University
of Michigan
Business
School

WORKING PAPER SERIES

Predicting Assembly Dimenions With Funcational Build

Karl D. Majeske
University of Michigan Business School

Patrick C. Hammett
University of Michigan
Transportation Research Institute

Working Paper 02-011

Research Support • Ann Arbor, MI 48109-1234 • 734/763-9266

Predicting Assembly Dimensions with Functional Build

Karl D. Majeske
The University of Michigan Business School
701 Tappan Street
Ann Arbor, MI 48109-1234
Phone: 734-647-6978
E-mail: kdm@umich.edu

Patrick C. Hammett
The University of Michigan Transportation Research Institute
2901 Baxter Road
Ann Arbor, MI 48109-2150
Phone: 734-936-1121
E-mail: phammett@umich.edu

Abstract

When using the functional build approach to manufacturing validation during new product development, manufacturers use pre-production assemblies to evaluate whether components within an assembly may build dimensionally correct products. This approach allows some individual component characteristics to ***not*** meet their original design specifications, provided the resultant assembly meets its requirements. In applying this functional build methodology, manufacturers assume that the pre-production assemblies provide data representative of what the manufacturer will encounter in the regular production process. This paper evaluates the predictive validity of the functional build approach by utilizing a design of experiment to examine the effect of two factors - build fixture and method of attachment - in constructing functional build pre-production assemblies of stamped sheet metal components. The results confirm the importance of using assembly fixtures that closely resemble regular production processing.

Key Words: Functional Build, Sheet Metal Stamping, Design of Experiments, Die Tryout, Automotive Body Assembly

Predicting Assembly Dimensions with Functional Build

I. Introduction

Most passenger vehicles have a structural body element composed of a collection of stamped metal panels that are welded together in an assembly process. As individual stampings, these panels may be quite flexible and subject to distortion during the assembly process. Once welded together, they form a rigid vehicle body. Historically, manufacturers spend a great deal of time and money during process development reworking stamped panels to produce them within original design specifications. Unfortunately, this reworking of stamping dies to change panel geometry does not necessarily correspond to desired changes in assembly dimensions. Due to the lack of rigidity in the individual panels, the relationship between component panel geometry and final assembly dimensions is not clear. This lack of relationship between components and assemblies, along with the absence of adjustment mechanisms in the stamping dies, has lead automobile manufacturers to adopt functional build techniques. The functional build process evaluates the stamped panels within an assembly collectively and does not always require changes to individual panels if they do not meet initial design specifications. Rather, functional build evaluates the acceptability of stamped panels to come together to form assemblies that are within design specification. In other words, if the assembly meets the design requirements, individual panels are approved regardless of their conformance to the respective measurement characteristics.

Functional build represents an integrated approach to product and process development – a form of concurrent engineering - that accelerates the time it takes manufacturers to bring new products to market. Abdalla [1] suggests that manufacturers can shorten product development, reduce costs, and improve quality by implementing proven concurrent engineering techniques. Hammett, Majeske, and Baron [2] motivate the need for using functional build by analyzing sheet metal and welded assembly data. They show that the correlation between component (sheet metal stamping) and assembly data is low and that dimensions shift, on the average, with assembly. Hammett, Wahl, and Baron [3] discuss using functional build as part of the manufacturing validation process. Majeske and Hammett [4] provide an approach for using functional build to develop final product design tolerances. Some manufacturers are also experimenting with math-based or virtual functional build using computer assembly simulation models [5]. This approach is still under development as simulation models often have difficulty replicating the movement of sheet metal due to clamps and non-rigid components.

When designing a vehicle body, a manufacturer specifies the completed product final design specifications (the nominal or target value and the tolerance band) for each assembly and then specifies design specifications for the components that go into the assembly. During process development, the manufacturer then develops the tooling – stamping dies in the case of automotive body manufacturing - with the intention of producing individual components at the target value. Once completing a set of stamping dies, the manufacturer will produce and measure a sample of panels. With the functional build approach, the manufacturer uses the sample data to assess the process capability measure C_p [6] to determine if the assembly tooling can accommodate the part-to-part variation. However, the manufacturer will not attempt to modify the stamping process to eliminate any potential mean deviations from design nominal or manufacturing biases.

Once all component processes have been developed, the manufacturer will use the parts produced by these processes to make pre-production functional build assemblies. Since the production assembly process may not be completed at this stage in product development, the manufacturer may construct these functional build assemblies in a non-production environment. For example, some manufacturers use non-automated assembly weld tools to locate parts while others use assembly check fixtures that also are capable of locating individual components prior to assembly. These fixtures often are referred to as part coordination or match check fixtures. It is common to use screws or rivets to attach stamped panels in the functional build assembly process rather than spot welds, which are used in regular production. This use of screws to attach panels in functional build assemblies has lead some manufacturers to refer to functional build as the "screw body process."

While constructing functional build assemblies, the manufacturer will evaluate the ability to use the components, in their current state, to make dimensionally correct assemblies. The manufacturer then approves the component design and manufacturing process based on the ability of these components to functionally produce an acceptable assembly. Making inferences from these functional build assemblies assumes that they are representative or valid predictors of the assemblies that will be produced in regular production. This research suggests that failure to replicate assembly conditions in functional build processing may provide biased estimates of the mean and variance of production assembly dimensions.

The remainder of this paper has the following organization. Section II provides a description of a four-component automotive quarter panel assembly studied in this research. This section also describes how manufacturers measure stamped sheet metal panels and shows the specific measurement locations of the components and the quarter panel assembly. Section III provides a measurement systems analysis for the two gages used to measure the stamped quarter panel and discusses potential measurement fixture issues. Section IV presents the experimental design used to study the functional build assembly construction process and Section V contains the results of the experiment. Section VI then examines the predictive relationships between component stamped panels and their corresponding assemblies. In Section VII we provide conclusions from the study and make recommendations on how to construct functional build assemblies to improve the manufacturing validation strategy.

II. Case Example: Automotive Quarter Panel Assembly

This research uses an automotive quarter panel assembly - the rear portion of the side of a passenger car – as shown in Figure 1. This assembly consists of four main stamped panels: quarter panel, belt reinforcement, shelf extension, and extension support. The quarter panel is a large, flexible stamped part that forms a portion of the exterior surface of the vehicle body. The belt reinforcement lends rigidity to the assembly and provides for improved safety in a side impact accident. The shelf extension forms one-half of the shelf behind the back seat just below the rear window. The extension support provides additional rigidity to the quarter panel in the location where the shelf extension is attached. The assembly process attaches the three smaller, more rigid stampings to the quarter thus creating a quarter panel assembly.

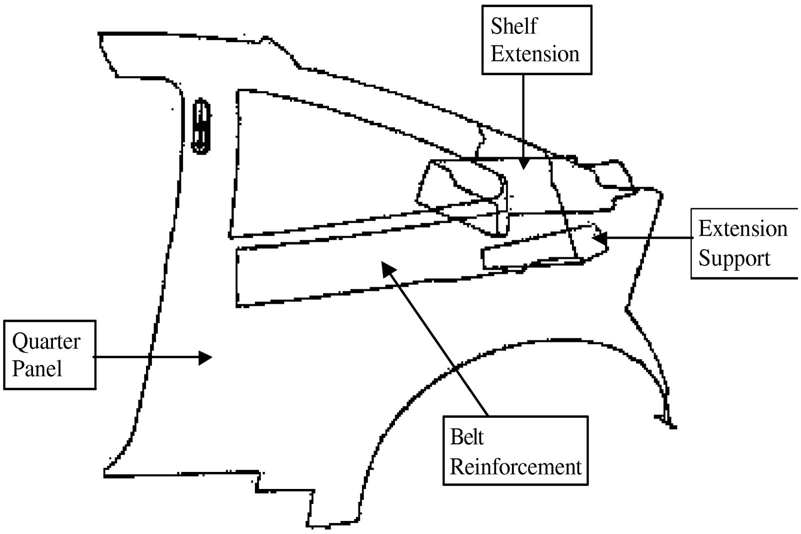

Figure 1: Stamped Component Panels in the Quarter Panel Assembly

Manufacturers assess the quality of stamped panels by taking a series of discrete measurements to define feature and contour locations. Manufacturers take these measurements in three-dimensional space using the axis: Fore / Aft (F/A), Cross Car or In / Out (I/O), and Up / Down or High / Low (H/L). These measurements require placing the assembly in a locating fixture and then measuring the specified locations with a Coordinate Measuring Machine (CMM) or another type of data collection device. Automotive manufacturers treat these discrete measurement points as independent response variables. Currently, manufacturers are experimenting with replacing these discrete measurement points with part surface scans. For example, Hofling, Aswendt, and Neugebauer [7] suggest using *phase reflection*, comparing the reflected image of a stamped panel to a design standard, to determine if automotive sheet metal stampings conform to design specifications. Still, functional build manufacturers continue to rely on evaluating components and assemblies at discrete physical locations.

For the stamped panels shown in Figure 1, the manufacturer measured 17 discrete locations on the quarter panel, six locations on the shelf extension, and nine locations on the belt reinforcement, and took no variable measurement data on the extension support. Once completed, the manufacturer measured the assembly in 13 locations to assess conformance to customer requirements. Figure 2 identifies the location and direction of the 13 measurement points on the assembly under study. A point that is measured at the same physical location on both the component and the assembly is referred to as a coordinated measurement point. Of the 13 points measured on the quarter panel assembly, eight (points 3, 5, 6, 7, 8, 9, 11 and 12 on Figure 2) were coordinated points.

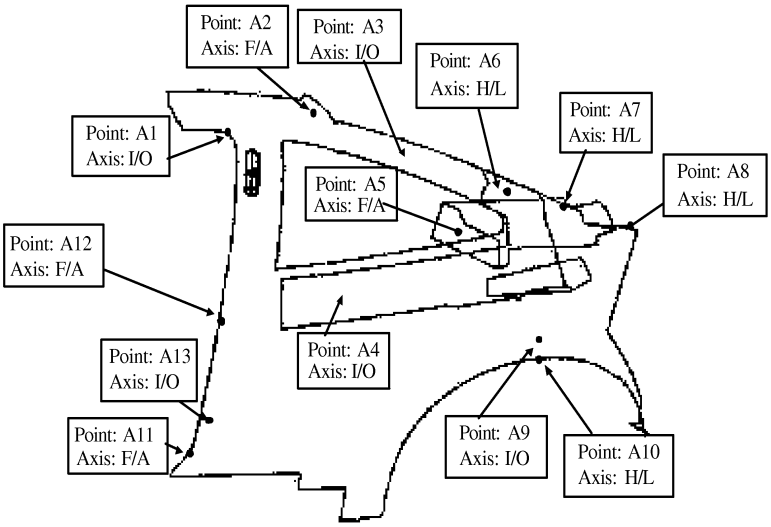

Figure 2: Quarter Panel Assembly Measurement Points and Axis of Measure

III. Measurement System Analysis

Manufactures use measurement system analysis (MSA), commonly referred to as gage studies, to quantitatively assess the ability of the measurement system to generate valid data. The Automobile Industries Action Group (AIAG) [8] has developed a common MSA approach used by many automotive manufacturers and suppliers. Among the potential sources for measurement error are the fixture construction and the orientation of the part in the fixture. A common concern in automotive body assembly is whether the stamping detail fixture locates and orients the component similar to the assembly process and assembly measurement fixture. For example, manufacturers have been known to use different part locating strategies (i.e., different datums) across processes.

Figure 3 shows the three different orientations for the quarter panel under study. The stamping plant measures the stamped quarter panel in the detail fixture that rotates the panel 90 degrees from car position making. This orientation reduces gage cost and makes the exterior metal surface visible to the gage operator. The assembly weld tool orients the panel with the interior surface pointing up, a –90 degree rotation, to allow weld gun access. The assembly check fixture measures the quarter panel assembly in car position to minimize the potential for measurement error. One concern with changing orientation is the potential effects due to gravity given a non-rigid panel, i.e., gravity may pull features in different directions depending on orientation. Weckenmann, Knauer, and Killmaier [9] provide a comprehensive listing of all the factors that may induce error into the measuring of automotive sheet metal stampings.

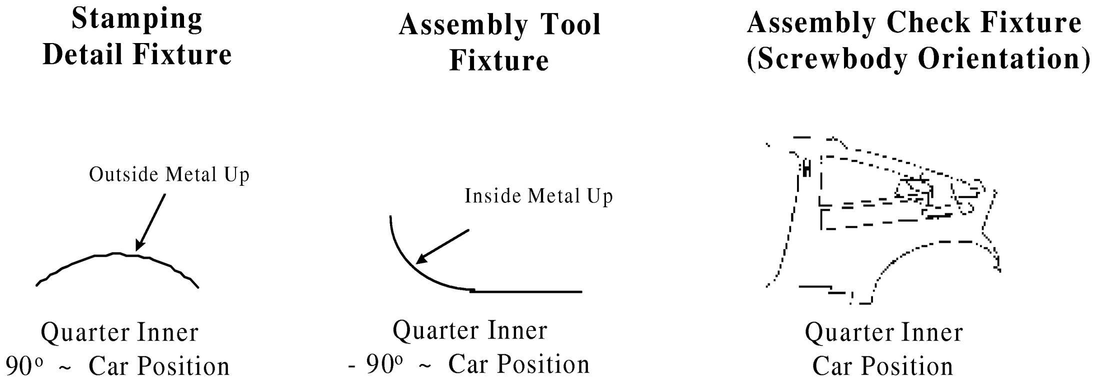

Figure 3: Panel Orientation at Various Stages of the Process

In this section, we evaluate two fixtures capable of measuring the quarter panel stamped component: the detail stamped panel fixture and the assembly check fixture. The stamping plant measures the panels in the detail fixture while the assembly plant uses the assembly check fixture, which has the ability to measure both the completed quarter panel assembly and the stamped quarter panel. The detail fixture measures 17 panel locations while orienting the panel in laydown position as shown in Figure 3. The assembly check fixture orients the panel in car position and measures 11 locations on the quarter panel. These measurement points represent the locations on the assembly that reside on the stamped quarter panel (all locations on Figure 2 except A5 and A7).

Manufacturers often evaluate a measurement system using the precision to tolerance ratio $\frac{P}{T}$. Letting TOL represent the width of the design tolerance, and σ_g denote the standard deviation of the gage error, one can determine the precision to tolerance ratio as

$$\frac{P}{T} = \frac{6\sigma_g}{TOL}. \qquad (1)$$

Montgomery [6] suggests that gages with a $\frac{P}{T}$ of 0.1 or less should be adequate. The Automobile Industries Action Group (AIAG) [8] provides three ranges for the precision to tolerance ratio:

1) $\frac{P}{T} < 0.1$ the gage is capable

2) $\frac{P}{T} > 0.3$ the gage is not capable

3) $0.1 < \frac{P}{T} < 0.3$ the gage may be capable

Majeske and Andrews [10] suggest evaluating a measurement system using the theoretical correlation in repeat measurements

$$\rho = \frac{1}{1 - \frac{\sigma_g^2}{\sigma_p^2}} \tag{2}$$

where σ_p represents the standard deviation of the measured dimension. The theoretical correlation in repeat measurements provides an indication of the gage's ability to discriminate between parts. Majeske and Andrews also show that

$$\rho = \frac{1}{1 + \left(\frac{P}{T} C_p\right)^2} \tag{3}$$

or the correlation is a direct function of $\frac{P}{T}$ and the measure of process capability C_p. They suggest specifying a maximum allowable $\frac{P}{T}$ value and a minimum acceptable C_p value and then using equation 3 to solve for the correlation criteria. For this study, we used the AIAG

[11] criterion of Cp > 1.67 along with a criterion of $\frac{P}{T} < 0.3$ to obtain a correlation criterion of 0.8.

To quantify the error associated with the two measurement systems, we conducted single operator gage studies [6] on each gage using the same set of 38 stamped panels. For each gage study, the operator took two measurements on each of the 38 panels. We modeled each measurement location as an independent response variable and fit the resulting data with one-way random effects ANOVA models [12]. We then estimated the variance of the gage (measurement system) σ_g^2 with the mean squared error (MSE) as

$$\hat{\sigma}_g^2 = MSE.$$

Letting n represent the number of measurements per panel, we estimated the variance of the panels σ_p^2 from the ANOVA model as the variance of the random factor

$$\hat{\sigma}_p^2 = \frac{MS_{factor} - MSE}{n}.$$

We then estimated $\frac{P}{T}$ and ρ by plugging the estimates of σ_p and σ_g into equations 1 and 2, respectively.

Table 1 contains the $\frac{P}{T}$ and ρ values estimated for the 17 locations measured using the quarter panel detail fixture where highlighted values failed to meet the specified criteria. The detail fixture fails the $\frac{P}{T}$ criterion on three of the 17 locations. Locations P13 and P15 exceed 1, indicating the gage error distribution is wider than the design tolerance. This suggests that repeatedly measuring a given part could result in values below the lower specification, above the upper specification, and within tolerance. For these two locations, data generated with this gage could lead to erroneous conclusions regarding the quality of the stamped panels. The detail fixture fails the correlation criteria on four of the 17 measurement locations. Locations P5, P13, and P15 also failed the $\frac{P}{T}$ criterion, and it is this excessive gage error that prohibits the gage from producing correlated repeat measurements. Location P4 fails the correlation criteria due to low product variation. For this location, the gage can adequately determine if panels are within design specification but cannot differentiate panels from each other.

Location	Design Tolerance	Sigma Gage	$\frac{P}{T}$	Sigma Part	ρ
P1	4	0.022	0.032	0.043	0.803
P2	3	0.032	0.065	0.264	0.985
P3	2	0.033	0.098	0.165	0.963
P4	2	0.016	0.048	0.005	***0.100***
P5	2	0.204	***0.613***	0.225	***0.547***
P6	2	0.024	0.072	0.053	0.827
P7	3	0.085	0.170	0.246	0.893
P8	3	0.043	0.087	0.232	0.966
P9	3	0.086	0.171	0.210	0.857
P10	2	0.029	0.088	0.132	0.953
P11	2	0.037	0.112	0.288	0.983
P12	2	0.061	0.182	0.136	0.834
P13	2	0.347	***1.042***	0.174	***0.201***
P14	2	0.035	0.106	0.124	0.925
P15	2	0.407	***1.220***	0.186	***0.173***
P16	3	0.052	0.104	0.363	0.980
P17	2	0.043	0.130	0.216	0.962

Table 1: Detail Fixture Gage Study Results

Table 2 contains the $\frac{P}{T}$ and ρ values estimated from the gage study for the 11 measurement locations on the quarter panel using the assembly check fixture. The assembly fixture meets the $\frac{P}{T}$ criterion on all 11 locations. However, the assembly fixture does not meet the correlation criterion on four of the 11 locations that depend on the ratio of gage error to product variation. It is the low level of product variation, relative to gage error, that limits the ability of this gage to produce readings that correlate.

		Assembly Fixture			
Location	Design Tolerance	Sigma Gage	$\frac{P}{T}$	Sigma Part	ρ
A1	2	0.083	0.249	0.125	***0.696***
A2	2	0.058	0.175	0.121	0.811
A3	2	0.025	0.074	0.064	0.869
A4	2	0.054	0.162	0.056	***0.523***
A6	2	0.042	0.127	0.143	0.919
A8	3	0.048	0.096	0.179	0.933
A9	3	0.052	0.105	0.175	0.918
A10	3	0.105	0.209	0.186	***0.759***
A11	3	0.113	0.227	0.082	***0.343***
A12	2	0.023	0.070	0.067	0.891
A13	2	0.032	0.096	0.154	0.958

Table 2: Assembly Fixture Gage Study Results

The two gages that measure the stamped quarter panel measure eight locations in common. Table 3 shows $\frac{P}{T}$, ρ , and the average reading for each gage by measurement location. For these eight locations, the two gages have similar levels of gage error and both gages have the ability to correlate repeat measurements. The difference between the gages is their estimates of the process average. With the exception of locations A13 – P5, each location has a significantly different average reading with differences in the 0.5 mm to 1.0 mm range. The differences in the average readings indicate that measuring a panel on one fixture gives minimal information regarding the reading of the other fixture. This provides a plausible explanation for why the stamping and assembly plants had difficulty agreeing on the geometry of the panels. More importantly, these findings suggest that changing the orientation from laydown (detail fixture) to body position (assembly fixture) may result in a dimensional shift of component mean deviations. This result supports the need for a functional build strategy to evaluate component acceptability, particularly when non-rigid parts change orientation at various stages of the manufacturing and assembly process.

Table 3: Comparing the Assembly Fixture and the Detail Fixture

		Assembly Fixture			Panel Fixture		
Assembly Location	Panel location	$\frac{P}{T}$	ρ	Average	$\frac{P}{T}$	ρ	Average
A1	P3	0.249	0.696	-1.326	0.098	0.963	-0.260
A2	P17	0.175	0.811	0.783	0.130	0.962	0.358
A6	P11	0.127	0.919	-0.203	0.112	0.983	0.417
A8	P9	0.096	0.933	0.038	0.171	0.857	-0.470
A9	P8	0.105	0.918	0.569	0.087	0.966	-0.428
A10	P7	0.209	0.759	0.996	0.170	0.893	0.618
A12	P6	0.070	0.891	-0.679	0.072	0.827	0.104
A13	P5	0.096	0.958	0.669	0.613	0.547	0.739

IV. Functional Build Assembly Process Experimental Design

Functional build manufacturers use different methods for constructing pre-production prototype assemblies as part of process validation. This section presents a design of experiment (DOE) used to study the functional build assembly construction process and assess the ability to use these prototypes to predict production assembly dimensions (means and variances). We examine the effect of two variables, build fixture and method of attachment, on the dimensional readings of functional build assemblies. For this experiment, we purposely selected a quarter panel assembly in current production to allow a comparison between the functional build assemblies and those produced using the regular production process.

When constructing functional build assemblies, manufacturers must decide on a method of attaching panels. In production, manufacturers usually attach panels using spot welds, so we selected this as one level for the attaching method experiment factor. Most manufacturers utilizing the functional build approach use sheet metal screws to attach panels for evaluation. Thus, screw assembly represents the second level of the attaching method factor. One question this research wanted to address is whether this change in attaching method induces error (bias and / or precision) into the predictions of assembly dimensions.

A second functional build implementation issue is how to hold or fixture the stamped panels when attaching them to produce functional build assemblies. Many practitioners of functional build use the assembly check fixture, a.k.a. the part coordination fixture, which represents one level of the fixture factor. Using the part coordination fixture allows manufacturers to evaluate stamped panels prior to assembly weld tool validation. In addition, the automated assembly tooling process may not have sufficient clearance for the drills and screw guns used to construct the functional build assemblies. Further, using the automated weld process can be difficult to "slowly and deliberately" assess panel-by-panel joining. The production weld tooling served as the second level of the fixture factor in this study. The obvious advantage of using the production weld tooling is that it utilizes the production assembly sequence and part locating strategy (e.g., datums, locating surfaces, clamps, and pins), which has been shown to affect product geometry [13]. A drawback to using production weld tooling is that it requires the manufacturer to develop more of the assembly process earlier in the product development cycle.

Another objective of this study was to determine if a manufacturer could reduce the variance in functional build assemblies by using stamping panels closer to the center (mean) of their individual distributions. To accomplish this, we created an additional run in the experimental design using the most common functional build approach of attaching panels with screws located in the assembly check fixture. However, for this run we used the non-random approach (biased sample) of Hammett, Baron, and Majeske [14] to select input components.

Table 4 describes the five runs in the designed experiment used to study the build fixture, attaching method, and component selection factors. The assemblies welded with the weld tool were built in the current production process and serve as the baseline for analysis. Any differences among the baseline group and the other groups represent biases in the various possible applications of the functional build methodology. To determine the sample size of n = 10, we used a statistical power approach [15] by specifying the magnitude of factor effects we desired to detect and the probability (statistical power) that we would detect the effect. Table 4 also contains the actual number of assemblies (sample size) produced for each DOE run.

Table 4: Functional Build Process Configurations and Sample Size

DOE Run	Fixture	Attaching Method	Panel Selection	Sample Size
1	Weld Tool	Weld	Random	11
2	Weld Tool	Screw	Random	10
3	Assembly Check	Weld	Random	10
4	Assembly Check	Screw	Random	8
5	Assembly Check	Screw	Representative	6

To conduct the experiment, we obtained fifty sets of the four stamped panels. The quarter panel, shelf extension, and belt reinforcement (see Figure 1) were measured and these data were used to assign panels to DOE runs. In an attempt to capture long run process variation in the component panels, we selected 10 panels from each of five different die setups because batch-to-batch variation is a significant source of stamping variation [16]. Figure 4 shows a plot of the measurements of location P7 on the quarter panel by stamping die setup to graphically depict this batch-to-batch variation in the stamped panels.

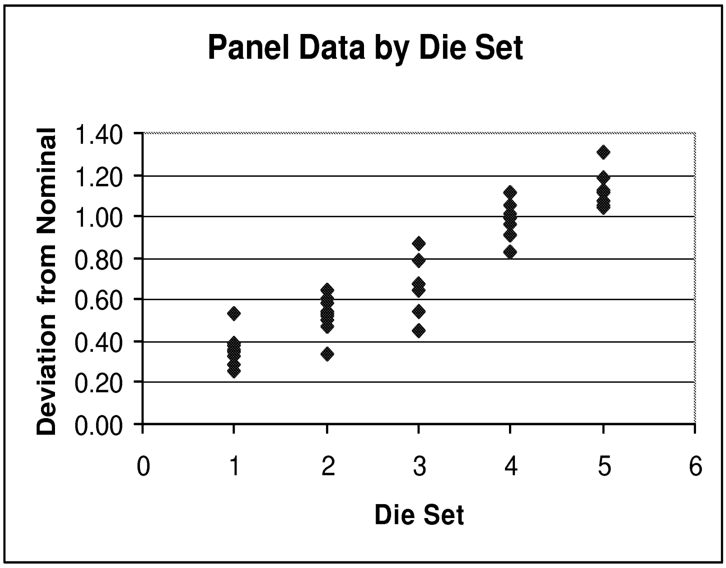

Figure 4: Quarter Panel Location P7 by Die Set

Figure 5 shows the measurements from location P7 on the quarter panel, by DOE run, to illustrate how panels from the die sets were allocated to the five DOE runs. The panels were assigned to DOE runs 1 through 4 such that no statistically significant differences existed in the mean or variance. For run 5, we used a multivariate method to select panels closest to the center (vector of means) of the panel distribution [14].

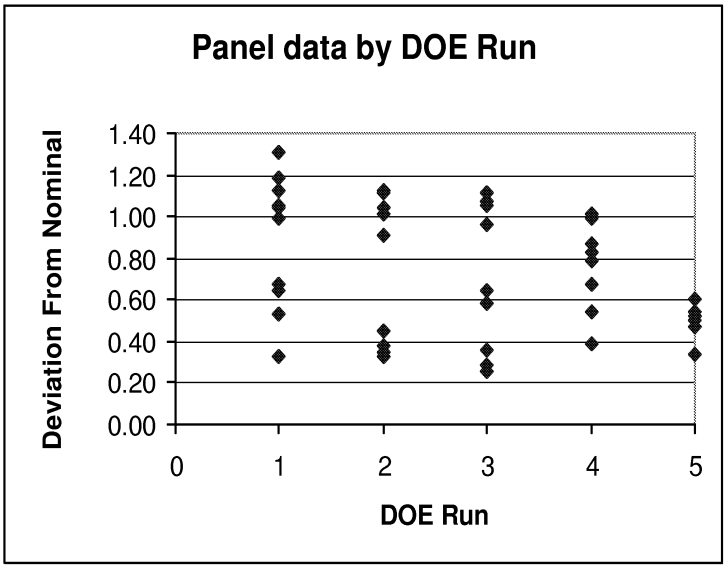

Figure 5: Quarter Panel Location P7 by DOE Run

V. Experimental Data

This section analyzes the measurement data of the completed quarter assemblies. One objective of the study was to determine if we could increase the precision (reduce variance) of the predictions (functional build assembly dimensions) by using a biased sample of component panels. In other words, we wanted to determine whether selecting panels near the population mean would result in assemblies closer to the population mean, i.e., less variation. To evaluate the component selection factor we compared functional built assemblies from DOE runs 4 and 5 that held the fixture and attaching method factors constant. We performed two-sample hypothesis tests of the mean and variance for each of the 13 measurement points and concluded that none of the locations had significant differences in either the mean or variance. This suggests that reducing variability levels in stamping would unlikely result in less variation in assemblies. This result contradicts studies that conclude reducing variation in stamped panels can reduce variation in assemblies [17]. Since we did not find a significant difference between DOE runs 4 and 5, we combined the assemblies in further analysis, which we will now call DOE run 4. This results in a 2 by 2 factorial design [12] in the fixture and attaching method factors.

The other objectives of the study were to determine what, if any, influence the fixture and attaching method had on the mean and variance of the assembly measurement points. We modeled both the fixture and the attaching method as fixed factors. Since the attaching method depends on the fixture (welding in the assembly weld tool used three dedicated weld guns while welding in the assembly check fixture used a single portable weld gun), the attaching effect is nested within the fixture effect. We used multiple regression to fit the nested analysis of variance model [15] to each of the 13 measurement locations. For these two level factors, the estimate of the effect is twice the regression model coefficient that represents the predicted difference in average between assemblies built at the two levels of the factor. Table 5 summarizes the estimated effects (in millimeters) for each of the 12 measurement locations where a blank cell indicates the effect was not significantly different from zero at alpha = .05.

Table 5: Factor Significance by Assembly Measurement Point

Measurement Location	Fixture Effect	Attaching Method Effect	
		Weld Tool	Check Fixture
A1	0.39	0.32	-0.46
A2		0.30	
A3	-0.31	-0.20	-0.28
A4	0.64		
A5	1.25	-1.81	
A6	-1.02	-0.28	
A7		0.44	1.78
A8	-0.25	0.42	
A9	0.34	-0.79	0.34
A10	0.24	-0.44	
A11	0.13	-0.13	
A12	0.09	-0.19	
A13			

The fixture effect column represents a difference in the average between assemblies built in the assembly part coordination fixture and those built in the assembly weld tool. The fixture effect is significant on 10 of the 13 measurement points with seven of these effects exceeding 0.25 mm and two exceeding 1 mm, which represents 50% of the tolerance. This suggests that functional build assemblies made in assembly part coordination fixtures may induce dimensional biases in the predictive data. This may be due to differences between part coordination fixtures and the assembly process in locating, orienting, and clamping components. When clamping a part in a fixture, the non-rigid sheet metal panels will change shape per the part locating strategy. After assembly, the panels often form a rigid assembly that resembles the geometry of the panels as they are located in the fixture. If using rigid components, this fixture effect could be less drastic. One interesting issue is why manufacturers do not have complete matches between part coordination fixtures and assembly weld tools. One explanation for the lack of exact matches is ineffective coordination and communication among engineering functions, particularly as engineering changes are required to the body design. Thus, this experiment is important to body manufacturers as it clearly demonstrates the limitations with using assembly part coordination fixtures to evaluate stamped components with functional build assemblies.

Since attaching method is nested within the fixture, Table 5 contains two columns for the estimates of the attaching method effect (one for each fixture). We found the attaching method significant on nine points when using the assembly weld tools, yet only four points when using the assembly part coordination fixture. This implies that the attaching method has a more profound effect when using assembly weld tools. Using screws to construct functional build assemblies in part coordination fixtures requires additional manual clamps in the location of screws to simulate the clamp load applied by the weld gun. Thus, additional manual clamps were added in this experiment for welding in the assembly part coordination fixture to replicate the screw body process. However, no additional clamps were used in the current production process. Therefore, the additional manual clamping effect was confounded with the attaching method in the weld fixture but not in the assembly part coordination fixture. These additional manual clamps may explain some of the apparent inconsistency in the attaching effect results. This finding supports the use of assembly weld tools for functional build evaluations as they obviously correlate stronger to the regular production process.

Table 6 shows the observed standard deviation by DOE run for each of the 12 assembly measurement points. We identified measurement points that have significantly different standard deviations by DOE run using Bartlett's test [15] at alpha = .05. For the six measurement points with significantly different variation, the minimum value appears in bold. We noticed that DOE run 2 (screwing in the weld tool) resulted in the smallest variation for five of these six measurement points. This finding has significance for manufacturers using functional build. Since the functional build process builds one assembly and uses the resultant geometry as a prediction of the population average, an approach with smaller variation will result in less error in the estimate of the mean. Stated another way, a single functional build assembly is closer on the average to the theoretical functional build assembly mean than a single production assembly is to the production assembly mean.

Table 6: Standard Deviation By DOE Configuration

Measurement Location	Standard Deviation			
	Run 1	Run 2	Run 3	Run 4
A1	0.26	***0.13***	0.14	0.33
A2	0.18	0.17	0.17	0.16
A3	0.29	0.16	***0.05***	0.13
A4	0.32	0.31	0.23	0.17
A5	0.78	***0.26***	1.04	0.38
A6	0.31	0.23	0.29	0.30
A7	0.52	***0.32***	0.47	0.76
A8	0.16	0.22	0.16	0.14
A9	0.60	***0.18***	0.47	0.19
A10	0.52	0.36	0.29	0.23
A11	0.09	***0.09***	0.22	0.16
A12	0.11	0.06	0.10	0.06
A13	0.14	0.16	0.31	0.29

Figure 6 contains box plots of measurement point 6 by DOE run. This plot graphically demonstrates the conclusions regarding the mean and variance of assemblies by DOE run. The difference in average between runs 2 and 4 shows the fixture effect. The difference in average between runs 1 and 2 shows the significant attaching method within the weld tool fixture effect, while the smaller difference in average between runs 3 and 4, attaching method within check fixture, is statistically insignificant. The difference in widths of runs 1 and 2 shows the reduction in variation associated with using screws in the assembly weld tool.

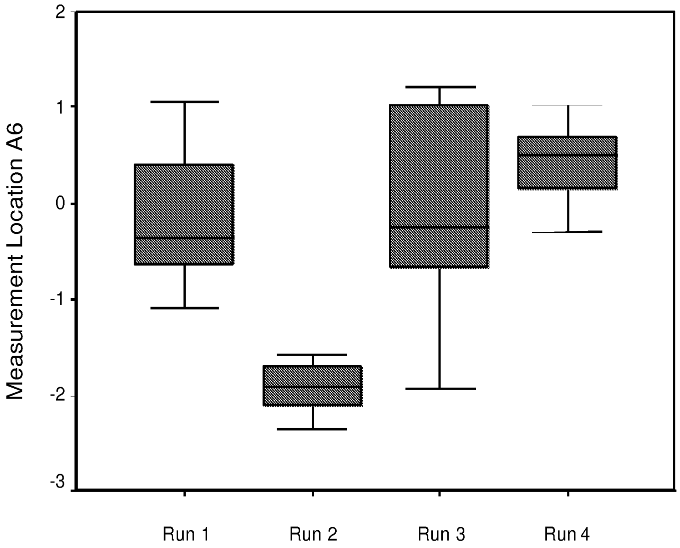

Figure 6: Box Plot of Assembly Measurement Point A6 by DOE Configuration

VI. Predicting Assembly Dimensions with Component Measurements

For many types of assemblies, manufacturers model assembly dimensions as a linear function of the component dimensions, implying one can predict assembly dimensions from component part measurements. For example, if you let $X_i \ i = 1,2,\ldots,n$ represent the dimensions of n components in an assembly, and Y represent the resultant dimension of the assembly, then the manufacturer would assume

$$Y = \sum_{i=1}^{n} X_i \, .$$

If the manufacturer assumes that the variances of the components are independent of one another, then the variance of the assembly is the sum of the component variances or

$$\sigma_y^2 = \sum_{i=1}^{n} \sigma_{x_i}^2 \, .$$

Takezawa [18], a production engineer at Toyota, uses observational data to show that variances do not always add linearly in automotive body manufacturing. Specifically, Takezawa suggests that the variance of an assembly can be less than the sum of the component variances, and that assemblies may be closer on average to a target value than the sum of the individual components. A main reason for this phenomenon is that automotive body assembly often involves combining less rigid parts to more rigid reinforcements, which act as variance reduction agents.

To assess the ability to predict assembly dimensions with data from stamped panels, we measured a sample of 11 quarter panels and then manufactured these panels into quarter assemblies that were also measured. Table 7 below contains the correlation, a measure of the predictive validity, between stamping and assemblies for the eight coordinated measurement locations. Measurement locations A1 and A13 had the highest sample correlations, 0.635 and 0.667 respectively, and were the only two values statistically significant at alpha = 0.05. This is partially due to the small sample size, but this also suggests that dimensional readings on stamped metal panels may be poor predictors of assembly dimensions.

Table 7: Quarter Panel to Quarter Panel Assembly Correlation

Measurement Location	Panel to Assembly Correlation
A1	0.635
A2	-0.052
A6	-0.354
A8	0.474
A9	0.411
A10	0.050
A12	0.477
A13	0.667

A commonly used explanation for the lack of correlation between stamped panels and assemblies is that sheet metal deforms during the assembly process. Shiu, Shi, and Tse [19] support this argument and further claim that changes in component shape are not permanent and the components within the assembly remain in residual stress. In other words, if the assembly were taken apart, the components would relax and thus change shape again. To study this effect, we measured a set of 11 stamped quarter panels and had them assembled into quarter panel assemblies. We then took apart the assemblies and measured the stamped quarter panels again. This study used the assembly check fixture to measure the stamped panels and used nine of the measurement locations shown in Figure 2. The first two pairs of columns in Table 8 provide summary statistics (means and standard deviations) for the 11 panels before and after assembly. The last three columns provide comparisons of the panels before and after assembly (correlation, absolute mean difference, and standard deviation increase) where blank cells indicate an insignificant value. Four of the nine measurement locations had a significant correlation, and six of the nine locations had a significant change in their means, indicating that some areas of the panels do experience a permanent shape change in the assembly process.

We found it interesting that the sample standard deviation was larger after assembly on all nine locations; however, only two of these increases were statistically significant.

Table 8: Comparing Stamped Panels Before Assembly and After Disassembly

	Before Assembly		*After Assembly*		*Comparison*		
Measurement Location	Mean	Standard Deviation	Mean	Standard Deviation	Correlation	Mean Difference	St Dev Increase
A1	-1.05	0.13	-1.36	0.24	0.60	0.32	0.11
A2	1.06	0.16	0.91	0.19		0.15	
A6	-0.45	0.18	-0.47	0.18			
A8	0.11	0.20	0.24	0.28	0.71	0.13	
A9	-0.80	0.26	-1.23	0.46	0.60	0.43	0.20
A10	1.54	0.34	1.31	0.41	0.86		
A11	-0.58	0.10	-0.84	0.15		0.26	
A12	-0.78	0.06	-0.86	0.10		0.08	
A13	0.70	0.10	0.68	0.13			

VII. Conclusions and Recommendations

One underlying assumption of the functional build approach is that functional build assemblies provide unbiased predictions of product geometry obtained during regular production. This research includes a study of three factors in sheet metal assembly geometry: holding fixture, attaching method, and panel selection. This study revealed that the fixture used in the functional build process has a dramatic effect on the average dimensional readings of the assemblies, the attaching method has less impact, and the selection method was insignificant.

When constructing functional build assemblies, manufacturers should use fixtures with similar datum schemes and clamp locations, in the clamping sequence they will use in production assembly tooling. As a result of this and other studies, some manufacturers are now constructing and evaluating functional build assemblies using production weld tools, rather than part coordination fixtures. This approach is particularly useful in less automated weld tool processes where operators have greater access to screw the assemblies together.

When performing functional build, manufacturers typically use a single assembly, or a sample of size one, to predict the population mean. This research studied the ability to reduce the variance in functional assemblies thus providing more precise predictions of the population mean. The lack of significant differences between responses for DOE configuration 4 and 5 suggests that the variance in assemblies is robust to a decrease in input components. Therefore, the manufacturer doesn't need to allocate resources to measuring additional panels and implementing a sophisticated panel selection methodology.

This study suggests that using screws rather than welds to attach components in these pre-production functional build assemblies may produce biased estimates of production assembly variance. Thus, pre-production functional build assemblies should primarily be used as a tool to evaluate/predict component mean stack-up and assembly feasibility, and not as a potential assembly variation capability. The study results, in terms of the attaching method impact on the mean, are not as clear as those of the fixture method. Some significant differences in the mean response were solely attributable to the attaching method. This may have to do with the heat applied during the welding process. While not intentionally studied, this research suggests that clamping clearly plays a significant role in the dimensions of sheet metal assemblies. Thus, using additional non-production intent clamps in the functional build assembly construction process may have a dramatic impact on mean response.

References

1. H.S. Abdalla, "Concurrent Engineering for Global Manufacturing," *Int. J. Production Economics* (v60,1999), pp251-260.

2. P.C. Hammett, K.D. Majeske, and J.S. Baron, "Functional build: Integrating automotive body-design & process-development," *Proceedings of the Annual Reliability and Maintainability Symposium* (1998), pp321-327.

3. P.C. Hammett, S.M. Wahl, and J.S. Baron, "Using flexible criteria to improve manufacturing validation during product development," *Concurrent Engineering: Research and Application* (vol7, 1999), pp309-318.

4. K.D. Majeske and P.C. Hammett, "The Functional Build Approach to Tolerance Development," *IEEE Transactions on Engineering Management* (v47, 2000), pp493-496.

5. A. Jeang, "Computer-Aided Tolerance Synthesis with Statistical Method and Optimization Techniques," *Quality and Reliability Engineering International* (v17, 2001), pp131-139.

6. D.C. Montgomery, *Statistical Quality Control,* 3rd Edition (New York: John Wiley & Sons, 1997).

7. R. Hofling, P. Aswendt, and R. Neugebauer, "Phase reflection – a new solution for the detection of shape defects on car body sheets," *Optical Engineering* (v39, 2000), pp175-182.

8. Automotive Industries Action Group (AIAG), *Measurement Systems Analysis,* 2nd Edition (Southfield MI: AIAG, 1997).

9. A. Weckenmann, T. Knauer, and T. Killmaier, "Uncertainty of Coordinate Measurements on Sheet-metal Parts in the Automotive Industry," *Journal of Materials Processing Technology* (v115, 2001), pp9-13.

10. K.D. Majeske and R.W. Andrews, "Evaluating Measurement Systems and Manufacturing Processes Using Three Quality Measures," to appear in *Quality Engineering* (v15, 2002). This paper can be viewed on the internet at http://eres.bus.umich.edu/docs/workpap/wp01-012.pdf

11. Automotive Industries Action Group (AIAG), *Production Part Approval Process*, 2nd Edition (Southfield MI: AIAG, 1995).

12. D.C. Montgomery, *Design and Analysis of Experiments*, 5th Edition (New York: John Wiley & Sons, 2001).

13. S.A. Choudhuri and E.C. DeMeter, "Tolerance Analysis of Maching Fixture Locators," *Journal of Manufacturing Science and Engineering, Transactions of the ASME* (v121, 1999), pp273-281.

14. P.C. Hammett, J.S. Baron, and K.D. Majeske, "Evaluating Multi-Dimensional Sheet Metal Assemblies Using a Biased Sample of Stamped Components," *1997 International Body Engineering Conference* (Stuttgart, Germany, 1997).

15. J. Neter, W. Wasserman, and M.H. Kutner, *Applied Linear Statistical Models*, 3rd Edition (Homewoood, IL: Irwin, 1990).

16. K.D. Majeske and P.C. Hammett, "Identifying Sources of Variation in Sheet Metal Stamping," University of Michigan Business School Working Paper 01-009 (University of Michigan Business School, 2001). This paper was submitted May 2001 to

International Journal of Flexible Manufacturing Systems and can be viewed on the internet at http://eres.bus.umich.edu/docs/workpap/wp01-009.pdf

17. X.R. Cao and Z. Zhou, "Correlation Analysis in Quality Control of the Lift Gate Assembly Line," *Quality Engineering* (v5, 1993), pp601-609.

18. N. Takezawa, "An Improved Method for Establishing the Process-Wise Quality Standard," *Rep. Stat. Appl. Res., JUSE* (v27, 1980), pp63-75.

19. B.W. Shiu, J. Shi, and K.H. Tse, "The Dimensional Quality of Sheet Metal Assembly with Welding-induced Internal Stress," *Proc Instn Mech Engrs Part D*, (v214, 2000), pp693-704.

Authors Biographies

Karl D. Majeske is a Lecturer in the Statistics and Management Science Department at the University of Michigan Business School. His areas of research include automotive body manufacturing, warranty and reliability data analysis, and developing methodologies to evaluate measurement systems. Dr. Majeske received the B.S., M.S., and Ph.D. degrees in Industrial and Operations Engineering from the University of Michigan in 1985, 1991 and 1995, respectively and has worked for the University of Michigan since 1991. Dr. Majeske has previously held University of Michigan appointments as an Assistant Research Scientist at the Transportation Research Institute and Adjunct-Assistant Professor in both the College of Engineering and the College of Literature, Science and the Arts.

Patrick C. Hammett is the Manager of the Manufacturing Systems Group for the Office for the Study of Automotive Transportation at the University of Michigan Transportation Research Institute. He is also an Adjunct Professor in the Department of Industrial and Operations Engineering at the University of Michigan. His research focus involves developing and implementing world-class manufacturing, quality, and process validation strategies in the production and development of the automotive body. Dr. Hammett received his MS and PhD in Industrial and Operations Engineering for the University of Michigan, and his BS in Industrial Engineering from Purdue University.