
Integrated build: a new approach to building automotive bodies

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Abstract: This paper introduces three auto body build concepts: net build (NB), functional build (FB) and integrated build (IB). Most manufacturers design and validate their vehicle launches using the NB concept. This concept is shown to be expensive, time consuming and not effective value added. Functional build has found growing acceptance as being preferable over NB. Functional build has tended to find the greatest acceptance as a die buyoff procedure for individual parts based on subassembly quality. Aspects of FB are shown in a case study where the manufacturer claimed to use FB for die development, but critical elements were omitted and opportunities lost.

The integrated build (IB) process is an extension of the FB approach. It is a more inclusive process that considers the entire vehicle and requires closer coordination with product design. Aspects of IB are also shown in two case studies. In the first, IB concepts were included in the design process, which enabled the company to implement an effective material introduction strategy. The second is a comparison of the product development timelines of two companies and shows how IB concepts can shorten lead and production ramp time.

Keywords: net build; functional build; integrated build; tooling validation; die design; automotive body development; process capability; lean product development.

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1 Introduction

The automotive body is perhaps the most important vehicle system in terms of impact, time, cost, and customer satisfaction.

- *Impact*: the body defines the vehicle platform, which has many model variants. Models are often redesigned, often requiring completely new bodies.
- *Time*: the body is always on the critical vehicle development path, as obtaining and installing the tooling in an organised fashion to stated quality requirements always seems to take more time than is available. Often tooling is reworked until the project schedule dictates that it be finished.
- *Cost*: the body is arguably the most costly vehicle system, second only to the power train. However, the power train is often developed once for many vehicle models, whereas the body is redesigned for every model. When introducing a new vehicle model, costs associated with changes in the body are usually dominant.
- *Customer satisfaction*: a customer's first impression, and hence their willingness to further consider the vehicle for purchase, is often based on the physical appearance of the vehicle body.

The vehicle body is also one of the most complex systems to design and manufacture. It requires the coordination of many disparate groups (product design, formability analysis, assembly design, ramp team, die suppliers, assembly tool suppliers, stamping suppliers, etc.) under tight time constraints to build and manufacture a system that is not well understood. Not only are the interrelated systems not well understood, but also the underlying technology is constantly changing:

- die design and stamping is still considered an art, although recent research has made it much more of a science [1]
- the geometric effects of welding are still considered an art, although recent research has made it much more of a science [2]
- new manufacturing forming technologies, such as hydroforming [3] and hot metal gas forming [4,5], as well as new joining technologies, such as laser welding and adhesives are being introduced
- new materials, such as aluminium, high strength steels, and plastics are constantly being developed and introduced [6].

Basic science and software have not been able to keep pace with these hardware developments. There are few design tools, and car companies are expending tremendous resources in such areas as springback prediction, welding effects prediction, deviation of compliant parts during assembly, etc. The knowledge of these new materials, processes, and technologies varies widely from company to company. In addition, the specific domain expertise that affects the cost, quality, and time of vehicle development and launch is distributed among hundreds of suppliers around the world.

Another difficulty is that the business environment is also constantly changing. There is intense pressure to introduce new models in order for automobile companies to remain competitive in the marketplace, but cost is often the limiting constraint. Everyone is under increasing competitive pressure to reduce lead time, reduce cost, and improve quality. This translates into changing business models, increased collaboration and outsourcing, and new manufacturing and business practices. Suppliers are being asked to develop and deliver entire modules at lower cost, which results in outsourcing of engineering and project management functions from the car companies to the supply base. Joint ventures and other forms of cooperative agreements are being formed between suppliers to provide a wider range of integrated services. Lean concepts are being pushed further down the supply chain to die shops and other custom product providers. And these changes are occurring while price pressures require suppliers to reduce the price of their goods and services every year.

The above factors require ever increasing interaction between the various parties around the world to create a successful vehicle launch: product design, stamping and formability analysis, assembly design, ramp team, stamping, die suppliers, tooling suppliers, other part suppliers, etc. These groups can better interact with each other within a formalised structured methodology. Most formalised, science based methodologies are design oriented [7,8,9]. There are no such formalised methodologies that deal with the launch of a vehicle body. There are, however, certain assembly and validation philosophies that are dominant in the industry. In this paper these philosophies are called net build, functional build, and a new concept: integrated build.

2 Net build

Net build (NB) is the traditional design, manufacturing, and assembly approach. Parts are designed, (i.e. specified geometrically with a nominal and tolerance specification), manufactured to the specification (at a required quality level or production yield) and assembled into a product. It is assumed the parts are rigid bodies, and the assembly process does not affect the individual part dimensions. Given these often unstated assumptions (and a few other mathematical ones), the assembly quality can be predicted using tolerance analysis techniques [10].

Tolerance analysis simply states that the variation in an assembly is a function of the sum of the variation of the individual part dimensions. Hence, if one knows the desired assembly tolerance, one can derive acceptable part tolerances. It then follows that good parts will result in good assemblies. In other words, assembly quality is maximised if individual part means are produced to target specification with minimum variation. Similarly, it follows that to tighten assembly tolerances one must tighten component tolerances.

Thus, simultaneous engineering is often concerned with determining the appropriate part tolerances based on manufacturing process capability. This often becomes a negotiation between the tolerances design requires for the assembly (and from the determined tolerance analysis that is required for the individual component) and what manufacturing can produce. The tolerances agreed upon then decouple design from manufacturing. This then leads to a sequential process of design and manufacturing validation based on individual component dimensions meeting Cp and Cpk requirements.

Generally in an NB process, design and manufacturing validation are relatively independent of one another. Specifications (both nominal and tolerance) are finalised by design using tolerance analysis techniques, and manufacturing must determine how to make parts, sub-assemblies, and final products that meet the specifications. Most, if not all design methodologies, such as concurrent/simultaneous engineering environment and design for manufacturing and assembly (DFMA), assume that the specifications set by design are rational and must be met to ensure a quality assembly or product.

In car body manufacturing practice, manufacturers allow manufacturing systems validation to occur with non-conforming parts, or delay validation while they wait for suppliers to correct parts or integrate late engineering change orders (ECOs). The problems are exacerbated in final assembly validation, as new problems are discovered and parts and systems are reworked. In addition, some problems that could not be resolved in component validation are not a problem in assembly validation. Hence, one questions the validity of the original part specifications as well as the significance of achieving the required Cpk. Although more effort in design may alleviate some of these problems, the vast majority are not design problems and transcend our current ability to eliminate them in design.

The main reason for this situation is that the fundamental assumptions of NB, namely rigid parts and assembly systems that do not change component dimensions do not apply in sheet metal assembly. The sheet metal components are often flexible and compliant, and welding systems routinely bend and deform components through clamping forces and heat distortion.

What is necessary is an understanding that product design and manufacturing system validation are not separate activities but rather concurrent activities; specifically, that final specifications should not be set until manufacturing validation is complete. This is a radical departure from the net build philosophy. It implies that component specifications (in sheet metal assembly) are and should be a function of what manufacturing can achieve. Further, it is currently difficult to predict what manufacturing can achieve, because so little is known about the impact of assembly.

3 Functional build

Functional build (FB) is an alternative to net build and is gradually gaining acceptance by many OEMs in the world today [11,12]. It was first introduced by Baron in 1992 [13] and has been further developed at the Center for Automotive Research in Ann Arbor. FB bases the acceptability of individual components on functional requirements, in this case, assembly specifications and not on the component specifications. If the assembly is acceptable, then the component is acceptable, regardless of whether the component meets its original design specifications.

Functional build as practiced by US companies consists of ensuring that components meet an assembly processing window, as opposed to a component tolerance window. The processing window is typically much wider than the tolerance window. This is because the assembly process is often very robust to incoming component variation. For example, compliant sheet metal parts that deviate from their nominal shape in their free-form state are often held very close to their nominal shape during the assembly process by clamps on the welding fixtures. When the parts are welded together and the assembly is released, the assembly is often closer to the desired nominal shape than would be predicted from a net-build based tolerance analysis of the original free form parts. The reduction in the stack-up of variation is manifested in the residual stress in the assembly.

Since FB is focused on obtaining assemblies that meet specification, the serial NB component evaluation methodology that is based on the Cpk index is no longer appropriate. The FB evaluation process typically involves the construction of 'screw-bodies' or other forms of body assembly evaluation methods. The FB evaluation typically occurs in two phases. The first occurs at the die source and is used to determine whether the dies can be shipped to the production facility ('die buy-off'). The primary concern is to correct problems that are known to cause assembly problems, while delaying die rework decisions for non-conforming issues with unknown impacts. The second FB evaluation occurs on the home-line and is used to determine the final acceptability of the dies. The evaluation process varies between manufacturers, but generally consists of stamping three to several hundred parts over multiple set-ups. The first requirement is that the stamping process indicate stability. If the process is stable, then the mean of each checkpoint is evaluated for acceptability in the assembly. A possible decision is to accept parts out-of-specification and to change the specification to match the manufacturing output, assuming acceptable assembly quality. Another decision may be to rework certain within-tolerance dimensions to improve assembly quality.

FB also improves body quality by having an acceptable level of residual stress in areas while maintaining the desired level of dimensional quality. Under NB, one can argue that since not all parts of a vehicle body are made completely to specification, that all vehicle bodies have some level of residual stress. Unfortunately, it is not known how much or where. With FB the vehicle team will be able to make conscious decisions about where residual stress can be accepted and where it cannot. For example, through the screw-body evaluation the team will see areas that exhibit unacceptable levels of part interference or gaps, and require something be done to remedy the situation, regardless of whether the parts meet specification or not. Conversely, areas where there are no interference or gaps will not require any alteration, even if both parts are not within specification. Hence, the team will now know where residual stress may be a problem and have some control as to the degree of stress built into a vehicle body.

Since FB focuses on part function as opposed to part specifications, the evaluation criteria are also different (see Table 1). Several parts (30) are measured and evaluated, and the mean and range or variance of each part dimension is computed. Unlike NB, where meeting specification is important, and a Cpk or similar criteria is used, the FB approach evaluates the mean and variance separately. First, part variation must be stable, and in general, a $C_p = 1$ is considered acceptable. Second, it is known that many assembly operations can compensate for mean deviations. However, excessive deviations will also result in poor assemblies. A general FB criterion is to require 80% of the means of each point distribution to be within tolerance with no mean greater than 0.5 mm

beyond the tolerance. If these two conditions are met, then the part will have a high probability of acceptance. If not, the part may have to be reworked.

Table 1 Comparison of net build versus functional build die buyoff criteria

<i>Type of variation</i>	<i>Net build criteria</i>	<i>Functional build criteria</i>
Mean conformance		80% means < tolerance
	Cpk > 1.67 (100 piece sample)	100% means < tolerance + 0.5 mm
Part-to-part		Cp > 1.33 (30 piece sample)

It is important to note that the evaluation criteria presented above are based upon part tolerances of ± 1 mm. The current trend is to create parts with ± 0.5 mm tolerance. This drive to tighter component tolerances is generally indicative of a NB philosophy: tighter component tolerances should lead to tighter assembly tolerances. Remember, this is not true, because of flexible components and assembly processes that alter component dimensions. Part tolerances should be based on physical requirements, such as assembly process sensitivity to incoming part variation, or assembly tolerance allocation. Unfortunately, they are often based on past practice or the designers desired level of quality based on a NB philosophy. Hence, part tolerances are almost always tighter than the required assembly or vehicle tolerances. The increase in assembly tolerance relative to individual part tolerance is indicative of a net build philosophy that dictates part variation is additive in an assembly.

3.1 Case study 1: lower cost

One western European company claimed to practice functional build. They had a thorough data collection system during tryout at the die source and home line for the individual components and the assembled components. They utilised cross-functional teams that poured over the data, noting each out-of-specification dimension, and constructed a prioritised list of die changes. In general, if the cost and time were insufficient, and the assembly was acceptable, then the dies were not reworked. In a desire to improve their process, they requested an analysis of their procedures based on data from their latest vehicle launch.

The data represent dimensional measurements on a door inner panel and a door assembly. In each tryout run they would measure 300+ dimensions on one door inner panel and 25+ dimensions on seven to 25 door assemblies. Further, they would conduct a capability analysis at the second tryout run and have production data after the start of production (SOP).

The analysis results are quite revealing. Figure 1 shows the percentage of points on the inner panel that were within specification (IP w/i spec), out-of-specification (IP OOS), and accepted beyond the specification (IP OK OOS), as well as the percentage of points within specification on the door assembly (Ass'y w/i spec) at each die rework cycle. First, the percentage of inner panel points within specification remains approximately constant between 55% and 65% across all rework cycles. This implies that the rework cycles did not actually bring more points within specification. Second, the percentage of assembly points within specification is much higher than the percentage of inner panel points indicating that many of the OOS inner panel points had no impact on the assembly. Third, one can see the assembly quality improving, i.e. the percentage of

points within specification is increasing over time, whereas there is no change in the inner panel quality. Lastly, the percentage of points that were accepted beyond the specification rises sharply just before SOP. This is a strong indication of a net build philosophy, where components are accepted OOS when time runs out.

Figure 1 Percentage of inner panel (IP) and door assembly points within specification (w/i spec), out-of-specification (OOS), and accepted beyond the specification zone (OK OOS)

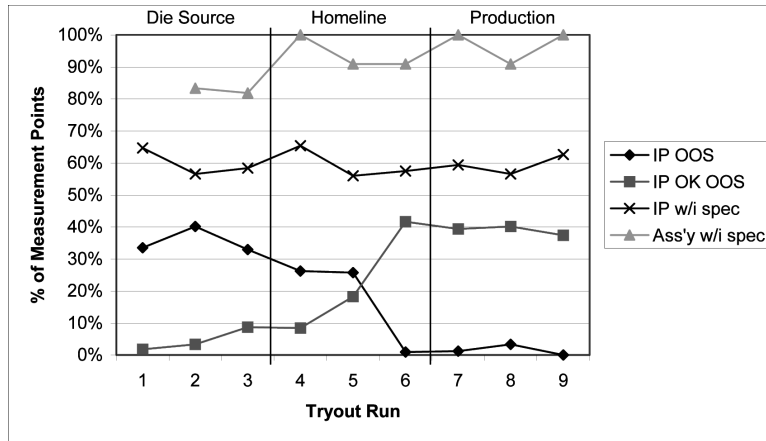
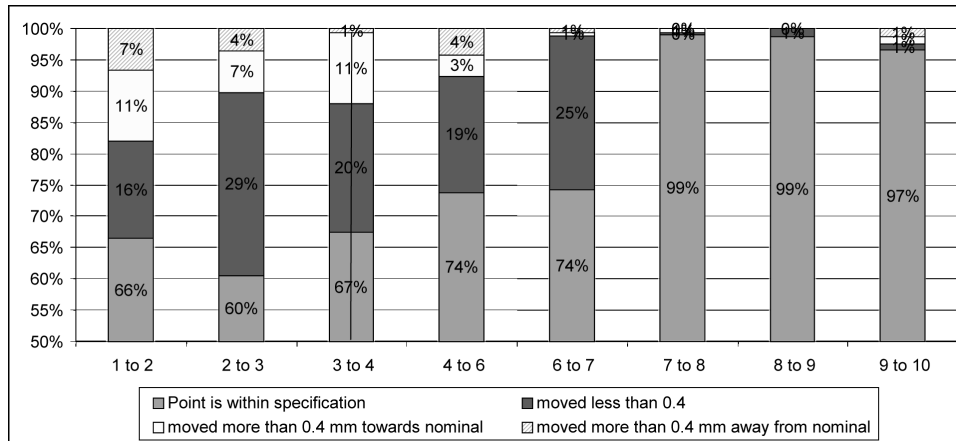


Figure 2 Die rework effectiveness over nine die tryout cycles



From a functional build point of view, Figure 1 shows that many die changes were not necessary, i.e. assembly quality improved without an appreciable improvement in component quality. Figure 2 shows that many die changes were not effective, i.e. a change in the die to get OOS points within specification did not result in more points moving within specification. A common perception within the industry is that when a part dimension is OOS, a die change correction will alleviate the problem. Figure 2 shows the effectiveness of the die changes between each die rework cycles. Changes are classified into 4 categories:

- the point was within or accepted as within specification and remained within specification
- the point was beyond the specification and moved closer to the nominal dimension
- the point was beyond the specification and moved further away from the nominal dimension
- the point did not move.

The concept of a point moving was dependent on the stamping process capability, determined from process capability data. If a measurement point differed by less than its 3-sigma limit computed from the process capability data, it was not considered to have moved a statistically significant degree. In other words, any die rework that resulted in a change of less than 3 sigma was considered insignificant – one would never see the change in actual production because of the inherent process variation.

If die changes were effective, one would expect the percentage of points moving towards nominal to be large, the percentage of points moving away from nominal to be small, the percentage of points that do not move to be small, and the percentage of points that are within specification to increase. As one can see, the first 3 rework cycles were somewhat effective, in that a relatively large percentage of points were moved closer to nominal, with fewer points moving away from nominal. Thereafter, the percentage of ineffective die changes increases. Few points are moved at all, and more points seem to move away from nominal than towards nominal. Please remember that after SOP, the percentage of points within specification jumps not because the points were fixed, but because they were accepted out-of-specification, as was shown in Figure 1.

3.2 Conclusions

If one defines functional build as accepting parts beyond the specification, then one can conclude that they practiced a form of functional build. All companies are forced to accept parts that do not meet their dimensional requirements when deadlines are upon them. However, the company did not practice functional build using the FB evaluation criteria, although they had assembly data. The data clearly showed that die changes after the fourth rework cycle were not value added. They would benefit from the FB process, which would have shown that parts could have been accepted earlier, die rework would not have been necessary, engineering resources could have been refocused, and time and money could have been saved. Since we presented our results, they have implemented some of our recommendations and have reduced their validation lead time for a new model launch by eight weeks.

4 Problems with functional build

FB as practiced suffers from some problems. First functional build is traditionally viewed almost exclusively as a die buyoff and validation process where the focus is on the acceptance criteria (see Table 1). It has had almost no effect on design, where the NB philosophy is alive and well, whilst the FB philosophy is growing in manufacturing. Other aspects of automotive body design, process engineering, and manufacturing

validation, such as dimensional engineering (datuming, tolerancing, measurement strategy and part fixture design), assembly fixture design and validation, joining process validation (welding and non-welding), and process control have not changed to take advantage of the FB approach. Without encompassing these aspects as well, many design and validation processes will continue to be completed serially or at best independently of one another. Hence, large opportunities for shortening lead time, improving quality, and reducing cost through simultaneous joint optimisation of the various processes are lost.

The second problem is that FB, as currently practiced, is usually applied up to the subassembly level and not the whole vehicle level. Manufacturers often believe that subassemblies are rigid and apply net build approaches from the subassembly up to the vehicle, or body-in-white level. However, a recent study on door assemblies shows that good assemblies, i.e. assemblies with high Cpk values, do not necessarily result in high customer satisfaction [14]. Conversely, assemblies with poor Cpk values do not always result in low customer satisfaction. The data suggest that other significant factors exist in body assembly that cannot be controlled by the typical net build approach assumed to be appropriate above the subassembly level.

With the move towards modularisation, the need for a strong integration methodology at the complete body level that considers the total system's cost in terms of time, money, and quality, including the cost to suppliers, becomes evident.

5 Integrated build

Integrated build (IB) is an evolving philosophy that is under development. It expands the functional build concept to the whole body design process. Vehicle launch is no longer considered to be separate from design. In the IB approach one cannot separate planning from implementation or design from manufacturing launch. Rather some design decisions will be postponed until the manufacturing launch phase.

The philosophy of IB is to focus on getting the entire system up and running as quickly as possible, to get a body-in-white (BIW) produced from stable production parts and with production intent tooling as early as possible. Then one looks back at the whole system and identifies the areas that require additional resources and makes the most appropriate decisions to increase vehicle quality and decrease system cost as quickly as possible. The principal criterion in moving through the development process is stability; parts must be produced and processes must operate consistently if meaningful adjustments are to be identified. The benefits of delaying design decisions have been documented in the Toyota design system [15].

Philosophically, IB is a holistic approach to design, manufacture, and validation of a car body. It is characterised by a strong customer focus derived from the functional perspective. Vehicle level tolerances are derived from vehicle level functional requirements to meet customers' expectations. So, if gaps and flush are 'smaller-the-better' characteristics, then vehicle level gap and flush tolerances must also become smaller. In contrast, individual part tolerances are largely irrelevant to the customer. Individual part tolerances should be based on manufacturing and assembly functional requirements. In other words, the next level assembly process sets the individual part's functional requirements. If the process is sensitive to incoming part variation, then the

part tolerances must be set tightly. This is especially true of small, thick/rigid components. If it is relatively insensitive to incoming part variation, then they can be set loosely. Since most auto body sheet metal parts are relatively compliant, i.e. their form can be altered by the assembly system, it is frequently the case that individual part tolerances may be looser than the functional vehicle tolerance requirements. This is in direct conflict with traditional net build philosophies.

Further, since the assembly system is relatively insensitive to incoming part variation, and its impact on the subassembly and final product dimensions is unknown, it is reasonable to postpone determining part specifications/tolerances until a functional evaluation of the entire body has taken place. In other words, the final design of the vehicle should be delayed until a BIW has been constructed using production parts and assembly tooling, and the impact of the current design implementation with all its complexity and ramifications is understood and evaluated. This approach not only reduces cost, but improves quality because die rework and weld tool optimisation are focused on the more important attributes rather than randomly across all attributes that are out-of-specification.

Since functional specifications are set at the body level, IB has a body level perspective. IB is not a method that can be limited to the part and subassembly level, as is commonly done with FB. It encompasses the entire vehicle. With outsourcing of entire modules, module integration strategies and methods will gain in increasing importance. For example, the hanging strategy for doors, as well as the implementation and validation strategy will gain increasingly in importance. In a traditional NB or FB, designers would set the hanging strategy based on the nominal design (which is a reasonable approach), and focus during validation to get the door assembly as close to nominal as possible and optimise the hanging process for a nominal door and a nominal body side. The IB approach is to optimise the hanging process during the validation phase based on actual doors and body sides, meaning both the door and body side may be out-of-specification, but may fit well. If they do not fit well, then the decision alternatives become:

- alter the door assembly (welding or dies)
- alter the body side (framing, body side assembly, or dies)
- alter the hanging process (locators, clamps, hinge attach process)
- some combination of the three, regardless of the specifications.

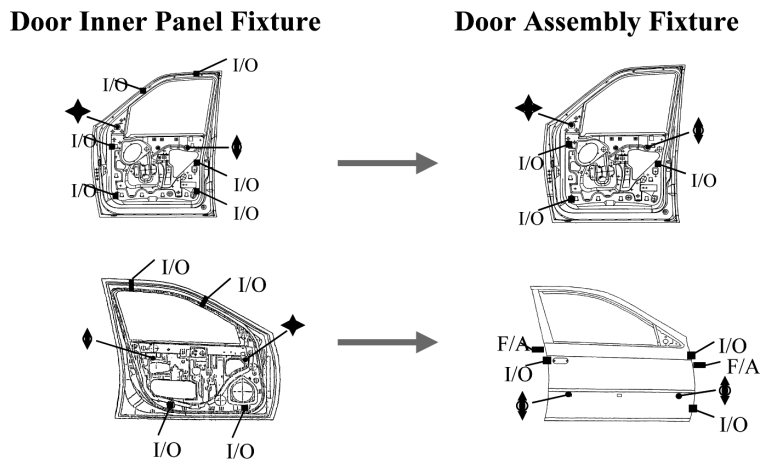
IB encompasses more than die tryout and validation, as is commonly assumed in FB. IB includes all aspects of dimensional engineering including:

- customer and dimensional functional requirements determination
- datum structure determination and datum continuity
- measurement strategy and fixture design (check point locators)
- tooling tryout (à la FB)
- assembly tooling validation
- stamping and assembly control (process control)
- tolerance determination
- part approval.

Many of these areas, such as customer requirements determination, tooling tryout, and process control are well known and understood from NB and FB approaches. That is not to say that the tasks are easily performed or that mistakes are not still made. However, the existence of these steps and their importance to the vehicle launch are well recognised. Other areas, such as part datuming, measurement strategy and fixture design, and tolerance determination although well understood under NB, must be rethought within the IB paradigm.

The question of datum reference frames (DRFs) is directly related to the question of metrology strategy. Using the door example again, there is a fixture that locates the door inner panel during door assembly based on an inner panel datum reference frame (DRF). There is another fixture that holds the door during door hanging according to the door assembly DRF (see Figure 3). Question: should the door assembly measurement fixture, used to measure the door after assembly but prior to hanging, use the door inner panel DRF or the door hanging DRF? The answer depends on the purpose of inspection. If the purpose is process control of the door assembly process, then the measurement fixture should use the inner panel DRF since the assembly process builds up the door using the inner panel and its datums. If, however, the purpose is to determine whether the door will fit into a vehicle correctly, then the door hanging fixture DRF should be used.

Figure 3 Different door assembly datum reference frames: the top is good for door assembly process control: the bottom is good for door hanging prediction



However, even determining the exact datum reference frame (DRF) is performed differently in IB than in NB. Traditionally in a NB environment, datuming is fairly straightforward. One must have sufficient datums to restrict the parts many degrees of freedom (dof). Rigid parts have six dof, and compliant parts can have more. In general, the goal is to constrain the part to the point where repeatable measurements can be taken. Hence, many parts are measured in a close to free form state. Second, the datums are based on mating features. However, one must question in auto assembly what are the mating features? Should one use the weld clamp points as datums? There are usually many more clamp points than are needed to hold the part in its free form state. The exact clamp locations often do not have an appreciable impact on part function from a designer's point of view, but can have a profound impact from an assembly point of

view. Perhaps, certain DRF aspects should be left purposefully ambiguous and finalised only during validation. There is no simple answer to these questions and it is beyond the scope of this paper to make recommendations. However, it should be noted that many dimensional engineering concepts were based on an NB philosophy and will need to be re-examined within an IB philosophy.

Tolerance determination is another area that is not well understood. Typically net build concepts are applied and it is assumed that if an assembly consisting of two parts has a tolerance of ± 1 , then each part should have a tolerance of ± 0.5 (under worst case tolerancing). However, it is known that the assembly system can often produce acceptable assemblies from parts with much greater variation. In other words, since the assembly process is relatively insensitive to incoming part variation, it acts as a variation compensating process. In such cases, variation is not additive! Since, the impact of the assembly process is not typically known a priori, manufacturing tolerances should be set after the sensitivity of the assembly process to incoming part variation has been assessed. Part tolerances should be determined by the assembly process window. Subassembly process tolerances should be based on subassembly hanging/assembly parameters. Final vehicle tolerances on gap and flush should be determined from customer requirements/expectations. In such a situation, it is likely that the part tolerances will be the greatest, as individual parts are relatively flexible and subassembly processes are relatively insensitive to incoming part variation. Rigid subassemblies that must fit with other rigid subassemblies will have the tightest tolerances, as they will behave similarly to net build structures.

The assessment of sensitivity of the assembly process to the incoming part variation typically occurs during validation, as the assessment has to be made with production parts on the production tooling; again, a delay in decision making. This in turn means that upstream decisions, such as die rework during tryout cannot be made using C_p , C_{pk} or other tolerance based process metrics during die tryout. Hence, process statistics, such as mean and range within and between setups are required to make process decisions.

The complexity of the problem requires an integrated approach, which will lead to delayed, more efficient decision making. The decision-making process becomes more iterative across various teams (design, dies, stamping, assembly tooling, validation, etc) and hence, more simultaneous. From the third case study one will see how the goal of creating the body-in-white earlier drives all processes to a relatively quick, albeit incomplete end, so that all groups can see the interactions and effects of their decisions on the product. All groups then make decisions simultaneously as they evaluate the impact of their previous decisions.

5.1 Case 2: strategy enabling

Another western European company used some of the IB concepts to enable a particularly novel new material introduction strategy. There are many new materials being developed and utilised in the automotive body, such as aluminium and high strength steels, to varying degrees of success. One of the major concerns with these new materials is the degree of springback these parts exhibit.

A typical North American approach to introducing these materials would be to learn about the material through limited experimentation. Based on these experiments one would develop adjustments to one's formability code and attempt to predict springback.

Based on the springback prediction it would be possible to compensate for the springback in the various part dies.

There are several problems with this approach. First, it is often difficult and time consuming to update the formability software with the information required to predict springback to the degree required that one could accurately cut the dies to compensate for the springback. Second, new materials are constantly being developed at such a rate that updating the formability software becomes the major bottleneck for material introduction. Since material introduction often cannot wait, the material is applied to component geometries for which it is not well suited, extensive trial and error is necessary to determine the correct degree of compensation required, and the whole process becomes a very time consuming and risky proposition.

By contrast, one western European manufacturer has utilised some of the IB process elements in their new material introduction strategy. They understand that some parts are compliant and others are not (or at least less so). They have a method by which they designate parts as 'slave' and 'master.' The slave parts are relatively flexible and will conform to the master parts, which are relatively rigid. They manufacture the master dies to relatively tight tolerances and the slave dies to very loose tolerances in a very short amount of time. They then use FB procedures to determine the location of assembly problems and what to do about them.

This IB oriented design philosophy supports their new material introduction strategy. They understand the difficulties of attempting to predict the springback in software and so do not attempt it. Instead, they use formability simply to determine stress, potential wrinkles and tear conditions. Then using the IB process, they design, manufacture, and assemble parts to determine where and by how much springback is a problem. They then either compensate in those areas or develop restrike dies to hit only in those areas. They obtain parts that vary dimensionally to within 10% of similar mild steel parts; and they can apply this strategy to almost any material. This process is particularly efficient when they wish to simply manufacture an existing part with a new material. Again, after a simple formability analysis is completed, the empirical determination of the problem areas and their resolution is performed faster and more cost effectively than with extensive computer based analysis.

The company claims that tryout takes longer than for mild steel, but is faster than using trial and error compensatory techniques, which would otherwise be required for these materials. They also claim the strategy is more flexible, enables them to introduce new materials more quickly, and supports their parametric engineering strategy.

5.2 Case 3: project timing implications of FB

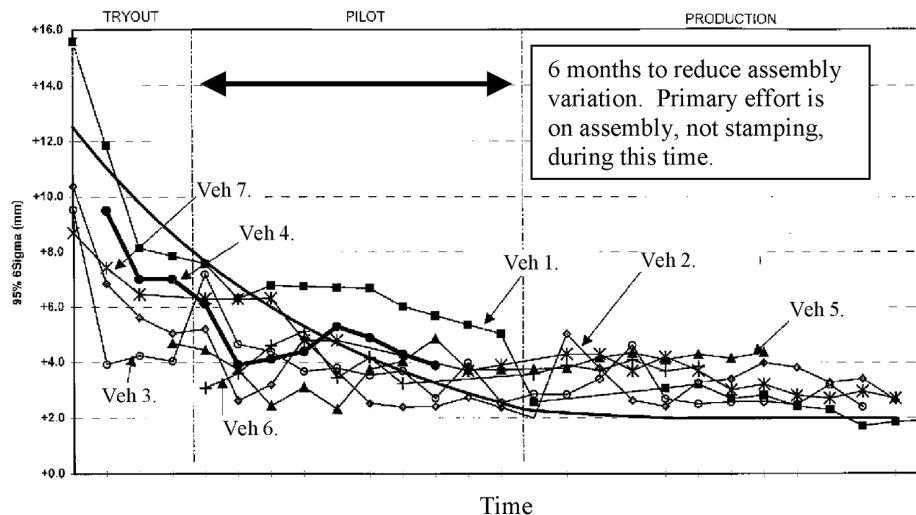
Whether one practices NB (which allows a sequential design, tooling manufacture, and facility launch process) or IB (which requires an integrated approach to design, tooling manufacture, and facility launch) it has a profound impact on project timing. The timing associated with shipping dies to the home production presses and setting up the assembly weld tools at the assembly plant is a reflection of a net build or integrated build strategy. Companies not practicing the IB strategy generally prefer production tools (dies and assembly tools) to arrive at the production location close to the start of production. These facilities (stamping and assembly plants) are often focused on meeting current production requirements, and management prefers not to be imposed upon by trying out new tools for future models. The net build philosophy purports near production-ready tools prior to

their arrival at the plant. This approach, however, as mentioned earlier, often leads to higher tooling costs as the tools are 'optimised' on non-production equipment.

There are two significant sources of variation associated with stamping and assembly. The first is that due to differences in die tryout presses and production presses, precise estimates of stamping part dimensions are often not available until the dies are run on the production press. Efforts are underway in the industry to reduce these differences, such as by controlling and communicating operating conditions including tonnage, lubrication, and other key parameters. However, it has been shown that the correlation between tryout and production dimensions is very poor, and differences in dimensions of 0.5 mm or more are not unusual [13]. Consequently, until tryout and production are better coordinated, the best estimate of production dimensions occurs when the dies are on the production press.

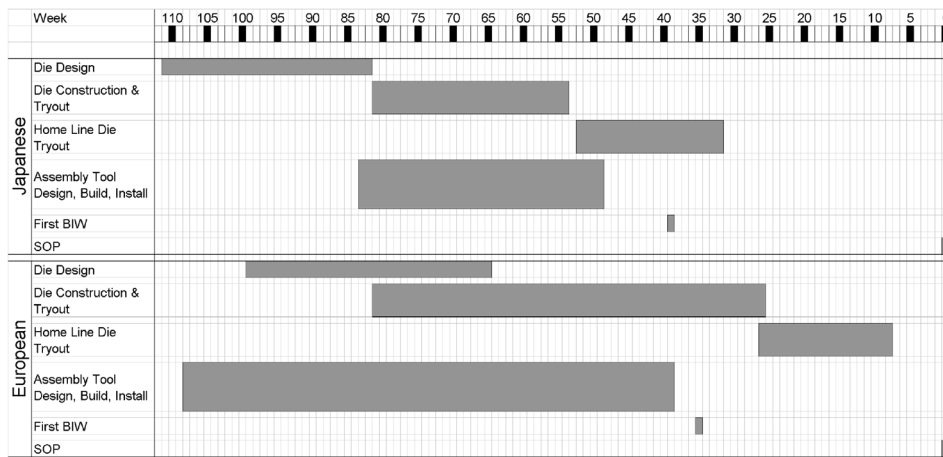
The second key source of variation comes from the assembly process. Obtaining parts meeting specification is not adequate (or even sufficient) to guarantee dimensionally acceptable assemblies. Consequently, both the stamping dies and weld tools need to be evaluated together. But since the dies need to be finalised on the production presses, the weld tools need to be set up during stamping tryout. Once the tools are set up, an optimisation process is required where the variation coming from the welding process is minimised. It has been shown by several internal industry studies that the welding assembly process often follows a decreasing exponential curve in terms of declining process variation. Figure 4 shows a typical general variation curve where the six-sigma quality level requires approximately six months to reach 2mm for the body-in-white. Typical variation reduction initiatives during this phase often entail adjustments to material handling, part clamping, weld spot location, and part datum locators. If achieving stable variation requires six months in complex assembly processes, then this 'tune-in' phase should start six months before production, or high variation will continue into production.

Figure 4 Six-sigma glidepath: the curves show how long it took a particular vehicle program to improve assembly quality levels during launch



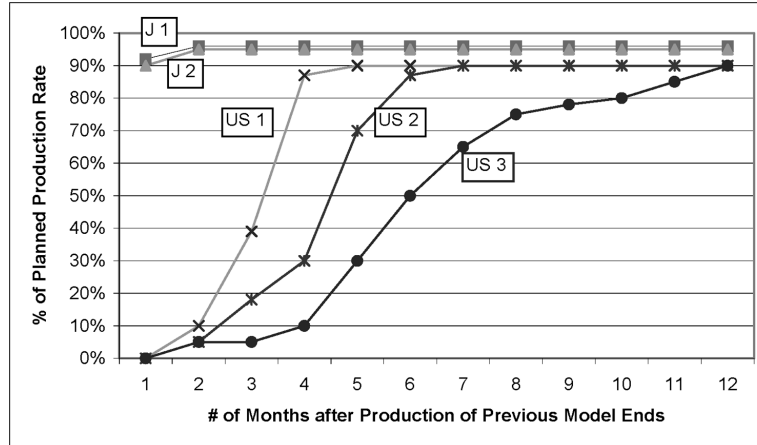
The timing chart in Figure 5 compares the net build and integrated build timing of a European and Japanese company. The charts are from two 2001 model vehicles and represent the planned, as opposed to executed times. The executed times were within two weeks of the planned times. The bottom chart (European company) shows the production dies being tried out on the home line as late as ten weeks before the start of production, leaving little time to simultaneously tune-in assembly weld tools. This company finishes weld tool tryout well before the dies even begin tryout on the home line. A company conducting home line tryout this late in the process expects the dies to require almost no rework, and therefore, imposes very strict conformance requirements during die construction tryout.

Figure 5 BIW timing chart for Japanese and European auto manufacturer



The top chart (Japanese company) shows the tryout of the production dies on the home line being completed at about week 30. This company’s objective up to this point was to make gross weld tool and die corrections (thus at lower cost relative to the net build company). Then at week 30, six months are still available to optimise the weld and stamping line simultaneously to reach the desired quality level prior to SOP.

One of the primary benefits is then seen in the post SOP ramp-up phase. Figure 6 shows the time it takes for IB (J-1 and J-2) and NB companies (US 1, US 2, and US 3) to reach full capacity after SOP. The data were published in *Automotive News* in the early 1990’s and clearly show the benefits of the IB philosophy. The IB philosophy helps a company get through launch and up to full production more quickly and with better quality than a company following the NB approach.

Figure 6 New model production as a percentage of capacity (months after old model stoppage)

6 Conclusions

The emphasis of this paper has been philosophical rather than methodological; it has described the complexity of the vehicle launch problem, the traditional net build, the growing functional build, and emerging integrated build philosophies. Several issues were raised on how an IB philosophy is capable of influencing every aspect of the complex problem of vehicle launch. However, it also requires the re-examination of several issues, such as design tolerances, datuming, metrology strategy, and so on. Some of IB's potential benefits include:

- improved quality, because the entire vehicle body has been optimised with respect to dimensional and residual stress
- lower cost, because engineering efforts are focused on value added activities
- shorter launch time, especially on ramp, because dies reach the production line sooner, allowing joint die and assembly tooling optimisation.

Further, in today's increasingly competitive environment, the IB process may enable the smoother and more cost-efficient introduction of other strategies such as new material introduction, modularity, portfolio level designs, alternative product development processes, and strategies not yet conceived.

IB is just beginning to emerge as a viable methodology. Its applications have not yet been fully realised. It may have occurred to the reader that IB is not a process that is limited to automotive bodies, but may also apply to other applications, such as starter motors, [16,17]. The general concept of integrating, as opposed to segregating planning and implementation, which leads to the concept of delaying decisions until sufficient data is available to understand the impacts of current design are at the core of the IB philosophy.

IB takes a more holistic view of design and manufacturing. It redefines what are currently viewed as problems. Also it is a strategy enabling process, a process that enables the organisation to rethink how it plans on facing the many challenges of the future.

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