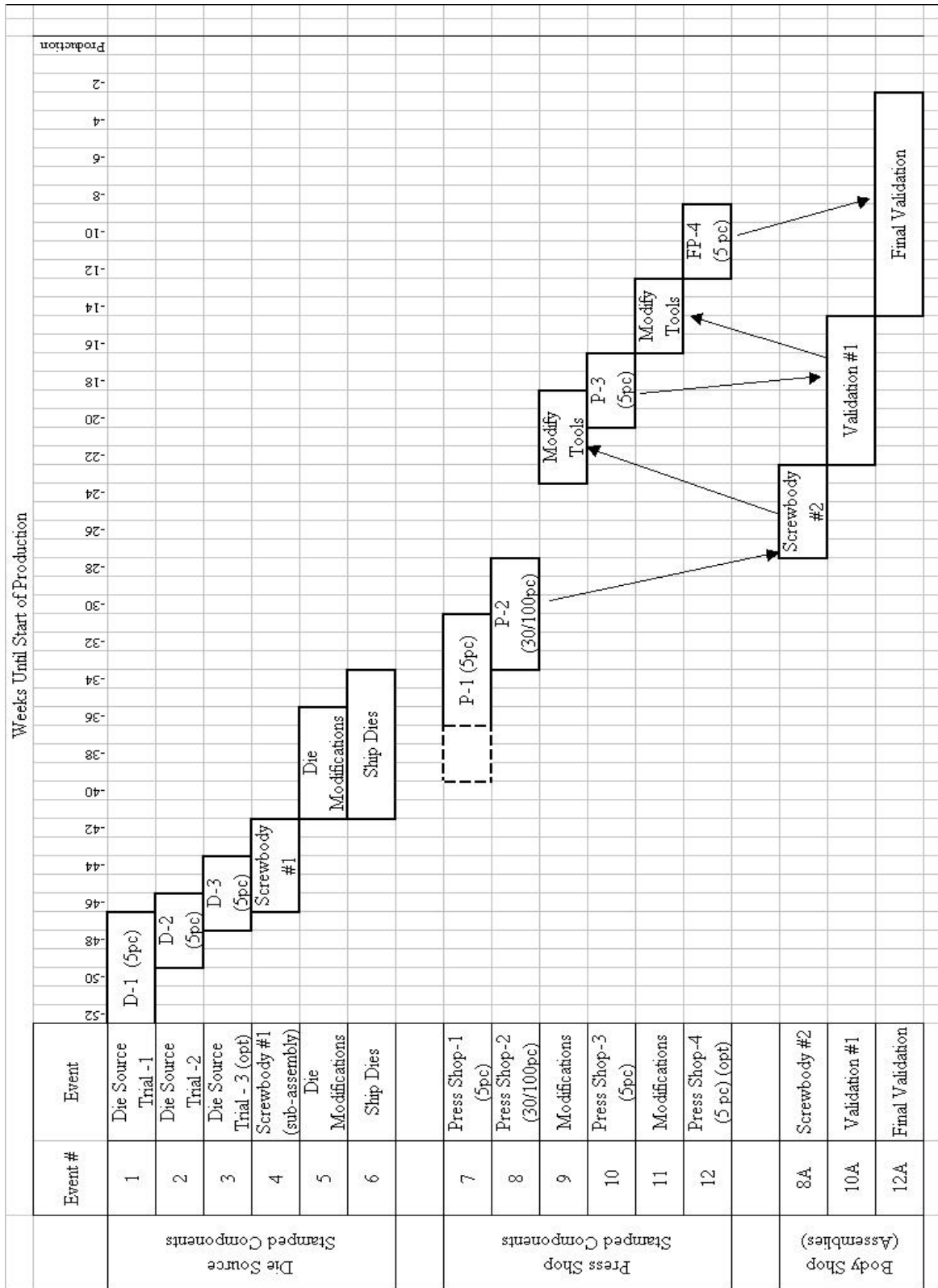


Figure 20. Timing Process

5.1 Die Source Tryout

To validate dimensional conformance at the die source, an iterative process of five-panel dimensional studies is recommended, which examines mean conformance relative to nominal. The purpose of functional build submittal criteria is to insure a high likelihood of approving the part dimensionally. In this situation, the functional build team's primary role is to (1) evaluate those dimensions in the dimensional gray area, (2) identify any potential build concerns such as short trim on a weld flange and (3) identify any design errors. Of course, an effective prototype process strongly minimizes the need for identifying design errors. Figure 21 proposes a dimensional validation process at the die source for parts classified as functional build parts.

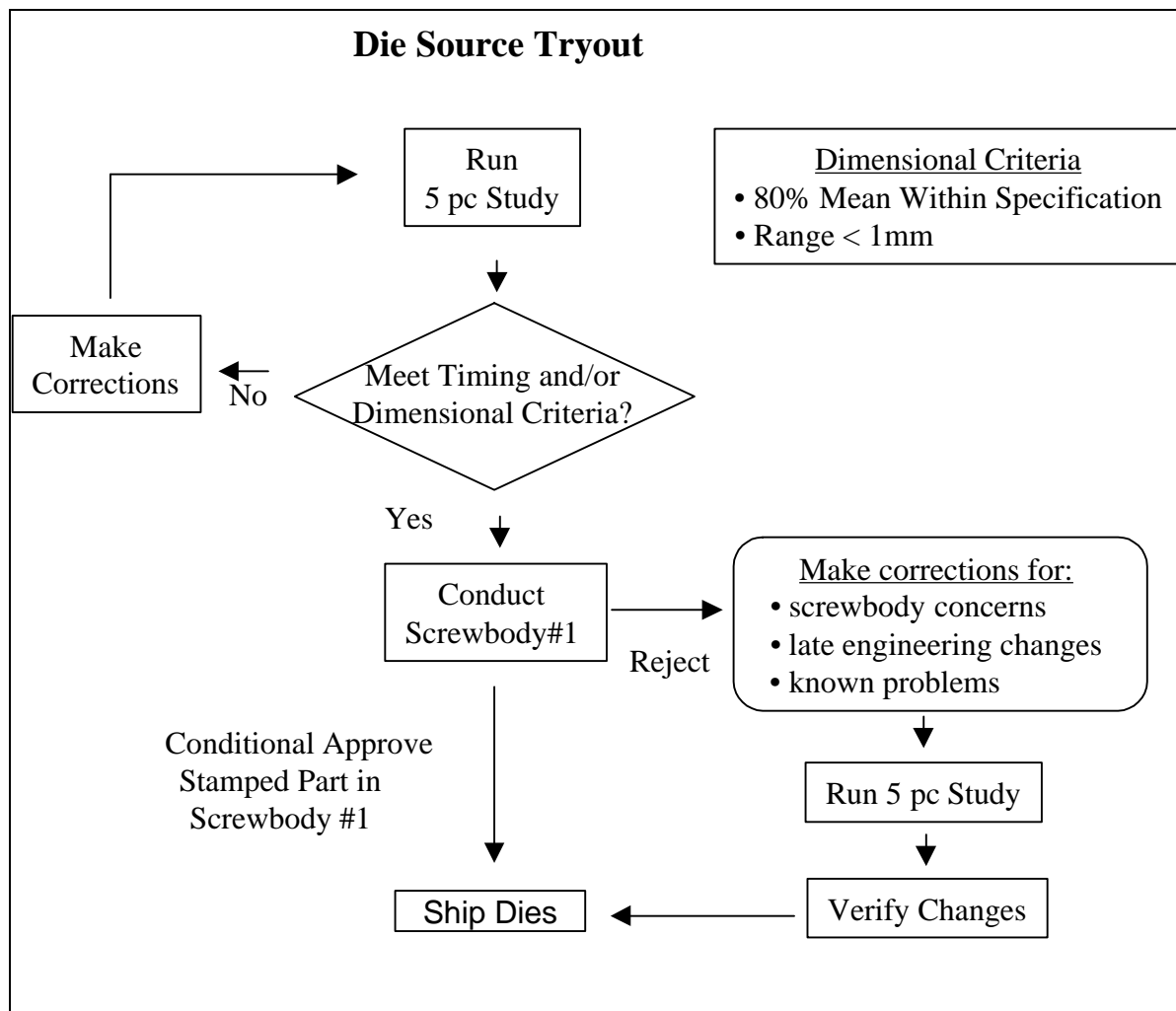


Figure 21. Die Source Tryout Process Flow

Under these proposed criteria, manufacturers potentially could approve a dimension with a mean equal to the specification limit. (Note approximately half the samples would be out of specification in this situation). Historical evidence, however, suggests that assembly processes usually may compensate for dimensions meeting all of these proposed criteria. This study asserts that the potential savings in lead-time and rework costs far outweigh the additional risk of later rework to insure that 100% of the sample panels are within the original specifications. In two functional build case studies, no instances existed where a dimension with a mean in specification later required rework to fix an assembly problem.

5.2 Production Source Tryout Process

Figure 22 recommends a flow chart for production source tryout (press shop). A common evaluation process is recommended for home line tryout regardless of the part categorization (functional build and non-functional build parts). According to this process, the existing practice of conducting multiple die sets for process validation should continue. For scheduling issues, manufacturers typically should limit the time in a press for a tryout run to no more than 4 hours.

The dimensional evaluation process at home line tryout should be aimed at four primary objectives:

1. Insure that stamped parts are capable within a stamping run (meet CR requirements),
2. Insure that the stamping facility demonstrates an ability to establish a stable mean between die sets (i.e. control mean shifts between die sets),
3. Insure that a quality assembly (all assembly dimensions within specification) is feasible given the stamping mean deviations and
4. Finalize production mean targets and tolerances for stamped components.

The significant differences between this proposed approach and the PPAP recommended approach are additional criteria on the control of the mean between runs, and the elimination of C_{pk} as the part approval criteria. With the elimination of C_{pk} , this approach requires that the functional build and assembly validation teams verify that the stamping mean deviations (once they are shown stable) may produce dimensionally correct sub-assemblies. Inherent in this

assumption is the responsibility of assembly buyoff teams to make any necessary adjustments to produce a good assembly. In other words, adjusting the assembly process to correct an out-of-specification condition usually is preferred over reworking a stamping die if either action resolves the problem.

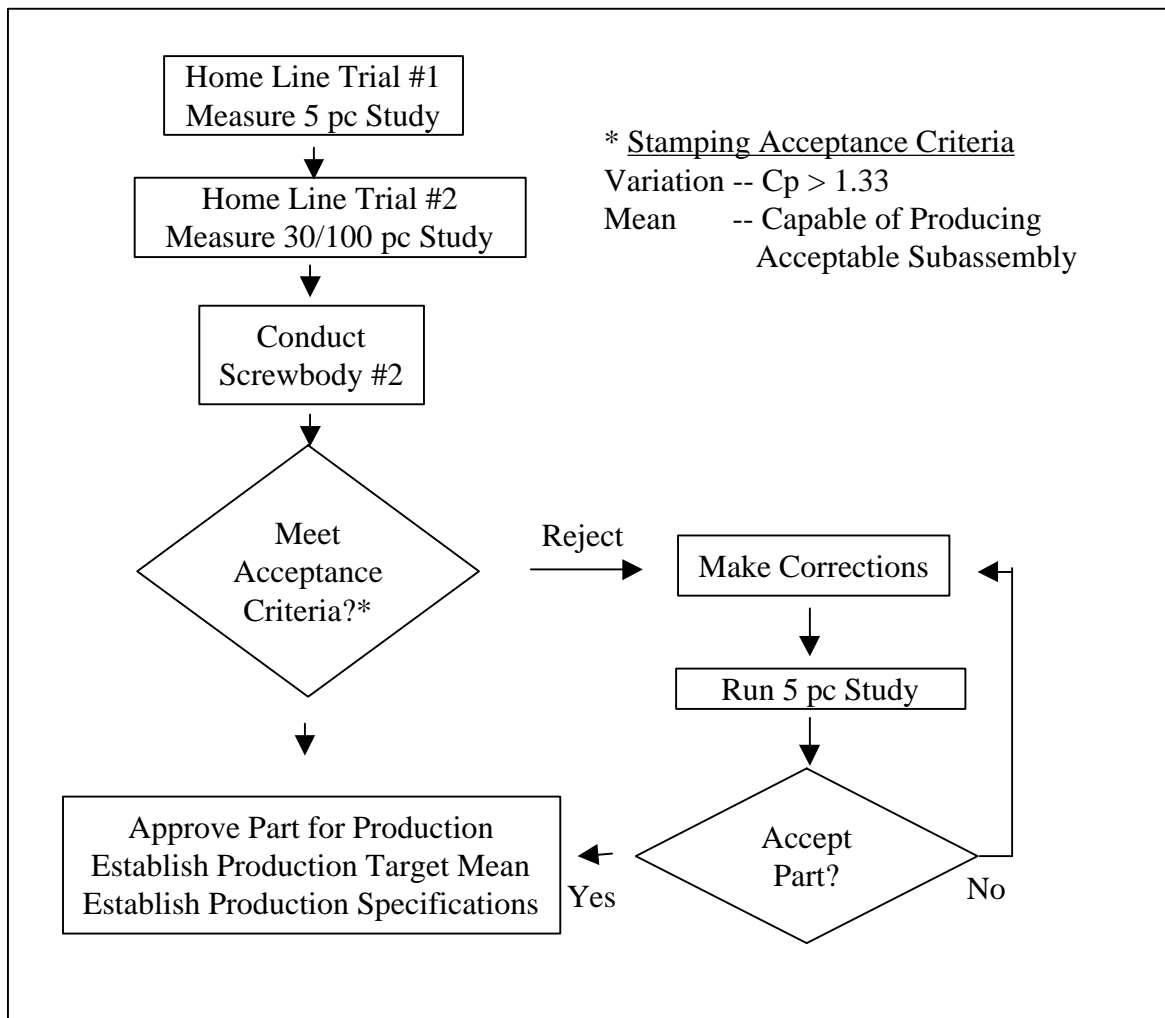


Figure 22. Press Shop Tryout

Another modification to the current process is a requirement that demonstrates the ability to setup dies repeatedly without significant mean shifts. It is recommended to require that all dimensions exhibit mean shifts less than 0.5mm across repeated die sets. Although this requirement may create additional stamping runs during secondary tryout, compliance insures

that the functional build process is evaluating representative panels and that stamping plants have their processes in-control for regular production.

The results of this study also support a reduction in sample size for the PPAP run. PPAP requires a measured sample of 100 out of a run of 300. This study recommends a sample of 30 from a run of 100. Historical evidence suggests that measuring large samples from a single run is resource intensive and provides minimum value. Moreover, relatively few dimensions (an estimate of 2 to 4%) would be affected by reducing the sample size to 30. However, the savings in inspection costs and timing for decision-making offset the additional risk.

6.0 The Future of Functional Build

This report presents a new paradigm for body validation. Manufacturers that continue to embrace new methodologies and business practices not only will remain competitive in the global market but also set the benchmark for competition. By using an integrated validation approach like functional build, manufacturers may accelerate the product development life cycle while saving costs in manufacturing process development.

An important issue facing functional build manufacturers is its future application. Functional build involves an additional validation step to construct screw-body prototypes and it requires greater coordination between development functions. Several manufacturers using functional build hope they will eventually develop the manufacturing knowledge necessary to identify when rework is value-added without having to construct screw-body prototype assemblies. The goal is to replace these prototypes with process simulation or math-based functional build. Even with this approach, two fundamental principles behind functional build will remain. First, manufacturers should never rely solely on statistical indices to make tooling and validation decisions. Incorporating process knowledge with dimensional data results in more effective decisions than those based purely on quantitative results. Second, development functions must integrate their product/process knowledge, and focus on the final customer product and not necessarily individual components.