Managing Variation During Preproduction Activities

by
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Abstract

Variation in piece parts, subassemblies, and final assemblies of automobiles significantly impacts the quality of the vehicle. The loss in quality is very costly to the auto maker because of low customer satisfaction and because of scrap or rework of parts that do not fit properly. Traditionally, the major efforts to resolve the build variation problem have occurred during the production phase through optimization of local processes using statistical process control, designed experiments, and other variation detection and prevention tools. Unfortunately, addressing the variation problem in the production phase misses the opportunities that exist during earlier preproduction phases to design vehicles that are more robust against inherent variation in the vehicle manufacturing process.

This thesis studies how the variation problem can be addressed during the up front design phases of a vehicle program. The first part of the thesis outlines a variation management process to design robust vehicle systems. This process represents a synthesis of different variation management activities practiced at many automotive companies. In discussing the variation management process, the study identifies the specific design issues that need be addressed at each stage of the design process, as well as a number of tools and design approaches that can be employed to both predict and reduce the effects of excess variation.

The variation management process relies on intelligent design decisions of both product and process designs; in order to make intelligent decisions early in the design process, reliable, accurate information from many functions within the organization is required. Accordingly, the thesis also examines the information flows necessary to effectively implement and execute a variation management effort. Finally, by making use of an ideal information flow model, an existing variation management program is analyzed to uncover opportunities to improve the program under study and to suggest "critical enablers" for any variation management effort.

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Section 1
Introduction

Recently, a luxury car maker, featured a popular advertisement showing a small metal ball rolling smoothly along the gaps between the closure panels of an upscale vehicle. At an engineering level, this short exhibition demonstrated the auto maker's ability to manufacture and assemble an automobile to extremely tight tolerances. For the rest of the automotive industry, the advertisement hightened customer sensitivity to a manufacturing challenge that every auto maker--and every manufacturer, for that matter--has struggled with for years: process variation. In my brief career at General Motors, I have seen and read of a number of quality improvements efforts, throughout the auto industry, initiated to attack the variation problem. In spite of the substantial improvements acheived through these efforts, holding variation in piece parts, subassemblies, and final assemblies of automobiles within allowable limits continues to be a major challenge facing auto makers. Is there an approach beyond some of the traditional methods like statistical process control and designed experiments to address the variation problem, and if so, how can this approach be implemented and managed successfully? This thesis attempts to answer these questions by studying and building upon a variation management initiative at the Cadillac division of General Motors.

1.1 Background

Before a thorough discussion of new approaches to variation management, a brief overview of the costs caused by undue variation and the limitations of current methods to address these concerns is provided to convey the need for and the importance of an alternative approach to the variation problem.

The Cost of Variation

Excessive variation in manufacturing and production processes results in significant costs; specifically, these costs stem from the following sources:

- *Quality Loss:* Excess variation can inhibit the functional performance of the vehicle and/or prevent quality fits of closure panels and interior and exterior components, causing a poor aesthetic appearance. In either case, an inferior product is delivered--leading to low customer satisfaction and ultimately lost sales.
- *Costs Due to Rework:* In an effort to prevent these quality problems, manufacturers spend a tremendous amount of resources to rework and finesse parts that do not function or fit properly. In many automotive assembly plants, it is not uncommon to see line operators dedicated solely to finessing closure panels and other components that cannot be assembled exactly to specification because of undue variation. This added manpower obviously increases the labor content in each vehicle and, accordingly, the cost per vehicle.
- *Costs Due to Scrap:* In instances where on-line quality control procedures have been implemented, parts that do not fall within dimensional specification are pulled from production lots and very often scrapped. This is a cost burden due to both material costs of scrapped parts and lost throughput of machines and operations used to manufacture and assemble those defective parts.

- *Hidden Costs:* Finally, a number of indirect expenses are absorbed in products because of the hidden costs incurred in reworking machines and processes that contribute unacceptable levels of variation. Who knows how many engineering and maintenance resources are expended during prototype, pilot, and production phases to take corrective actions to resolve build problems caused by off-nominal parts? In the worst case, one could imagine a production launch being delayed because the vehicle cannot be manufactured within acceptable quality levels.

(See Phadke, 1989 and Sherkanbach, 1987 for a more detailed discussion of these costs.) Clearly, the costs stemming from excessive variation in piece parts, subassemblies, and assemblies is substantial and deserves a significant amount of attention. In fact, in recent years a number of variation detection and reduction techniques have been developed and practiced throughout the automotive industry. Unfortunately, in many cases these techniques do not efficiently resolve the problems caused by undue variation.

The Limitations of Traditonal Variation Reduction Methods

As evidenced by the attention that statistical process control and designed experiments receive in current literature, these methods are presently two popular techniques for attacking the variation problem (Tipnis, 1992; Phadke, 1989; James, 1993). The strategy for both of these techniques consists of identifying the key contributors of variation in a process and then implementing some form of control procedure to make certain that the key parameters lie within an acceptable range. Certainly these techniques have definite merits and have led to large gains in quality levels for many businesses; still, without discounting the need to employ these methods, there are some limitations to their effectiveness:

- *Often traditional efforts are reactive:* Very often these techniques are used in a reactive mode: a quality problem is identified and then variation detection and reduction strategies are used. While a permanent solution to the problem is investigated, vehicles are produced with quality defects that must be corrected through costly rework procedures.
- *Traditional procedures assume that a root cause of the problem has been identified:* In order to use designed experiments to optimize a process, for example, it is first necessary to identify the process step that causes the quality problem. When one considers the hundreds of process steps that are required to produce an automobile, identifying the root cause of a quality problem can often prove a very difficult task. This dilemma compounds the problem cited above--as the root cause of the problem is pursued, vehicles with quality defects continue to be produced.
- *In cases where these techniques are not used in a reactive posture, how can we be certain that the correct processes are being optimized?* A logical solution to the first limitation would be to optimize processes before a quality problem occurs. The challenge with this approach lies in identifying the processes that will cause problems, which may be difficult to predict. Further, optimizing processes that do not contribute to quality loss would be a waste of time, money, and resources.

Therefore, in spite of the many successful applications of some traditional variation detection and reduction techiques, there do exist some limitations that suggest an additional, more unifying approach needs to be developed.

An Alternative Approach

An alternative strategy to resolving problems caused by excessive variation exists in predicting for and designing around variation problems during pre-production activities. With this approach, variation problems are considered early in the product and process design phases, and are then tested through statistical techniques to ensure that the designs will produce the desired results. This process allows designers and engineers to quantify the effects of variation very early on and to consequently take corrective measures through optimal product and process designs. Even during prototype and pilot phases, by employing intelligent and efficient troubleshooting strategies, off-nominal parts can still be used to produce high-quality vehicles. In short, this alternative approach focuses on variation management during pre-production phases as opposed to variation reduction during production activities.

Because the unwanted effects of variation are detected and then resolved through optimal product and process design, a much higher probability of achieving quality goals is ensured. In addition, this approach provides a number of other advantages:

- *Greatly reduces the inefficient problem detection/problem resolution strategy:* Because designs are selected and proven on paper to be capable of meeting quality goals, the number of quality problems during production should significantly decrease. In turn, this will lessen the need to utilize the problem solving techniques discussed.

- *Eliminates the costly rework and redesign of products and processes during pilot and production phases:* Again, since the effects of variation are considered early in the design phase, a higher probability exists for achieving quality goals. This will reduce the need to rework and redesign parts and processes during pilot and production phases, generally a costly time in a vehicle program to make changes.
- *Reduce the costs of variation:* At the beginning of this section, a number of costs associated with excessive variation in manufacturing processes were outlined. A variation management approach will help to mitigate the quality problems caused by excessive variation, and thereby reduce these unwanted costs.

In sum, the key strength of the variation management approach is that variation problems are addressed early in a vehicle design program when the greatest opportunities exist to efficiently and inexpensively resolve these problems.

1.2 The Scope of This Thesis

Recognizing the limitations of past efforts to resolve problems caused by excessive variation, Cadillac Motor Car Division (now called Cadillac/Luxury Car Division, CLCD, after a recent reorganization) implemented the Precision Build Process. The Precision Build Process was an effort to focus on upfront variation management activities for the 1994 Sedan Deville vehicle program. This thesis represents primarily a study of the variation management processes used at Cadillac, other General Motors divisions, and GM's main competitors.

The goal of this thesis is twofold: first, to describe a variation management process that can be used to address the variation problem during pre-production activities; and second, to look at the Cadillac process and find continuous improvement opportunities for the Precision Build Process.

A brief overview of the thesis follows:

Section 2: This section describes a variation management process and details a number of engineering and design approaches that can be used to produce a vehicle that is substantially more robust against variation. The goal of this discussion is to synthesize a number of variation management techniques that are practiced at different automotive companies into one unified variation management process.

Section 3: In order to implement and effectively carry out a variation management program, the flow of information from many sources must be effectively managed. This section focuses on the information flow requirements and the organizational requirements needed for a successful variation management program. Ultimately, this discussion will provide an ideal process flow for a variation mangement program, as well as a look at different organizational structures that can be employed to promote successful execution of variation management activities.

Section 4: In this section, the focus is on the Precision Build Process highlighting areas for improving the process. The ideal process flow developed in Section Three will serve as a template to evaluate opportunities for continuous improvement. Though the information presented is most useful for Cadillac, this analysis does provide some insights for other readers regarding pitfalls that should be avoided when instituting a variation management process.

Section 5: The conclusion summarizes the recommendations for improving the Cadillac Precision Build Process and suggests opportunities for future research on variation management.

1.3 Research Methods

The variation management process documented in Section Two is a culmination of information attained through interviews, plant tours, and literature surveys. My goal in this research effort was to identify and compare the variation management activities that are practiced both within General Motors and at other automotive companies. Through this research, I attempted to assimilate the "best" practices from each company into the variation management process outlined in Section Two. The most significant of the information sources were the interviews and plant tours. Specifically, I interviewed variation management coordinators at five General Motors automotive and truck divisions (including Cadillac), and toured many of their facilities. In addition, I gained insights to foreign competitors' variation management techniques through discussions with GM employees who had visited competitors' operations and/or had worked at the New United Motors Manufacturing Inc., NUMMI, a joint venture facility between GM and Toyota. Unfortunately, little has been written about variation management as a unified approach; however, a number of authors (Liggett, 1993; Baron, 1992; Tipnis, 1992) address individual variation management techiques in considerable detail. Again, through the inputs of each source, I was able to assimilate an ideal variation management process as described in Section Two.

The second part of the thesis, Section Three and beyond, focuses primarily on the Cadillac Precision Build Process. Although Section Three does include research gathered from the sources mentioned above, the majority of the data derives from interviews with key individuals involved in the Precision Build Process. Included in these interviews are engineering managers who oversaw the entire process, team champions who managed the design efforts of the individual design teams, and engineers and designers involved in those teams. In total, over fifty interviews were conducted during two prolonged rounds of interviews. The goal of the first round was to gain general insights from those involved in the program on how the process functioned. From this set of interviews, the ideal process flow presented in Section 3 was developed. Using this ideal process flow as a template, a second round of interviews focused on how the Precision Build Process could be improved to function like the ideal process.

The discussion that follows represents the culmination of seven months of field research conducted to further develop the strategy of approaching variation difficulties during pre-production activities. Hopefully, this research effort will provide some key insights that assist manufacturers in producing higher quality products with lower costs.

Section 2
Methods and Tools for Managing Variation

From stamping metal parts to welding subassemblies to injection molding components, variation exists in every manufacturing and assembly process needed to produce an automobile. Considering the number of parts that are assembled together to create a complete vehicle, the variation in each of the processes added together can result in a product that is unappealing in appearance and unacceptable in functional performance. To avoid these problems, it is therefore critical to design component, subassembly, assembly parts and processes that are robust against the inherent variation of manufacturing processes.

This section outlines a process to design vehicle systems that are substantially more robust against the effects of variation in the manufacturing and assembly processes. The specific activities and issues that need to be addressed at each phase of the variation management process are discussed along with certain methods and design approaches that can be used to support those activities. The variation management process described in this section is a synthesis of different variation management activities practiced at both Cadillac and other companies in the automotive industry.

2.1 An Overview of the Variation Management Process

During each phase of a vehicle program, from concept to production, a number of opportunities exist to design vehicle systems that are robust against variation. A variation management process that can be used to accomplish this task is diagrammed in Figure 2.1 within a generic four phase framework.

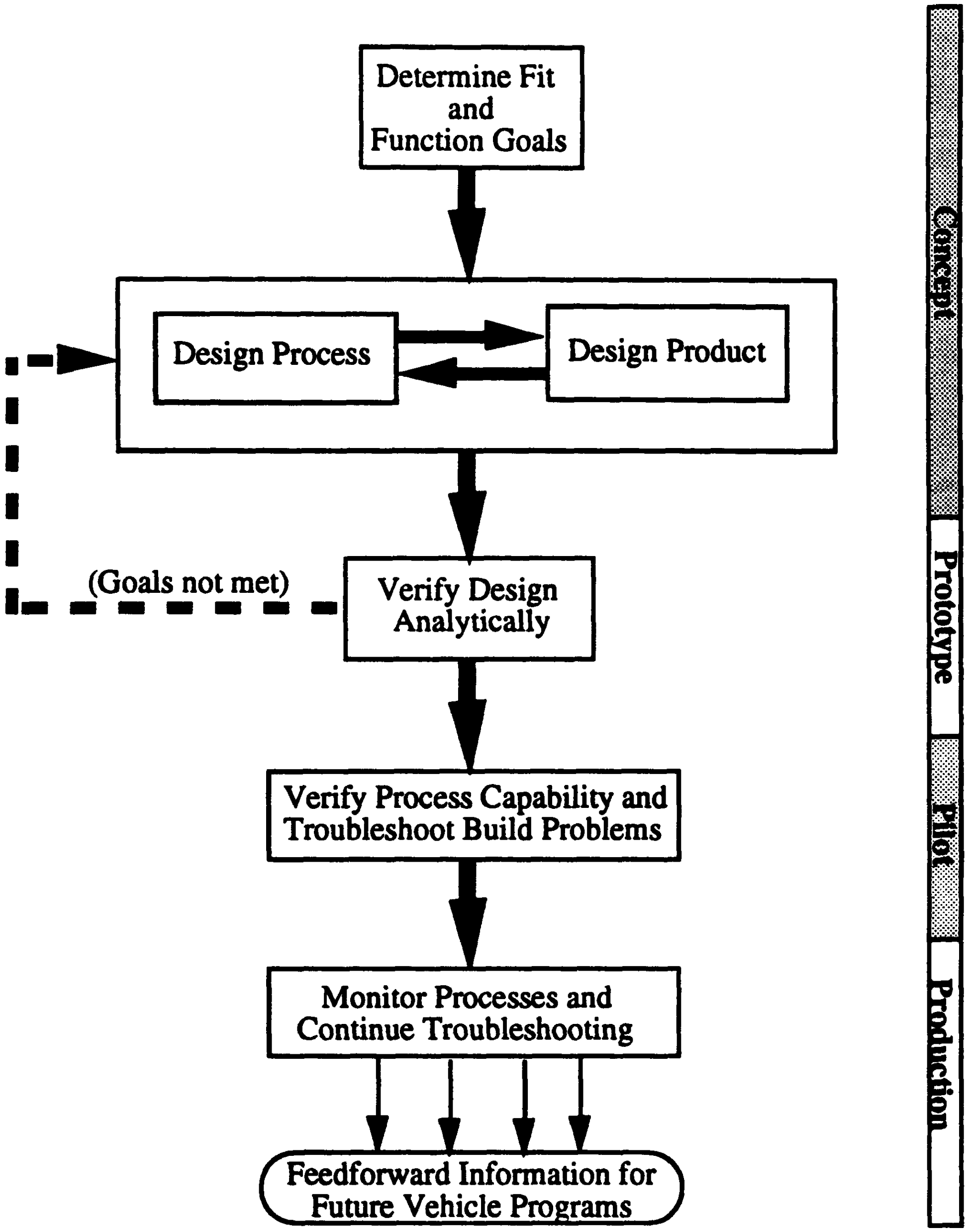
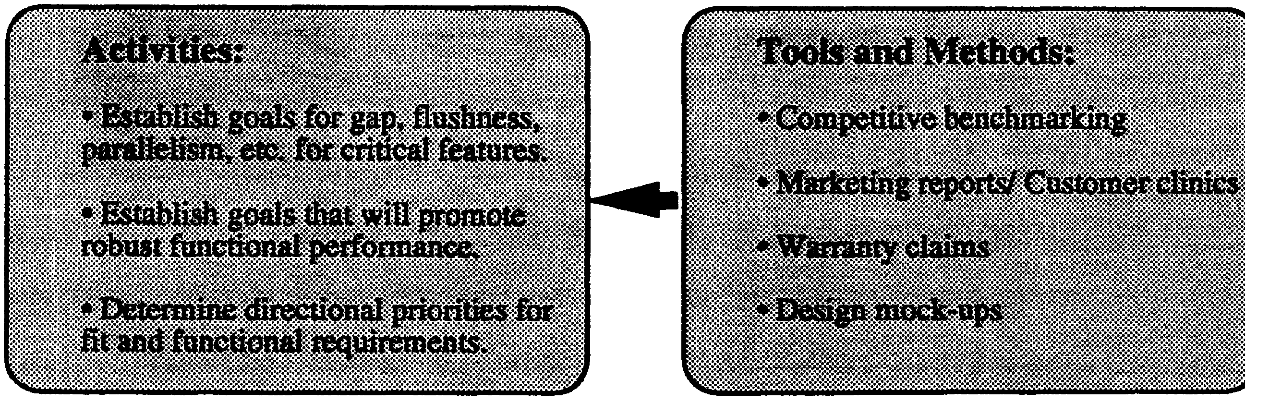


Figure 2.1, A process for variation management

In general, the process begins by capturing the voice of the customer during the earliest stages of concept development and deploying customer expectations into fit and function goals. Having defined the targets, the next step is to simultaneously design the processes and the components, subsystems, and systems that will enable a vehicle to be manufactured that meets the stated goals. By using predictive tools such as root mean squares calculations or variation simulation modeling, which will be discussed later in the section, the product and process designs can be checked to determine if the intended goals can be met. If the goals cannot be met, then the product and process designs must be reevaluated to find a way to meet the target. Once all of the designs have finally been verified analytically, the next step is to verify that the processes are able to produce parts to design specification. Finally, after all build problems are resolved production activities begin. Again, during the production phase, parts are monitored to ensure conformity to design requirements; any deviations from nominal are resolved in the most efficient manner possible. The entire process ends for one vehicle program and begins for another by feeding forward production information and opportunities for continuous improvement into the next vehicle program.

This, then, is a quick overview of the variation management process. The remainder of the section discusses in detail each of the steps in the process and provides a survey of tools and methods to support each of the activities of the process.

2.2 Determining Fit and Function Goals



Activities:

- Establish goals for gap, flushness, parallelism, etc. for critical features.
- Establish goals that will promote robust functional performance.
- Determine directional priorities for fit and functional requirements.

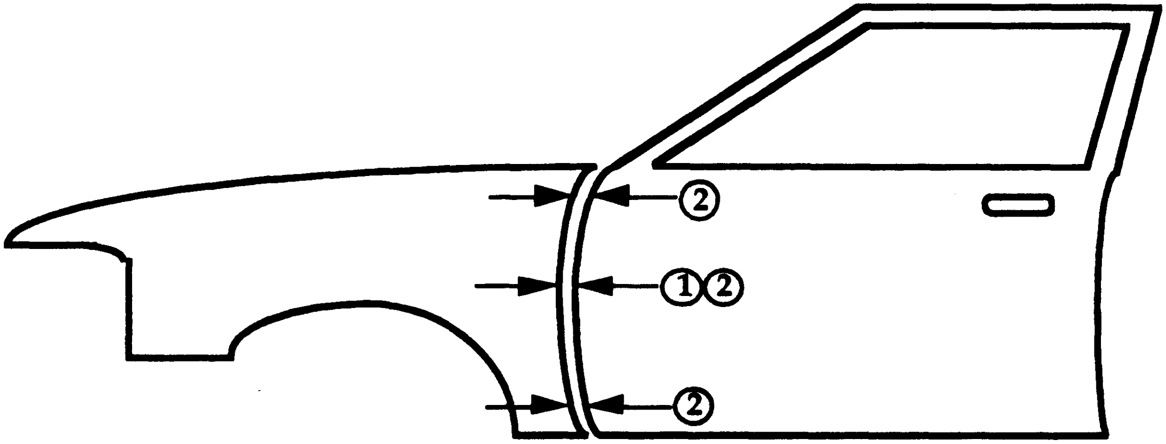
Tools and Methods:

- Competitive benchmarking
- Marketing reports/ Customer clinics
- Warranty claims
- Design mock-ups

At the very outset of the vehicle program, the voice of the customer is brought into the process by translating customer expectations into fit, function, and directional priority goals. These goals must be defined early in the vehicle program to ensure that the subsequent product and process design alternatives can be evaluated in light of customer expectations (Held, 1993). The various goals that need to be considered along with examples of each are given below.

Fit Goals: In specifying fit goals, the main focus is on setting targets that will result in a vehicle that is aesthetically pleasing. The final fit goals usually refer to gaps, parallelism, and flushness between closure panels like fenders and doors, and between interior trim components like instrument panels and door trim pads. A gap is the distance between the adjacent components, while parallelism constitutes the extent to which the gap between the closure panels remains constant along the entire surface of the mating panels or components. Flushness is defined as the distance that one surface lies above or below the adjacent surface. Again, the objective is to specify a nominal dimension and a tolerance band for gaps, parallelism, and flushness between mating components that will meet the customers' expectations of the vehicle's appearance. Figure 2.2 provides an example of a gap, parallelism, and flushness goal for a fender to door fit.

		Goals:	
Item	Feature	Nominal	Tolerance
1	Gap	6.0 mm	+/- 1.5 mm
2	Parallel	0.0 mm	within 2.0 mm
3	Flush	0.0 mm	+/- 1.0 mm



Fender to door gap, parallel goals

Fender to door flushness goal

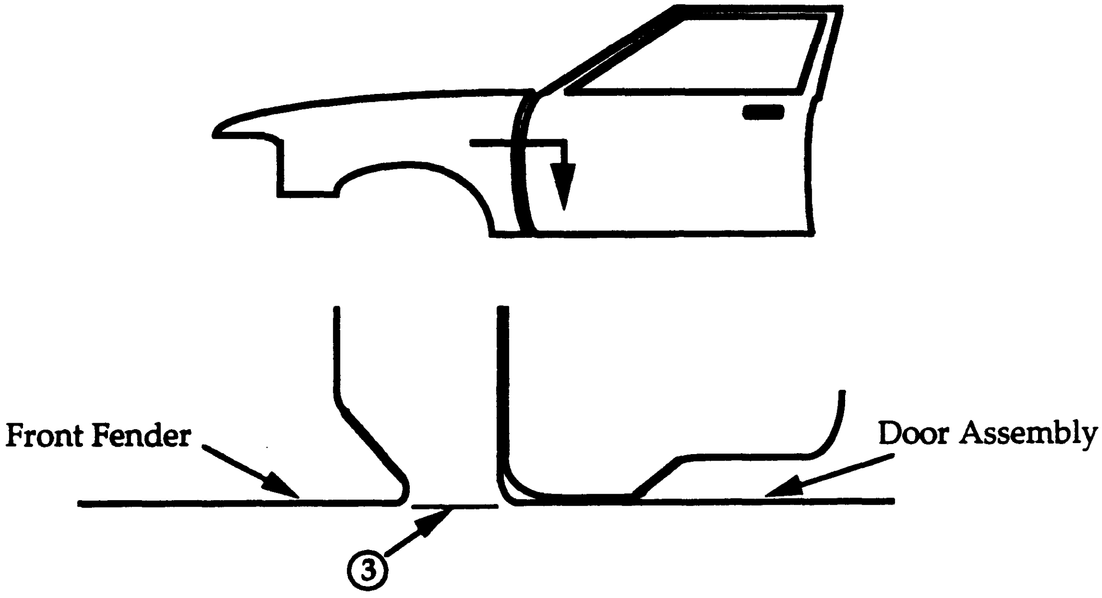


Figure 2.2, Illustration of gaps, parallelism and flushness

Functional goals: A number of functional performance characteristics of an automobile are affected by variations in the assembly process. For example, consider a functional performance feature that is important to all vehicles: door closing efforts. The force required to close a door is impacted by the compression of a rubber weather stripping that runs along a flange in the door opening. The compression of the weather stripping is in turn influenced by the gap between the door and the door opening. Variations in the assembly of the door and door opening can result in a gap that is too tight causing excessive force to be required to close the door. Conversely, if the gap is too large, wind noise will result, also a customer dissatisfier.

This illustration shows the importance of establishing a target value and a tolerance band for the gap between the door and the door opening that will meet customer expectations for one of the many functional characteristics of the vehicle. Some other examples where excessive variation can affect the performance of the vehicle are: excessive gaps between closure panels and body openings that can result in water leaks; variations in the poise of the vehicle from wheel to wheel that can impair road handling, and undue variations in flushness between the fender, doors, and quarter panel that can also contribute to excessive wind noise. In each of these instances, goals to hold variation to prescribed limits must be defined so that robust functional performance is pursued during subsequent design steps.

Along with the goals that will promote vehicle performance that meets the expectations of external customers, goals for internal customers need also be developed. Assembling components like headliners, instrument panels, and moldings to the vehicle requires attach points in the car body to be held within a certain tolerance. Excessive variations can cause the assembly of these components to be difficult, if not impossible. Again, early in the vehicle program goals that will allow routine assembly of components in downstream operations must be considered.

Directional Priority: One General Motors division advocates defining the directional priority for final fits of panels; or more simply put, to determine the feature or area of a component that is most critical to control. To illustrate, consider a fender panel: the location of the fender panel in the fore-aft direction affects the gaps between the front door on one side and the cornering lamp on the other. In the up-down direction, the flushness to the hood is set. In the in-out direction, the gap between the hood and the fender and the flushness of the fender to the door are determined.

Ideally, the gaps and flushness between all of the components and panels that are adjacent to the fender would be held to similar specifications. However, due to production variation this is never the case; therefore, during the design phase, decisions need to be made about where to design slip planes and how to locate and hold the part--decisions that affect which areas of the vehicle absorb the variation. (Note: slip planes and locating methods are discussed later in this section.) Establishing directional priority for final fits assists in reconciling some of these design decisions.

It should be noted that unlike the fit and function goals, the directional priority goals are not usually measured during the assembly process. Instead, they serve more as a criteria for design tradeoff decisions, as in the example described above. Because they are not measured characteristics of the vehicle and because they play a more limited role in the design process, this set of goals was not included in the overall process model in figure 2.1. Still, since directional goals can help with some design decisions, gaining knowledge of the critical areas to control is a worthwhile endeavor.

Methods for Capturing the Voice of the Customer

A number of tools exist to identify the fit, function, and directional goals that will meet customer expectations; some of the more popular methods are described below.

Competitive Benchmarking: Customer expectations will obviously be influenced by the best product available; therefore, it is important to identify the performance of competition. In the context of variation management, fit and function goals must be set that meet or exceed the capabilities of other auto manufacturers. For example, at Cadillac, spider charts were used to document the final panel fits of competitors' vehicles.

Marketing Reports/ Customer Clinics: Marketing departments play a significant role in determining proper design goals by sponsoring customer clinics. These clinics are used to identify expectations by interviewing a sample of customers.

Warranty Claims: By reviewing warranty claims, unacceptable features of previous vehicles, according to customers, can be identified, and design goals that will eliminate these problems from future vehicles can then be properly defined. One of the teams at Cadillac sent questionnaires to dealerships asking service departments to help identify the features on doors that customers complained about most frequently.

Design Mock-ups: A design mock-up is typically a prototype of two or more adjacent parts that are mounted on a flexible fixture. Using these flexible fixtures, design teams can move parts relative to one another and identify the limits of the gap, flushness, and parallelism conditions that will be acceptable to the customer. At Cadillac, corporate auditors, whose charter is to represent the voice of the customer, were involved in the design mock-up meetings to identify customer expectations as the various goals were being set. In order to even more accurately identify customer perceptions, perhaps an improvement would be to show these design mock-ups to actual customers, thus enabling customers to directly assist in setting design goals.

At the end of this step in the variation management process, all of the goals that will meet the needs of both internal and external customers are identified. This is a crucial step because later process and product decisions will be driven by the fit, function, and directional goals set. Failure to adequately identify customer expectations will result in a product that may meet design targets but will still fail in the marketplace (Clausing, 1994).

2.3 Determining Product and Process Design

The next step in the variation management process is to select product and process designs that will ensure that the goals set previously can be achieved. This is a very crucial activity because the design decisions made in this phase will have a major impact on the amount of variation in the assembly process and the robustness of the vehicle against variation.

Both product and process design decisions must be considered simultaneously (Tipnis, 1992). If the product is designed before processes are selected, there is a high probability that for some components and assemblies, no adequate processes exist, given cost and throughput constraints, that can manufacture and assemble the parts to specification. Conversely, selecting processes in isolation of product design will result in manufacturing processes that may or may not be able to produce parts and assemblies to their required dimensional specifications. The best approach is to iterate between product and process concepts and select the combinations that will achieve the fit and functional goals that meet customer needs; Figure 2.3 summarizes this point.

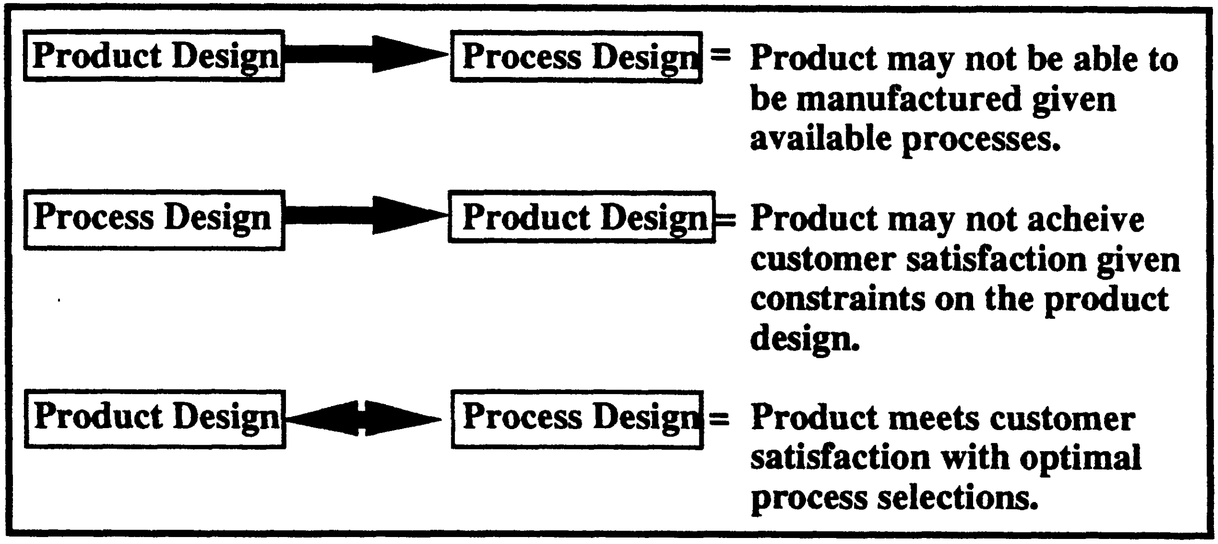
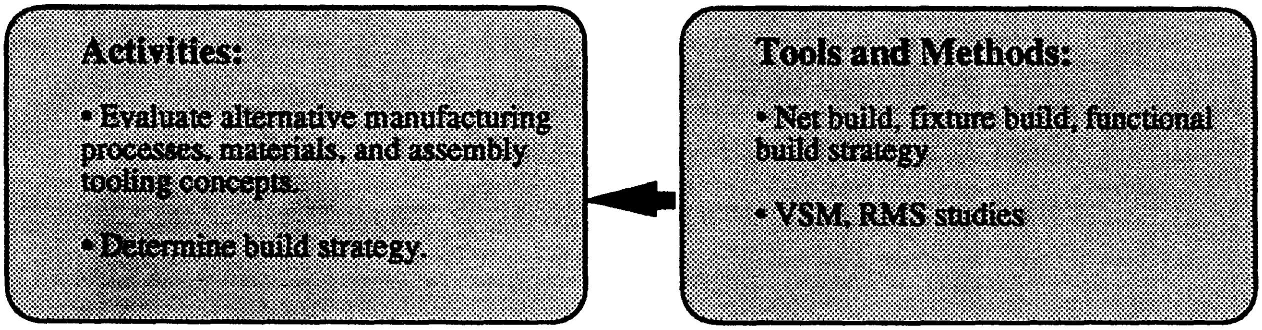


Figure 2.3, Importance of concurrent product and process design

2.3.1 Selecting Process Designs



One of the key activities in this step is evaluating different manufacturing processes, materials, and assembly tooling concepts, and choosing those that will enable the design targets to be met. To illustrate, some examples of different processing, material, and tooling alternatives are provided.

Manufacturing processes: An example of different manufacturing processes that might be considered are space frame assembly (tube space frame similar to that in race cars) versus traditional body frame assembly. Using a space frame process, the body frame can be manufactured with less variation; however, this must be weighed against the costs and inherent difficulties of introducing a new technology.

Materials: Aluminum and plastics are replacing sheet steel in the outer skins in many vehicles. For some applications, these alternative materials may introduce less variation, and therefore may be preferably used over traditional sheet steel.

Assembly tooling: Innovations in assembly tooling occur almost constantly. At Cadillac, a new tool was installed for the '94 model program that detects deviations from nominal between the fender and the rear quarter panel and adjusts the locating holes for the door hinges. This helps to reduce the variation in the gaps between the fender, the doors, and the quarter panel.

Many other manufacturing, material, and tooling concepts evolve during the course of a vehicle program. It is important to evaluate each of these concepts relative to the design goals to determine whether the investment in the new technology promotes the desired results. The objective then, is not to merely select low variation processes and minimize variation locally, but rather to select low variation processes that will control variation in the areas that are critical to meeting customer requirements.

The second key issue in process selection is determining the build strategy for different vehicle systems. In general, three different build strategies exist: net build, fixture build, and functional build.

Net Build: A net build strategy uses a feature on one part to locate a mating part. For example, consider the locating of a fender: a stud in the motor compartment rail (the part on which the fender is mounted) would align with a hole in the fender to locate the fender. The advantage of using a net build strategy is that it is a very simple process, no precision tools or locating fixtures are required to assemble to two parts. However, because one part locates the mating parts, the sum of all of the variations in each of the locating details can cause major variations in the complete assembly. Therefore, the parts must be held to very tight tolerances.

Fixture Build: A fixture build strategy uses jigs or fixtures that locate mating parts. Again, drawing on the fender example, the fender would be held in a fixture that would locate the part in relation to the motor compartment rail as the two parts are attached. The advantage of a fixture build is that since fixtures locate the parts, the main cause of variation in the assembly is the variation of the fixture itself, a less severe problem than a net build scenario. The disadvantage associated with this strategy; however, is the cost to build the precision fixtures.

Adjustable Build: With an adjustable build, the assembly operators locate or "finesse" mating parts to achieve the best possible fit. The advantage of this strategy is the same as the net build strategy–no expensive fixtures. However, with an adjustable build strategy, the final fits are determined by subjective evaluations made by different operators, contributing variation to the process; additionally, often a number of operators are required to finesse the parts to achieve a good fit, adding cost to the assembly process.

Table 2.1 summarizes each of the three build strategies. Different companies define each of these build strategies differently; nevertheless, it is important to understand the implications associated with each build strategies, and more importantly how choosing one strategy over another ultimately will impact the ability to achieve design goals. If a net build strategy is chosen, the parts must be held to very tight tolerances, lest the sum of the variations in each of the parts that comprises a complete assembly will prohibit the fit and function goals from being met. Choosing a fixture build strategy requires that the locating fixture be built to high degree of precision and that it be maintained properly to ensure dimensional accuracy. Finally, an adjustable build relies on operators to make judgments on whether the specified goals are being achieved, creating a large source of variation. The build strategy selected for each system must take into account each of these factors and be weighed in conjunction with the design goals.

	Advantage	**Disadvantage**
Net Build	Eliminates cost of precision fixtures.	Part tolerances must be held very tight to ensure good fits.
Fixture Build	Requires less stringent tolerance specifications.	Cost of building and maintaining precision fixtures.
Adjust. Build	Also eliminates the cost of tooling requirements.	Relies on subjective evaluations of good fits.

Table 2.1, Summary of the different build strategies

2.3.2 Selecting Product Designs

Activities:

- Select piece part, subassembly, and assembly designs that minimize variation.
- Select styling features that ensure innovative design, but that are robust against perceived variation.
- Select datums and specify tolerances.

Tools and Methods:

- DFM
- "Soft" styling features
- Slip planes
- Geometric Dimensioning and Tolerancing

Concurrent with the process design, the piece part, subsystem, and system designs must be chosen, typically a complex task with the longest lead time in bringing the vehicle to market. In spite of the complexity, however, there are some simple methods to design a product that is substantially less affected by variation.

Design for Manufacturability: One of the goals of design for manufacturablility (DFM) is to reduce the number of piece parts in an assembly. Reducing the number of components also reduces the number of process steps: because every part and every process contributes a certain amount of variation, an assembly that requires fewer parts and fewer process steps should result in a complete assembly with less variation (Noaker, 1992). As an example, at Cadillac DFM methods were used to redesign the side ring, the part on which the doors and roof are attached. The new side ring became a one piece assembly as opposed to the three piece assembly of previous models in order to reduce the dimensional variation in this critical part.

"Soft" Styling Features: Some simple design techniques can be used in the styling of a vehicle to allow for more variation without the added variation

detracting from the appearance of the vehicle. One way is to round edges and corners of panels and components. For example, consider the fit of the head lamp to the cornering lamp. By rounding the adjacent edges of these two components, any deviations from nominal in the gap and flushness between the two parts become more difficult to ascertain. Sharp edges and corners; in contrast, act like gauges--showing any deviations in fits--and therefore should be avoided.

Another way to minimize the perception of variation is to avoid difficult feature lines. Feature lines are used to provide an innovative look for the vehicle, but from a variation standpoint they can be very difficult to align. Usually the feature line will run from the fender to the rear fascia, as shown in Figure 2.4. The problem that this creates is that this feature line must align at each adjacent panel or exterior component (like the rear fascia): the feature line on the fender must align to the feature line on the front door; the feature line on the front door must align to the feature line on the rear door; and so on through to the rear fascia.

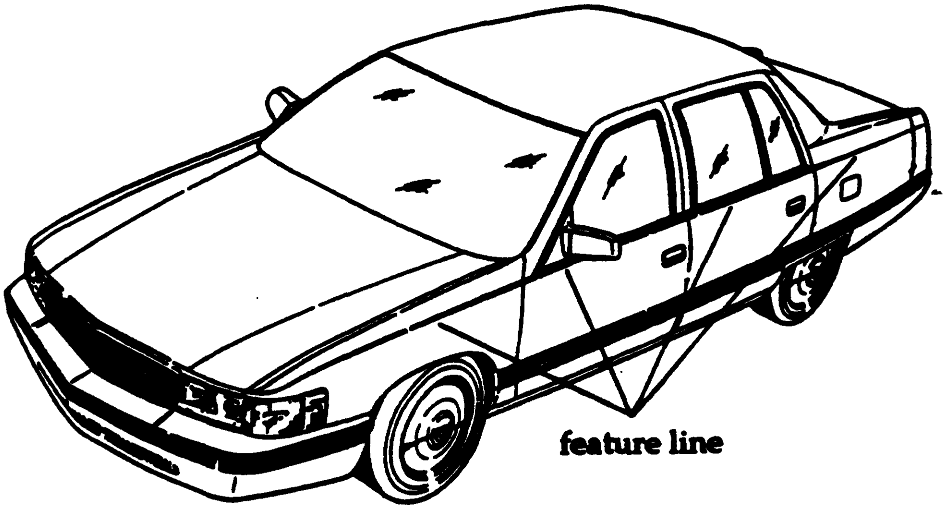
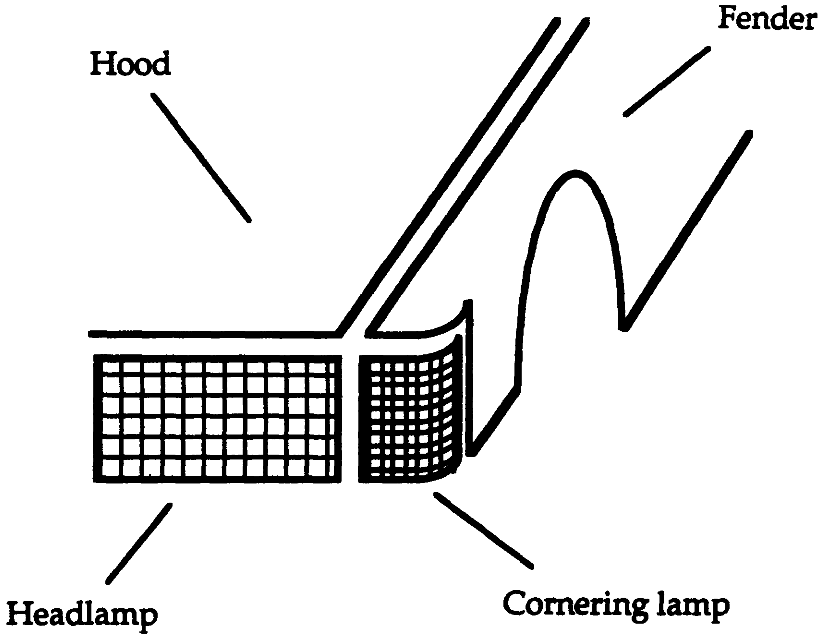


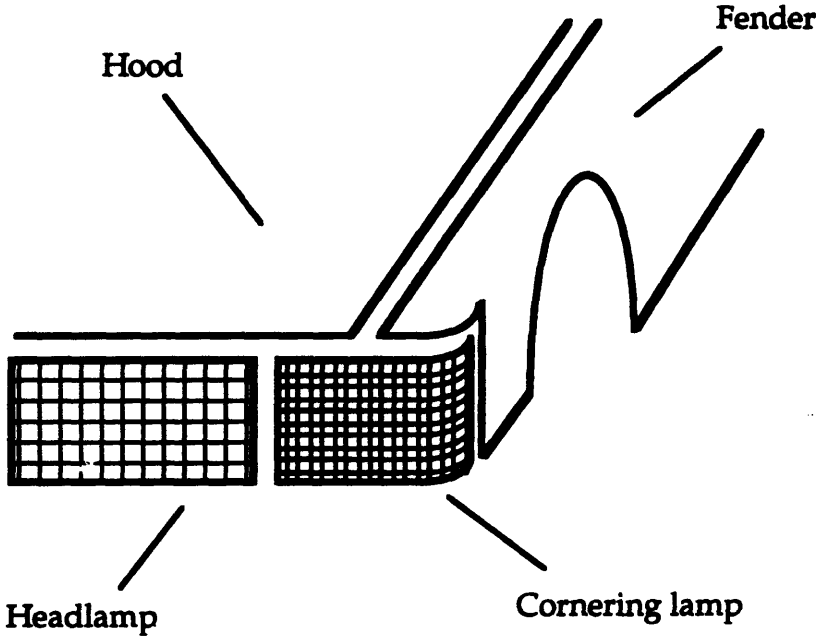
Figure 2.4, Illustration of a feature line on a vehicle

This feature line, then, becomes a visual reference to determine whether the panels are positioned properly, and deviations are easily noticed if the feature lines are misaligned. In sum, the unique styling appearance that feature lines provide must be weighed against the ability to accurately position panels and exterior components so that easily detected poor fits in the vehicle are minimized.

Finally, the way in which the cut lines (the location of the edges of panels and exterior components) of the vehicle are designed can also have strong impact on the amount of variation that is perceived in the final fits by customers. To show how cut lines can hide variation, consider the cut line locations of the fender, hood, cornering lamp, and head lamp (See Figure 2.5). When the cut lines of the four components meet at a corner, as shown in Figure 2.5a, deviations from nominal location in any of the components is more easily noticed. For instance if the gap between the hood and the fender is smaller than specification while the gap between the cornering lamp and the head lamp is at specification, one gap will obviously appear larger than the other and detract from the appearance of the vehicle. In contrast, if the cut lines are designed as shown in Figure 2.5b, the gap between the hood and the fender or the gap between the cornering lamp and the head lamp can be off-nominal without being easily noticed. In this manner, the location of the cut lines helps to reduce apparent variation.



a) A design with cutlines that are sensitive to variation.



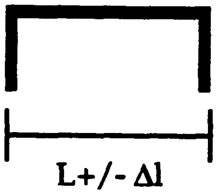
b) A design with cut lines that are less sensitive to variation.

Figure 2.5, The location of cut lines can reduce perception of poor fits

Slip planes: Slip planes, simply put, are surfaces where one part is free to "slide" relative to its mating part. The key advantage of a slip plane is that it reduces the effects of the piece part variations when assembling components (Nagel, 1991). A simple example of the advantage of using slip planes shown in Figure 2.6.

An interesting example of the use of slip planes in the design of the '94 Cadillac vehicle is the door to hinge assembly. One of the critical dimensions in the door to hinge assembly is the position of a locator hole in the hinge relative to the door. This hole locates to a pin in the frame of the vehicle, setting the location of the door, so any variation in the door to hinge assembly will translate to variation in the positioning of the door. Figure 2.7 shows two ways to design the door to hinge assembly. One way to design and process the hinge, Figure 2.7a, would be to pierce the hole in the hinge and then mount the hinge to the door. The problem with this design derives from the number of sources of variation that contribute to the variation of the assembly. A better way, Figure 2.7b, which makes use of the slip plane concept, is to attach the hinge to the door, then hold the door on its locating points and pierce the hole in the hinge. In this manner, the locating hole in the hinge is exact (within the tolerances of the piercing unit and the holding fixture) relative to the principle dimensions of the door. As this example illustrates, designing with slip planes can significantly reduce the variation in any assembly.

- **Consider an assembly made of three of the following brackets:**



a) Assembly without a slip plane:

$$\sigma^2_{assembly} = \sigma^2_{part1} + \sigma^2_{part2} + \sigma^2_{part3}$$

b) Assembly with a slip plane designed in bracket:

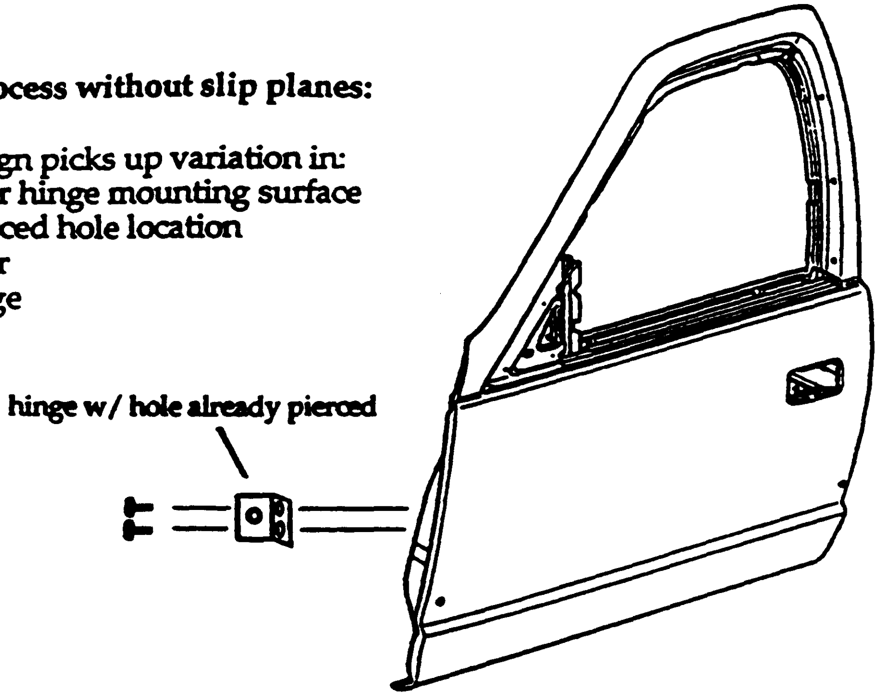
$$\sigma^2_{assembly} = \sigma^2_{fixture}$$

- **Note that by adding a slip plane to the bracket (b), the part to part variation was eliminated, leaving only the variation in the precision fixture.**

Figure 2.6, The advantage of designing with slip planes

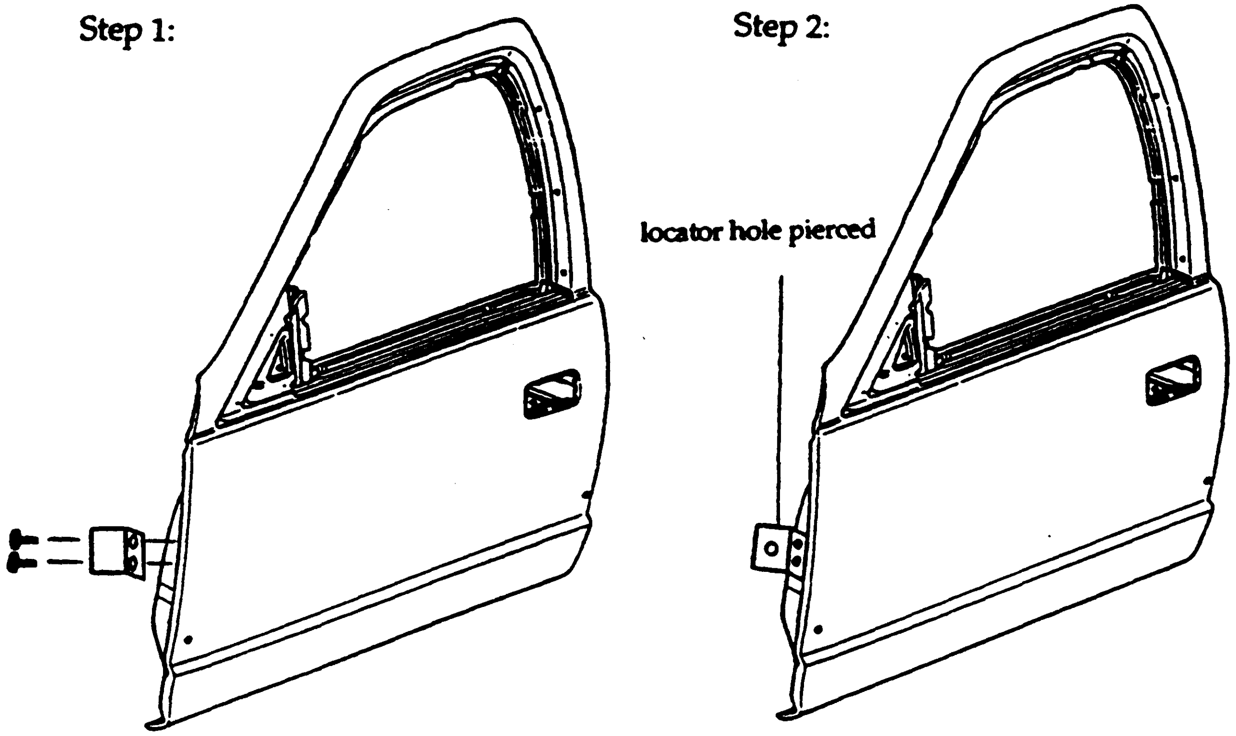
a) Door process without slip planes:

This design picks up variation in:
- door hinge mounting surface
- pierced hole location
- door
- hinge



b) Door process with slip plane operation:

The only contributor of variation in this design is from the piercing tool.

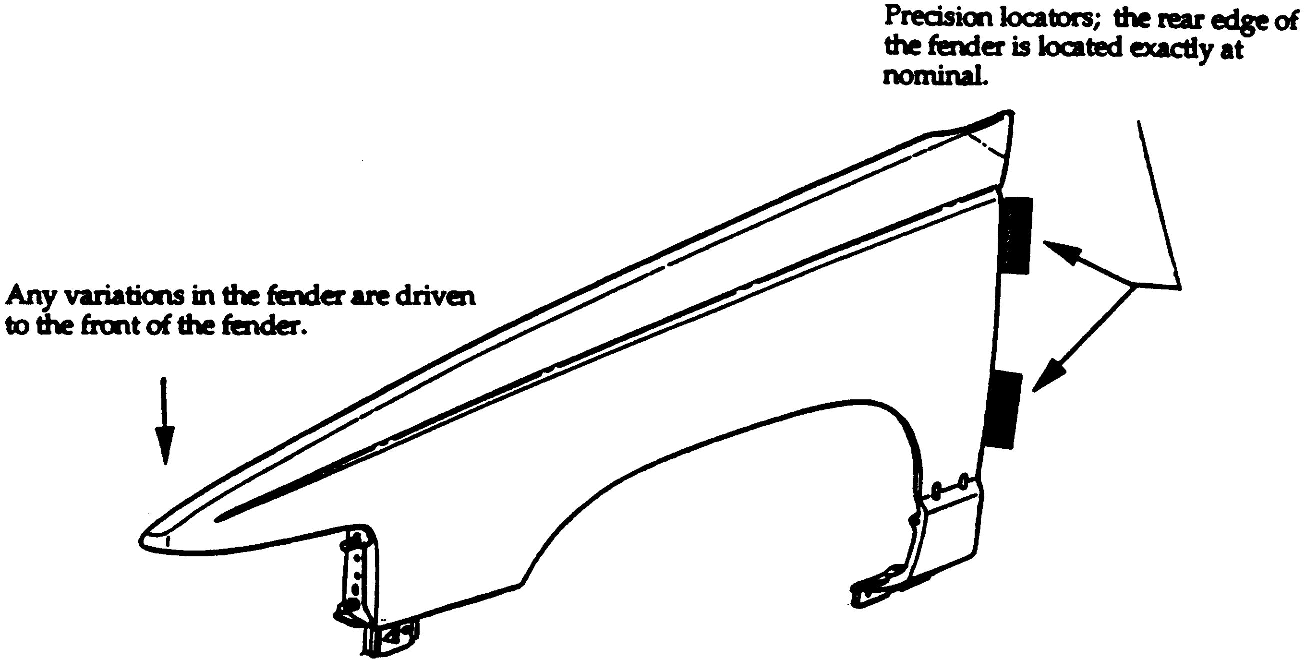

Step 1:

Step 2:

Figure 2.7, Using the slip plane concept in a door assembly operation

Datum Selection: Intelligent selection of datums can also be used to control variation in critical areas of the vehicle. Datums serve as the reference points on a part for specifying dimensions and tolerances; functionally, datums are the principle locating points that are used to precisely locate the part in tools and fixtures. Usually, a 3-2-1 datum scheme is used for each part. Three datum points are selected for the largest surface, two datum points are selected for the second largest surface, and one point is selected for the smallest surface (Liggett, 1993). Using these datum points as locators, a fixture precisely positions a part in three dimensional space relative to the vehicle's three dimensional coordinate system. Since any variations in the parts occur relative to the datum locations, the selection of datums determines where the variation will exist.

Figure 2.8 illustrates how the selection of datums can be used to control variation in critical areas, again using the fender to front door fit as an example. If it were determined that controlling the variation of the gap between the fender and the front door was crucial to customer satisfaction, then the fore-aft datums for the fender and for the front door should be on the meeting edges. Because the assembly fixtures that will locate the door and the fender to the vehicle will hold the parts at those points (again, those locating points are exact in space relative to the vehicle's coordinate system), the variation in the panels will be driven to the other ends and the gap will be at nominal. In a similar way, the variation of any part can be driven to areas of the vehicle that are less sensitive to variation or less important to customer satisfaction.



The precision locators position the rear of the fender exactly to nominal (in the fore-aft direction) relative to the vehicle's three dimensional reference system. Since the rear of the fender is true to nominal, any deviations in the length of the fender will be driven to the front of the fender. By locating the datums in this manner, the gap between the door and the fender can be better controlled, although at the expense of the fits between the front of the fender and the mating components.

Figure 2.8, Datum location can control variation in critical areas

Selecting Tolerances: The final step in the design of the product is specifying the tolerances of the piece parts, subassemblies, and assemblies. A significant amount of research has been and is currently being conducted on methods for selecting tolerances (Baron, 1992 and Tipnis 1992), but for the purposes of this discussion, and simply stated, the tolerances selected must accurately represent the process capabilities of the process designs selected and to the extent possible incorporate process capability information from data collected on carryover production processes. This is important because the tolerances will serve as the basis for the analytical predictions (discussed in the next subsection) that forecast the fits and functional performance. These predictions will only be as accurate as the information--the tolerances--that are used in the calculations.

A Final Note on Product and Process Selection

By the end of this phase, the piece parts, subassemblies, and assemblies have been designed and the processes to manufacture and assemble the components have been determined. Because the product and process design decisions were driven by the previously defined design goals, there is a high probability that the final fits and functional features will meet customer expectations. To close a point made earlier, by now the necessity of concurrent product and process design should be clearer. If for instance "soft" styling features are used in an area of the vehicle, then the processes that manufacture and assemble those parts do not necessarily need to be held to very tight tolerances; consequently, lower quality and lower cost processes can be selected. Similarly, if a new material that can be manufactured to very tight tolerances is selected, then intricate styling features can be incorporated without experiencing a loss in the quality of the appearance caused by excessive variation. The key is to recognize the tradeoff decisions that need to be made in designing both product and processes, and to select an optimal product and process strategy that ensures that customer satisfaction will be met.

2.4 Verifying the Design

Activities:

- Perform build predictions based on selected datums, tolerances, and processes.
- Resolve situations where predicted variation exceeds targets by changing process or product design.

Tools and Methods:

- RMS studies
- VSM studies
- HLM analysis

Now that the product and process designs are complete, a statistical analysis is performed to verify that the design will meet the fit and function goals. The two statistical methods that are most commonly used are root mean square analysis (RMS) and variation simulation modeling (VSM).

RMS: RMS calculates the variation of an assembly dimension (i.e. a gap between two panels) by summing the tolerances of the components and the tolerances of any assembly tooling that contributes variation. The general equation to calculate stack-up tolerance of an assembly is:

$$T_{assy} = \sqrt{t1^2 + t2^2 + t3^2 + \ldots + tn^2}$$

where; t_i=the tolerances of each component (nominal ± t_i)

Tassy=the predicted tolerance of the assembly

Although the component tolerances may have statistical distributions other than normal distributions, a normal distribution is usually assumed since the calculation of a stack-up tolerance becomes very complicated if each of the component tolerances do not exhibit the same statistical distribution. Assuming a normal distribution for all parts (since *most* parts do in fact exhibit a normal distribution) greatly simplifies the analysis. The specified tolerances, then, are generally assumed to be the six-sigma distribution ($\pm t_i=6\sigma$) for each component. Therefore, the predicted tolerance range of the assembly represents six-sigma of the distribution as well, meaning that 99.73% of the time the assembly dimension in question will fall within the calculated assembly tolerance.

Some literature (Liggett, 1993) recommends that the assembly tolerance be multiplied by a factor to compensate for component distributions that are not centered at nominal. (The RMS prediction also assumes that the tolerance distributions are centered at nominal.) This multiplication factor makes the RMS prediction more conservative. At Cadillac, a factor of 1.5 (known as the Bender factor which was an empirically derived coefficient by a former GM statistician) was used in the RMS predictions.

RMS calculations work well in instances where the stack-up is in one direction. Unfortunately, when stack-ups are not linear, it is necessary to use trigonometry to derive the proper variation contribution of a component, which can be very complicated. Overall, RMS provides quick, accurate estimates of stack-up tolerances when normal distributions are reasonable estimates of component distributions and when the assembly stack-up is in one direction. Table 2.2 summarizes when the RMS calculation should be used versus VSM.

VSM: Variation simulation modeling uses a computer to perform a Monte Carlo simulation to predict the tolerance stack-up of an assembly dimension. The variation simulation model is set up by inputting the distributions of the components and specifying the nominal locations of the components in the assembly. The computer then uses a random number generator to select dimensions for each of the components based on the specified distribution, and "assembles", or adds, each of the components to form the assembly. This process is repeated hundreds or thousands of times until ultimately a histogram for the resulting assembly is derived to show the expected range and distribution.

One of the advantages of a VSM analysis is that any statistical distribution can be used. Also, since almost all VSM software has locating and part positioning routines built into the program, any two-dimensional or three-dimensional stack-up can be studied without having to perform difficult trigonometric calculations required with the RMS method. One of the criticisms of VSM remains that it takes a long time to model an assembly and then run the Monte Carlo simulation. However, software specifically designed for performing VSM analyses has considerably reduced the effort needed to perform a simulation. As another advantage, a VSM analysis provides a high-low-mean (HLM) study which reveals the components that are the largest sources of variation. The computer accomplishes this by running a simulation that varies the dimensions of one component while holding the other components to nominal. After each component is analyzed in this method, a Pareto chart of the relative impact of each part on the total variation of the complete assembly is shown. This study is beneficial when the assembly does not meet the design goal because the parts that contribute the most amount of variation are shown and are therefore good candidates for redesign. The table below summarizes the relative advantages of RMS and VSM.

Predictive Tool:	Use when:
RMS	• Normal distributions are known (or assumed). • Stack-up is one dimensional.
VSM	• Distributions are not normal. • Analysis is complex. • Analysis is multi-dimensional.

Table 2.2, RMS vs. VSM

Using either of the predictive tools discussed, the designs can be studied to determine whether the goals can be met, well before prototype parts are produced. In cases where the predicted tolerances exceed design goals, product and process selections must be reevaluated to find a way to meet the customer expectations. The ability to make early predictions on how the vehicle will build is very important: because the manufacture of dies and assembly tools must occur early in a vehicle program (die manufacturing is a very long lead time event), the ability to make changes to part designs is very limited after early prototype phase. Early knowledge of problematic designs, therefore, greatly enhances the opportunity to make optimal design changes before it becomes too costly to rework the dies and other tooling that have already been built.

2.5 Verifying Process Capability and Troubleshooting Build Problems

Activities:

- Ensure that components, subassemblies, and assemblies can be mfg. within specification.
- Identify and resolve situations where variation is excessive in features that the customer will notice.

Tools and Methods:

- Cp, Cpk studies
- Functional build/ "Screwbody" event

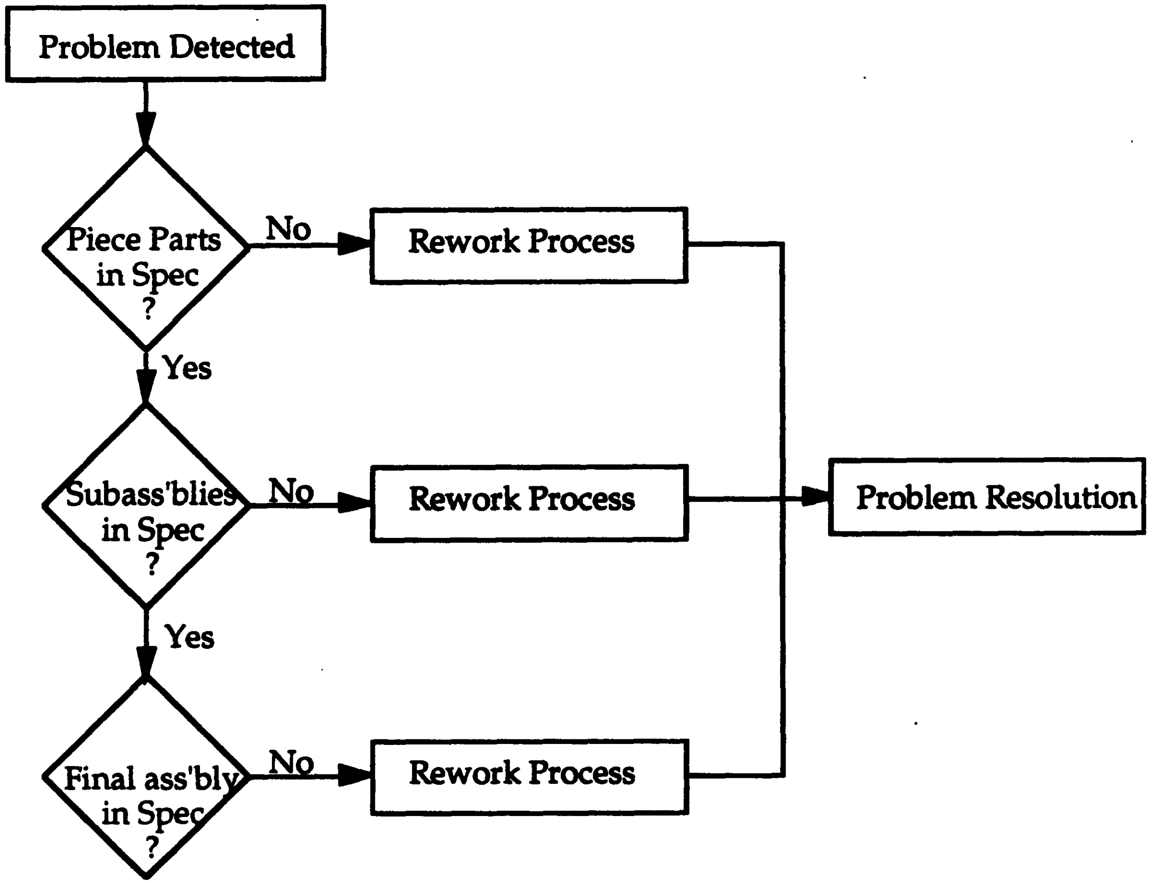
At this point in the process, the vehicle and the processes to manufacture the vehicle have been proven analytically capable of meeting the fit and function goals. The pilot phase provides the opportunity to verify that the vehicle can be built on production processes to achieve the design goals. During the pilot phase, the piece parts, subassemblies, and assemblies need to be checked to ensure that each can be manufactured within specified tolerances. The best way to confirm that processes are within specification is to perform a process capability study on a batch of parts produced from the tooling and processes that will be used during production.

In cases where parts do not fall within specification and cause defects that the customer will notice, some form of corrective action must be taken to resolve the problem. The traditional problem solving approach has been to systematically check each part that could contribute to the problem, and then rework the processes that are producing the off-nominal parts. The problem associated this approach is that reworking the root cause of the variation problem is often both expensive and time consuming. Reworking dies, for instance, to bring the dimensions of the part to within specification is a costly solution. Instead, intelligent troubleshooting of build problems can save considerable time and money--the goal of the functional build approach.

Functional Build Method: The functional build approach attempts to identify the most efficient solution to build problems. The motivation for the functional build strategy is to recognize that a main source of deviation is mean shifts that result from the stamping operations that produce the piece parts. Ideally, the dies used in stamping operations would produce parts with distributions centered at nominal; however, because of errors in the machining processes that manufacture the dies and because of the effects of springback during the stamping of metal parts, to mention a few drivers of off-nominal conditions, this can be a very difficult task. Therefore, instead of trying to rework dies--again a very costly venture--the mean shifts are detected and simple adjustments are made to assembly tooling in order to build using the off-nominal parts and still meet the design goals (Gibson, 1992).

The process for troubleshooting build problems with a functional build approach compared with the traditional approach is shown in Figure 2.9. With the functional build strategy, when a problem is detected, the parts and processes that comprise and build the assembly are checked to make certain that they are, in fact, able to be produced within the specified tolerance *range* (this does not mean that the parts are within specification, but rather that the parts are within the allowable variation limits). When processes are deemed capable of producing parts without exceeding the tolerance range, then the simplest possible adjustment is sought. For example, suppose that the gap between the fender and the front door was found to be too large because the fender was consistently produced too small. Rather than reworking the die that produces the fender to correct the out of specification dimension, the course of action that would be taken under the traditional approach, perhaps the tool that locates the fender to the vehicle could be adjusted to locate the fender aft of nominal, and thereby reduce the gap. Obviously, consideration must be given to competing factors such as the fit of the fender to the cornering lamp, but this simple example illustrates the concept. Again, the overriding philosophy is that the customer only notices the off-nominal fits and poor functional features, not the off-nominal parts; if the off-nominal parts can still be used with simple, low cost adjustments, why waste the additional money and resources to correct a problem that does not contribute to the quality loss of the vehicle?

Traditional Troubleshooting Strategy:



Functional Build Troubleshooting Strategy:

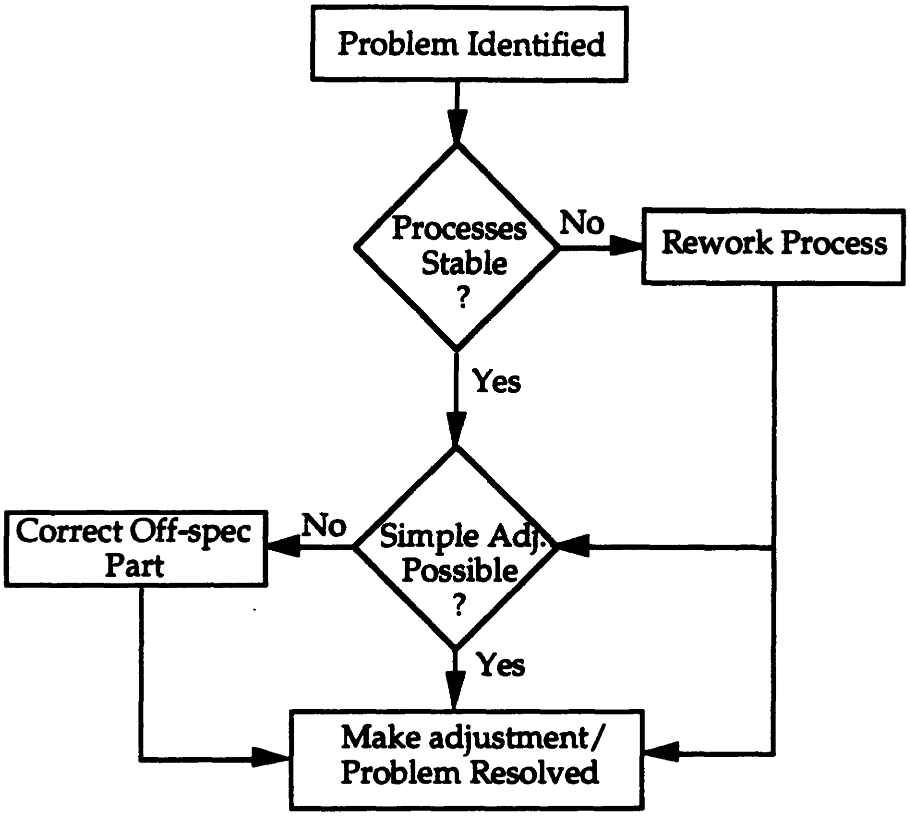


Figure 2.9, A comparison of the two troubleshooting strategies

"Screwbody" Approach: Many Japanese auto makers have extended the functional build concept to what is known as a screwbody approach. The goal of the screwbody process is to identify during early pilot (and sometimes prototype) activities the mean shifts in the parts produced at the stamping plant, as opposed to waiting for the pilot vehicles to indicate that a problem has occurred with the final fit and functional performance. A screwbody is, very simply, a model that is assembled using stamped parts and held together with screws and rivets. This model's parts, especially closure panels like

fenders, doors, roofs, deck lids, etc., are finessed to achieve the nominal values of the original design goals. Unless any parts are grossly off specification and need to be reworked, the dimensions of this vehicle then become the nominal design dimensions and assembly tooling is set to build to these new dimensions. Through this process, variations caused by mean shifts in the stamping operations are absorbed, eliminating the need for costly rework. At the same time, no loss in quality is perceived by the customer (Baron, 1992). Figure 2.10 shows the screwbody development process.

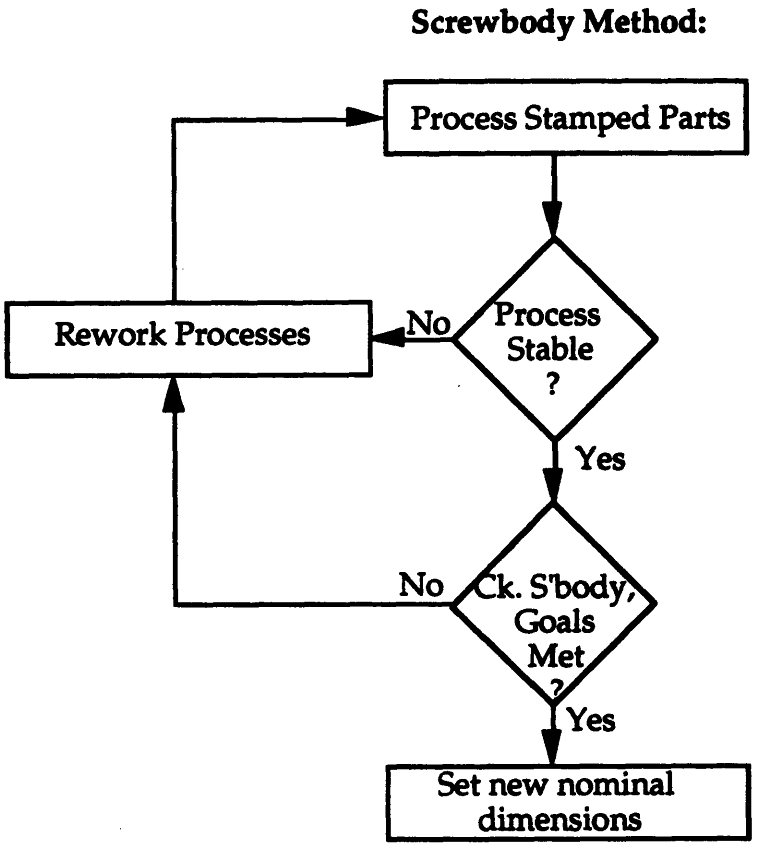
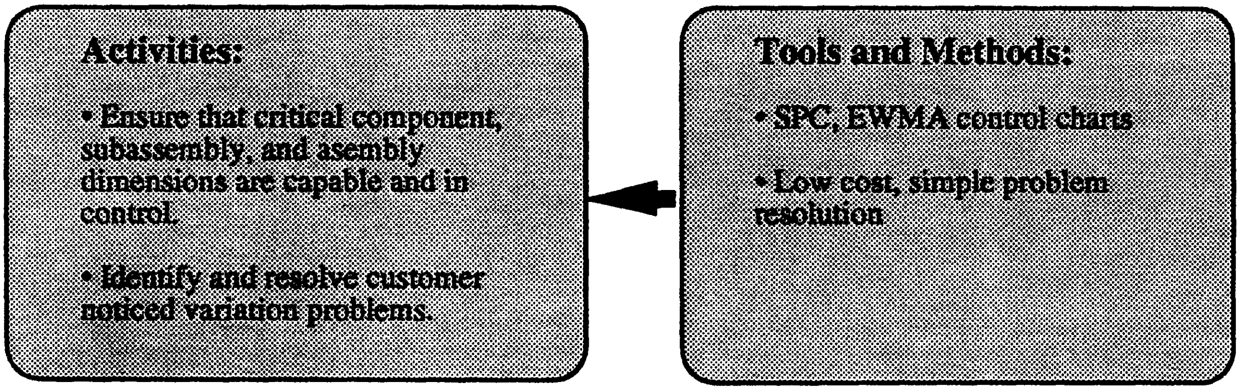


Figure 2.10, The screwbody process

In order to use the screwbody approach, the processes that make the piece parts must be capable (again, the 6-sigma spread for the process distribution must be less than the tolerance). In addition, the parts that are used for the screwbody model must represent the average of a production run; otherwise, the new dimensions will not actually be the nominal dimensions. Further, since the screwbody event occurs during the early pilot phase, it is imperative that the processes used to produce the screwbody parts accurately reflect the processes that will be used during production; otherwise, the adjustments that are made from the original design may be erroneous. The screwbody process requires a disciplined effort to make certain that each of these issues are appropriately managed; however, this process saves costly die rework and eliminates the iterative adjustments that must be made in the assembly plant every time part dimensions change because of rework in the stamping processes.

2.6 Monitoring Assembly Processes and Troubleshooting Build Problems



Activities:

- Ensure that critical component, subassembly, and asembly dimensions are capable and in control.
- Identify and resolve customer noticed variation problems.

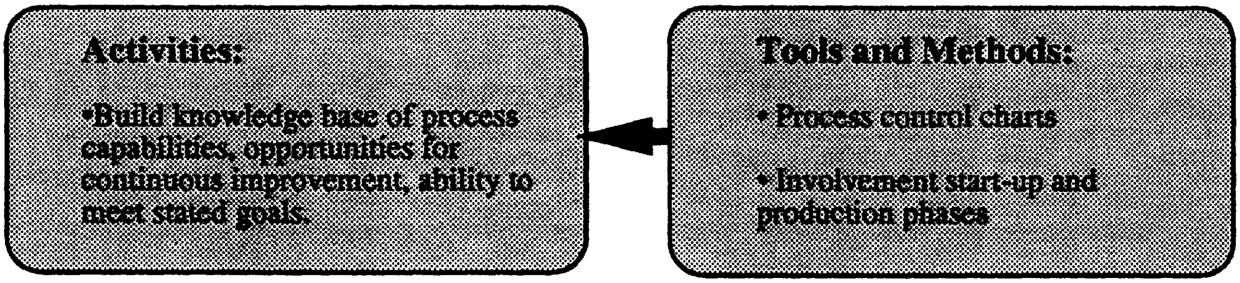
Tools and Methods:

- SPC, EWMA control charts
- Low cost, simple problem resolution

By the time pilot production has ended, all build problems have been resolved and the processes that will be used for production have been shown capable of meeting design goals. At this point very little can be done to manage the effects of variation. Rather, during production the focus is more on reducing variation through designed experiments and other process optimization techniques.

Still, during the production phase the assembly processes should continue to be monitored to make certain that parts are being produced and assembled to specification. Statistical process control using Shewhart control charts or EWMA charts are common tools for in-process monitoring. In addition, any necessary preventive maintenance should be performed to ensure that the assembly tooling is free of wear and damage which can create variation, and that all processes are running at correct settings of critical parameters. When build problems do arise, again the goal is pursue low cost, simple problem resolutions.

2.7 Feeding Forward Information to Future Programs



The final step in the process is to transfer the knowledge gained from the current vehicle program to future vehicle programs. Specifically, a knowledge base should be gained of true process capabilities, opportunities for design or process improvements, and the ability to meet the stated goals. Process control charts and other on line quality control data provide an excellent indication of process capabilities of current production processes. Further, the lessons learned, the unknown sources of problems, from the pilot and start-up phase need to be captured to ensure that the same mistakes are not repeated in future design processes. This knowledge is best gathered through involvement in pilot and start-up activities since this is when many of the problems--and thus opportunities for future improvement-- first surface. This final step is crucial in the variation management process because it represents an opportunity to gain the profound knowledge that will lead to significant improvements in the product and process designs and ultimately increases in customer satisfaction--the overriding goal of this entire process.

Section 3
Information and Organization Requirements

Having discussed a variation management process from an engineering and design perspective in Section 2, the focus now shifts to process management issues involved in implementing a successful variation management program. Specifically, this section addresses the information requirements that must be developed and communicated throughout a variation management process, and then describes some organizational structures that can be used to enable successful information flow. Even with the best engineering methodologies at one's disposal, a design program will still fail without careful consideration of how to link critical information conduits through a well designed organizational structure. This discussion, then, will provide key insights into not only *what* variation management is, but also *how* a variation management effort should be executed; and these insights ultimately will reappear in later discussions that specifically address improvement opportunities in Cadillac's variation management program.

3.1 Information Requirements

Critical to any design effort is the flow of information to and from different departments engaging in numerous development activities. To establish a truly successful design process, it is crucial to manage the key linkages across the broad range of developmental activities so that required information flows in an efficient and timely manner (Clark and Fujimoto, 1991). Accordingly, to effectively implement a variation management initiative, the information requirements, such as process capability or product and process design information, need to be examined to ensure that the key information sources, such as plant engineering, manufacturing engineering, and design groups, are prepared to provide these critical inputs required in making optimal design decisions.

Figure 3.1 overlays the information requirements within a detailed process flow diagram. The numerous variation management activities discussed in Section 2 are displayed in the boxes, while the required information to effectively carry out that activity are shown flowing into those boxes. Additionally, flowing out from below the boxes are the key information outputs of each activity. This diagram was developed with input from engineering managers and senior engineers involved in the Cadillac variation management program, and can be viewed as an ideal process flow for a variation management program, showing the key linkages of information from one activity in the variation management process to another.

As an aside, although this diagram models a variation management process, in general a diagram of this type can provide some key observations about any design process. Specifically, the diagram: identifies the key resources or departments that must be integrated in the design effort; shows the required inputs and outputs from each of these resources; and conveys the timing for each of these inputs depicting when these critical resources must be involved in the process. In short, such a diagram can serve as a potential planning tool for managers showing critical requirements that must be considered to ensure successful execution of the design process.

Returning to the process model in Figure 3.1, the process flow/information requirements diagram is fairly self explanatory; however, a few important observations regarding a variation management effort are worth discussing at this point:

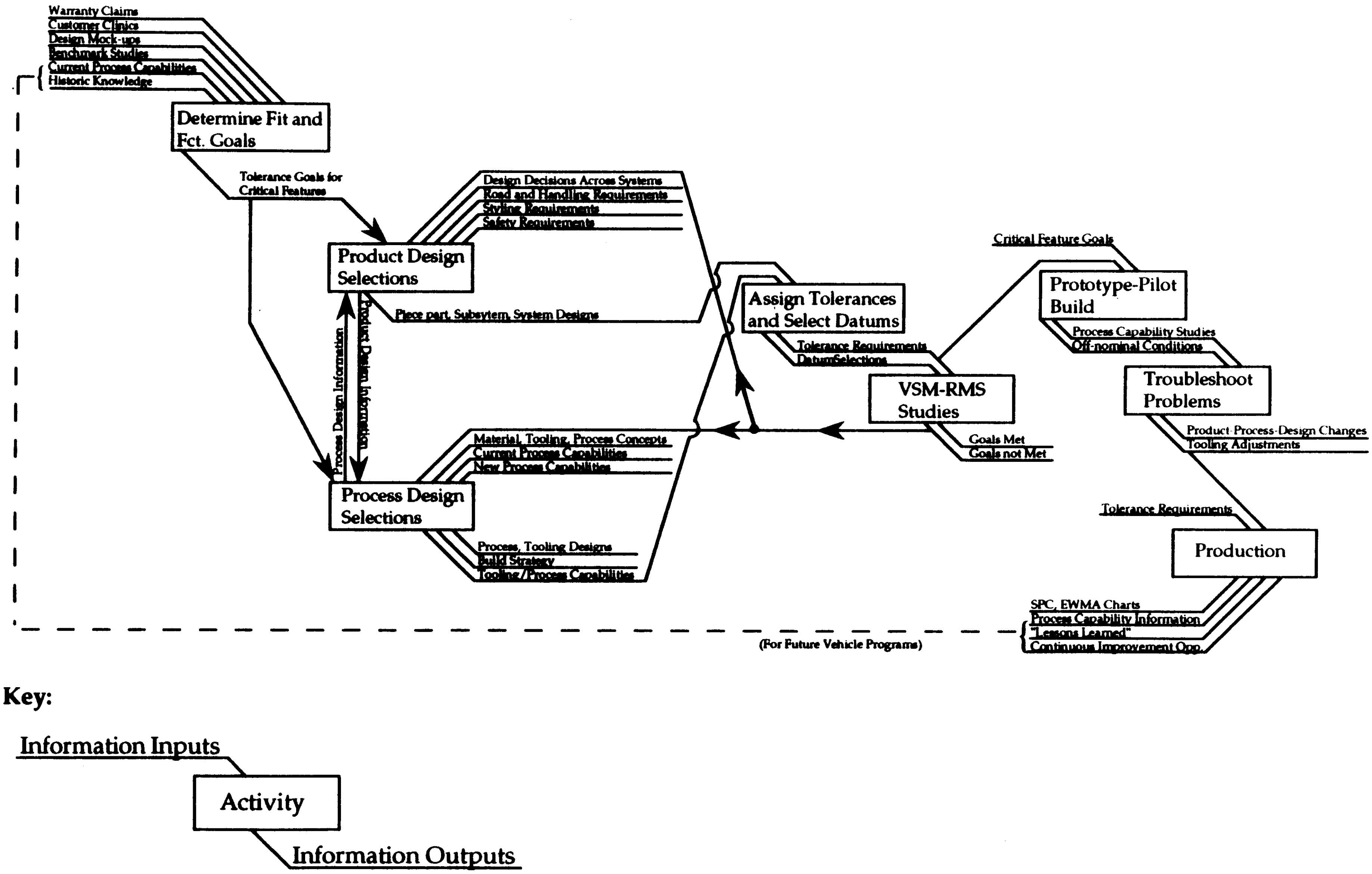


Figure 3.1, "Ideal" Process Flow/Information Flow Diagram

- *The ideal process is an iterative process:* As the diagram shows, iterative loops exists between the product and process design selections and between the VSM-RMS predictions and product-process design selections. These iterative loops can cause delays in design activities because of additional steps required to handle the design tasks. For example, when critical feature goals are shown statistically unable to be met, the product and process designs must be reviewed, in effect adding extra steps to the design process. Thus, it is important to ensure that the proper communication channels exist to handle these iterative tasks in an efficient manner so that the opportunity to make required design changes is not missed because of unnecessary lengthy delays caused by design iteration. (For more information on iteration in design processes, see Eppinger and Smith, 1993.)
- *The ideal process is a feed forward process:* In Section 2, the need to feed forward information to future vehicle programs was discussed. The dashed line in the diagram indicates information flowing from one vehicle program to the next that should be used to improve future designs, thus connecting future programs to the current variation management process. Since these "lessons learned" from one program provide continuous improvement opportunities for the next program, careful consideration must be given to how an organization links one program to the next to transfer this knowledge.
- *The ideal process requires a multi-functional effort:* In looking at the different information inputs and outputs, it becomes readily apparent that many different functional groups within an organization must be involved for a successful variation management

program. Specifically, marketing, product engineering, manufacturing engineering, plant engineering, and design groups, are but a few of the departments that must provide input to this process. Additionally, the diagram depicts other vehicle requirement information, such as styling and safety requirements, flowing to the product design selection activity. Sometimes, these requirements create situations where tradeoff decisions must be made. In these cases, input from other vehicle development activities must be incorporated into the variation management process. The important point to note is that managing the communication links between the various functional departments becomes an additional challenge facing managers in implementing a successful variation management process.

Again, the overall goal of the process flow/information flow diagram is to identify the critical linkages between the different activities and functional departments in implementing a variation management process. This diagram also provides a more detailed picture of the requirements of each of the variation management activities discussed in Section Two, and ultimately, will be a valuable tool when focusing on the variation management program at Cadillac.

3.2 Organizational Requirements

One factor that will have a major impact in promoting the required information flow is the organizational structure that is employed by an organization to carry out a variation management program. A properly configured organizational structure will ensure that critical linkages between the different activities and departments are in place (Hollins and Pugh, 1990), thereby promoting a higher probability that the needed information is available to perform a design task. In studying variation management programs, I have seen three different organizational structures used to execute the necessary variation management activities: one approach makes use of simultaneous engineering teams; the second approach takes a functional department structure; and the final approach is a hybrid configuration which incorporates both of the previous two structures. Each of these structures has their own merits which will be discussed in turn.

Team Approach: Figure 3.2 depicts the typical composition of a multi-functional variation management team. Like most simultaneous engineering teams, representatives with responsibilities for similar vehicle systems but from different functional departments form the core of the team. For example, manufacturing engineers, product engineers, designers, etc., responsible for designing, manufacturing, and assembling doors collaborate on one team to focus on variation management issues for door systems. Included on these teams are VSM and RMS modelers, and datum and tolerancing experts to help support the activities of these variation management teams.

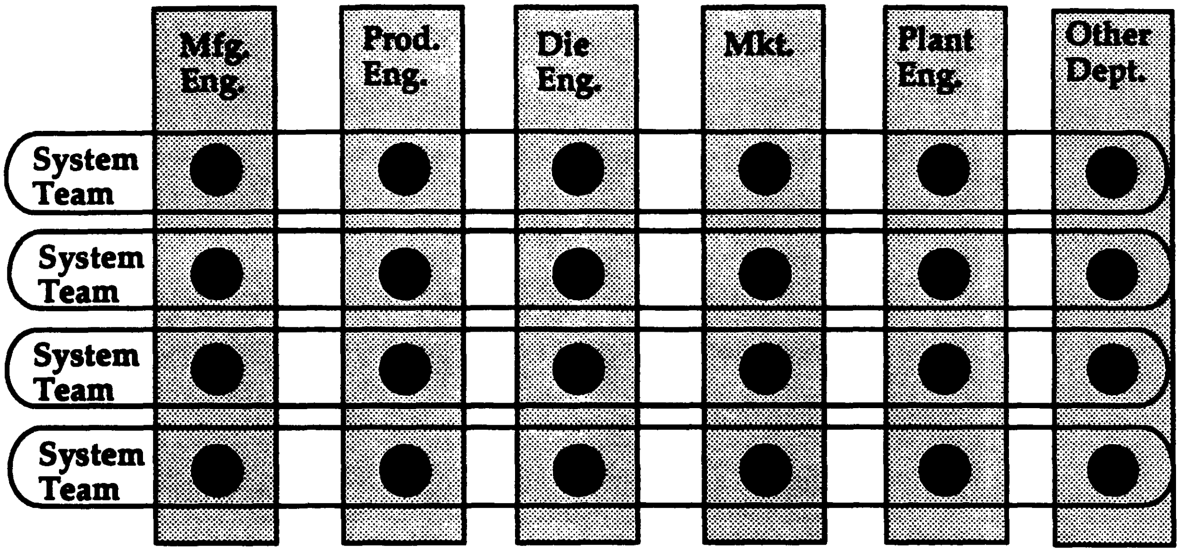


Figure 3.2, Typical composition of variation management teams

The advantages of simultaneous, multi-functional engineering teams have been well publicized in recent years (Clark and Fujimoto, 1991 and Womak et al, 1991). Without engaging in a lengthy discourse on simultaneous engineering, I will attempt to highlight a few advantages that are especially relevant to implementing a successful variation management program:

- *Facilitates communication:* The information flow diagram showed that a number of different departments provided input to the variation management activities. A multi-functional team provides an excellent forum for communicating this information among the functional groups. Since these teams facilitate the flow of information, they enable design decisions to be made more rapidly since the required inputs will necessarily be delivered faster.
- *Taps expertise of all functional groups in design decisions:* With a multi-functional team, key design decisions are made by representatives

from each functional group. Because more input is involved in the design decisions, the team approach promotes a greater probability that the best possible designs are selected. This is especially significant considering the importance of simultaneously designing both product and process: the team approach brings the responsible manufacturing and product engineers and designers together to make optimal product and process design selections.

- *Involves those who can make a difference in managing variation:* Manufacturing engineering, product engineering, plant engineering, etc., are the groups that have ownership for product and process designs; consequently, they are the individuals who must take responsibility to make necessary product and process changes to design a more robust vehicle. By employing a team approach, these key groups are directly involved in the variation management effort; responsibility for executing variation management activities is driven to those who can make a difference.

A number of sources (Clark and Fujimoto, 1991; Clausing, 1994; and Womack et al, 1991) list other advantages of simultaneous engineering which would also apply to a variation management team. This short list, however, is intended to highlight a few of the key advantages that a team based organizational structure provides in instituting a successful variation management program.

Functional Group Approach: As the name implies, this is a functional group that is solely dedicated to addressing variation management issues for the entire vehicle program. Typically, the variation department will consist of

VSM-RMS modelers, tolerancing experts, and systems engineers. It is the responsibility of these systems engineers to facilitate the information flow among the other functional departments and to make certain that each of the variation management steps for their vehicle system is followed. Figure 3.3 conveys the typical communication flow to and from functional groups. The variation management group will: set goals for critical features; deliver these goals to the appropriate engineers; analyze the design selections; and in cases where goals are unable to be met, identify the key contributors of variation and deliver the pertinent information to the responsible engineer. The remaining variation management activities are carried out in a similar manner with the systems engineer serving as the information conduit to the engineering and design groups. In sum, with a functional group approach, the variation management group acts as a support group that assists in designing robust assemblies.

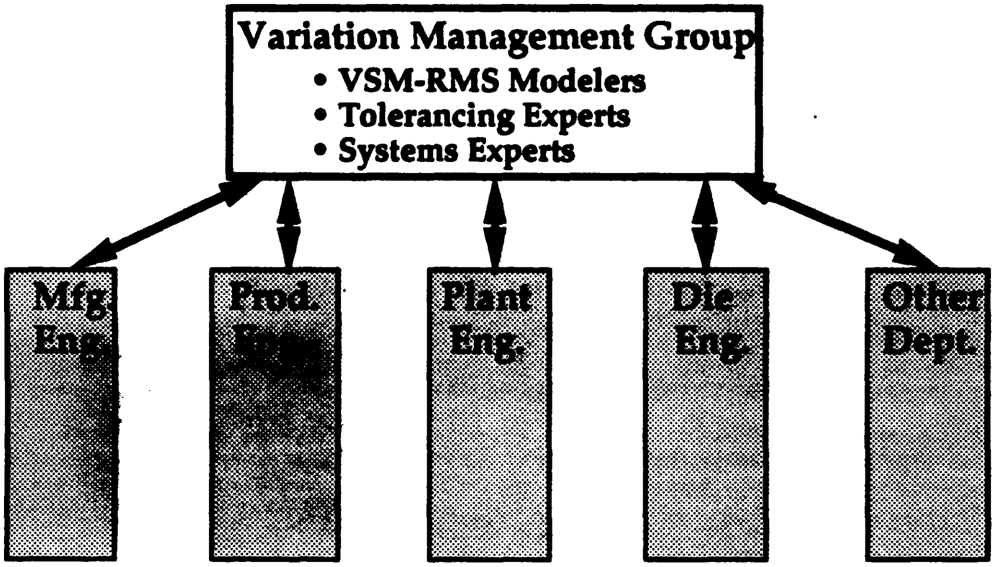


Figure 3.3, Information flow with a functional variation management group

The following list describes some of the key advantages of a functional variation management group that were cited by variation management department coordinators:

- *Develops experts in variation management:* This is the most often cited advantage of the functional group approach. Because engineers are dedicated solely to focusing on variation management issues, they develop a very broad knowledge base of effective variation management techniques. Also, since systems engineers are responsible for one vehicle system, they develop a thorough understanding of what it takes to achieve dimensional stability of that system. Further, when innovative and unique approaches to variation problems are developed, sharing this knowledge within the variation management group becomes routine since all variation management representatives reside in the same department. In sum, the single-minded focus on variation management issues coupled with a separate group that facilitates transfer of knowledge, results in an expert variation management group.
- *Provides a natural variation management facilitator:* This benefit is closely related to the previous advantage. Because experts in variation management are developed, engineers who understand the systems in detail and who comprehend variation management clearly possess the requisite skills to facilitate execution of variation management activities. Unlike the team approach which requires representatives from other departments to carry out the variation management process, the functional variation management group

provides representatives who understand the process in detail to execute the process activities.

- *Facilitates cross-system communication:* Very often, critical feature goals overlap vehicle systems, in which case more than one team of engineers is responsible for designing to meet those goals. Since the variation management systems engineers reside in the same group, these engineers can meet to determine a design strategy to meet the critical feature goal--a much simpler process than bringing two teams together to discuss a build strategy. Also, the variation management group serves as a clearinghouse for any design changes, so a design change that affects more than one system is forwarded to the responsible systems engineers.

Clearly, the functional approach offers some distinct advantages over the team based structure. Still, neither organizational structure is clearly superior to the other: the advantages of one approach are the weaknesses of another. In an effort to exploit the merits of each approach, a structure that has begun to evolve in a number of organizations is what I term a hybrid structure.

Hybrid Approach: The hybrid structure is actually very similar to the team based approach previously discussed. The key difference, however, is that a complete functional variation management group, consisting of systems engineers, tolerancing experts, and VSM-RMS analysts, exists to help facilitate the variation management process. To represent this subtle, yet important difference, Figure 3.4 is an amendment to Figure 3.2 showing a variation management department with representatives serving on the various variation management teams. The members of the variation management department, then, act as facilitators for the team to ensure that the variation management activities are properly addressed. In short, the hybrid approach is best characterized as a well developed simultaneous engineering team.

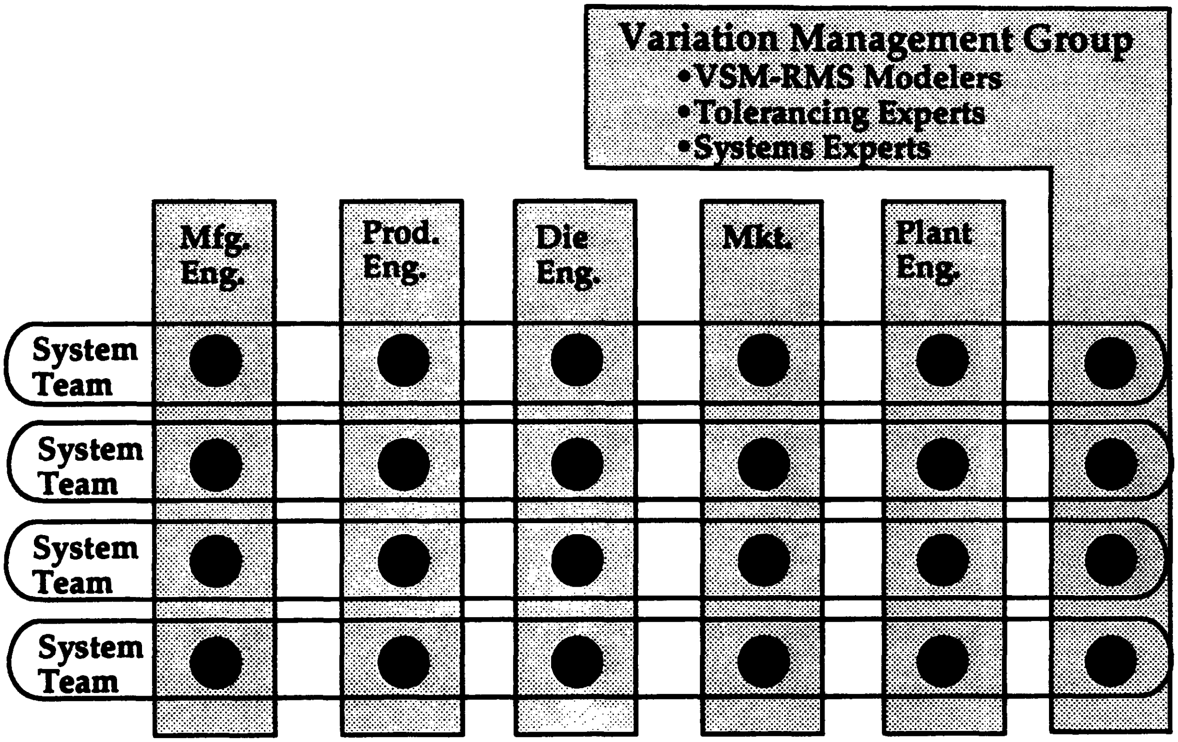


Figure 3.4, Team composition with hybrid approach

The advantages of this type of structure lie in the fact that it captures the merits of both the functional and team approach. Specifically, the hybrid approach incorporates both the development of experts in variation management, the key advantage of a functional department, and the advancement of communication across groups, a key advantage of multi-disciplinary teams. Because of these advantages, the hybrid structure is becoming more commonly used: as one variation management coordinator noted, as a separate group they could not influence the necessary changes;

however, by including a team structure, they became almost immediately recognized as a key resource to design activities.

In sum, the organizational structure will be a key determinant of how effectively information flows from one variation management activity to another; consequently, the organizational structure will serve as a key factor in the success of the variation management effort. When implementing a variation management program, an organization must consider carefully how effectively the chosen structure facilitates the flow of information and thus enables the variation management activities to be properly executed. This section has attempted to describe some common organizational structures and their impact on the variation management process. Hopefully, this brief discussion will provide some insights on how to effectively implement and execute a variation management process.

Section 4
Evaluating a Variation Management Process

In previous sections, this thesis focused on a generic variation management process showing the engineering, information, and organizational requirements for successfully executing a variation management effort. Throughout this discussion, I incorporated a number of insights and observations obtained from variation management processes at many different organizations; however, I have yet to critically evaluate any particular company's process. In this section, then, I pursue an in depth evaluation of one organization's variation management process. Specifically, this section addresses the Precision Build Process, the variation management program instituted at Cadillac.

In this section, I will: briefly describe the Cadillac Precision Build process; discuss the methods used to evaluate the process; detail some of the weaknesses of the process; and finally, recommend ways in which the Precision Build process can be improved. By looking at a company's variation management program, hopefully two outcomes can be achieved. First, for Cadillac, the specific continuous improvement recommendations will strengthen the variation management process, leading to even higher quality vehicles and therefore greater customer satisfaction. For other companies, especially those considering implementing a variation management program, this discussion will provide some insights into crucial areas that can be potential failure modes to successful implementation, and perhaps more importantly, the recommendations will serve as a list of "critical enablers" required to achieve a high quality design effort.

4.1 The Cadillac Variation Management Process

In order to make the discussion that follows more meaningful, it is first important to provide a background by giving a brief overview of the Cadillac variation management program, the Precision Build Process. As discussed in Section 1, the Precision Build Process was implemented for the 1994 Deville vehicle program with the goal of further increasing the quality of aesthetic appearance and functional performance for the entire vehicle. The program was Cadillac's first effort to institute a variation management program organization wide. In fact, the Precision Build Process evolved from a small scale variation management effort on a previous vehicle program that focused variation management activities on a limited number of vehicle systems. Because of the success of these previous efforts, a group of middle level engineering managers pursued implementing a total system variation management program.

From an organizational perspective, the Precision Build Process most closely resembled the hybrid approach described in Section 3. Multi-functional teams were formed with variation management experts, provided by an outside engineering firm, residing on these teams. The key difference between the Cadillac organizational structure and the hybrid structure previously discussed, however, was that there were no variation management systems engineers to facilitate execution of the variation management process. Instead, a senior engineer from one of the other functional groups, such as the product or manufacturing engineering group, acted as team leader, while the variation management members served in more of an ancillary, support role.

In total, twenty-one teams were formed to address variation management concerns for each major vehicle system, such as doors, decklids, fascia, and exterior trim. Figure 4.1, below, shows the typical composition of a Precision Build team.

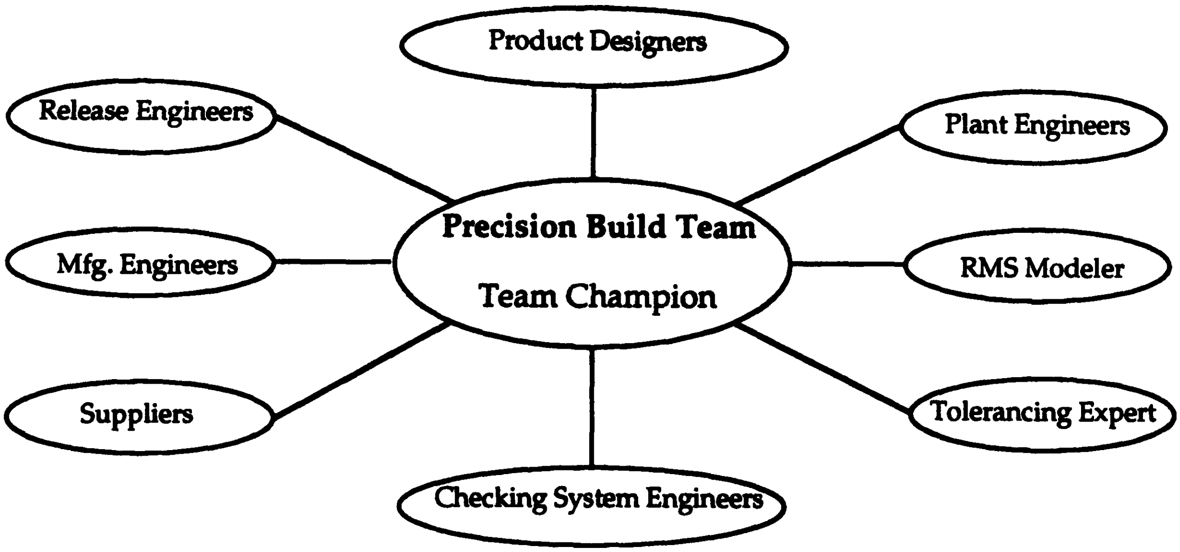


Figure 4.1, Composition of Precision Build Teams

As mentioned, typically a senior engineer from one of the functional groups served as team champion; however, in some cases first level engineering managers filled that role. In addition to the system teams, a steering committee, also comprised of middle level engineering managers, was established to oversee the entire process. In general, this group's primary responsibilities included: managing design concerns across teams; procuring capital and personnel resources from upper management to implement the process; and ensuring that teams were able to execute their tasks in a quality and timely manner.

On a final note, it should be mentioned that the Precision Build Process represented a first level management initiative: the process was not a division strategy sanctioned by top management at Cadillac. This fact is important because, as we will see in the following subsections, since the drive to implement this process originated with lower level management, some concerns regarding the empowerment of teams, including the steering committee, surfaced.

4.2 Methods for Evaluating the Precision Build Process

One of the challenges of evaluating a large scale design effort is eliminating the subjectivity of the analysis. As I found during preliminary discussions with engineers and managers involved in the process, it seemed that everyone had an opinion, based on their position and perspective within the organization, as to the success of the process and possible future improvements. In an effort to make the analysis more scientific and as objective possible, the ideal process flow/information flow diagram presented in Section 3 was used. Recognizing that the goal in analyzing the Precision Build Process is to enable the process to function like the ideal process flow diagram depicted in Figure 3.1, this diagram was used as a template for evaluating the Precision Build Process.

Very simply, then, using this diagram as a template, I interviewed each of the team champions and steering committee members and obtained input on where and why the process did not function as the ideal process. Once these problems were uncovered, the next step was to create a list of recommendations, developed by a team consisting of team champions and steering committee members, to resolve these problems and, ultimately, to improve the Precision Build Process so that it functions as the ideal process. This approach to evaluate and recommend continuous improvement opportunities for the Cadillac variation management program is depicted in the figure below.

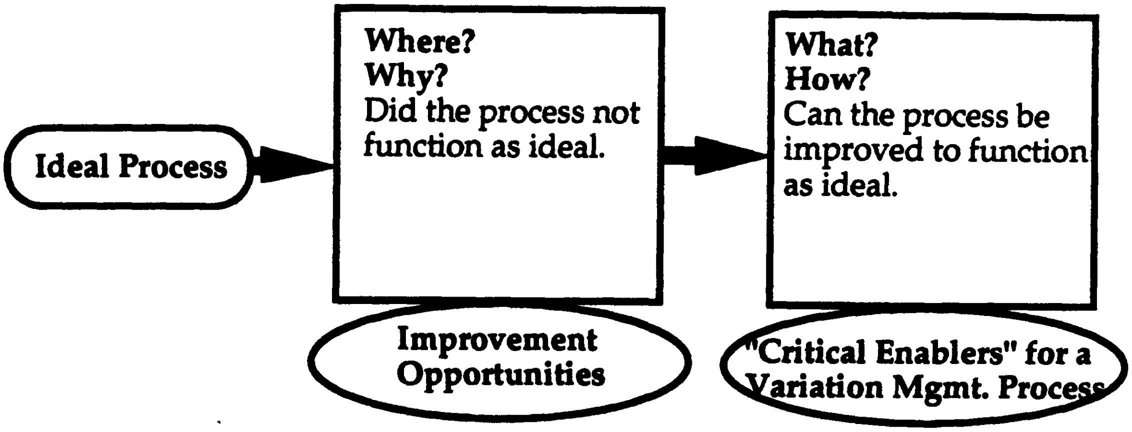


Figure 4.2, Method for Evaluating the Precision Build Process

4.3 Improvement Opportunities in the Precision Build Process

The following pages describe in detail the problems uncovered through the interviews with team champions and steering committee members involved in the Precision Build Process. The discussion of each problem includes an explanation of the cause and the impact that the problem had on the process. The recommendations developed by the panel to resolve the problem are presented after the problem discussion. Additionally, in parentheses next to each problem statement is a number which shows the relative importance of each weakness, on a scale of zero to five with five signifying most critical, as determined by surveying a number of participants in the process. (Note: the problems are presented in descending order of importance.) Appendix B details the data collection and results. Through this survey, it becomes apparent which problems are most significant to resolve, and logically which recommendations are most crucial to implement.

Before presenting the problems and recommendations, I hope to impress upon the reader that although the list of problems is fairly extensive, in no way should it be construed that the program failed to make significant accomplishments. On the contrary, as the survey results show, those involved in the process responded with an average rating of 4.7 out of 5 (a five signifies "strongly agree") to the statement: "The Precision Build Process was a valuable initiative". Further, the same rating was given to the statement: "The Precision Build Process should be used for future programs". These high ratings certainly convey a strong support for the program. The goal of the following list of problems and solutions, then, is to provide insights into how to further improve an already strong design program.

1. ***Problem:*** *Troubleshooting build problems during the prototype phase was difficult because teams were not confident that the prototype problems reflected actual production problems. (4.5)*

Teams were sometimes reticent to suggest tooling adjustments or design changes because prototype vehicles were not built entirely with production intent tooling or production processes. As one team champion stated, there was a belief that the prototype problems would go away once production tooling was used.

Recommendation: *Study prototyping techniques to identify ways to improve the accuracy of data collected during the prototype phase.*

Our team decided that this problem was outside of the control of the variation management effort. Resolving this problem will require fundamental changes in many different areas of the organization, from the speed with which the die fabrication groups can procure working dies to the methods with which the plant actually assembles the prototype vehicle. Thus, the recommendation is not so much a specific action step, but rather a proposal for further investigation.

2. ***Problem:*** *Cross system design issues were not efficiently managed. (4.4)*

In spite of the effort to decompose the design tasks to account for interface areas on the vehicle, some cross system design issues still exist such as door to fender fits, front end sheet metal to grille and fascia fits, and deck lid to rear fascia and quarter panel fits. In these situations, two (or more) teams must make optimal design decisions to meet the goals for that critical feature. Unfortunately, in some cases, the cross team communication was limited. In one example, neither team would commit to making the necessary changes because neither team would accept responsibility for the problem. As mentioned, a steering committee existed to help manage these problems; however, as one team champion put it, the steering committee became a record keeping committee to report to management how many goals had been met rather than a committee that would help manage cross team issues. Representatives of the steering committee, in turn, suggested that by the time these cross team concerns were surfaced, it was too late in the program to drive the required design changes.

Recommendation: *Initiate "concept build" meetings to discuss cross team design issues.*

The key to this recommendation is to bring team champions (with cross team design concerns) and other key team members together during the early design phase to identify critical design requirements needed to meet the fit and function goals. By initiating these discussions, one team can convey their requirements to other teams, and since these meetings will occur during early design activities, the risk of failing to identify these cross team design expectations will be eliminated before it becomes too expensive to make design changes. The main difficulty in implementing this recommendation exists in adequately identifying design concerns during the early stages of the design phase. To alleviate this problem, it becomes even more crucial to feed forward design concerns from program to program. Additionally, as unexpected problems are surfaced through statistical analyses, similar "concept build", cross team design meetings should be *immediately* instituted to provide a forum to efficiently resolve these design problems.

***Recommendation:** Institute a cross discipline scheduling system.*

Additionally, scheduling critical dates should be based more on simultaneous engineering concerns. Therefore, if one team's vehicle system is coupled with the designs of another team, then both teams' design release dates should coincide. This will eliminate the problem that exists when a team still in the design development mode requests a design change of a team that has already released its design and begun to build tooling--when it is too late to make a design change.

3. ***Problem:** The process did not begin early enough in the vehicle program. (4.3)*

The majority of teams did not form until preliminary designs had been released. This delay had a detrimental effect because the teams had little opportunity to influence early styling and design decisions. Since the teams did not form during the early concept phase, they often had to cope with the designs that had already been selected.

***Recommendation:** Begin the process the early, during the outset of the concept phase.*

This is a fairly intuitive suggestion, but it is crucial that the management committee ensure that teams are formed early so that the variation management activities can be properly executed.

***Recommendation:** Train team champions and others involved in the program focusing on process oriented issues.*

One of the causes of this problem was that few participants, especially team champions, understood at the outset how the process should function and what activities needed to be performed. A training program was initiated for the Precision Build Process; however, the focus was on statistical analysis and tolerancing techniques. The training must also teach how the process should be executed to convey the timing and the required outputs of each activity.

4. ***Problem:** Actual process capability data was not available when required. (4.3)*

The need for process capability data is critical to the variation management process, especially during the tolerance step because the accuracy of the tolerance information directly impacts the accuracy and the quality of the predictions. A number of team champions stated that there was a definite need to use more data collected from checking fixtures and CMM machines. Two of the most significant obstacles that prevented actual data from being used were: 1) the data was not available because of constraints on CMM machines; and 2) the data that was collected was not always meaningful since the data was referenced to vehicle's datum scheme rather than the part's datum scheme.

***Recommendation:** Enlist plant ownership for part checks.*

The stamping plant and the assembly plant have a major stake in overcoming the obstacles discussed in the problem description. The plant must strive to increase the number of checks that can be made on the CMM machines and must incorporate more part checks in the checking routines. The goal of this recommendation, then, is to convey the importance of part checks to the plant checking departments and to assist in developing a strategy to ensure that the required checks are made to support the variation management process.

Recommendation: *Allocate additional resources to collect and process the required data.*

Even with the plants assisting in collecting the required data, untold amounts of data will be collected requiring, a focused effort to study the raw data and transpose it to meaningful process capability studies. This effort will not succeed if this responsibility lies with team members who also have numerous duties beyond the variation management process; instead, additional manpower resources must be allocated to assist in processing the data for the teams.

5a. ***Problem:*** *Difficulty getting all of the information inputs and key decisions made because key representatives did not attend meetings and participate in the process. (3.4)*

This problem focuses on the product-process design activities. A number of team champions said that they needed more plant representation to assist in making design decisions that would impact their areas of the plant. One team leader discussed a situation where the manufacturing engineer did not participate; thus, the tooling that was built did not have the required level of precision. Yet another team champion discussed the frustration he experienced in forcing a product engineer to make the necessary product design changes.

5b. ***Problem:*** *Team champions were not empowered to drive design changes and enforce participation on teams. (4.2)*

A number of team champions felt powerless in the process because their rank was not high enough (as mentioned, most were senior level engineers) to pressure key members to participate in the process or to influence other departments to spend the necessary resources to make design changes. This weakness actually represents one of the root causes of the preceding problem that addressed difficulties due to the lack of participation.

Recommendation: *Empower the variation management process by enlisting top level management support.*

As noted earlier in this section, the Precision Build Process was not driven by top level management, but rather was driven by first level engineering managers. By obtaining top level management support and guidance, the credibility and importance of the program will be greatly enhanced. The end result will be strong support for the process from all levels within in the organization, providing the teams and the team champions the empowerment required to successfully execute the variation management activities.

6. ***Problem:*** *The Precision Build Process did not formally carry on through production. (3.5)*

Each of the precision build teams discontinued meeting well short of the production launch; in fact, the teams usually disbanded once the statistical analyses predicted that all the fit and function goals would be met. While many of the engineers who participated in the Precision Build Process were reassigned to pilot action teams in the plant, most team champions felt that the teams should stay intact during the transition to the plant because the teams would serve as effective troubleshooting resources and because the team members could then see opportunities for improvements for future vehicle programs.

Recommendation: Formalize the transition from Precision Build teams to production launch teams by assigning variation management responsibilities to team members as they relocate to the launch teams.

It was determined by the panel that it would not be feasible to keep the Precision Build teams intact during the production launch phase because of the changing responsibilities of the team members. During the launch phase, a number of the team members were required to focus their time and effort on production launch issues, while a number of others needed to turn their attention toward future vehicle programs. However, during this temporary break-up of the teams, it is still necessary for some team members to bring the knowledge from the variation management teams to the production launch teams, and to serve as conduit to assist in resolving variation problems. Therefore, the role of variation management coordinator must be formally assigned to one of the team members involved in the production launch.

7. ***Problem:** Fit and function goals were not defined at the outset of the process. (3.4)*

As the ideal process flow diagram indicates, the process begins by defining fit and function goals so that these goals can then drive the design decisions. With the Precision Build Process, the typical process flow was to perform the statistical analysis and then determine whether this predicted tolerance would be an acceptable goal. Unfortunately, operating in this manner necessarily leads to designs made external of customer requirements, and when the analysis shows that customer goals are not met, the number and types of design changes permissible may be limited because of the design release dates.

Recommendation: As before, offer training focused on how the process should be executed.

This difficulty, like the previous one, stems from a lack of understanding of how the process should function. Teaching the variation management process will help alleviate this weakness since team champions and team members will understand why the fit and function goals must be developed at the outset of the process.

8. ***Problem:*** *No forum/process for feeding forward lessons learned to future vehicle programs. (3.1)*

No process for capturing lessons learned existed in the Precision Build Process evidenced by the fact that most teams had not met since the Fall before the vehicle launch (in July). Most team champions felt that a review process would be an important activity; however, no forum to carry out this step had been instituted. It should be stated that the impending reorganization left a number of team members feeling that this was not a living process and thus, did not feel the need for a post mortem review. Still, it is doubtful that any formal review activities would have taken place even without the reorganization since such an effort was never planned into the process.

Recommendation: *Establish a post mortem review process for teams to discuss lessons learned.*

This issue caused considerable debate among the panel. A few of the team members believed that this problem was a special cause and that if not for the impending reorganization this difficulty would have resolved itself since the teams would naturally have resumed the same responsibilities for the next program. Still, the author contends that it is worth addressing this problem since it is a critical step in the variation management process as discussed in Section 2 and 3. Instituting a post mortem review represents a formal process for ensuring that the knowledge base is transferred from one program to the next. During this review process teams can identify the key continuous improvement opportunities for the next design program.

9. ***Problem:*** *Efforts to capture the voice of the customer were not adequate. (2.9)*

Whereas the previous difficulty regarding identifying the voice of the customer--problem seven--focused on the timing in which customer expectations were identified, this problem addresses the methods used to capture customer expectations. The first step in the ideal process flow diagram--determining fit and function goals--shows a number of key information inputs to help capture the voice of the customer. A number of team champions felt that the efforts to identify the customer expectations were not as thorough as the ideal process recommends. Corporate auditors did review each of the fit and function goals to provide input to the process, and one team even surveyed service departments at dealerships to identify critical features of their vehicle system. Still, these efforts fall short of the expectations identified in the ideal process diagram.

Recommendation: *Aggressively pursue benchmarking competitor's vehicles.*

At one of GM's other divisions, team members visit competitors' dealerships to inspect panel fits of vehicles in the same market segment. The team decided that this would be a simple yet important addition to the Precision Build Process.

Recommendation: *Involve marketing representatives during early concept phases.*

Marketing can play a major role assisting teams in identifying customer expectations. Although customer clinics may be unwieldy for 130 or so critical feature goals, the marketing group can help gather warranty data and any other pertinent fit and function data from clinics. Further, by obtaining marketing support, perhaps other, more creative ways to capture the customer requirements can be uncovered.

4.4 Some Final Notes on the Improvement Suggestions/"Critical Enablers"

In an effort to capture each of the suggestions in one list, the following bullet items restate each of the continuous improvement recommendations (prioritized according to the significance of the problem which each attempts to resolve) developed in the preceding discussion:

- *Institute "concept build" meetings to discuss cross team design issues.*
- *Institute cross discipline scheduling.*
- *Begin the process sooner, during the outset of the concept phase.*
- *Train those involved in the Program focusing on process oriented issues.*
- *Enlist plant ownership for part checks.*
- *Allocate additional resources to collect and process required data.*
- *Empower the variation management process by enlisting top level management support.*
- *Formalize the transition process from variation management teams to production launch teams.*
- *Establish a post mortem review process for teams to discuss lessons learned.*
- *Pursue benchmarking of competitor's vehicles.*
- *Involve marketing representatives during the early concept phase.*

Again, the goal of thoroughly analyzing the Precision Build Process is to uncover additional insights into how to successfully implement and execute a variation management initiative. The above list represents a number of suggestions that will lead to an improved variation management program at Cadillac, and that will promote a quality process for others attempting to institute a variation management program. Before moving to the final section of the thesis, some final notes are given regarding the analysis of the Cadillac program.

Failure to address the issue of prototyping. One of the key problems uncovered in the analysis–in fact, based on the survey results the most significant problem–was the limitations of the knowledge gathered from the prototyping phase because prototype builds do not imitate production builds. This has significant impact on the variation management efforts because the prototype phase offers the opportunity to ascertain whether the product and process designs will meet the critical feature goals. Without an accurate representation of how the vehicle will build during prototype, the problems that should have been identified during this phase will instead not be uncovered until production. Further, if an organization chooses to pursue the screwbody concept (See Section 2), crucial to initiating such an effort is the ability to imitate production builds during prototype. Clearly, prototyping techniques can severely impact the overall success of the variation management program. Thus, this underscores the importance for both Cadillac and other companies to study and ultimately improve prototyping techniques.

Failure to directly link the voice of the customer to the variation management process. In response to the problem of not adequately identifying customer expectations, the team recommended benchmarking competitors' vehicles and involving marketing representatives at the outset of the program. Certainly these recommendations represent steps toward more accurately capturing the voice of the customer; however, the recommendations still do not link customers directly into the Precision Build Process. As discussed in Section Two, identifying customer requirements constitutes possibly the most important step in the design process since customer requirements drive the product and process designs and thus ultimately determine whether the product will be successful in the marketplace. Direct customer involvement in setting fit and function goals remains the only way to ensure that fidelity to the voice of the customer is maintained. Therefore, in addition to implementing the recommendations already posed to problem nine, engineers, designers, and especially marketing representatives must also use forums such as customer clinics to directly solicit customer input in developing design goals.

The overlap of the list of recommendations with organizational change literature. In reflecting on the list of improvement suggestions, it is interesting to note the similarities between these suggestions and recommendations for organizational change found in a number of literature sources. To illustrate, a few excerpts from current literature on the topic follow:

In discussing steps toward enhancing a manufacturing organization, Clark, Hayes, and Wheelwright (1988) discuss the importance of training programs:

> "... one should initiate an education and development program. Whether it simply provides instruction on using the aforementioned tools or is a more ambitious effort to develop strategic skills of those in manufacturing, a systematic educational effort can provide significant dividends."

The significance of initiating training efforts is also addressed by Himmelfarb (1991):

> "Constantly improving capabilities at all levels of the company

> make it more likely that new product development will be a successful venture. A commitment to ongoing training will yield benefits in many ways: more and better ideas for new products, improved technological capabilities, better understanding of the marketplace, improved project team management and participation skills and improved morale."

Himmelfarb also discusses the importance of top level management involvement in a design program:

> "A senior management that says the right words but, in reality, is committed to the status quo is the most serious barrier of all. People who are trying to initiate new product development will be frustrated, and everything will grind to a halt or not get started in the first place."

The list of improvement opportunities for the Precision Build Process includes studying prototyping methods. Dr. Deming (1986) states that inadequate testing of prototypes is one obstacle preventing successful transformation of an organization:

> "A common practice among engineers is to put together a prototype of an assembly with every part very close to the nominal or intended measured characteristics. The test may go off well. The problem is that when the assembly goes into production; all characteristics will vary."

Finally, lack of participation from all functional areas was shown to be a weakness of the Precision Build program. Clark and Fujimoto (1991) discuss how other organizations face similar challenges:

> "In practice, these mechanisms for achieving product integrity tend to focus on internal integration. In the literature on organizations and in the experience of a wide range of companies, we have found coordination to be the primary objective of most project managers, committees, and liaison groups. Most are trying to get the functional groups to work together better."

The intent of this brief literature survey is not to engage in a discourse on organizational change, but rather to show the overlap between the topics discussed in organizational change literature and the problems and recommendations developed from analyzing an actual variation management program. Intuitively, this overlap does make sense: at the most rudimentary level, any new design effort is actually an attempt at organizational change--to force a company to adopt new methods and systems. The interesting point in observing the commonalty between the problems in the Cadillac process with the excerpts from organizational change literature is that the classic barriers to successful product development activities appear to also plague this variation management program. In final analysis, we can conclude that successful implementation of a variation management program must also include some consideration of organizational change obstacles so that these classic weaknesses are not continually repeated in future programs.

In conclusion, this section, through an analysis of the Precision Build Process, has provided a few insights into additional requirements for implementing and executing a successful variation management program. Certainly, for Cadillac, the recommendations developed will enhance an already successful program. For other organizations attempting to initiate a variation management program, disclosure of these key issues will provide a means to move more rapidly along the experience curve toward achieving a productive variation management program.

Section 5
Conclusions and Future Research Opportunities

5.1 Review of Thesis Contents

We began our discussion of variation management by detailing the costs of excessive variation to auto manufacturers and then showing how traditional approaches, like statistical process control and designed experiments, are limited in fully addressing the problems of undue variation. The goal of this thesis, then, was to identify and describe an new approach to answer the challenge of controlling manufacturing variation. The new approach focused on managing variation during preproduction phases of a vehicle program.

Section 2 presented a unified process for managing variation, listing many design and engineering methods and activities, from the concept phase to the production launch, that need to be employed to address variation issues. In this section we saw: methods for capturing the voice of the customer; product design techniques for controlling variation in critical areas; process design opportunities for holding variation to required limits; statistical models to predict the tolerance for critical features; and problem solving methods to be used during prototype and pilot phases that can be used for efficient troubleshooting of variation problems.

In Section 3, I surmised that implementing a successful variation management program requires more than intelligent engineering and design practices: additionally a successful program also requires attention toward the organizational issues that impact how successfully the program will be integrated into development activities. To uncover some of these important organizational issues, such as the importance of addressing the multi-functional and iterative nature of a variation management program, the process flow/information flow diagram was developed. We also saw how the organizational structure used to execute a variation management program will factor into the success of the program. Three organizational structures–functional, team, and hybrid–were examined to identify the relative merits of each approach toward enabling a successful program.

In Section 4, my goal was to evaluate a company's, Cadillac's, variation management program to identify continuous improvement opportunities for their program and to detect some additional critical requirements for successful implementation of a variation management process. Using the ideal process flow/information flow model, a list of weaknesses in the Precision Build Process was created, followed by a development of recommendations, as determined by an intraorganizational team, to address these problems.

The remainder of this section will present additional recommendations for Cadillac to further improve their variation management efforts and will list opportunities for further research of topics addressed in this thesis.

5.2 Recommendations for Cadillac

The following list presents some additional recommendations regarding the Cadillac Precision Build Process. This short list underscores some of the important topics covered in this paper that will lead to an even stronger variation management program at Cadillac. As with the recommendations cited in Section 4, these final notes on improving the Precision Build Process also highlight some of the key points for any organization's variation management program.

1) *Continue the Precision Build Process and tap the advantages of the experience curve.* As the survey in Appendix 4 shows, the managers and

engineers involved in the Precision Build Process strongly support the program; in fact, these results should be viewed as a resounding endorsement of the program. Throughout the interview process, I was impressed with the enthusiasm with which team champions and team members spoke of the process. A common comment was that the process worked very well, but that it merely needed some fine tuning. By continuing a variation management program, improvements to the process will necessarily be achieved because of the effects of the learning curve; thus, participants will have a better understanding of the process and ways to improve their vehicle systems. As one team champion commented, "If we could do this process again, I would really understand what to do the next time around."

2) *Implement the recommendations proposed in Section 4.* This is a fairly obvious suggestion since the suggestions developed in Section 4 were derived from a detailed analysis of the Precision Build Process. These suggestions should enable the Precision Build Process to function like the ideal process documented in Section 3.

3) *Train those involved in the variation management effort about specific techniques for managing variation.* One of the recommendations in Section 4 suggested teaching participants how the variation management process should be executed. In addition to this training, I also recommend that the engineering and design methods discussed in Section 2 also be presented. In this manner, all team members will be knowledgeable in each of the specific techniques that can be employed to control variation in critical areas of their systems.

4) *Conduct an investigation of prototyping methodologies and identify ways to more accurately imitate production processes.* The importance of obtaining

accurate information from prototype vehicles was discussed in Section 4. Once again, I urge Cadillac to conduct further research into this important issue.

5) *Pursue implementation of the screwbody process.* In Section 2, the screwbody process was introduced as a possible means to cope inexpensively with off-nominal conditions. Of all the variation management techniques introduced in the second section, this is possibly the most promising new concept for Cadillac since most of the other engineering techniques are used in some form. Implementing the screwbody process, though, will require careful management of a number of factors, including prototyping techniques. Introducing this process to all vehicle systems may be too much to manage; however, perhaps one system team could implement the screwbody concept for their system to test the applicability and the critical requirements to successfully implement the process. If successful, other teams could then follow their lead.

6) *Develop a true hybrid organizational structure to execute the process.* As we saw in Section 3, the hybrid structure is becoming increasingly used at other divisions because it best promotes successful execution of the variation management process. The team aspect of this structure is certainly in place at Cadillac, but the development of expert systems engineers appears to be lacking. I recommend that if manpower allocation allows, Cadillac should develop a separate group to study and to concentrate solely on variation management and assist in executing the Precision Build Process.

7) *Enlist more plant support and plant input in the process.* One of the complaints that I heard often during interviews was that the plant personnel needed to be more involved in the process. Interestingly, from plant representatives I was told that they were often not asked to be included in the process. Without laying blame, there does appear to exist a disconnect in this

important information source--the assembly plant. Whether it be holding team meetings at the plant or meeting one on one with key plant personnel, both managers and team champions must make efforts to include plant representation in future programs.

5.3 Opportunities for Further Research

In my literature survey of variation management, I was surprised to find a limited number of resources addressing the topic. Thus, this topic poses a number of interesting research possibilities which are listed below:

- *Prototyping methods:* I have suggested that Cadillac improve their prototyping methods. Perhaps this could be accomplished through an in-depth study of other company's prototyping methods with the goal of identifying the best practices among these companies.
- *Tolerancing techniques:* The method by which measurement data of vehicle components is converted to tolerance numbers has been the subject of a number of studies. Baron lists a number of these tolerancing methods, from simple process capability calculations to Taguchi's method of linking tolerances to the quality loss function. An excellent opportunity for additional research involves critically evaluating each of these tolerancing methods and determining under what circumstances one method would be preferable over another.
- *Linking the variation management process with marketing:* One of the recommendations in Section 4 suggested involving marketing representation on the teams. However, opposition existed to this proposal because it was felt that determining critical feature goals for over one hundred areas of the vehicle would be arduous. I recommend that additional research be initiated to determine how marketing can assist in defining the voice of the customer for a

program like this. This research would have broader implications for any design program where engineering requires a significant amount of detailed customer information.

- *Reducing variation in fixtures:* As discussed in Section 2, using fixtures to locate mating parts during the assembly process constitutes one strategy to build assemblies with tight tolerances. The key assumption in this build technique is that fixtures introduce very little variation. In touring different plants and talking with a number of engineers, I was suprised to find many different opinions on how best to design fixtures, from the locating details to the optimal areas on a part to hold a fixture. An interesting and important study would be to perform a gauge repeatability and reproduceability study of fixtures using different designs and clamping techniques. From this study, guidelines to designing fixtures that introduce the least amount of variation could be developed.
- *A collection of case studies of successes in managing variation:* In Section 2, I cited a few examples of how variation management techniques could be used to control variation in critical areas. To supplement this analysis, a larger investigation could be conducted to study how different companies have employed each of these techniques to improve the fit and function quality of a number of vehicle systems. Even if companies are not willing to disclose proprietary product and process designs, a benchmarking of vehicles currently on the market could be performed to identify innovative styling techniques. A detailed analysis of different companies practices would provide a more thorough look at how each of the tools and methods can be implemented, and will show which techniques appear to be the most widely used and thus the most significant in improving quality levels.

5.4 Final Comments

A common theme that runs through the material presented in this thesis is changing the way in which an organization views and executes its design function. In looking at a vehicle design from the customer's perspective, it is apparent that the features that customers notice exist primarily at the systems level, not the piece part level. For example, customers do not notice how accurately a front door outer panel is built, but they do notice how well the door aligns to the rear door and the fender. Therefore, engineers and designers can no longer focus solely on piece part designs; instead, they must develop more of a systems approach to design by identifying systems requirements and using these requirements to drive the detailed piece part designs. Many of the methods and issues outlined in this thesis are relatively straightforward, yet successful implementation of a variation management program ultimately hinges on approaching the design process from a systems perspective. Understanding how piece part designs influence a vehicle system, then, becomes a new mindset for engineers and designers to adopt: with more of a systems approach, variation management will be greatly improved.

In final analysis, planning for and addressing variation issues during preproduction activities presents an excellent opportunity to make quantum leaps in quality and cost savings. Like DFM methods where manufacturing improvement opportunities are identified during design phases, variation management also focuses improvement efforts during early phases of a vehicle program when the greatest opportunity exists to make large improvements. This thesis has presented and defined a set of variation management activities and provided a roadmap for sucessful implementation of a variation management process. In conclusion, hopefully this thesis will serve as a guide to Cadillac and other companies enabling each to achieve the potential gains of an alternative approach toward resolving variation problems--managing variation during preproduction activities.

Appendix A
KJ Diagram

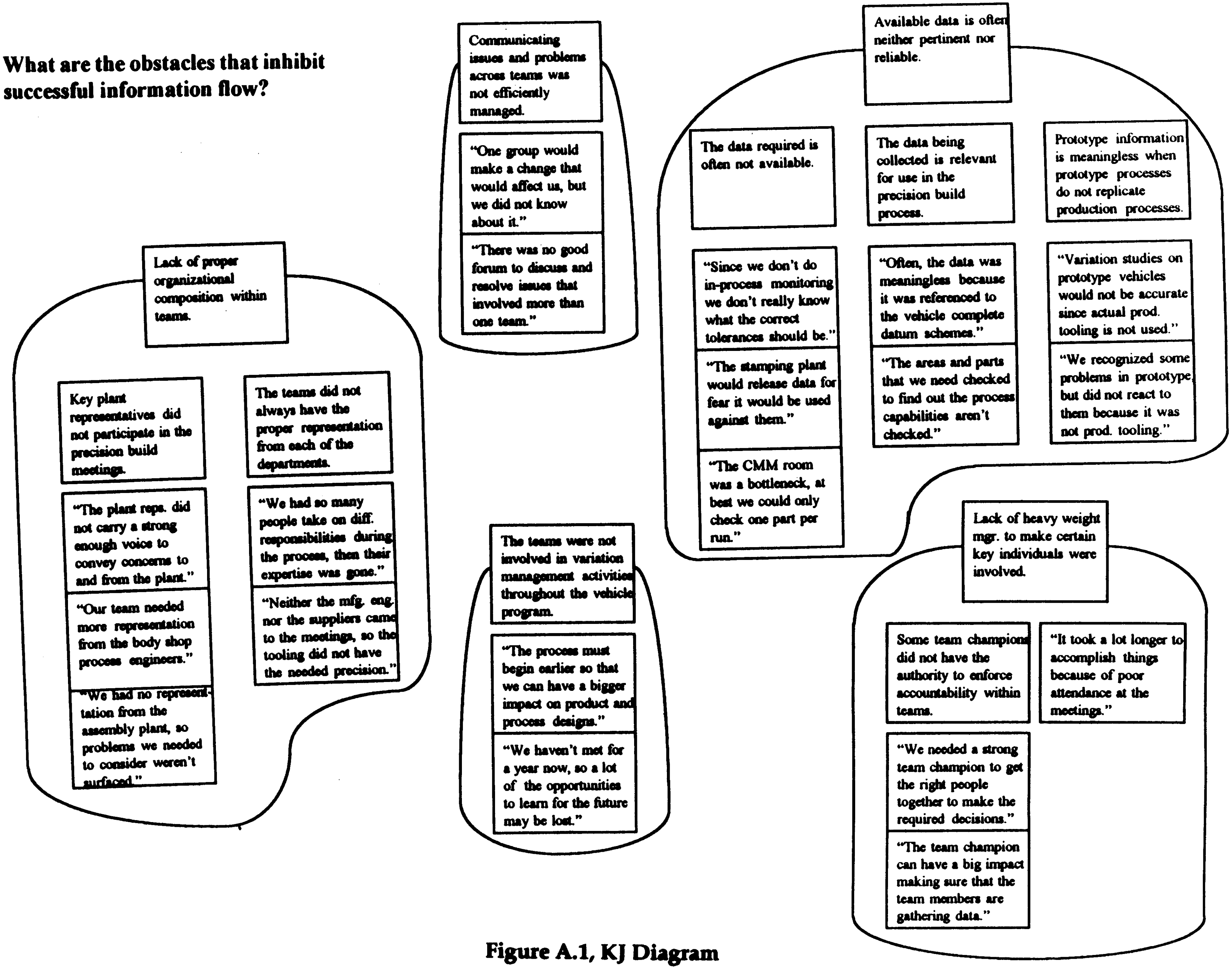
Before developing the ideal process flow/information flow diagram that would be used as a template for the variation management program, an initial round of interviews was conducted to understand some of the obstacles that teams faced in carrying out the design activities. By initiating a preliminary analysis of the obstacles preventing successful execution of the program, we could then best determine a strategy to study the program and recommend improvements. From these interviews, a KJ diagram was developed to extract the common themes expressed in comments made by Precision Build participants.

The KJ diagram was introduced by a Japanese anthropologist, Jiro Kawakita. This tool is successfully applied when dealing with large amounts of qualitative data, such as data gathered through interviews. In short, the KJ process begins by transcribing detailed comments onto small note cards, and then grouping together the remarks (or other forms of data) that express a common theme. From these groupings, a more general statement is formed that captures the common theme in the group of comments. This process is continued until a few, usually three to five, high level statements or themes are developed. Shiba (1990) provides a thorough discussion of the KJ process and its applications.

The KJ diagram developed from the interviews of team champions and team members is shown in figure A.1. This diagram was composed by the author to answer the question "What were the obstacles that inhibited successful information flow?" As we have seen, information flow represents a key determinant of the success of a design program; therefore, I believed the question posed to be crucial to understanding and improving the Precision Build Process. The diagram shows five main areas, listed in the top squares of each grouping, that impacted the success of the program. Although a more structured approach to identify additional weaknesses in the Precision Build Process was employed–the ideal process flow/information flow diagram--the KJ diagram was useful in providing a quick snapshot of some of the key issues needing to be addressed: as the reader will note, a number of entries in the KJ diagram reappear in the problem statements in Section 4.

Based on my experience using the KJ diagram, I believe this tool is an excellent method to pick out crucial, broad range issues based on seemingly narrow, focused comments. Just as the KJ diagram helped to provide some insights into the Precision Build process, I am certain that the KJ diagram can assist managers in identifying improvement opportunities in any design program.

What are the obstacles that inhibit successful information flow?



Lack of proper organizational composition within teams.

Key plant representatives did not participate in the precision build meetings.

"The plant reps. did not carry a strong enough voice to convey concerns to and from the plant."

"Our team needed more representation from the body shop process engineers."

"We had no representation from the assembly plant, so problems we needed to consider weren't surfaced."

The teams did not always have the proper representation from each of the departments.

"We had so many people take on diff. responsibilities during the process, then their expertise was gone."

"Neither the mfg. eng. nor the suppliers came to the meetings, so the tooling did not have the needed precision."

Communicating issues and problems across teams was not efficiently managed.

"One group would make a change that would affect us, but we did not know about it."

"There was no good forum to discuss and resolve issues that involved more than one team."

The teams were not involved in variation management activities throughout the vehicle program.

"The process must begin earlier so that we can have a bigger impact on product and process designs."

"We haven't met for a year now, so a lot of the opportunities to learn for the future may be lost."

Available data is often neither pertinent nor reliable.

The data required is often not available.

"Since we don't do in-process monitoring we don't really know what the correct tolerances should be."

"The stamping plant would release data for fear it would be used against them."

"The CMM room was a bottleneck, at best we could only check one part per run."

The data being collected is relevant for use in the precision build process.

"Often, the data was meaningless because it was referenced to the vehicle complete datum schemes."

"The areas and parts that we need checked to find out the process capabilities aren't checked."

Prototype information is meaningless when prototype processes do not replicate production processes.

"Variation studies on prototype vehicles would not be accurate since actual prod. tooling is not used."

"We recognized some problems in prototype but did not react to them because it was not prod. tooling."

Lack of heavy weight mgr. to make certain key individuals were involved.

Some team champions did not have the authority to enforce accountability within teams.

"We needed a strong team champion to get the right people together to make the required decisions."

"The team champion can have a big impact making sure that the team members are gathering data."

"It took a lot longer to accomplish things because of poor attendance at the meetings."

Figure A.1, KJ Diagram

Appendix B
Survey Results

In order to gauge the importance of each of the problems identified during the analysis of the Precision Build Process, a brief survey was conducted. The following pages show the survey that was given to participants in the process and the results of the survey. In total, fifteen participants responded to the survey. This group of respondents included six team champions, six team members, and three steering committee members.

As the questionnaire indicates, participants were asked to rate the importance of each problem on a scale of 0-5. The statistics used to analyze this data are very elementary, the mean and the range. A histogram showing the frequency of each response is also included.

The results of the survey convey some interesting insights beyond the relative importance of each problem. First, for a number of problems, the range of responses is very large (in no case was a problem unanimously given low ratings), suggesting that each problem possessed varying levels of importance for different teams. Thus, even though a problem may have received a low score, that issue still represents a major obstacle hampering the performance of some teams and should still be considered important to resolve at some point. The other interesting result of the survey is the overwhelming support for the Precision Build Program. As the results show, eleven of fifteen respondents gave a "strongly agree" to the statements that the process was valuable and that the process should be used for future programs. I believe that these results provide a strong endorsement for the program, and provide empirical evidence of the importance of a variation management program.

Precision Build Improvement Opportunities Survey

Please respond to the following survey by indicating on the scale how significant you believe each of the ten weaknesses of the Precision Build Process are.

Note: '5' signifies 'very imporant; '0' signifies 'not important'.

0 1 2 3 4 5 1. The process did not begin early enough in the vehicle program.

0 1 2 3 4 5 2. Fit and function goals were not defined at the outset of the process.

0 1 2 3 4 5 3. Cross system design issues were not efficiently managed.

0 1 2 3 4 5 4. No forum/process for feeding forward lessons learned to future vehicle programs.

0 1 2 3 4 5 5. Actual process capability data was not available when required.

0 1 2 3 4 5 6. Troubleshooting build problems during the prototype phase was difficult because teams were not confident that the prototype problems refelected actual production problems.

0 1 2 3 4 5 7a. Difficulty getting all of the information inputs and key decisions made because key representatives did not participate in the process.

0 1 2 3 4 5 7b. Team champions were not empowered to drive design changes and enforce participation on teams.

0 1 2 3 4 5 8. The Precision Build Process did not formally carry on to production.

0 1 2 3 4 5 9. Efforts to capture the voice of the customer were not adequate.

The following two questions are intended to gauge the overall impressions of the Precision Build Process:

Note: '5' signigfies strongly agree; '0' signifies 'strongly disagree'.

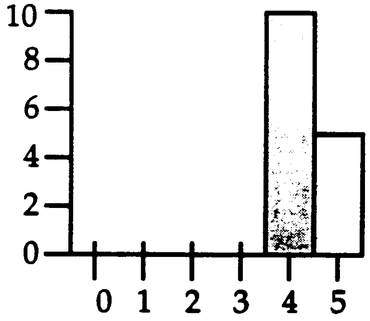
0 1 2 3 4 5 1. The Precision Build Process was a valuable initiative.

0 1 2 3 4 5 2. The Precision Build Process should be used for future model programs.

Survey Results

No. of Respondents: 15

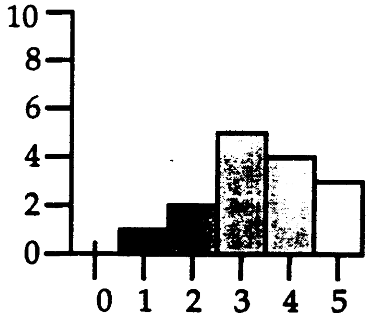
Frequency of Responses: **Problem:**



1) The Process did not begin early enough in the vehicle program.

Mean: 4.3

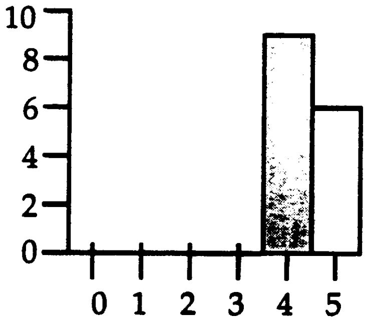
Range: 4-5



2) Fit and function goals were not defined at the outset of the process.

Mean: 3.4

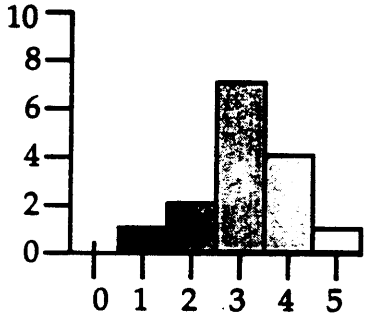
Range: 1-5



3) Cross system design issues were not efficiently managed.

Mean: 4.4

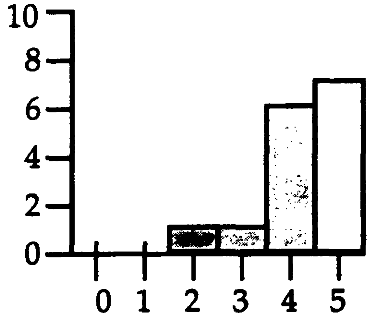
Range: 4-5



4) No forum/process for feeding forward lessons learned to future vehicle programs.

Mean: 3.1

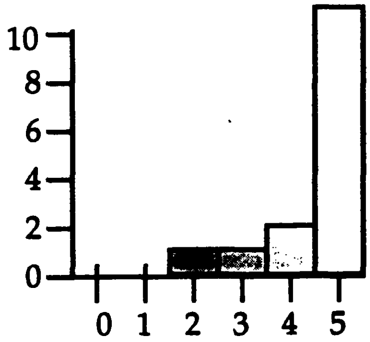
Range: 1-5



5) Actual process capability data was not available when required.

Mean: 4.3

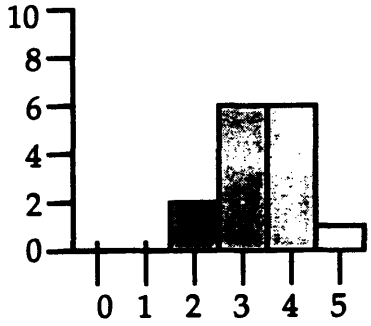
Range: 2-5



6) Troubleshooting build problems during the prototype phase was difficult because teams were not confident that the prototype problems reflected actual production problems.

Mean: 4.5

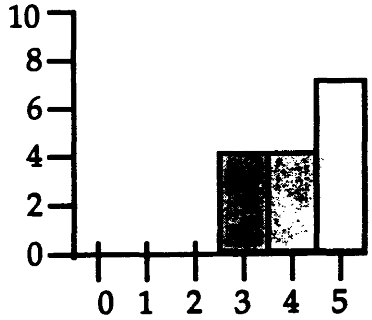
Range: 2-5



7a) Difficulty getting all of the information inputs and key decisions made because key representatives did not participate in the process.

Mean: 3.4

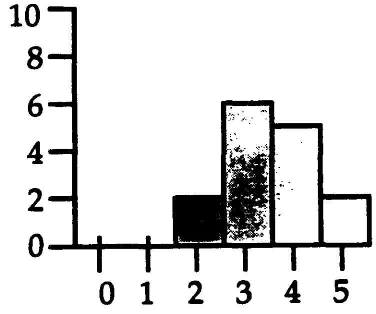
Range: 2-5



7b) Team champions were not empowered to drive design changes and enforce participation on teams.

Mean: 4.2

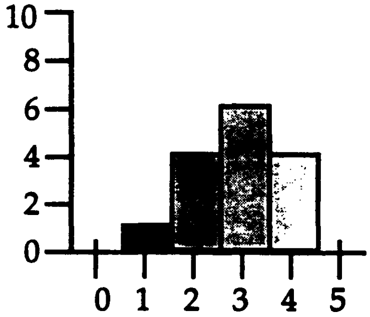
Range: 3-5



8) The process did not formally carry on to production.

Mean: 3.5

Range: 2-5

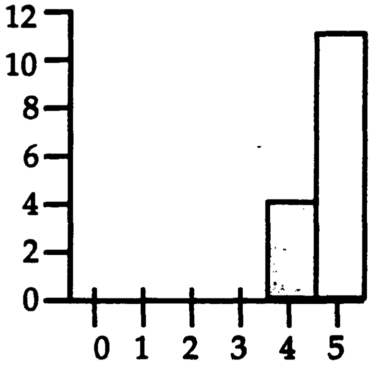


9) Efforts to capture the voice of the customer were not adequate.

Mean: 2.9

Range: 1-4

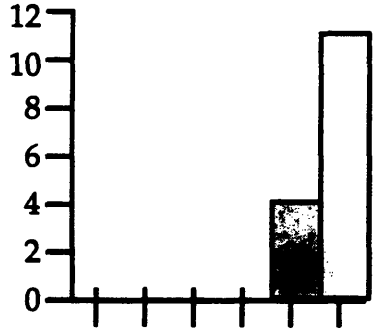
The following are the responses regarding overall impressions of the program.



1) The Precision Buid Process was a valuable initiative.

Mean: 4.7

Range: 4-5



2) The Precision Build Process should be used for future model programs.

Mean: 4.7

Range: 4-5

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